SCIENCE SECRETARIAT

Special Study No 2

PHYSICS IN CANADA
Survey and Outlook

Prepared by a Study Group
of the
Canadian Association of Physicists
headed by
D. C. Rose

PHYSICS IN CANADA

SURVEY AND OUTLOOK

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SCIENCE SECRETARIAT
PRIVY COUNCIL OFFICE
OTTAWA

Meta autem scientiarum vera et legitima non alia est quam ut dotetur vita humana novis inventis et copiis.

Sir Francis Bacon, Novum Organum I.81.

Corrigenda

p. vii: Bottom of page, add:

"On y recommande la création de plusieurs instituts dans lesquels les scientifiques des laboratoires des universités, du Gouvernement et de l'industrie pourraient utiliser conjointement les équipements spéciaux, dont l'entretien et l'emploi efficace seraient trop coûteux pour des laboratoires privés".

p. 23, Section 3.2, line 4: change "15" to "12"

p. 24, para. 3, line 7: change "175" to "288"

p. 30, Table I, line 2: change "$UD" to "$US"

p. 34, line 4: change "21%" to "26%"
line 6 and line 9: change "Table I" to "Table II"

p. 49, para. 3, line 5: change "predict" to "determine"

p. 62, Section 11, line 5: change "none was" to "very few were"

p. 76, line 6: change "$145 million" to "$147 million"

PREFACE

The impact of science and technology on the economic and social structures in our twentieth century society makes it essential that Canadian Governments concern themselves with the problems and challenges associated with scientific research. Modern research methods require very substantial levels of public financial support; good research, wisely planned and properly executed, followed by active development is, nevertheless, a wise investment for a progressive society since it leads rather directly to many material and cultural benefits. The problems are how to encourage good research and in what fields, and also what are the sensible levels of support for both pure and applied research relative to the wealth and productivity of the society.

This report was initiated by Dr. F.A. Forward, Director of the Science Secretariat of the Privy Council Office, in a letter to the Canadian Association of Physicists, requesting assistance in carrying out a comprehensive review of physics research in Canada and in assessing future needs. At its annual meeting in June 1966, the Association gave unanimous support to the proposal that its executive enter into contract with the Science Secretariat to carry out this review and assessment. (The Memorandum of Agreement and some relevant early correspondence is reproduced in Appendix C). Dr. D. C. Rose, retiring from his post as Associate Director in the Division of Pure Physics of the National Research Council of Canada, agreed to take overall charge of the project as Chairman of the Steering Committee.

The steering committee defined twelve subdivisions of the field of physics and appointed a chairman to each subdivision. Subdivision chairmen, in consultation with Dr. Rose, chose committee members to help carry out the survey and active work began in September of 1966. May 1, 1967, was set as the target date for completion of the report in order that it could be distributed to members of the Canadian Association of Physicists for study, and for discussion at the annual meeting in June. Faced with an almost impossible schedule, subdivision chairmen and their committees have responded generally with energy and enthusiasm. The steering committee takes this opportunity to express its gratitude to the dedicated members of subdivision committees who gave so generously of their time to the preparation of this report; also to the many members of the physics community across Canada who patiently filled in questionnaires and gave freely of their time and counsel; and to the members of the Science Secretariat for their cooperation and assistance at all times. The committee also wishes particularly to thank Professor R. C. Smith of the University of Ottawa for his painstaking efforts in gathering together the various parts of the report and acting as liaison with the editorial office of the Secretariat.

Basically, the report consists of two parts: the report proper, and the detailed subdivision reports. The subdivision reports are entirely the work of the subdivision committees; the opinions and recommendations expressed therein are entirely those of the committee members – aside from minor editing they have been reproduced intact as they were received by the steering committee. The report proper is the work of the steering committee – the views expressed and the recommendations made are ours and we bear the full responsibility for having made them. While the Canadian Association of Physicists agreed to undertake this work, and commissioned the steering committee through its executive to carry it out, the recommendations of the report do not necessarily represent the views of the membership-at-large. Naturally, we would be disappointed to find our views in any substantial disharmony with the consensus views of our colleagues in the Canadian physics community; otherwise we will have failed to discover the legitimate aspirations of this community. Individual disagreements will and should arise; we hope these will concern detail rather than broad principles, but one can never be sure. In any event, we submit this report with conviction, notwithstanding a substantial feeling of humility.

D. C. Rose, Chairman

J. M. Robson,

R. E. Bell,

A. C. Hollis Hallett

L. E. H. Trainor

Members of the Steering Committee

EPITOME

This report surveys the present state of research in physics in Canada. It finds the present effort heavily concentrated in the pure aspects, and relatively weak in the applied aspects of physics. It finds the support reasonable in the government laboratories, poorer in the universities, and insufficient in the industrial research laboratories.

It recommends that over the next few years, support should emphasize those aspects of Canadian research in physics that can encourage the wise use of our national resources or can benefit from our particular geographic location or scientific history.

It finds that the present overall growth rate is a great improvement over the level in the past and suggests that the normal expenditure on physics research should rise at a rate of 23% per annum.

It recommends that several joint institutes be created where scientists from many laboratories of the universities, the government and industry can jointly make use of outstanding facilities that would be too expensive for individual laboratories to maintain and use effectively.

EPITOME

Ce rapport est une étude de l'état actuel de la recherche en physique au Canada. On y constate que l'effort actuel est lourdement centré sur les aspects purs et faiblement sur les aspects appliqués de la physique; que l'aide financière apportée aux laboratoires gouvernementaux est raisonnable, aux laboratoires universitaires, moins considérable, et, aux laboratoires industriels, insuffisante.

On y recommande que pour les quelques années à venir l'apport financier souligne ces aspects de la recherche canadienne en physique qui peuvent contribuer à l'utilisation de nos ressources nationales ou bénéficier de notre situation géographique particulière ainsi que de notre passé scientifique.

On y trouve que le présent taux d'accroissement est une amélioration considérable sur le passé et l'on y suggère que les dépenses normales pour la recherche en physique augmentent à un taux annuel de 23%.

TABLE OF CONTENTS

APPENDICES

Part I

SURVEY AND OUTLOOK

Chapter 1

THE NATURE OF PHYSICS AND ITS SUBJECT DIVISIONS

The agreement between the Government of Canada and the Canadian Association of Physicists stated that:

"The Canadian Association of Physicists will carry out a comprehensive review of physics research in Canada, in Universities, Government, and Industry. Will assess the significance of research in the various subdivisions of physics and the balance between them, taking into account the problems of financial support, personnel and organization. Will study the future of physics research in Canada and make a considered projection for the next few years with particular reference to the objectives of the programmes."

This report is written to provide the review, the assessment, and the considered projection for the next few years as specified in this contract. It is necessary first to define the field of physics, and second to discuss what constitutes research in this field so that the boundaries and scope of this report may be clearly understood.

Physics has as its major objective the rational explanation of natural phenomena. Some say that a knowledge of physics is a knowledge of the laws of nature. "Nature" means the physical world, the world which the poets, the philosophers, and the scientists view with wonder and have viewed with wonder since the dawn of human intelligence. It includes the elementary particles of matter and the atoms and molecules which are formed from them, and which themselves form the larger organisms, living and inert, which comprise our universe.

Physics, defined in this way, is a vast subject and it is necessary to impose some boundaries for the purposes of this report. In one direction, that of the purest form of physics, it crosses into the philosophy out of which it originally grew. The early Greek philosophers included the nature of the physical world as part of their studies. It was not until the Seventeenth Century, when the development of the experimental approach made quantitative verification of theories a necessary condition for their general acceptance, that humanist and natural philosophy diverged. The divergence was slow, however, and in some parts of the world the branches of universities where physics is taught are still spoken of as faculties of natural philosophy.

In the other direction physics crosses into chemistry, biology, and, in fact, into most of the other branches of science as we know them today. Chemistry, the science of the structure of materials, both natural and artifically produced, depends on the laws of physics which govern the manner in which the atoms interact with each other to form molecules. Biology, though it started as the study of living things, is now intimately concerned with the physical laws which govern the behavior of molecules in cells. Astronomy, though it is often considered as a separate branch of science, is basically concerned with many results of pure physics for its interpretation of the heavens and relies extensively on applied physics for its measurement techniques. Thus it is easy to find links between physics and practically any other branch of science.

In addition to these external boundaries, this study has had to consider the internal boundaries between pure and applied physics and between applied physics and engineering. These boundaries are probably no more indistinct than the boundary between physics and philosophy, but the latter affects only a very few academics, while the former affects most of modern industrial development. In the applied field, physics becomes a precise science; it is as precise as is necessary for the construction of buildings, bridges, nuclear reactors, artifical satellites, automobiles, and everything else that the average man takes for granted. Applied physics had its beginnings in the necessity for accurate measurements and dates a long way back in the growth of natural philosophy. Trade, as soon as it evolved as a part of organized society, made fixed units of measurements necessary, and standards of length, weight, and capacity fixed by royal authority date as far back as Babylonian days, 2,500 years before Christ. Applied physics, is, however, much more than just measurements and standards. It is all that part of physics in which the discoveries and principles of pure physics are related to practical applications; it is the link between pure physics and engineering. It very definitely forms part of this study. In fact one of the principal results of this study is the realization that this area of physics is relatively very underdeveloped in Canada; our main recommendations are oriented toward strengthening the applied physics research effort.

On the other hand the purely engineering aspects of physics are beyond the scope of this report; however, some well-known ones, such as electronics and atomic energy, have been considered very briefly.

"Research" is a word that can be interpreted in many ways. Too narrow an interpretation would make this report of little practical value, too broad an interpretation would make it impossible to prepare. A restrictive interpretation would limit it to work that involves only the extension of knowledge of physical principles or new structures of matter. Though restrictive, such an interpretation would include most academic research in Canada, some of that in government laboratories, and a little in industry. An unrestrictive interpretation would include all of engineering development; using such a definition the present group of committees in the Canadian Assocation of Physicists would not be an appropriate body to undertake this survey. We have attempted to draw the line somewhere between the two definitions.

In dividing physics into various subdivisions we have had recourse to another oft-quoted definition. Physics is that body of knowledge studied by physicists. This is a useful definition in the context of this report because the range of knowledge and scientific investigation covered here has been delineated by a body of physicists, the Canadian Association of Physicists. The members of this association have a sense of fundamental unity that arises, not from the particular work that the individual members do, but from a common reliance on a basic core of knowledge and a common *modus operandi* in approaching specific problems. Always there is final appeal to the result of an experiment or to a physical measurement.

The subject divisions of mechanics, properties of matter, heat, optics, sound, electricity, and magnetism that served to specify more exactly the boundaries of physics in the last century are not satisfactory divisions for a catalog of present-day research efforts. However, those divisions, together with additions such as quantum mechanics, statistical mechanics, atomic and molecular physics, nuclear physics, and elementary particle physics, do form the central core of knowledge on which present-day research is based. Many research problems can be readily classified into divisions bearing these names, but there is a significant number that integrate parts of several of these divisions and cannot be classified comfortably into any one. Some division of the research into fields is clearly necessary in order to produce an effective and useful catalog of current research activities. Even if the division is arbitrary, such a useful catalog can be produced because once the divisions are stated, physics, as judged by physicists, is effectively defined, and one can determine quickly whether or not a certain scientific problem or area is included in this report.

There are further factors which can contribute an additional unity within smaller groups of physicists, and which suggest that an appropriate separate division be used. Some groups are distinct because the individuals are working on various aspects of a central problem and are in a field that is generally recognized as being, in some sense, an entity. Others do work centered about a central facility, or use a particular branch of theory to interpret their experimental results. Others again use a common tool. Considerations such as these have led to the following list of divisions; the Steering Committee does not pretend that this list represents an ideal or perfect ordering of the subject matter of current physics research in Canada, but it has been useful. A brief description of the type of work covered in each division follows.

1. Astronomy

This division includes astrophysics, and is concerned with the study of the stars and the planets using both optical and radio telescopes. It is concerned primarily with the investigations that lead to our knowledge of the distribution of stars in space, the formation of galaxies, and the life cycle of stars and their internal composition. Astronomical observations play a central role in cosmology, which is the study of the nature of the universe and the earth's part in it, and make possible tests of the fundamental physical laws embodied in the general theory of relativity. From a practical point of view, astronomical studies are very important because they underlie the determination of time and the calendar and our ability to navigate and to carry out surveys.

Astronomy is often considered as a scientific discipline in itself; it is one of the oldest because man has always been fascinated by the heavens, but logically it is hard to separate astronomy from the rest of physics. Astronomy has therefore been included as one of the divisions of the subject matter in this report.

Cosmic rays or energetic particles that come from outer space form an important part of cosmology and are consequently related to astronomy. They could therefore be treated as part of this subject division; they could equally well, however, be considered under elementary particle physics, or upper atmosphere and space physics, and in this report we have somewhat arbitrarily considered them in the latter subdivision.

2. Upper Atmosphere and Space Physics

Research in upper atmospheric and space physics does not represent a single discipline that can be distinguished clearly from others. Rather it represents the application of several disciplines developed in the laboratory to a new set of phenomena which occur in a new and challenging environment. In particular, there are problems of atomic and molecular physics, plasma physics, particle physics, electromagnetic theory and fluid dynamics that require solution in order to further an understanding of the outer reaches of the earth's atmosphere.

For purposes of this study, attention is concentrated on the phenomena that occur at distances of more than 50 kilometers from the surface of the earth but at distances smaller than those of interest to the astronomer. No clear-cut division of interest can be made between the space physicist and the meteorologist on the one hand and between the space physicist and the astronomer on the other. Indeed the photochemistry of the atmosphere is continuous across the 50 kilometer level, and there is an enormous transport of energy by radiation and by collisional processes in both directions across this level. At the other extreme the physics of the sun and solar-terrestrial interactions are of interest both in space physics and in astronomy.

Cosmic rays, which were mentioned briefly in the section on astronomy, are composed of charged particles, which therefore interact with the earth's magnetic field. Their energies cover a wide band and can be much higher than those that have been created in the laboratory. In striking the upper atmosphere they cause nuclear interactions, and these result in the formation of unstable elementary particles (many of which were first discovered in cosmic rays). Their study is included with upper atmosphere and space physics because of their ionizing effect on the upper atmosphere, and because the techniques used in their measurement are often associated with other measurements in space.

The methods of investigation used in upper atmospheric studies studies include direct measurements using rockets and satellites, and indirect measurements using balloons and ground-level optical or radio observations. Also included are those experiments performed in the laboratory that are directly related to upper atmospheric phenomena.

3. Classical Physics

The primary distinguishing factor of this division is that it does not make significant use of the ideas or concepts that arise from quantum physics or relativity. It is therefore concerned chiefly with a study of the bulk properties of matter, but excludes geophysics and oceanography (covered by division 4, earth physics) and also meteorology (division 5) in which there is enough activity to warrant separate divisions. As a result, this division includes such fields as metrology (the development and maintenance of fundamental standards such as those of mass, length, time, and temperature), acoustics, fluid dynamics (including aerodynamics), optics (including the design and performance of optical instruments), and electromagnetics (the study of radiation patterns from various types of antennae, and related problems).

4. Earth Physics

Earth physics encompasses the study of the physical processes occurring within the earth, and the study of the earth itself by physical means. These fields are normally considered to include the scientific study of the interactions of the earth with its immediate surroundings. Thus earth physics can include meteorology, physics of the upper atmosphere, and the effect at the earth's surface of such distant phenomena as solar disturbances. In order to make the present study manageable, meteorology and upper atmosphere and space physics are being treated as separate disciplines, and therefore our interests here terminate at the earth's surface. Because most of this surface is water-covered, physical oceanography and the physical limnology of large lakes are included as part of earth physics.

The techniques of earth physics are those of physics, mathematics, and chemistry, and the field is therefore closely dependent on those subjects. Its researches interact strongly with those of other disciplines. The interpretation of geophysical processes may contribute significantly to geological understanding as, for example, in mining and oil exploration.

5. Meteorology

Meteorology or meteorological physics is the physics of the lower atmosphere. A meaningful definition of where the lower atmosphere stops and the upper atmosphere starts is difficult to establish. A few years ago it was thought that the movements in the atmosphere that influence the weather did not extend above about 5 miles from the earth's surface, and that above that height the atmosphere was at a constant temperature and quite static. The ionosphere was known to be an ionized layer that was thought to start at about 60 miles and extend up to 300 miles or higher. The ionosphere is definitely part of the upper atmosphere, but it is now well known that turbulence due to disturbance at weather levels extends upwards to about 70 miles, and that ionization of the atmosphere sufficient to have a measurable scattering effect on radio waves, may extend down to about 30 miles. Meteorologists and ionosphere physicists now realize that the regions of their activity overlap.

The Science Secretariat's study on upper atmosphere and space physics (The Chapman Report) arbitrarily set a lower limit for their consideration at 50 kilometers (31 miles). We therefore also adopt 31 miles as the upper level for the purpose of this report.

6. Atomic and Molecular Physics

Atomic and molecular physics is concerned with the understanding of the nature of atoms and molecules *per se*, and with the observation and understanding of processes involving a very small number (one, two, or three) of atoms or molecules. The atoms or molecules may or may not be charged. It is the emphasis on the small number of particles that distinguishes atomic and molecular physics from solid state physics, from statistical mechanics and thermodynamics, and from plasma physics. However, since all the branches of physics that deal with many particles involve in some degree the properties of the individual particles, atomic and molecular physics has very nebulous boundaries with many branches of physics, chemistry, and astronomy.

This division is concerned with such topics as spectroscopy (in various energy ranges corresponding to microwave and to infrared, visible, and ultraviolet light), molecular and atomic beams, electron impact, paramagnetic resonance, and lasers. A substantial fraction of the work reported is being carried out in chemistry departments.

7. Nuclear Physics

Nuclear physics is concerned with the structure and behavior of atomic nuclei, in their normal and excited configurations, and with their strong electromagnetic, and weak interactions with other nuclei, photons, nucleons, and subnuclear particles such as mu-mesons. Phenomena associated with the interaction of single nucleons with photons and the subnuclear particles are considered in the report on elementary particle physics. Nuclear physics studied with accelerators in the 100 MeV to 1 GeV energy range has recently been called intermediate energy physics and has been treated separately from nuclear physics in some surveys. In this report those parts of intermediate energy physics that fit into the definition given above will be considered as nuclear physics.

Nuclear physics can be conveniently divided into two areas of endeavor: pure nuclear physics and applied nuclear physics.

Pure nuclear physics is concerned primarily with the attempt to understand the nature of the nuclear forces, nuclear reactions and the structure of nuclei, as well as the weak force involved in the nuclear beta decay process. Besides generating discoveries that have important practical applications, such as induced radioactivity and fission, pure nuclear physics has an intrinsic intellectual value. This report will be concerned mainly with this area of nuclear physics.

Applied nuclear physics is concerned primarily with the attempt to find practical applications of nuclear phenomena such as fission, spallation, and radioactivity. A good example is provided by the development of nuclear power reactors competitive with fossil fuel power stations.

8. Elementary Particle Physics

By elementary particle physics we mean the study of the so-called elementary particles (nucleons, baryons, mesons, and leptons) and their interactions; amongst those physicists active in the field the briefer, and perhaps more accurate phrase, "particle physics" is frequently used instead. The term "high energy physics" is an approximate synonym for elementary particle physics, because it usually requires high energy collisions to produce these particles.

It is one of the great historic aims of physics to understand the properties of macroscopic matter in terms of the properties of its ultimate constituents. In the last hundred years or so the "ultimate" constituents have changed from atoms, to nuclei and electrons, and now to "elementary particles". For the atomic physicist the atom is usually viewed as a nucleus surrounded by electrons, and for the nuclear physicist the nucleus is a manybody system of neutrons and protons. The elementary particle physicist seeks to understand the structure of the nucleons themselves (i. e. the neutrons and protons). In the collisions of nucleons that have been accelerated to high energies by large accelerating machines, a whole host of new particles with fascinating properties has been produced. It is a general belief among physicists that the study of these new particles through their mutual interactions is important for an understanding not only of the nuclear forces, but of the ultimate structure of matter and, indeed, of space and time as well.

Most experiments in particle physics are carried out at energies greater than 1 GeV, although there is some overlap with intermediate energy physics between 100 MeV and 1 GeV and nuclear physics below

100 MeV. We have adopted this definition for purposes of this report. Thus ING and TRIUMF, both intermediate energy facilities, have some interest for the elementary particle physicist, but are mainly within the scope of the nuclear physics divisional committee. Some discussion of the particle aspects of cosmic radiation is included in this division report since many of the elementary particles were first discovered in cosmic radiation. The main discussion of cosmic rays is, however, included in the report on upper atmosphere and space physics.

9. Solid State Physics

The subjects included in this division have an essential unity that arises because, in the solid state, the atoms which constitute matter are sufficiently close together for each atom to interact strongly with its neighbors. This interaction is the essential determining factor of the properties of solids, but can only be adequately described in detail for the particular case of a solid that has its atoms regularly arranged in a crystalline lattice. Thus, discussion of almost any property of a solid is based upon a common body of theory, which itself is being developed further and extended. The list of subjects included in this division is very large and deals with all types of solids: high polymers, glasses and ceramics, minerals, metals, semiconductors, and insulators, and includes almost all physical properties that can be measured: electrical, magnetic, thermal, mechanical, and optical. This division also includes studies of melting and other phase transitions, and of the molecular picture of simple liquids.

10. Plasma Physics

A plasma can be defined as a collection of free particles charged and neutral, with roughly equal numbers of positively and negatively charged particles so that the uncompensated space charge is small. The charged particles are usually ions of well-known atoms or molecules, or simply electrons. A plasma is the natural state of matter where the density is very low or the temperature very high. As such, the study of plasmas is closely related to atomic and molecular physics, but in treating the aggregate mass the plasma physicist considers the statistical distribution of the particles, and the matter is often considered as a continuum to which the laws of classical physics apply. In the process of maintaining the ionization of the particles and the emission or absorption of radiation, the laws of atomic and molecular physics, of course, are valid.

Until recently the people most interested in plasmas were the astrophysicists. This is not surprising since more than 99.9% of the matter in the universe is in the plasma state. Recent developments giving a strong impetus to plasma research were, first, the possibility of generating energy by the fusion of nuclei of the light elements and second, the possibility of propelling vehicles at high velocities into outer space. The current motivations for plasma research are:

(i) space exploration
(ii) thermonuclear fusion
(iii) electrical generation and propulsion techniques
(iv) defence associated with re-entry phenomena
(v) plasma devices
(vi) knowledge of the structure of matter.

11. Theoretical Physics

Theoretical physics is not just another field of physics; rather it is a division of activity in physics, as opposed to the experimental activity. An understanding of physical phenomena involves the construction of conceptual models and the testing of these models by experimentation. In practice, a certain interplay develops with new experimentation suggesting new models and vice versa. The complexity of modern physics has given rise to a useful division of activity between theorists who construct new models and experimentalists who put these models to the test. Since his physical models (or theories, as they are called) must be quantitative as well as qualitative, the theoretical physicist employs advanced mathematics as his language of expression. This tends to develop a common bond between theoretical physicists working in different fields and to give rise to common problems among them. For this reason, theoretical physics has been treated as a separate division, even though the activities of its members have already been included in large part under the various other subject divisions.

Within theoretical physics itself there is a natural division into two groups: those who use almost entirely the concepts of quantum physics (the so-called modern physics), and those who do not. Only the former is included in the discussions in this particular division of theoretical physics; the latter group is less well-defined in terms of common interest and background, and has not been separated out for separate discussion.

12. Biophysics

Biophysics is the study of biological or medical problems using the methods and concepts of physics. This definition implies that the biophysicist may be either a scientist engaged in making quantitative measurements on biological phenomena with a view to explaining them in physical and mathematical terms, or a scientist engaged in instrument development using physical principles, or even an engineer concerned with the application of biophysical knowledge to practical medical problems. A good deal of research in biology and medicine makes routine used of instruments that have been developed by engineers and biophysicists. This research, while valuable, does not fall within our definition of biophysics unless the investigator is primarily concerned with explaining basic mechanisms of the biological system in terms of physical principles.

Biophysics itself can be divided usefully into four main areas: (1) physiological biophysics, or the use of biophysical techniques to study basic physiological problems; (2) molecular biophysics, or the use of methods and concepts of physics to investigate cells and large molecules; (3) engineering biophysics, which involves the use of engineering concepts and methods in the study of living systems and the solution of medical problems; and (4) radiation biophysics, the use of electromagnetic radiation to perturb and study living systems.

We have also surveyed the work being done in radiological and health physics across Canada, although these fields perhaps cannot strictly be classed as biophysics.

Chapter 2

THE ROLE OF PHYSICS IN SOCIETY

A possible place to start describing the effect of physics on society would be with the invention in prehistoric times of the lever and the wheel. These simple forms of applied physics are so old and so common that it is hard to imagine any form of organized society without them. Or one might start with the Babylonian or Arabian studies of astronomy at the beginning of available historical records. These early studies were mainly concerned with the fascinating motions of the planets and stars, and with the constitution of matter considered on a basis of superstition and tradition. The Greek philosophers can be credited, so far as were know, with the beginnings of philosophical thought as applied to systematic observations on nature. The amazingly long interval between the Greek period of Aristotle and the awakening of new scientific thought represented by Copernicus, Galileo, and Kepler poses a fascinating challenge to the historians of human intellectual development. The advancement of the knowledge of nature and natural phenomena appeared to stagnate for over a thousand years.[1] It would be interesting to speculate on the state of current society if the advance in thought made by the Greek philosophers had continued uninterrupted to the renaissance.

The object of this chapter, however, is to try to present a picture of the influence of physics on modern society. It is difficult to do so without some history, just as it is impossible to conceive fully the effect of a modern, so-called "breakthrough" without some knowledge of the scientific background that led up to it. Rather than enumerate the great advances, such as that made by Copernicus in the understanding of the motions of the planets, or by Galileo in the concept of inertia, let us start with the background of a familiar piece of domestic equipment, the television picture tube.

For the history of this device we need go back only about two thirds of a century. J. J. Thomson discovered the electron, one of the

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[1] Whetham states in his book *A History of Science*, "Plato was a great philosopher but in the history of experimental science he must be counted a disaster."

stable elementary particles of matter, in 1897. He discovered it in studying cathode rays, or the rays formed in an electrical discharge through a rarefied gas. These rays are streams of electrons which can be deflected in electric or magnetic fields. Thomson's interest in these electrons was purely scientific; the well-know cathode ray tube, based on such beams of electrons, was not used as a laboratory measuring instrument until the 1930's, and its use became extensive only with the advent of World War II. Its application to the television picture tube itself was established before World War II, but entered our daily lives only within the last 15 years.

The development of the picture tube makes use of many applications of physics that originally were studied to get basic knowledge of physical principles. The emission of electrons from a heated filament, which is the source of the electron beam in the picture tube, was made practical only after studies in thermionics led to knowledge of the binding of electrons in atoms and in matter in its solid state. The focussing of the spot on the picture tube and the control of its motion are possible only because of early studies on the way electromagnetic lenses can control a beam of electrons. The earliest study of this action was made when J. J. Thomson used electric and magnetic deflection of a beam of electrons to prove that it was composed of individual particles. Other applications involving the same principles are the electron microscope and the focussed X-ray tube, both of which are now standard technical instruments.

There are many devices in the modern household that only a few years ago were parts of laboratory experiments designed to gain an understanding of the physical nature of matter or energy. The basic research was not carried out with the current application in mind, but rather to advance the frontiers of knowledge. Modern domestic refrigerators for example, are applications of a thermodynamic cycle that can move energy in the form of heat from one substance to a second at higher temperature. The thermodynamic cycle was understood a long time before other branches of technology made possible the compact machines now in use.

The development of nuclear energy is another example of an important application of physics that grew from basic studies of natural phenomena. Rutherford and the Curies, and their colleagues, studied radioactivity for its own sake, and Rutherford was eventually led to the idea of the nucleus of the atom. In addition to radioactivity, the study of isotopes and the precise measurement of relative nuclear masses formed an important part of the beginnings of nuclear physics.

The realization of the close relationship between mass and energy came with relativity; the possible conversion of mass into energy made it clear that enormous amounts of energy were stored in atomic nuclei. Rutherford knew this in the early days, but had little hope of ever putting it to use. It was only when the existence of the neutron was shown (1932) and when the fission process in heavy nuclei was discovered (1938) that the possible accessibility of nuclear energy became apparent. The subsequent development of nuclear energy for both military and peaceful purposes has had a profound effect on society.

The subjects in the last few paragraphs have been selected more or less at random from those familiar to everyone. The list could easily be multiplied. Communication by telephone, radio, and satellite is having social effects that are still not understood. The development of solid state physics and the invention of the transistor are recent applications of physics that grew out of scientific curiosity about the materials we see in everyday life. The study of meteorology and of aerodynamics has made modern air transport possible. We live in a world shaped by the application of discoveries in physical science.

In following the flow of a new scientific discovery from its first conception to industrial application and public use, a logical sequence of events may be traced. There will be an appreciable variation from case to case, but Table I shows one possible way in which the sequence may occur. The ten phases shown cover the range from basic research to actual use of a product like, say, a transistor or a radar, to take two extremes in size. The effort and manpower involved in each of the ten phases is not at all uniform, and will vary a great deal with the product.

On the right the sequence is divided into four overlapping parts that may be used to represent the different organizational needs of the ten phases. Part A covers pure research, which is mainly found in universities or in some branches of government laboratories, and less often in industry. This is the type of research in which a reasonable proportion of the scientific staff must be leaders in some specialized field and free from day-to-day problems of administration or management. They are not "mission-oriented" (if that popular term may be used), and are free to follow up interesting sidelines that look promising for the advancement of basic scientific knowledge.

It takes a large industry to support adequately even a small group of such scientists with the laboratory space, equipment, and technical support they need. The reason for this is clear; statistics show that the average cost of such independent scientists is more

Table I. – TECHNICAL PROGRESS CHART RESEARCH, THROUGH DEVELOPMENT TO USE

Phase	Description	Part and description
1	Scientific principle, invention or discovery of a new phenomenon	A Pure research withouth industrial motive (phases 1–3)
2	Preliminary measurement and analysis	
3	Basic research necessary to get an understanding of the phenomenon	B Applied research where scientific staff trained in A are required (phases 3–5)
4	Construction of first workable model with application in mind	
5	Development of prototype for demonstration	C Development by engineers with production in mind (phases 5–8)
6	Demonstration and evaluation to assess value for production	
7	Engineering design of production models	
8	Tooling and manufacture	D Manufacture, marketing and use (phases 8–10)
9	Inspection, quality control, and testing	
10	Marketing and acceptance by the public buyer	

Phases 4–6: This is the area where close attention by policy management first appears

Phases 10 → 4: Improvements and modifications than $40,000 per year per man, and they can be effective only when there are several such specialists closely coordinated.

Part B of Table I, applied research, bridges the gap between pure research and engineering design, often spoken of as development. In applied research, scientists with advanced training are essential, and many of them have considerable training in the kinds of activity that take place in part A. The major portion of the National Research Council's engineering and applied research divisions falls into this category. Further, there are rapidly growing groups in engineering faculties in universities carrying out work that would be included in this part. It differs little from part A in the complexity of the problems encountered, but is more mission-oriented and more likely in the short term to make important advances in technology. Industrial research laboratories are mainly in this category, and there is a growing amount of development work in Canadian industry. Generally it is necessary in an industrial research laboratory to have some pure research activity (part A in Table I) in order to keep the whole research team active and up-to-date.

The overlap between part B and part C is one of the most important features of this table. Part C is the engineering department, and here we refer to industries that may develop new products or techniques but make no attempts at real research. The overlapping phases 5 and 6 really represent engineering development. The lack of development activity in Canadian industry a few years ago was spoken of as the "development gap". There is no doubt that it was a serious gap and probably still is.

In the United States, much more than in Canada, trained scientists and engineers tend to work toward management positions and to be acceptable is them. Further, since World War II, a number of corporations that were started by groups of scientists have grown to appreciable size. This type of activity does not seem to have gone very far in Canada, except perhaps in very applied consulting engineering and in some applications of geophysics to prospecting or analysis of prospecting data.

Part D of Table I need not be discussed in detail here. It is the manufacturing, marketing, and sales part of putting science and technology into everyday use. Trained engineers are often used in manufacturing and marketing, but rarely research scientists. Part D represents by far the greatest use of manpower. It is where the cost and profits largely occur, but it is not the part of the social-industrial complex with which this report is concerned.

Attention is drawn to the bracketed group on the left of Table I enclosing phases 4 to 6. This is the first area where management policy must give attention to the possible contribution of new scientific and technological applications to industrial development. In the earlier phases 1, 2, and 3, basic research cannot be managed in the ordinary sense of direct control of day-to-day efforts of those concerned. Referring again to Table I, the arrow connecting phase 10 back to phase 4 is the line where modifications to existing products and more modern or more economical techniques get back into the R & D system.

Most industries, even those that have research and development branches, start at about phase 4, although some effort in phases 1, 2, and 3 is desirable. It was mentioned earlier that it takes a large industry with far-seeing management to support scientists in phases 1 to 3 without government subsidization. Nevertheless, a country that neglects these three phases cannot survive very long as an industrial society. Industries with good stable lines where competition is high may even see some difficulty in putting much effort into phases 4 to 6 of Table I. As a result, the responsibility for part A and an appreciable portion of part B (bearing in mind that the boundaries cannot be sharply drawn) has fallen largely on the universities and on government laboratories.

The remarks in this chapter apply to other branches of science as well as to physics. One of the tasks facing the Science Council in Canada is to advise the government on what might be the correct balance in the four parts, A, B, C, and D in Table I, or the balance between pure research, applied research, engineering development, and industrial growth in the country. Actually a correct balance has never been found as the growth of applied science in the postwar era has been too rapid to fix a norm.

Finally, we cannot close a section on physics and society without referring to the cultural and humanistic value of physics. The old name for physics was natural philosophy, and to many educated people the main attraction of the subject lies in its philosophical and aesthetic values. For these people, the arguments for supporting research are similar to those for supporting art galleries and symphony orchestras; indeed, usually it is exactly the same individuals who are working to support both the arts and the sciences.

Chapter 3

PATTERNS IN CANADIAN PHYSICS

Canadian research in physics has grown to its present state under the effect of three subtle but very powerful influences, the tendency to award support to individuals in universities rather than to their programs, the tendency in the past of the government to emphasize its own research operations rather than those of the universities and industry, and the tendency toward foreign ownership of Canadian industry. There are signs of change in the first two of these influences, especially the second, but they have to a large extent fashioned Canadian research in physics into the patterns in which we find it at present.

In this chapter we try to outline the present state of Canadian physics and to describe the influences under which it was produced. We start this by considering in the first section of this chapter the question of the size of research groups. We see that there are all sizes in Canada and in sections 3.2, 3.3, and 3.4 we consider their overall effect in the universities, in government, and in industry. We then try to describe in 3.5 and 3.6 the support mechanisms which forged this research in universities and in industry; we try to describe them factually with a minimum of recommendations at this stage, but inevitably some have crept in.

Finally, in section 3.7 we look to the future and ask ourselves how we would like to change things – what should our objectives be? We summarize our ideas for future support and end the chapter with an epitome of our philosophy for the support of physics research in the next few years. In Chapter 4, we amplify these suggestions into more formal and concrete recommendations.

3.1 THE QUESTION OF SIZE

It will be seen from the list of subject divisions that a great variety of research in physics is being carried out in Canada. Practically all branches of modern physics are being touched to some extent. The growth could hardly be said to have been planned, but rather advantage has been taken of opportunities. Except perhaps for the development of nuclear physics and radar in Canada during the war, the growth has come from the enthusiasm of individuals, most of whom can be identified. In many cases they have left a heritage of a research school in some particular field. Without the enthusiasm and drive of individuals such growth could not occur even if we had a national plan for the development of research. Such explicit national plans or objectives are mostly absent in the Canadian pattern. Though both provincial and federal governments have been reasonably generous, their objective has been largely that of fostering a general upswing in industrial technology with little or no planning.

The small-scale approach to an objective in any field of research, the one that has been traditional in Canada, is for one individual, usually in a university, to specialize in one branch of physics. He gathers one or two students around him and contributes to the world of science by publishing papers in academic journals. The good men can still make a tremendous contribution in this way but it is becoming increasingly evident that even they have less and less chance of contributing effectively as technology advances, except through the students whom they inspire. Such people must however continue to be encouraged, and their research must be supported, because every university must have accomplished professors in the main branches of physics. Not every university, on the other hand, can support large, highly specialized research institutes in many subjects. The proliferation of small universities that has taken place recently in Canada raises problems for the advancement of the nation's science. There is, of course, an upper size of diminishing returns in any scientific department. There is no need here for a discussion of this larger end of the size scale, because we are not likely to reach it for many years in Canada. Some organizations in the United States are showing signs of reaching that size now, though when they do they usually break up into separate highly specialized groups.

In Canada we have all sizes of research groups from the small ones mentioned above with one professor and one or two students to large organizations like NRC and AECL. Our problem in Canada is to maintain most of our groups at a size sufficient for an effective contribution. This minimal size is difficult to define in general terms, since it depends on the availability of first-class men, on interactions with other teams in related specialities, and on the availability of facilities such as machine shops, engineering assistance, and computers.

One way to outline the situation is by the example of a small research team in a branch of physics not requiring huge machines. A team consisting of one leader of senior professorial rank, one post-doctorate assistant, about two graduate students, and one or two technicians would be recognized as sufficient for effective work, provided it was equipped with reasonable apparatus and ancillary services. Such a team in isolation, that is in a physics department where it was the only research group of its kind, would in general be considered minimal to achieve results justifying the cost. If it were in an establishment with three or four other teams of similar size in related subjects, this team would be considered optimum for work in its particular speciality. Expand this picture to a few additional groups not related closely to these in objective, but each consisting of two or three teams of similar size, and we have an effective research institute. In the whole field of physics in Canada there are only a few such establishments; a few others are struggling to reach minimal size. We are, on the other hand, supporting many small teams, working in comparative isolation at small universities and well below the minimal size. No doubt this situation will continue.

This broad spectrum of sizes of research groups is not only typical of Canada but occurs in most other western nations. In all such groups the presence of one first-class man can have a profound effect and can make the question of size relatively unimportant. In any case first-class men tend to attract others around them and thereby form larger and more permanent groups.

We now look in more detail at the present state of physics research in Canada considering the universities, government laboratories, and industry in that order.

3.2 PHYSICS RESEARCH IN CANADIAN UNIVERSITIES

Standard handbooks list something over 40 universities in good standing in Canada. Of these, about 20 can trace their origins to pre-confederation times; a few originated in the early years of this century; and about 15 have grown up since World War II, at least nine of them since 1960. The Sheffield Report[1] shows clearly the rates of growth in the full-time enrollment in Canadian universities and colleges from

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[1] "Enrolment in Canadian Universities and Colleges to 1976-77," Association of Universities and Colleges of Canada, Ottawa, 1966.

the year 1951-52 to 1965-66, and the projected rates of growth to 1976-77. It is clear from this report that the rate of growth is not uniform, and at present (1966-67) Canadian universities and colleges are experiencing the largest rate of growth (14% per year) that has so far occurred; further, reasonable projections of the data indicate that this present rate of growth will continue for a few years before slackening. It is interesting to note that in the year 1965-66, 10.1% of the population in the age range 18 to 24 years were enrolled in Canadian universities and colleges; the corresponding figure for the US is nearly twice as large, 19.4%.

The growth of full-time student enrollment in the period between the academic years 1960-61 and 1965-66 represents an average growth rate in this period of nearly 13% per annum. Furthermore, the students included in these statistics are both undergraduate and graduate, and it is the graduate student enrollment that is of particular significance here because the graduate students in physics have produced, in the course of their training, the largest fraction of the university research surveyed in this report. The graduate student enrollment increased in this period by a factor of 2.6 from 6,500 to 17,200, corresponding to an average rate of growth of 22% per annum. The Sheffield Report does not attempt to project these figures, largely because Canadian universities did not have a common standard definition of a "full-time graduate student" with the result that these figures may not reflect accurately the magnitude of the activity that, say, a physicist would understand as graduate activity, and also because the main factors controlling a projection are unknown.

The staff lists of physics departments published in the Commonwealth Universities' Handbook or in the Directory of Physics Faculties in the US, Canada, and Mexico (published annually by the American Institute of Physics, New York), indicate that in the same period the number of physicists on the full-time teaching staffs of Canadian universities increased at the rate of 15% per annum. The number of NRC operating grants in physics has increased by 175 from 77 in 1960-61 to 365 in 1966-67, i.e. at an average rate of 26% per annum. This increasing desire of new staff members to carry out research is essential if the increasing student demand for graduate training in physics is to be met.

Individual universities are almost as varied in their range of offerings and administrative arrangements as it is possible for them to be. Yet in all this variety, the requirements of a single discipline such as physics set a standard of performance and a pattern of operation that is accepted as a norm by the physics departments of the majority of universities. The pattern of "honors" undergraduate programs is quite distinctively Canadian; the student enrolls in one of these on completion of his high school career with intent to specialize in a stated field, and the program is devised to give instruction of the specialized nature necessary to prepare him for a future graduate program in some field of the subject of specialization. The student graduating from this program with adequate standing may enter a graduate program for the Master's degree and begin immediately to learn to do research. Smaller universities, where the staffs in physics number less than about 5 or 6, have difficulties in providing honors programs of this type, but provision is generally made at the larger universities for graduates of the smaller universities to spend a year of study in preparation for entry to a graduate program.

Basically, the undergraduate is expected to be well grounded in basic physics and to have a detailed knowledge of the basic core subjects. On entry into graduate school he begins to learn research, spending roughly half his time on a research project and half on advanced courses of particular relevance to his chosen field of research. The research problem is generally devised by the university staff member who acts as the supervisor of the research, and is usually a facet of the general research program for which the supervisor has support from a grant.

The steering committee has conducted a survey of the physics departments of 25 Canadian universities, representative of the different sizes and ranges of activity to be found, in order to obtain some idea of time spent by the professorial staff on various functions. The results of the survey show that the typical physics professor in Canada devotes 10 to 12 hours per week on undergraduate affairs – preparing and delivering lectures, supervising laboratory and problem classes, counselling and advising students, and sitting on university committees that administer undergraduate affairs. There will be no universal agreement as to the length of the normal work week of the typical Canadian university physicist, but it is clear that he spends no more than one-quarter of his time on those specifically educational functions associated with a university. The remainder of his time is spent on research and graduate student training. According to our survey the typical Canadian professor of physics has 2.5 graduate students working under his direction and they contribute appreciably to his research output. Technical assistance has not, however, been adequately supplied in the past by universities or research grants, and in view of the advanced technology that is part of experimental physics this lack is becoming serious. An increase of 50% in the amount spent on the salaries of the non-academic staff of university physics departments would probably do more to increase the output of research from the university physicists than would the same expenditure on apparatus or equipment, or on the provision of more academic staff. It is clear, then, that the effectiveness of the physicist in doing research varies with the individual, with the number of graduate students under his supervision, and with other conditions, some of which may be local and some connected with his field of research. We have, therefore, not attempted to adopt for the divisional reports a standard assessment of the amount of time devoted to research by the university physicists in the different fields of research. The various reports use different assessments ranging from one third of full time to two thirds.

To complete this discussion of the pattern of research in Canadian universities, a brief discussion should be given of the postdoctorate fellow and his role in research. Postdoctorate fellows are by no means limited to the universities, for there are many working at NRC and other government laboratories. Perhaps a way will be found to introduce them into industrial research laboratories. This discussion is, therefore, relevant to the whole Canadian research scene.

Postdoctorate fellows are very valuable visitors to the research laboratory, since they bring, usually from another university and often from another country, a fresh outlook and a new experience. Since they have already had basic training in research, they require little direction from the permanent staff, and are able to devote full time to research. The term of fellowship is usually two years; this is a reasonable compromise between the desire to devote full time to research and the desire to achieve the salary and security of a permanent post.

In the universities, postdoctorate fellows help to provide continuity in the research program and, under favorable circumstances, contribute to the general supervision of graduate students. The net result is a considerable amplification of the professor's effectiveness in carrying out substantive research.

3.3 PHYSICS RESEARCH IN GOVERNMENT LABORATORIES

The National Research Council is the only government agency with an open mandate to undertake, assist, and promote scientific and industrial research. To enable it to do this, Parliament places appreciable funds at its disposal in three quite separate votes. One is for the support of research in universities, one for support of research in industry, and one for support of its own laboratories. Funds are not transferable from one of these to another.

The in-house activities of NRC are not described separately in the statistics given in the twelve subject divisions, but are included in this report wherever they apply with other in-house government research.

The activities of the National Research Council's laboratories applicable to this report are those that deal with physics research as defined in Chapter I. These include not only the work done in the Divisions of Pure Physics and of Applied Physics but also part of the work done in the Division of Radio and Electrical Engineering as well as some applied physics carried out in other divisions (such as the Division of Building Research and the National Aeronautics Establishment). Furthermore, the division between pure physics and pure chemistry is an administrative convenience rather than an operational fact in some phases of their work.

In general, NRC has research under way in most of the branches of physics discussed in this report. In some, such as theoretical physics, its activities are at present minimal, but in others such as atomic and molecular physics and classical physics it is making major contributions. It has always enjoyed a considerable degree of freedom in its activities and consequently fields of effort tend to grow and decline with the natural changes in the composition of its staff.

An estimate made recently of the relative amounts of pure and applied research led to the conclusion that in the entire NRC establishment the fraction of effort on pure science was 29%, on fundamental research with an applied objective 31%, and on applied research 40%.

The National Research Council in its in-house activities is by no means the only government agency carrying out research in physics. Atomic Energy of Canada Ltd., the DRB laboratories, and the Department of Energy, Mines and Resources undertake extensive research in physics. Their research is more "mission oriented" than that of the National Research Council. However, since any application of science can have defence implications, the terms of reference of the Defence Research Board are very wide. Energy, Mines and Resources includes both the Dominion Observatory Branch (in which astronomy and geophysics research in subjects like seismology, gravity, and geomagnetism are centered), and the Geological Survey, where exploration geophysics is carried out. Research in physical oceanography is also undertaken by this department in its Marine Sciences Branch. The

Department of Transport is the home of government research in meteorology and the Department of National Health and Welfare employs physicists in its investigation of radiation health hazards. All these are included in the subject division reports in Part II of this report.

The organization and financing of these departments is on a vertical basis; that is, each within its mandate is financed independently by parliamentary appropriations, with formal coordination through the Treasury Board. This does not lead to excessive duplication or serious overlapping in projects, largely because there is a loose but effective horizontal organization in various types of committees, which include not only government research workers but those in universities and industry as well. The present distribution of subject responsibility in various departments has grown for many years in a logical manner, and while responsibilities are occasionally shifted from one department to another, the more informal horizontal organization keeps alive a reasonable exchange of information and ideas. It is not often that research investigations covering closely duplicated fields become active in different government departments without exchange of information and efficient cooperation. Examples of such close cooperation might be cited. Radio astronomy is centered both in the Department of Energy, Mines and Resources and in the National Research Council's Radio and Electrical Engineering Division. Upper atmosphere research is carried out both by DRB and by NRC. In both cases appreciable research in universities is supported by NRC grants, and, in the case of upper atmosphere research, industry contributes significantly in the development of rockets and satellites.

The horizontal organization is carried out mainly through NRC Associate Committees or similar inter-departmental committees, and occasionally by more informal personal contact. Some of the major committees might be mentioned. The Associate Committee on Geodesy and Geophysics is one of the larger NRC associate committees. It is modelled somewhat after the International Union of Geodesy and Geophysics and has 13 subcommittees. The total membership of the committee and subcommittees includes about 212 scientists; they meet usually twice a year. These meetings are, in effect, symposia covering geophysics in such a way that most Canadian activity in this field is included. The committee represents Canada at the International Union and advises NRC on the choice of university members on the Canadian delegation. This committee, like most of the others, does not deal with financial matters except for travel expenses for the university members and the publication of the Canadian Geophysical Bulletin.

The Canadian Committee on Oceanography is very effective in marine science, and includes membership from the government departments concerned and from the universities. The coordination of ship time, supplied by the government for university research, is the responsibility of working groups of this committee.

The Associate Committee on Space Research is also responsible for the exchange of information in a wide group of related problems in the physics of the upper atmosphere and nearby space. One of its subcommittees acts as a scientific evaluation panel for upper atmosphere rocket experiments.

There are in all 45 NRC Associate Committees, which vary in size and in responsibility. Though appointed by the Council they are more or less autonomous in their activities, and can bring together on very short notice the best brains in the country on any specific problem relating to their subject. This was demonstrated forcibly in the early stages of World War II. Of the fields represented by the 45 associate committees, 15 are more or less related to the subject matter of this report although only 3 are mentioned above.

More formal organization of related research activities within government has often been suggested for administrative convenience; we would like to emphasize that such action would offer no likelihood of improvement and little chance of success. Research cannot be directed, and any research worker who does not know more about his individual problem than does his supervisor is not carrying out effective research. The present organization of government research in Canada, though rather subtle in its informality, is recognized throughout the scientific world as one that is effective. The selection of men counts much more than the organization and no group is more capable of selecting a scientific peer than a group of scientists themselves.

3.4 PHYSICS RESEARCH IN INDUSTRY

A foremost objective of research in a technologically developing country such as Canada must be the optimum translation of research and technology into economic, social, and cultural benefits. This point was made by Prime Minister Lester B. Pearson in the inaugural meeting of the Science Council on July 5, 1966, when he spoke of "science and technology to aid the development of our nation and the improvement of our society.'' With the accelerating technological ''explosion'', knowledge and innovation are emerging as the primary forces contributing to economic growth and development. This view has been stated recently by the Economic Council of Canada as follows: "It has already been indicated that in the years ahead much of Canada's growth must come in the secondary industries. Over the past several decades the fastest growing secondary industries in all the main industrial countries have been the science-based industries. Also, the products of these science-based industries have been the fastest growing element in world trade."[1]

Current Situation

The distribution of the total government expenditures on research between government, university, and industrial laboratories in Canada is markedly different from that in the US, as shown in Table I.

Table 1 – DISTRIBUTION OF GOVERNMENT EXPENDITURES ON RESEARCH (1963–64)[1]

	Canada	US
Total government research expenditures (millions of $UD)	275.5	13,400
Percentage spent in government laboratories	78.0	18.6
Percentage spent in universities	7.6	11.2
Percentage spent in industry	13.3	67.2
Percentage others	1.0	3.0

[1] Canadian totals from Dominion Bureau of Statistics Reports, US totals from "Basic Research and National Goals", US National Academy of Sciences Report, March 1965, p. 15.

Thus research in Canada is relatively weak in industry and is predominant in the government laboratories. This is in contrast to the situation in the US where 67% of the research is conducted in industry and the government pays for 77% of all the research conducted in basic physics. By government planning, in the US several national objectives were achieved rapidly with much of the research and development carried out in industrial laboratories. For instance, NASA spends

[1]Economic Council of Canada, "Economic Goals for Canada to 1970", Dec. 1964.

81% of its R & D budget in industry. A similar situation obtains for the R & D portion of the US defence budget. It must be kept in mind, however, that large parts of these budgets are expended on engineering development rather than research in pure and applied physics.

Clearly a well-developed industrial research capability would be of great advantage in translating the results of pure and applied research into tangible economic and social benefits. However, the question of how far Canada should move in this direction (i.e. of changing the balance between research done by government and university on the one hand and by industry on the other) requires a specialized study. In any comparison of the US and Canadian objectives, this point should be borne in mind: many industries in Canada in which it would be desirable to foster research activity are financially controlled outside the country.

We thus find a very complex picture of the state of physics research in Canada. How did it get this way? Largely by chance. A few outstanding men, pursuing their own particular interests in research, started small but successful research groups. These prospered and new groups sprouted and so the structure grew.

In government laboratories, financial support has presented few problems, but in industry and in the universities it has largely controlled the rate and form of growth. For this reason, we now take a look at the nature of the financial support that has been available to research physicists in universities and in industry.

3.5 GOVERNMENT SUPPORT OF RESEARCH IN UNIVERSITIES

Though other federal government departments award grants for research in physics, by far the major source of federal funds is the National Research Council. NRC operates its own laboratories and a system of scholarships and grants to assist university research. There is also an industrial research program, which will be discussed in section 3.6. In the year 1961-62 the research operations of the NRC laboratories cost $23.5 million and the university scholarships and awards cost $12.0 million. The operations figure includes only money for research, and not large capital items such as new buildings, expensive installations such as the high speed wind tunnel, or the cost of the Canadian journals of research. The grants and scholarships figure includes medical research. In 1965-66 the same figures were $31.0 million for in-house research and $34.2 million for university grants and scholarships. In 1961-62 the annual report shows no item for assistance for research in industry, whereas in 1965-66 an item under that heading shows $3.3 million, which was not included above. It will be noted that according to these figures the in-house operations have gone up by 32% while the university support has gone up by a factor of 2.8; nevertheless, the average size of an operating grant (about $7,000) has not changed appreciably.

The policy in awarding research grants during the past 50 years has been to support research where the greatest competence lies. Since the objective was to build a scientific community, the capability of the scientist applying for a grant was the primary consideration. The subject matter of the research need not have been related to any national program, but must have represented a sound objective in attempting to advance the boundaries of knowledge in the speciality concerned. Grants are still based on proven competence, but this is difficult to assess in young Ph.D. graduates, just starting a life of scholarly research. Even after a few years, competence in productive research is not always easy to judge. Therefore, in this report, special consideration is given to young men starting out.

The proliferation of research problems involving expensive equipment (running from a few hundred thousand dollars to a few million in cost) has led to an increasing use of NRC assisted research funds for major installations. The operation and maintenance costs of such major installations are often out of proportion to individual grants. There has also been a tendency during the past few years for groups interested in closely related or interdependent research to form an institute within their university, so that expensive equipment and operating expenses can be financed from a pool of several individual grants.

A complete analysis of NRC support of university research in physics would take a much more comprehensive study than the present one. Its record is well known. Criticisms of its operation are bound to be heard, but we are satisfied that its principles, based on 50 years of experience and continuously evolving to meet current requirements, are good.

The Atomic Energy Control Board also awards university grants in physics. These are mostly to support the operation of nuclear accelerators, but some are for plasma physics with a thermonuclear objective in mind. They are organized in close coordination with NRC. The amount granted in 1965-66 was $1.6 million.

Some other government organizations in addition to NRC and AECB give grants in physics to universities. To a large extent these are "mission oriented", in that the subject matter is associated with the interests of the department concerned, for example, DRB. Since many branches of science can have defence applications, considerable freedom in subject matter is possible, at least in principle. These grants are also given in close coordination with NRC, so that there is no unplanned overlap in support. The Defence Research Board budget for these purposes has not expanded during the past few years as has that of the NRC. As the universities have grown since World War II NRC has taken over support of some groups which earlier were partially financed by DRB; DRB now awards grants mostly for objectives specifically related to defence.

Mission oriented grants are also given for research in meteorology by the Meteorological Branch of the Department of Transport, and in astronomy by the Department of Energy, Mines and Resources. Again, close coordination is maintained with NRC grant committees in assessing grant applications.

Some research contracts, as distinct from grants, are also awarded by DRB, AECL, and by the Meteorological Branch. In all cases the research objective is defined.

Other government branches that give similar types of grants are the National Advisory Committee of the Geological Survey, and the Department of Northern Affairs. For the most part these are not for physics research, but cover subjects in which applied physics may be involved. Contracts may also be given by such departments. The amounts involved in physics research are considered to be too small to have statistical significance in this report.

The growth rate of NRC and AECB research grants in various branches of physics may be judged from the data given in Table II and displayed graphically in Fig. II. These data have been extracted from "Annual Reports on Support of University Research", published by NRC. It must be emphasized that Table I does not pretend to show all the grants that support research surveyed in this report, but only those that are reasonably clearly identifiable as being awarded directly for physics research. Although the data do not show the complete grant support of physics research from NRC, the trends and growth rates shown by these figures are believed to be representative and significant.

From Fig. II it can clearly be seen that the total NRC expenditure of these grants is increasing at approximately 31% per annum from \$1.34 million in 1959-60 to \$4.78 million in 1965-66. The number of operating grants awarded has increased from 75 to 253 in the same period, and the rate of increase in the number of awards is about 21% per annum. The fact that the rates of increase in the amounts awarded and in the number of awards were approximately the same in this period is reflected in the entry of Table I displaying the average NRC operating grant per applicant; this can be seen to vary but little from a value of about \$7,000.

Also included in Table I and Fig. I are data showing the number of bursaries and studentships awarded to graduate students in the various branches of physics covered by this report. The numbers given are probably slightly low, because the NRC reports used did not list the field of research of the recipient very specifically; thus, some individuals who were working in chemistry departments, for example, but doing research covered by this report, have probably not been counted. The number of students supported in this way increased from 69 to 207 in the seven-year period considered; this rate is approximately 15% per annum.

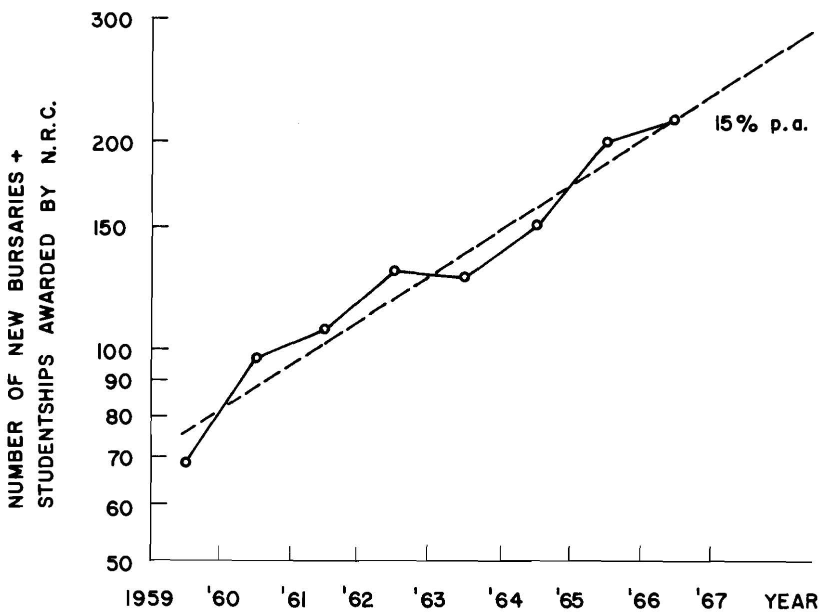

Fig. I Growth rate of number of new scholarships awarded (logarithmic scale).

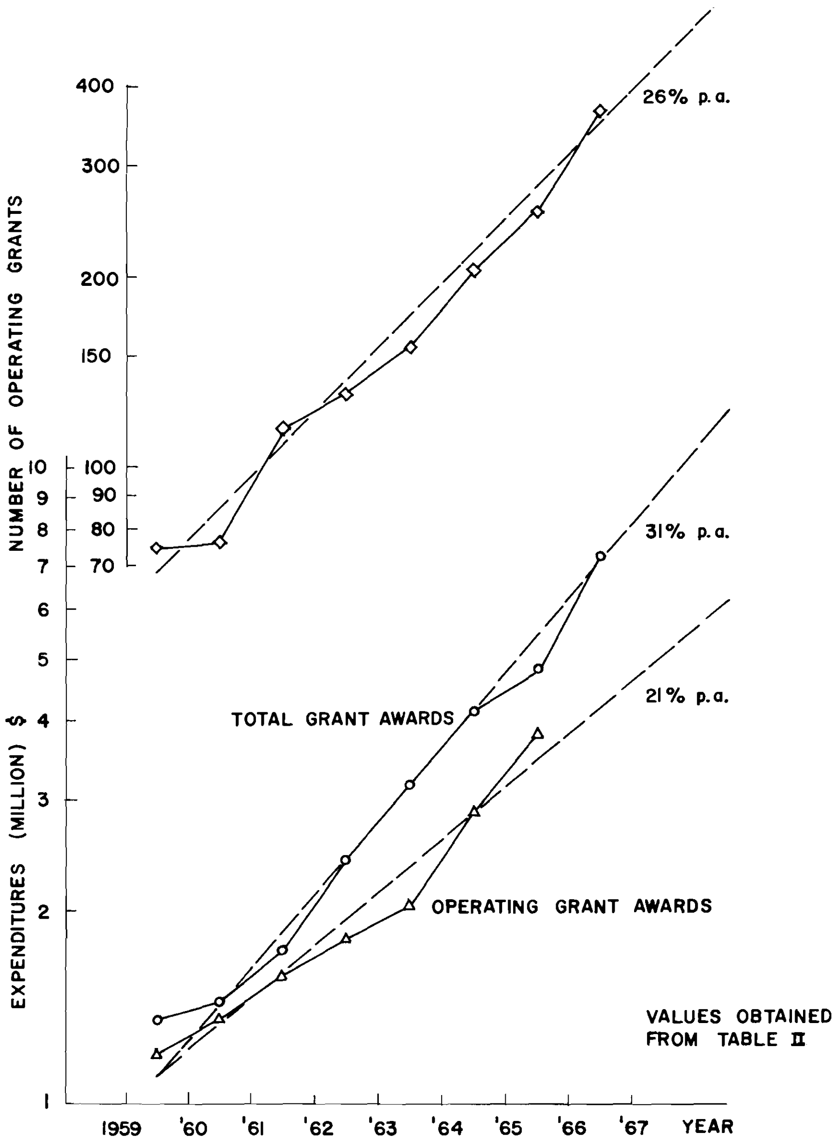

Fig. II Comparison of growth rates in number of operating grants, in operating grant expenditures and in total grant expenditures. Vertical scales are logarithmic.

The individual subdivision reports in Part II make numerous references, comments, and recommendations on the mechanism whereby grants are awarded by NRC; it is therefore appropriate that a description of the present mechanism be given so that the comments and recommendations can be clearly understood. The main types of awards are Operating Grants, Major Equipment Grants, and Major Installation Grants. In addition, the Council awards some Travel Grants to allow university staff members to attend conferences (normally outside the North American Continent) or to visit laboratories abroad for short periods, Computer Grants both for individual research projects and for the provision of a computing facility at a university, and also General Research Grants to the executive head of each Canadian university. Grants of the last type can be used by the grantee as he sees fit, for the broad support of scientific research at his institution. The Council also awards a number of Senior Research Fellowships, which allow university staff members to spend a period of time pursuing their research interests at laboratories outside Canada without teaching responsibilities; more recently, NRC has established the E.W.R. Steacie Memorial Fellowship, which enables an outstanding young scientist to devote his *full* time to research at his own university.

Operating grants are awarded to individuals who hold academic staff appointments at Canadian universities. As the name implies, the grants are regarded as contributions to the normal operating costs of the individual's proposed research project. The grants are regarded as contributions only; the regulations clearly state that they are not intended to cover the full cost of research, and the availability of space and basic facilities at the university concerned are prerequisites for the award of a grant.

Major Equipment Grants are awarded to individual university staff members to assist with the purchase of special research equipment, or components thereof, costing between $5,000 and $100,000.

There are also a very limited number of Major Installation Grants, similar in purpose to the Major Equipment Grants, but designed to assist with the cost and installation of special equipment valued in excess of $100,000.

The Council has stated a definite policy on the assessment of grant applications. It aims to provide support to the limits of its resources "for good research conceived and carried out by able and enthusiastic investigators. Accordingly, applications for grants are judged on the basis of our assessment of the scientific record of the applicant."[1] In order to provide this "assessment of the scientific record of the applicant" the Council has set up the grant selection committees which, for 1965-66, represented the fields of biology (2 committees), chemical and metallurgical engineering, chemistry, computers, earth sciences, engineering, and physics.

Each committee has a convenor appointed from the scientific staff of the Council, at least one member of the Honorary Advisory Council, and members with staggered terms appointed by the Council from the faculties of the universities. A study of the membership lists of the Grant Selection Committees for physics of the past 6 years suggests that the Council has succeeded in obtaining on its physics committees as diverse a group of specialists as it is possible to obtain in committees of manageable size.

Four comments can be made. First the 26% per annum growth rate of the number of applicants shown in Fig. II means that the number of applications to be assessed more than doubles in four years and almost quadruples in six. The number of applications being processed at the present time is such that the selection committees will soon find it impossible to cope adequately with the important task of grant selection without resorting to more than one sequence of sittings. If the rate of growth continues, some change from the present system will have to be devised in order to ensure that the quality of the assessment at least remains as good as that achieved in the past. We do not mean to imply that the Council's system has been rigid and static, and unyielding in the face of this growth. On the contrary, it has met these problems by increasing the number of its subcommittees by further subdividing the research applications into more specialized areas. This, however, has its difficulties, particulary if some uniform standard of judgement of applications common to all committees is to be maintained. We make this comment, however, to point out the difficulties of assessing grant applications as their number increases, knowing full well that the Council is just as concerned about this problem as are the members of the scientific community whose comments and recommendations are recorded in the individual surveys.

The second comment is that the method of assessment, whatever its shortcomings may be, does ensure that physicists' applications are assessed by physicists, the majority of whom are from the universities themselves and are therefore sensitive to the particular problems that the university physicist faces.

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[1]Awards to University Staff, NRC, 1967

The third comment is that the funds available for disbursement have been only sufficient to grant between 60% and 65% of the total amount requested by the applicants. In any year a few applications are received that should be rejected outright or cut substantially, either because the applicant is strictly ineligible to apply according to the regulations or because the proposed research is too ambitious for the applicant, considering the basic facilities at the university concerned and the applicant's proven capabilities. Nevertheless, the grant selection committees have generally recommended that for the following year they be given an increase in the amount to be distributed which is larger than that to be expected on the basis of the normal growth rate. In other words, there have been many occasions on which the committee has felt that its recommended award to a particularly promising applicant is too small to give the support and encouragement that the applicant's abilities warrant. It is difficult to say that a number of worthwhile research projects have actually have stifled by lack of adequate support, but it is certain that many researchers have been hampered, or at least prevented from proceeding at a pace sufficiently rapid to enable them to compete with researchers in other countries. By and large Canadian physicists have found the terms and regulations of the NRC grant system acceptable, and prepare applications that are well-considered and reasonable in the amounts requested. University physicists and the Council agree that the funds at present available for grants in support of research are too small, and both feel that an increase is justified so that a greater percentage of the amounts requested could be awarded.

The fourth comment concerns support of research by a young university professor who has only recently completed his doctorate degree and a period of postdoctorate training. His publications are generally few in number and are based on his supervised doctoral work. According to existing grant regulations, his abilities are not yet proved and, under these regulations, the best that can be arranged for him is a small, almost token, starting grant. The grant selection committees have been sympathetic to this problem and have felt that they have done the little which is in their power to do, namely, to continue to give relatively large grants to the more senior men who are known to be devoting more time to administration and similar non-research activities, in the expectation that much of the grant will be used to assist such new men in their own area of research.

In recent years there have been five specific changes in the details of the NRC program to which particular attention should be drawn, because they invoke particular comments in the individual surveys. One of these changes is the introduction of negotiated grants, instituted for the first time for the year 1967-68. A second change, introduced for the year 1966-67, altered the nature of the term grant. Prior to this date applicants could apply for a three-year period, and, if this term was granted, they would be assured (provided funds were available) of the stated award for each of three consecutive years without further application. The applicant could apply for a supplement to the term grant in any year if circumstances warranted the request for additional funds in that year. This procedure was discontinued for the year 1966-67, and replaced by a Biennial Grant requiring only one application and guaranteeing (subject to funds being available) the stated support for each of two consecutive years. However, the applicant for a Biennial Grant was ineligible to apply for a supplement for the second year. Probably because of this restriction, and the quite widespread experience of the applicants that the grants they received were generally less than those requested, very few applications were made for Biennial Grants.

A third change, also effective for the year 1966-67, was instituted when the Council discontinued Block Grants. These were awarded to an individual on behalf of a group of investigators at a university, to support joint research on one investigation or on a group of closely related investigations. The individual in whose name the grant was awarded had to be acceptable, as the administrative agent, to all parties concerned. In place of this system, the Council allowed arrangements to be made at the university for individual grantees to pool all or part of their grants to support joint research.

The fourth change arose from a closer cooperation than had existed in the past between AECB and the NRC Grant Selection Committee in the field of nuclear physics, for which each had awarded grant support. This change took the form of visiting committees which met with applicants at various universities and assessed their applications, the work in progress, and the basic facilities.

The fifth change to be noted took effect for the year 1966-67; the Council then discontinued its program of postdoctorate fellowships tenable in Canadian universities, which had been in operation for a number of years. Under this program, fellowships had been allotted to certain universities on a continuing basis, and other universities participated from time to time. The numbers of postdoctorate fellows in physics so appointed are shown in Table II. Beginning 1966-67, the burden of financing postdoctorate fellowships fell completely on the operating grants. Grantees had been permitted in previous years to pay postdoctorate fellows from their operating grants,

Table II.—PHYSICS RESEARCH IN UNIVERSITIES

(NRC Expenditure in millions of dollars)

	1959-60	1960-61	1961-62	1962-63	1963-64	1964-65	1965-66	1966-67
Physics								
Operating	0.41(61)	0.58(67)	0.69(98)	0.79(112)	0.89(134)	1.21(178)	1.62(226)	1.875(277)
Major equipment	0.15(15)	0.08(8)	0.15(7)	0.11(9)	0.06(10)	0.40(26)	0.48(29)	0.71(44)
**AECB*								
Operating	0.60(12)	0.60(8)	0.65(9)	0.77(11)	0.90(11)	1.25(12)	1.60(11)	2.0(11)
**Oceanography*								
Operating	0.18(2)	0.18(2)	0.18(2)	0.20(2)	0.20(2)	0.20(2)	0.24(2)	0.24(2)
**Space Research*								
Operating	–	–	0.07(6)	0.06(6)	0.07(8)	0.12(9)	0.18(10)	**0.84(71)
Major equipment	–	–	–	–	–	–	0.01(1)	0.22(14)
**Special Major Installations*								
Operating	–	–	–	–	–	0.11(3)	0.29(4)	
Major equipment	–	–	–	0.48(2)	1.05(4)	0.84(4)	0.46(5)	1.41(9)
Totals								
Operating	1.19	1.36	1.59	1.82	2.06	2.89	3.83	–
Major equipment	0.15	0.08	0.15	0.59	1.11	1.24	0.95	–
Grands Totals	1.34	1.44	1.74	2.41	3.17	4.13	4.78	7.30
Number of Operating Grants	75	77	115	131	155	204	253	about 365
NRC Operating Grant for Physics per Applicant (thousands of $))	6.7	8.6	7.0	7.0	6.6	6.8	7.1	6.8
Awards of Scholarships etc. in Physics (Numbers of new awards)								
Bursaries and studentships	69	97	106	128	127	150	198	207
Special scholarships	2	6	4	7	11	4	12	26
PdF (overseas)	6	6	6	10	16	19	23	24
PdF (in Canadian univ. including renewals)	15	16	11	17	20	19	22	discont.

The numbers in parentheses are the numbers of grants whose total is given by the immediately preceding figure.

* The distinction between operating and major equipment grants, in the sense used by the physics committee, is extremely difficult: this is emphasized by giving only the combined figure for the Special Major Installation Grants for 1966-67.

**The apparent large increase in the number of grants is due in large measure to a redistribution of grant applications between the space research committee and the physics committee.

but in 1966-67 they were also permitted to pay a travel allowance to fellows. A greater proportion of operating grants was probably spent in this way, particularly since the 1966-67 regulations also permitted the pooling of all or part of the grants of several individual grantees, so that several staff members could share the cost of one postdoctorate fellow.

3.6 GOVERNMENT SUPPORT OF RESEARCH IN INDUSTRY

We have attempted to examine the pattern of physics research in industry from information given to us by the Department of Industry, the Defence Research Board (DIR), and the National Research Council's industrial research support program. Thus we restrict ourselves to research programs that are partially supported by the federal government. The amount of physics involved in these cannot, of course, be estimated accurately without going into a special study of individual research projects. Whenever the appropriate information could be obtained the detailed analyses in the divisional reports included the programs discussed here.

(i) The Defence Research Board's DIR Program

The DIR program is one in which industries interested in defence applications may approach the government for assistance with research and development funds for some objective that is in line with their particular experience and that has commercial possibilities. The initiation of the research and definition of the objective is left to the industry. Financing is roughly on a fifty-fifty basis, the details being negotiated, but the government's grant is largely used for salaries of qualified scientists. Controls on the part of the government seem adequate. By agreement the results of the investigation belong to the industry, though a protection clause prevents industry from charging the government for royalties.

A review of the DRB-DIR program from inception in 1961 up to December 1966 indicates that approximately $23.5 million in company funds and $24.8 million in government funds have gone into this program (plus about $0.5 million contribution to cooperative projects from the US Air Force). The rate of expenditure of government funds in 1965-66 was $5.3 million per year and its forecast is for $10 million per year by 1970-71. The government report in its section on distribution by technical areas places 61.5% of the total expenditure in electronics and physics.

It is difficult to ascertain the exact fraction of this total that is physics, and even more difficult to separate the research from the development, since the DIR programs are heavily biased toward applied research and development.

(ii) The National Research Council's Industrial Research Program

This is roughly parallel to that of the Defence Research Board, but is not limited to objectives that have a defence interest. The conditions again are that the government finances about half the overall cost, which in most cases goes into paying the salaries of the staff involved. In these programs, also, the results of the research belong to the industry. It is important to note that again the initiation of the program starts with the industry, and must be along lines in which the industry is competent. Since the objective of the program is to assist industries in building up a research capability, long-term projects are rarely considered – the average duration is three to four years. Of course, new programs can be initiated upon the completion of others. It is hoped that this kind of assistance, together with tax incentive legislation now in effect, will lead to an industrial research capability in the country.

The National Research Council's Industrial Research Program started in 1962-63 at a level of about $1 million, but it was a year or more before industry took up the money made available for this purpose. The 1965-66 annual report puts the expenditure at $3.3 million, the larger part of which was spent in fields other than physics. The number of physicists involved in September 1966 was only 23, representing only 6.4% of the total professional employment under the scheme. (Only 8 of the 23 physicists employed had the Ph.D. degree). This is not unreasonable since only a fraction of the overall expenditure is in industries that might use physicists, and an industrial research and development program is, on general grounds, more likely to employ engineers than physicists.

(iii) Defence Development Sharing Program and Program for the Advancement of Industrial Technology

In addition to the programs just discussed, the Department of Industry administers two industrial development programs that border on research activities in physics but are too far down in the development and production area of Table I, Chapter 2, to be of much interest here. These are the Defence Development Sharing program and the program for the Advancement of Industrial Technology. A pamphlet supplied by the Department of Industry describing these, together with the DRB–DIR and the NRC – Industrial Research Program states:

> "These programs are designed to encourage and assist Canadian industry to engage in scientific research and development activities by sharing with industrial firms the cost of specific research and development projects proposed and undertaken by them."

The Defence Development Sharing Program makes no claim of supporting basic research, and therefore has little part in this report. It is appreciable, however, in cost in relation to the others mentioned because in 1966 $24 million were spent in support of 57 development projects. The amount of physics research and the number of physicists involved cannot be sorted out but we consider it relatively small.

The Program for the Advancement of Industrial Technology is still comparatively young. It was established in the Department of Industry in 1965. Its basic policy is to "help industry upgrade its technology and expand its innovation activity ...." Again it is a cost-sharing program, the department being prepared to contribute up to 50% of the total cost. Between the initiation of the program and March 1967, 70 projects have been approved and approximately $14.5 million in government funds have been committed. Again we cannot sort out of this the amount that can be attributed to physics since no information on the subject matter of these projects has been made available to us. We suspect, however, that it is also small.

(iv) Tax Incentives

In addition to the above, the Canadian government has given appreciable tax incentives to industry for expanding their research and development programs. These have led to a considerable upgrading of the development capability in Canadian industry. Their influence on physics research, however, and in particular on basic research, has been minimal, due to the relatively poor competitive position of Canadian science-based industry and to the pressures for short-term return on investment of industrial resources.

(v) Funding for Unsolicited Proposals

At present, there is no means by which an unsolicited idea from a scientist in industry can be funded by the Canadian government, except in rare circumstances where the idea may be in direct aid of a pressing unsolved defence problem. This situation is in contrast to that in the US, where at least ten government agencies are available to contract out research on a competitive basis in most of the areas of physics.

Apart from company-funded research to initiate programs, the only available course to scientists in Canadian industry, therefore, is to seek financial support from US sources. This is indeed being done and noteworthy programs have been obtained through US funding. This is, however, a highly undesirable situation, since the US naturally orients the programs toward its needs; also, it owns the rights and has prior access to results. This situation also has a very adverse effect on the retention of capable scientists in Canada. In addition, in many cases it can lead to the development of research activities which are optimized to US rather than to Canadian interests. In Section 4.6 we discuss this adverse situation further and propose a mechanism by which it can be rectified.

(vi) Fully Funded Contracts

We feel that there would be a more rapid enhancement of research capabilities in industry in Canada if fully funded research contracts could be awarded to industry. Such contracts would not necessarily be limited to investigations that result in some piece of hardware, but should also be granted for the acquisition of new scientific information related to fields of research that must be supported in the national interest.

Various government laboratories, particularly in defence, do contract out research and development to industry. These tend to be short-term projects, and usually represent a part of an in-house investigation, the part being very often related to hardware development. Giving industry a more comprehensive part in a mission oriented research program would require fully funded contracts, and lead to the enhancement of capabilities mentioned in the previous paragraph.

3.7 THE FUTURE – WHAT SHOULD OUR OBJECTIVES BE?

In this chapter we have looked briefly at physics research in Canada and have found a broad spectrum of subjects, some strong, some weak, some mainly worked on by isolated individuals and others by well-equipped large groups. This is a heritage from the past with its emphasis on the support of the individual – the good ones prospered and produced good schools, with a continuing tradition, the poor ones or the very isolated ones tended just to jog along or to stagnate entirely.

Recently there has been almost a technological revolution and it has tended to make the prosperous groups more prosperous and the weaker ones to fade further away. The old system of granting support irrespective of field or context now needs to be re-examined, but on what basis and with what objectives?

We have not found a simple answer to this question; in fact, we don't believe a simple answer could be acceptable or complete. We summarize our ideas below and we even hazard an epitome of them, but we doubt whether we could ever possibly satisfy everyone, or even ourselves, on all the aspects of physics research in Canada. Before presenting our epitome, however, let us first look at some obvious answers to our question.

One could perhaps strive to achieve a leading position for Canada in all branches of physics. Though we do not dismiss this as a very long term objective we are sure that most physicists will agree with us that it is not a practical immediate aim. Even in the United States, the National Academy of Sciences "Physics Survey and Outlook" suggests that they should not try to lead in everything – at least, not quite everything!

Perhaps we should put all our eggs in one basket and try to really excel in one single branch of physics. However, even if we succeeded in leading the world it would be at the cost of stifling all other branches and reducing our flexibility to the point where we could take little advantage of advances made elsewhere. We cannot afford a too narrow specialization.

Another approach might be to give the highest priority to those branches of physics that are reaching farthest into the unknown and are most likely to produce spectacular advances in scientific knowledge in the next decade. Two fields stand out in this respect, elementary particle physics and space physics, the first for its pure physical interest, and the second for its newness and sense of challenge.

Yet another approach would be to ask what programs of research are likely to take best advantage of Canada's natural resources or geographical position. Three examples immediately come to mind: solid state physics, applied nuclear physics, and upper atmosphere physics.

Another answer, and an easy one to give and implement, is simply to retain the status quo; continue to support strongly these fields which have grown strong and starve those fields we have undernourished in the past. Though clearly to the advantage of some, we are convinced that this solution would not be acceptable to the vast majority of physicists and we hope that the commissioning of this report suggests that it is not acceptable to the government.

After considering these and other answers we realize that there is no clearly defined way to express our conclusion. We cannot accept any or all of the simple solutions above; also we cannot totally reject any of them. The basic philosophy of our recommendations is along the following lines:

First, we feel that research in those parts of physics that can enhance our ability to use our own natural resources should be strongly emphasized. Some, such as applied nuclear physics and geophysics, are already strong and probably need little extra attention; others, such as solid state physics, both pure and applied, are weak and need greatly increased support.

Second, we support research in those fields of physics that take advantage of our geography. Upper atmosphere and space physics is one such field, and though the present expenditure on rocketry and its other engineering aspects may give the impression of strong support, in fact the support of the physics research done with these facilities is weak and we feel that it needs strengthening.

Third, we do not wish to slow down the support for those fields that are at present healthy. Atomic and molecular physics and pure nuclear physics are two such fields; Canada has established an enviable reputation in these areas and we hope that future support will enable her to continue to do so.

Cutting across these three suggestions is a basic feeling that Canada's effort in the applied aspect of physics research has been far too weak. We feel strongly that it should be strengthened, but in an absolute way and not at the expense of the pure research without which it will neither grow nor prosper.

Finally, we feel that the present support programs based purely on individual accomplishment must be supplemented in the near future. To this end we propose the creation of joint institutes where scientists from many laboratories can work together and enjoy the benefit of those large and costly facilities that individually they could not support or effectively use.

We have many more suggestions and they are all discussed and developed as more formal recommendations in Chapter 4. In conclusion of this chapter, however, we will try to do what we have just said is almost impossible: we will try to epitomize our recommendations in one sentence.

We propose that the support of physics research in Canada during the next few years emphasize those fields that can lead to an improved use of our national resources or can benefit from our geographical situation or scientific history.

We suggest that this might be called a national objective approach.

Chapter 4

RECOMMENDATIONS

Canada is richly endowed with natural resources. Ever since Confederation its inhabitants have had to decide between the easy life of 'hewers of wood and drawers of water' and the more exciting but more harrassed life of an industrial nation. Economic conditions have led Canadians to choose finally the latter course; the decision has, however, been gradual and has been made more difficult by the readiness of other countries to pay well for their raw materials.

This gradual decision has been accompanied by a slow growth in research which, to some extent, has been haphazard with little planning; occasionally, however, usually as a result of special circumstances, research in a certain field has developed more rapidly than in the others. Consequently in reviewing the state of research in physics in Canada we have found some fields such as atomic and molecular physics, nuclear physics, and geophysics to be in a more developed and healthier state than most; some, such as solid state physics, are in urgent need of special consideration.

It would not be reasonable to expect Canada to excel in all fields in the near future though we think there is no reason to consider that this cannot be an ultimate long-range goal. The immediate problem, and the one that led to the commissioning of this report, is to try to predict how we should plan for the immediate future, keeping in mind such a lofty ultimate aim.

The subject division reports contain a large number of recommendations aimed at improving the strength of the Canadian research effort in their particular fields. From these and from our own discussions we have tried to draw some general conclusions. We present these in the following manner:

We first present and briefly discuss our general recommendations in Section 4.1. Each subdivision is then considered separately in Section 4.2 with an assessment of its present situation and some detailed recommendations. In Section 4.3 we outline our guidelines for financial support and make recommendations for the rate of growth of the support of physics research in existing types of laboratories over the next five years. In 4.4 we consider special large projects and make some recommendations concerning the creation of joint institutes. Our recommendations for the mechanism of support of research in universities, in industry, and in government follow in Sections 4.5, 4.6, and 4.7.

4.1 GENERAL GUIDELINES

In this section we present eight general recommendations as a basic structure for the orientation of government policy on physics research during the next five years. We have used these guidelines in proposing our more detailed recommendations outlined in Sections 4.2 to 4.7.

1. Pure and applied physics

The distinction between these two aspects of physics research has already been outlined. We feel that whereas pure research is in a reasonably healthy state and is continuing to improve, the same cannot be said for applied physics. *Our first general recommendation is that special consideration must be given to strengthening the research effort in applied physics.* In particular, the universities must be encouraged to undertake more research oriented toward applied physics in order to improve the flow of graduates with an interest in such work, and Canadian industry must be encouraged to undertake more of its own research in Canada. To enable it to do this it needs more incentives, and with this in mind we offer more specific recommendations in Section 4.6.

2. Applied and interdisciplinary aspects of physics in the universities

In order to put our first recommendation into effect it is of paramount importance that the universities recognize applied physics as an honorable part of physics. Though this recognition must clearly take place at the graduate level it is equally important that it begin at the undergraduate level. The same may be said about such interdisciplinary aspects of physics as geophysics and biophysics. *Our second general recommendation, therefore, is to urge more universities to create prestige honors courses in physics with special options oriented toward applied physics and the interdisciplinary aspects of physics.*

3. Fields of physics that are healthy at the moment

It would be folly to withdraw support from fields in which Canada has already succeeded in making notable contributions and has good prospects for continuing to do so. *Our third general recommendation is, therefore, to continue support of such fields at a rate such that they are likely to maintain or improve their present position.*

4. Fields connected with our natural resources

We consider that a major aim of our research effort in the near future should be to enable our own industries to take better advantage of our immense natural resources. This is a logical consequence of the decision of Canadians not to be merely diggers and exporters of their wealth. *Our fourth general recommendation is, therefore, to greatly increase the support for all forms of research in basic and applied physics that are connected with the conservation or rational exploitation of our own natural resources.*

5. Peculiarly "Canadian" fields

Due to its geography Canada provides a unique area for research in fields of physics that involve large land areas, a long sea coast, arctic conditions, and northern latitudes. Furthermore the tilt of the earth's magnetic axis toward northern Canada makes measurements in Canada, of certain phenomena, necessary for the solution of many problems related to the physics of the earth as a planet. We feel that such research, which makes use of our geographical position, should be strongly encouraged. *Our fifth general recommendation is, therefore, to maintain at an adequate level and, where necessary, to increase substantially, support for fields of research for which our terrain and location give us a natural advantage over other countries.*

6. Joint institutes

There is a well-recognized tendency for the cost of the facilities needed for research to increase rapidly with time in several fields of physics. As progress is made, increasingly complex problems are tackled and increasingly more complicated equipment is needed for their investigation. In nuclear physics this takes the form of large accelerators; in astronomy it is telescopes; in solid state physics it is magnets, electron microscopes, and other complex measuring equipment. Such facilities are, in general, far too expensive to build and to operate to be just associated with one laboratory, even a large government laboratory. They must be shared between physicists working at many different laboratories. *Our sixth general recommendation* *is, therefore, to set up joint institutes that will provide major facilities for the use of several laboratories.* Such institutes must not be under the exclusive control of government laboratories but must be operated in a manner that permits universities and industry to share in their control. In Appendix E we attach a memorandum on this subject, submitted to the Spinks report by Professor H. L. Welsh of the University of Toronto. We are in complete agreement with the principles expressed in this memorandum. We discuss this recommendation in more detail in Section 4.4.

7. Theoretical physics

The committee on theoretical physics clearly emphasizes that this subject is more than a single branch of physics; it is a vital part of each branch. The report also emphasizes that in some fields the level of the theoretical program is well below the level appropriate to the existing experimental program, and that in some areas it is even dangerously low. *Our seventh general recommendation is, therefore, to give sufficient support to theoretical physics in the broad sense to enable it to come into balance with experimental physics in all fields and in all major research laboratories.*

8. Fundamental pure physics

The strengthening of research in applied physics, which we have emphasized in some of our general recommendations above, can only be effective if it rests on a firm foundation of continuing research in pure physics. This type of research also makes a vital contribution to Canada's cultural development, and we hope that our desire to strengthen applied physics will not be interpreted as a suggestion to weaken pure physics.

Our eighth general recommendation is, therefore, to continue to increase support for research in pure physics in order that it will always form an adequate base for an increased engagement in applied physics, and in order that Canada will continue to contribute to man's fundamental knowledge of matter.

4.2 ASSESSMENT AND DETAILED RECOMMENDATIONS

In this section the main findings of the individual subdivision committee reports are summarized, data are presented on the number of physicists found to be active at present in research in the field concerned, and an estimate is made of the average cost of research per scientist per annum. Included also are reasonable projections of the number of scientists involved and the expected average annual cost for the year 1971-72. The data given in this section are summarized in Tables I and II of Section 4.3, and, in many cases, will appear to differ slightly from the figures printed in the individual subdivision reports. The differences arise because the development of a standard rule for assessing the costs of research could not be established until the subdivision reports were received by the steering committee and the detailed problems of assessing costs re-evaluated. From a study of the reports a rule was formulated to include estimates of salaries (both of the physicists and supporting technical staff), maintenance of equipment and facilities, routine purchase of supplies and auxiliary apparatus, and some assessment of the capital cost amortized in a suitable manner dependent on the equipment used. Costs of studies for such major items as the Queen Elizabeth II telescope, ING, and TRIUMF have *not* been included here; they are considered separately in Section 4.4. Furthermore, in the cases of oceanography and meteorology no account has been taken of the maintenance or capital costs of ships, of the meteorological stations or data acquisition and analysis systems. In some cases particular circumstances forced the steering committee to make an estimate themselves; this was done using both the committee members' personal experience of research, and advice from their colleagues; values estimated in this way are indicated by asterisks in Tables I and II.

Particular recommendations of the subdivision committees that are not covered in the general recommendations and that the steering committee felt should be given particular emphasis and prominence, are briefly stated here. These do not include all the recommendations of the subdivision committees, and the reader is directed to the individual reports for the detailed recommendations for each field.

1. Astronomy

In Canada, research in optical astronomy is carried out in the government observatories at Ottawa and Victoria, and in the University of Toronto, the University of Western Ontario, and Queen's University. A Department of Astronomy has recently been created at the University of Victoria. In radio astronomy there are the telescopes at Penticton, B.C., established by the Dominion Observatory, and in Algonquin Park, Ont., established by the National Research Council, as well as smaller observing facilities at the University of Toronto and at Queen's University. At present (1966-67) there are about 20 astronomers on university staffs and about 60 in government laboratories. Assuming that the university staff member devotes half his time to research, the approximate cost of research per full time equivalent university staff member is about $55,000 per annum and in the government laboratories is $80,000 per staff member per annum.

At present, the research effort is greater in the government laboratories than in the universities. This is an unfortunate situation, particularly since the universities are the source of manpower for astronomical research, and cannot provide enough graduates even for the government laboratories alone. However, the existing university departments are expanding, and new ones are being established, so that some improvement can be noted. Of particular importance to the healthy development of Canadian astronomy is the establishment of a national observing facility; this could be provided by the Queen Elizabeth II telescope, for which a site on Mt. Kobau in British Columbia is being seriously studied. It is recommended *that such a national observing facility be built without delay and that it form the nucleus of a joint institute of the type suggested in general recommendation 6 and discussed further in section 4.4.*

It is estimated that by 1971 the growth will be such that there will be about 45 staff members of universities and about 100 members in government observatories, and that the research cost per FTE will rise to about $83,000 in both the universities and government laboratories.

2. Upper Atmosphere and Space Physics

Most of the present activity in this field is directed toward studies of the mechanical and chemical behavior of the ionosphere. This research is distinctly Canadian, since it arises from the unique character of the ionosphere in Canada due to the presence of the auroral zone, which cuts across the country in an arc from northern Quebec, through Churchill, Man., to the Yukon. Research is conducted using rockets and satellites, predominantly by the Defence Research Telecommunications Establishment (DRTE), the Canadian Armament Research and Development Establishment (CARDE), and the National Research Council of Canada (NRC); and also in ground-based laboratories of which several are maintained by universities and one by industry. The present level of government expenditure in this field is about $17.7 million per year, of which slightly more than half is spent in industry for engineering development and engineering support of the program.

Approximately 125 university staff members are conducting research in this field, and they are assumed to devote half their time to research (this includes many engineers in support activities). The cost of research per full-time equivalent staff member is estimated to be about $43,000 each per annum, and this is expected to increase to about $45,000 each per annum by 1971, when the number of staff members in this field will be about 300. In government laboratories there are now about 110 research scientists in this field and by 1971 this number is expected to increase to 150. The cost of research per scientist is now about $70,000 per annum and is expected to fall to about $60,000 per researcher per annum by 1971.

The increase in activity is likely to be greatest in the universities, and it is important that the present satisfactory balance between vehicle-borne research and ground-based research be maintained during this growth period. To this end *we recommend that the universities be encouraged to participate more in vehicle-borne research.*

There are also about 9 scientists in government laboratories and 13 in the universities conducting research in cosmic rays, with total expenditures of about $350,000 in government laboratories and $250,000 in universities. Canada maintains 9 ground stations in various locations ranging in latitude from the Arctic to Ottawa. It is estimated that by 1971 the government laboratories will have about 12 scientists in this field costing a total of about $0.5 million per year, and the universities about 25 scientists costing a total of about $1.0 million per year.

3. Classical Physics

Included in this part of the survey is much of the area generally referred to as applied physics which, for many fields in industry, forms a very effective link between pure research and development. At present about $8 million per year is spent on research; government funds supply about 76% of the total, of which about 55% is spent by the government, 26% by industry and 19% by universities. In the universities there are about 53 staff members, many in engineering departments, assumed to be devoting one half their time to research at an effective cost of $50,000 per annum per full-time equivalent staff member. In government laboratories there are about 100 scientists (at an average cost of about $45,000 each per annum) and in industry about 70 (at an average cost of about $30,000 each per annum) engaged in research.

In view of the great value of this field of physics to industry and technology, the level of activity is disturbingly low. The total number of scientists active in this field represents only about 13% of the total number of physicists counted in this survey; in the US about 37% of all physicists are employed in activities covered in this field.

It is hopefully anticipated that by 1971 the numbers of researchers in the universities, government laboratories, and industrial laboratories may grow to about 115, 175, and 130 respectively, with estimated costs per full-time equivalent staff member of about $46,000, $44,000, and $30,000 each per annum respectively.

A very great difficulty in meeting the necessary demands for manpower in this field lies in the fact that classical physics or applied physics has no proper "home" in the majority of universities. All students of physics must study classical physics in their basic program, but the research interests in most universities have swept classical physics aside in their reach for newer and more exciting fields. In fact, of the money spent by universities for research in this field, only 9% was spent in physics departments; the balance was spent in engineering departments. *We recommend strongly that at least some universities be encouraged to develop centers of strength in classical physics, and that adequate research funds be specially earmarked for basic and applied research oriented toward the special problems and development of Canadian technology.* We have emphasized this in our second general recommendation of Section 4.1. Furthermore, there should be a great increase in the research done in industry, and industry should be represented on the grant-awarding committees concerned with research in this area.

4. Earth Physics

The survey includes oceanography as well as solid earth geophysics. It is found that there is a great deal of activity in industry, particularly in petroleum geophysics and well-logging, but very little research. The research activity is highest in government laboratories, where there are about 110 scientists (at an average cost of about $68,000 each per annum), next highest in the universities, where about 70 staff members (devoting an assumed 40% of their time to research) are active at an average cost of about $46,000 each per annum, and lowest in industry where about 20 scientists do research at an average cost of about $25,000 each per annum.

It is felt that the present position of research and its rate of growth is quite satisfactory, but that a substantial increase in industrial research of a fundamental nature would greatly aid the exploitation of Canada's great mineral wealth. Reasonable projections for the future suggest that by 1971 the numbers of research scientists in universities, government service, and industry will respectively be about 140, 170, and 70, with average research costs of $68,000, $66,000, and $36,000 each per annum respectively. There is presently a lack of adequate accommodation for earth physics research in university buildings and this will hamper the desirable growth unless remedied. Furthermore it is estimated that a fraction somewhat in excess of 10% of the total research support in the universities comes from sources in the US. Should this be terminated, some research would have to be discontinued unless equivalent Canadian funds could be supplied.

5. Meteorology

Because the Canadian economy rests in large measure on farming, forest products, and water resources, the dependence of these assets on the weather and climate makes the environmental sciences of particular importance for Canada; the annual value of the meteorologically sensitive parts of the Canadian economy is in excess of $10 billion. The greatest activity in meteorological research takes place in the Research Division of the Meteorological Branch, Department of Transport. Other government departments (including some provincial ones) carry out research, as do about 10 universities. At present about 30 university staff members are estimated to devote about 40% of their time to research in this area, at an average cost of about $54,000 each per annum, in addition to about 65 scientists in government laboratories, at an average cost of $58,000 each per annum. Reasonable projections to 1971 indicate there will be about 45 research men in the universities and 90 in government laboratories, each costing $95,000 and $73,000 per year respectively. No research activity in industry has been found.

The limitations on growth in research in this very important field seem to lie in the dearth of competent manpower more than in lack of financial support. *We strongly recommend further development and strengthening of meteorology in the universities, together with some increase in the support of university meteorological research, in order to attract and train more Canadians.* Again this is emphasized in our second general recommendation of Section 4.1.

6. Atomic and Molecular Physics

Research in this field, which is well established in Canada, is conducted in over 50 industrial and government laboratories, as well as in both physics and chemistry departments in the universities. In university physics departments there are about 120 staff members, assumed to be devoting one-third of their time to research, at an average cost of about $47,000 each per annum. There are about 45 researchers in government laboratories, at an average cost of about $25,000 each per annum, and 4 in industry at the same average annual cost. Reasonable projections to 1971 indicate that the research interests of the physics departments will grow to include about 250 staff members at an average annual cost of about $60,000 each. In government laboratories we expect about 75 researchers at an average cost of about $35,000 each per annum, and in industry 8 researchers at an average cost of about $40,000 each per annum.

7. Nuclear Physics

Nuclear physics research is well established at universities and at government laboratories, and is particularly strong at the Chalk River Nuclear Laboratories of Atomic Energy of Canada Ltd. Research in the universities has grown rapidly in recent years; there are now about 80 experimental physicists on university staffs (assumed to be devoting 50% of their time to experimental research) at an average cost of $148,000 each per annum. In government laboratories there are at present about 20 staff members doing experimental research, 16 of them at the AECL laboratories, costing an average of about $180,000 per annum each. Theoretical nuclear physics has been included in the theoretical physics section.

The projections for future growth take into account the fact that by about 1970 present university facilities will be severely strained by graduate student demand for nuclear physics training, and also by the necessity of updating existing facilities and providing new ones. These projections do not take into account the current proposals for special major facilities, which are discussed in Section 4.4. Thus the growth should be large in the universities where, by 1971, there should be about 120 nuclear physicists at an average cost estimated to be about $143,000 per annum per man. The growth in government laboratories during the same period is expected to be smaller, reaching about 25 physicists, each costing about $230,000 per annum.

It is clear that very large facilities will become a feature of nuclear physics research in the future. Two of these, the Tri-University Meson Facility (TRIUMF) and the Intense Neutron Generator (ING), which were proposed by particular groups of scientists, are presently being actively discussed. *We urge that such facilities form the nuclei of joint institutes of the type proposed in our sixth general recommendation.* Such institutes are discussed further in Section 4.4, where, in particular, we consider TRIUMF and ING in more detail.

Such very large facilities should be regarded as complementary to the smaller accelerators located at universities on which graduate students, particularly in the first two years of their training, can learn basic techniques in the more intimate environment that such machines make possible.

The field of applied nuclear physics is also actively pursued at the laboratories of AECL. In all there are at present 102 permanent staff members working in fields which they consider to be associated with applied physics; 40 of these are associated with reactors; 15 with the design of accelerators; 24 with concept evaluation, physics at power projects, and policy direction; and 23 with various technological programs. We have not included these physicists in Table II, since we have felt that they are all associated in one way or another with the country's nuclear power program and will receive adequate growth support as that program develops. The same may be said about the applied nuclear physicists in those industries associated with atomic energy.

8. Elementary Particle Physics

This survey has restricted itself to physics at energies greater than 1 GeV, and has included theoretical as well as experimental activity because it was felt that continued progress in this field relies on their continued close collaboration. Thus, the survey has some overlap with that of the theoretical physics subdivision, but the amount of overlap is clearly indicated.

At present there are 11 experimentalists, 8 in universities and 3 in government laboratories, engaged in research in collaboration with groups in the US carrying out experiments with accelerators there, and 20 theorists, all on university staffs. The average cost of the experimental research program is presently $60,000 per annum per man in the universities (where staff members are assumed to devote about three-fifths of their time to research), and about the same in the government laboratories.

The borderline of knowledge in the primary structure of matter and its relationship to the human capability of understanding nature lies more in elementary particle physics than in any other area. Our present activities in this field are so small that they are barely marginal. In a balanced culture such a basic field should not be neglected.

We therefore recommend that Canada's effort in the field of elementary particle physics be built up to a reasonably effective size during the next few years.

We suggest a continuation of the cooperation with the US in carrying out our experimental work at large US particle accelerators, but look forward to a more independent activity during the 1970's.

The present experimental work is concentrated in three groups, but there are also theoretical physicists in many universities. The situation regarding our theoretical strength is quite healthy, and should continue to be so by maintaining the present rate of growth for the next 5 years. Each experimental group, however, is at present just short of the threshold size of about 6 staff physicists that would enable it to make an effective contribution as a group in this very collaborative field of research. It is therefore recommended *that the first priority in financial support be given to these experimental groups before other new groups are started.* Assuming that these three groups, together with one new one, grow to the threshold size in 5 years and begin to contribute to the actual experiments in the US, it is estimated that there will be about 30 experimentalists in universities costing about $110,000 per annum each. It is also expected that there will be about 5 experimentalists in government laboratories (collaborating with a university group) at a cost of about $100,000 per annum each.

No proposal for a major facility is presented at this time. Because progress in this field is at present so rapid, however, it is quite possible that a proposal may be presented before 1971. If such a proposal is forthcoming *we recommend that funds be made available for its study and that the facility be considered as a nucleus for a joint institute.*

9. Solid State Physics

Research in this relatively new field is now well established in universities and in government laboratories, and has obtained a foothold in industry where, following the experience in other countries, its benefits are beginning to be felt. There are at present about 100 staff members (assumed to be devoting one-third of their time to research) in the universities at an average cost of about $57,000 per annum each, 35 physicists in government laboratories at an average cost of about $43,000 per annum each, and about 45 in industry at an average cost of about $56,000 per annum each.

Natural growth in the universities, based on the pattern of graduate student enrollment and the interest in establishing solid state physics laboratories in newer universities, suggests that by 1971 there will be about 200 solid state physicists in the universities at an estimated cost of about $130,000 per man per annum. In government laboratories the number of physicists is expected to double to about 70 at an average cost of about $100,000 each per annum. Hopefully, the greatest growth should occur in industry, producing about 200 research physicists by 1971 at an average cost of about $80,000 per annum each. We recommend strongly *that all possible incentives be provided to increase research in this field in industry and to attract the Ph.D. graduates from the universities to research positions in Canadian industry*. Even with these projections it is likely that the supply of Canadian Ph.D. graduates will only barely supply the numbers which we hope industry will demand.

It is also recommended *that there be established joint institutes for solid state physics and materials science, fully accessible to the universities and industry*, where special facilities such as provisions for high magnetic fields, high pressures, and crystal growth and purification can be concentrated.

10. Plasma Physics

Since 1958 there has been a growing research activity in this field distributed in universities, government laboratories, and industry. At present there are about 30 university staff members who are assumed to devote half their time to research, at an average cost per man of $53,000 per annum. In government laboratories there are about 10 research physicists in this field, at an average cost of about $50,000 per annum each, while in industry there are 15, at an average cost of about $27,000 each per annum. Much of the work reported under this heading complements closely the research reported under upper atmosphere and space physics, and has an inherent potential of contributing significantly to industrial development. Reasonable projection to 1971 indicates an increase by a factor of about 3 in universities, government laboratories, and industry alike, to provide in the respective organizations about 90, 30, and 45 research physicists at average costs of about $56,000, $43,000, and $42,000 per annum each.

At present plasma physics research in Canada exists primarily because of the efforts of a few isolated individual physicists, and because of the importance of the subject in modern physics and technology, there is a grave danger that the key men may be lost to other countries. We recommend *that the growth in manpower be such that a number of groups, of an effective size of 5 or 6 professional staff, may be formed, both in universities and in government laboratories.* Also, because of the fragmented nature of the research effort at present, there is a serious need for a coordinating body to provide liaison between the different groups; this would reduce duplication of effort and increase the effectiveness of the research. The same body should maintain a surveillance of new developments, and be in a position to support specific projects that are likely to be of particular benefit to Canada.

11. Theoretical Physics

The committee has found 125 theoretical physicists in the universities who, on the assumption that they devote half their time to research, represent an average cost of about $22,000 each per annum. In addition, there are 20 in government laboratories at an average cost of about $20,000 per man per annum, but none was reported in industry. The present strength and rate of growth in theoretical physics might be regarded as reasonably satisfactory if the subject division were considered as an isolated field standing by itself. Because of the complementary nature of theoretical studies to experimental work, however, the present balance is too heavily weighted on the side of the experimentalists, and we have already stated in our seventh general recommendation that special attention should be given to increasing the strength of theoretical physics in order to improve this balance. In particular, we find that in the field of solid state physics the theoretical activity is disturbingly small and *we recommend particularly that special efforts be made to improve our strength in theoretical solid state physics.* Considering these factors, and the acceptable demand of graduate students for training in theoretical physics, reasonable projections to 1971 indicate 250 staff members in universities at an average cost of $38,000 per annum each and 50 in government laboratories at $20,000 per annum each. We also feel that industry will benefit from the presence of theoretical physicists in their research laboratories, and allow for 50 by 1971 at an average annual cost of $20,000 each.

12. Biophysics

Included in this report are those scientists who are making quantitative measurements on biological phenomena with a view to explaining them in physical or mathematical terms, and those who are engaged in instrument development for the biological field where the development of the instrument is an essential step. Engineers concerned with the application of biophysical knowledge to practical medical problems are also included. There are at present about 130 scientists in the above categories in the universities who are assumed to be devoting about 70% of their time to research at an average cost of $44,000 each per annum. In government laboratories there are about 43 at an average cost of $28,000 each per annum, and in industry 4 were found. The subdivision report outlines in some detail the many needs of this field, and reasonable projections to 1971 give about 260 such scientists in universities at an average cost of about the same as at present, $44,000 per annum each, about 65 in government laboratories at $26,000 per annum each, and about 5 in industry.

In order to meet the demand for manpower which this growth requires, it is *recommended that the universities give serious consideration to the inclusion of options in biological subjects in the higher years of honors physics programs, and also to the development of a new course for those students who are more interested in applying physics to research in other fields than in pursuing a research career in pure physics*. This is stressed in our second general recommendation of Section 4.1. Finally it should be recognized that biophysics has now reached the status of an independent discipline and it is recommended *that a grant selection committee be established for assessing the applications for grants in aid of research in biophysics.*

4.3 RECOMMENDATIONS FOR THE INCREASE OF FINANCIAL SUPPORT

Before stating our recommendations for financial support we wish to emphasize that there is a considerable delay between the inception of a research project and its effect on the consumer market. This has already been mentioned in Chapter 3 and is, we believe, a powerful argument for divorcing the level of support from the short-term fluctuations in the nation's business. It is more realistic to establish a long-term policy for its growth. This is especially important for the level of support of research in the universities, which are also the suppliers of the manpower for the country's entire research effort.

In this section we consider the support of research in the laboratories now in existence. The additional support needed for the joint institutes mentioned in our sixth general recommendation is considered separately in Section 4.4.

From the subdivision reports the steering committee has attempted to extract statistics on the numbers of staff and their support, both for 1966-67 and for 1971-72. This information was supplemented by a separate questionnaire to subdivision chairmen and by some interpolations and inspired guess-work on the part of the steering committee. It is presented in Tables I and II, and the totals are listed in Table III. The steering committee wishes to emphasize two things:

1. The divisional committees cannot be held responsible for all the data in these tables. The steering committee does, however, believe that the data are in substantial agreement with the thinking of the divisional committees.

2. There is inevitably some overlap between subdivisions. For example many theoreticians will have been counted twice in the totals. Furthermore some subdivisions went beyond university physics departments in their quest for physicists engaged in the universities; in particular, we have included the biophysicists in hospitals under the heading of universities.

The headings in the tables have the following meanings:

Staff consists of all physicists on staff and includes those with Ph.D. degrees as well as those whose last degree was M.Sc. or B.Sc.

FTE is the full time equivalent of the staff and is obtained by multiplying the staff numbers by a factor, f, representing the fraction of time spent on research. In cases where f was not available from the divisional committees (indicated by asterisks) a value of 0.5 was used for universities. We decided to use $f = 1$ in our calculations for government laboratories and industry, on the theory that the sole purpose of such physicists is to do research, even though, once engaged by their laboratories, they are often called upon to do non-research tasks. At universities, however, physicists are hired to teach as well as to do research.

Total support is the total support, including total salaries.

Salaries are the total salaries of the physicists uncorrected for the f factor. In the cases where no figures were available from the subdivisions an average salary of $11,500 was used for 1966 and $15,000 for 1971.

Research cost is the cost of supporting the research efforts of the physicists. It is equal to (Total support) – (1-f) (Salaries).

Cost per FTE is the research cost divided by the full time equivalent staff.

We first establish a growth rate in the support for physics research by considering the number of physicists who are willing to participate in the nation's research over the next five years. Table III shows that our survey predicts an increase from about 1,700 in 1966 to about 3,400 in 1971, equivalent to an average annual increase of 15%. It also shows that we expect the highest average annual increase of 27% to be in industry, an average annual increase of 16% in universities, and a relatively low average annual increase of 10% in government laboratories. Our prediction of 16% for universities may be compared with the present average increase of 14% per annum in the number of staff members in physics departments and the predicted increase of 12.5% per annum in the total student enrollment over the next five years[1]. Our number refers to staff active in research and would be expected to be slightly higher than the other two figures since very few staff members are now being hired by universities merely to teach. It is, however, less than the average annual increase in the number of physics grant applications to the NRC over the last five years. This is partly on account of the abandoning of block grants by the NRC and consequent increase in the number of individual applications, and partly because the fraction of the staff doing research is rising, as discussed in Chapter 3.

To see whether the universities will be able to supply the extra 1,700 physicists, which our survey suggests are needed over the next five years, we have used the graduate enrollment figures listed in Table 1.3 of the Vogt report. This table lists the student enrollment in the physical and earth sciences from 1958 to 1964, and an extrapolation suggests a total of 3,800 students by 1966. Table I of our survey shows an actual enrollment in the subjects covered by our report of about 1,400 students, from which we deduce that about 37% of the students listed in Table 1.3 of the Vogt Report are in our subjects. We assume that 40% of them are first-year graduate students

[1]Enrollment in Canadian Universities and Colleges – E.F. Sheffield, 1966.

and that for each beginning graduate student 0.4 graduate two years later with a terminal M.Sc. degree and 0.3 graduate five years later with a Ph.D. Upon carrying out the necessary arithmetic on the graduate enrollment figures, it is found that a total of 860 physicists graduated between 1962 and 1967. The enrollment has been increasing at an annual rate of 17%; if this rate of increase is applied to the numbers graduating we arrive at a total output of about 1,600 physicists over the next five years. Our calculation seems to be conservative since it predicts a graduation of 143 in 1963 compared with an actual graduation of 153 M.Sc.'s and 62 Ph.D.'s. This suggests that, though there well may be some shortages in particular fields, the output over the next five years will be roughly in equilibrium with the demand.

We thus consider an average annual increase of 15% in the total number of physicists active in research in Canada to be a reasonable estimate for the next five years. To estimate the cost of supporting these people we add 7% to cover scientific inflation (the extra amount needed by a scientist in successive years to achieve the same output) and arrive at the rate of 22% per annum for the increase in financial support. This, we emphasize, is the minimum average annual rate of increase needed to support the increasing physics research community over the next five years, without reducing the average capability of each member.

Even though we consider this to be a minimum average annual rate of increase over the next five years it leads in 1971-72 to an expenditure on physics research 2.7 times the present expenditure; if applied to research in all fields it would increase the percentage of the GNP spent on research and development from the present value of 1.1% to 2.2% by 1972, assuming an annual increase of 7% in the GNP.

Table III also shows the present overall level of support of physics research and what the physics community estimates it will be in five years' time. These figures are $70 million and $61 million; they are broken down between universities, government, and industry. If this increase occurs uniformly over 5 years it will require an average annual increment of 19% in terms of constant dollars. Allowing a 4% annual inflation, which we expect will be slightly higher for scientific services and equipment than for general purchases, we find a value of 23% for the average annual rate of increase needed for physics research and development. The similarity of this figure to the previously derived figure of 22% suggests that there has been no artificial boosting of the projections and that the figures are reasonably self-consistent. Combining an increase of 4% for inflation with our total support increases from Table I leads to the following recommendation in terms of real dollars.

Our first financial recommendation is that the average annual increase in the support of research in physics should be 23% per annum during the next five years. This should be made up of a 25% annual increase to universities, a 15% annual increase to government laboratories, and a 44% annual increase in the support of research in industry.

We emphasize again that this recommendation only covers the normal expenditures on physics research and specifically excludes the cost of the joint institutes mentioned in our sixth general recommendation. The additional cost of these institutes is discussed in Section 4.4.

We now examine in more detail the meaning of the 25% average annual increase recommended for universities. We first estimate the grant research funds available for the support of physics in 1966.

The latest figures readily available were for 1965-66; these were extracted from the Bonneau report and from a perusal of individual NRC awards. We find that the total amount available from NRC was $17.22 million and that $3.18 million was awarded for physics research. We therefore use the fraction of 18.5%, obtained from the NRC awards, as a guide in interpreting grants from other organizations, except that we use 100% for grants from the Atomic Energy Control Board (AECB) and, somewhat arbitrarily, 10% for awards from the Medical Research Council (MRC).

The totals and amounts for physics are summarized in Table IV. From this table we see that the grant support of physics research in 1965 was about $8.8 million, which we correct by 20% because of the present growth rate to give $10.6 million for 1966.

The total support of physics in universities in 1966 was about $28 million. Subtracting $11 million for staff salaries leaves a non-salary support of $17 million. Apparently $10.6 million of this came from grants and $6.4 million from university budgets.

Since formula financing is upon many universities, and around the corner for others, this latter figure is unlikely to rise at a rate faster than the anticipated 13% increase in total undergraduate enrollment. In fact, due to the increasing salary demands on university budgets, we expect that the amount available for the non-salary support of research will rise at only about 10% per annum. This would make $10 million available by 1971.

Table I.–STAFF AND SUPPORT IN UNIVERSITIES

Subdivision	Staff		Total support (millions of dollars)		Salaries (millions of dollars)		FTE		Research cost (millions of dollars)		Cost per FTE (thousands of dollars)		Students (M.Sc. + Ph.D.)	
	1966	1971	1966	1971	1966	1971	1966	1971	1966	1971	1966	1971	1966	1971
Astronomy	22	45	0.8	2.2	0.3	0.7	11	23	0.6	1.9	55	83	35	65
Upper atmosphere	125	300	3.3	8.1	1.3	3.0	62	150	2.7	6.6	43	45	110	600
Classical	53	114	1.6	3.4	0.6*	1.7*	26*	57*	1.3	2.6	50	46	101	243
Earth	70	140	1.7	5.0	0.7	2.0	28	56	1.3	3.8	46	68	60	120
Meteorology	28	45	0.9	2.5	0.4	0.7	11	22	0.6	2.1	54	95	81	130
Atomic and molecular	121	250	2.8	10.0	1.4	5.0	40	125	1.9	7.5	47	60	198	500
Nuclear	81	120	6.4	9.5	0.9*	1.8*	40	60	5.9	8.6	148	143	181	350
Elementary particle	8	30	0.4	2.2*	0.1	0.5*	5	18	0.3	2.0	60	110	28	100
Solid state	100	200	2.7	10.4	1.2*	3.0*	33	66	1.9	8.4	57	127	190*	380*
Plasma	31	90	1.0	3.2	0.4	1.4	15	45	0.8	2.5	53	56	65	113
Theoretical	125	250	2.1	7.5	1.5	3.5	62	165	1.4	6.3	22	38	195	300
Biophysics	132	256	4.6	9.0	1.7	3.8	92	180	4.1	7.9	44	44	179	426
Totals	896	1,840	28.3	73.0	10.5	27.1	425	967	22.8	60.2	54	63	1,423	3,327

FTE ÷ Staff = fraction of time, f, spent on research.
Research cost = Total support − (1−f) Salaries.
*Estimated by steering committee and discussed in Sections 4.2 and 4.3

TABLE II.–STAFF AND SUPPORT IN GOVERNMENT AND INDUSTRY

	Government Laboratories						Industry					
	Staff		Total support (millions of dollars)		Cost per staff (thousands of dollars)		Staff		Total support (millions of dollars)		Cost per staff (thousands of dollars)	
Subdivision	1966	1971	1966	1971	1966	1971	1966	1971	1966	1971	1966	1971
Astronomy	56	100	4.6	8.3	82	83						
Upper atmosphere	119	162	8.1	9.5	68	59						
Classical	101	174	4.4	7.5	44	44	70	133	2.1	4.0	30	30
Earth	110	170	7.5	11.1	68	66	20	70	0.5	2.5	25*	36*
Meteorology	65	90	3.8	6.5	58	73						
Atomic and molecular	46	75	1.1	2.5	24	34	4	8	0.1*	0.3*	25	40
Nuclear	20	25	3.6	5.8	180	230						
Elementary particle	4	5	0.2	0.5*	60	100						
Solid state	35	70	1.5	6.6	43	95	43	200*	1.6	16.2	56	81
Plasma	10	30	0.5	1.3	50	43	15	45	0.4	1.9	27	42
Theoretical	20	50	0.4	1.0	20	20	10*	50*	0.2*	1.0*	20*	20*
Biophysics	43	65	1.2	1.7	28	26	4	5	0.1	0.1		
Totals	629	1,016	36.9	62.3	58	60	166	511	5.0	26.0	31	51

Table III.—STAFF AND SUPPORT BY TYPE OF EMPLOYER (DOLLAR FIGURES ARE IN CONSTANT 1966 DOLLARS)

Subdivision	Staff		FTE		Total support (millions of dollars)		Research cost (millions of dollars)		Cost per FTE (thousands of dollars)	
	1966	1971	1966	1971	1966	1971	1966	1971	1966	1971
Universities	896	1,840	425	967	28.3	73.0	22.8	60.2	54	63
Government laboratories	629	1,016	629	1,016	36.9	62.3	36.9	62.3	58	60
Industry	156	511	166	511	5.0	26.0	5.0	26.0	31	51
Totals	1,681	3,367	1,220	2,494	70.2	161.3	64.7	148.5	53	60
Average annual increase in total		15%				19%		19%		
Average annual increase: Universities		16%				21%		22%		
Average annual increase: Government		10%				11%		11%		
Average annual increase: Industry		27%				40%		40%		

However, by 1971 the total support less salaries will be about $46 million, so that $46 million minus $10 million, or $36 million, should be available from grants. The non-federal grants are unlikely to increase by more than 13% per annum, that is to say to $4.3 million; $32 million is thus left to be provided by federal agencies. These agencies are now providing $8.2 million and must therefore increase their annual awards by a factor of 4 over the next five years. This is equivalent to an average annual increase of 32%. These figures are all in constant dollars and to convert to real dollars we add 4%. *Our second financial recommendation is, therefore, that federal government grants for the support of physics research should be increased at an average annual rate of 36% over the next five years.* We emphasize that this figure refers to the grants awarded by all the federal agencies. It may, therefore, be necessary for the major granting agency to increase its awards at an even higher rate to compensate for a more static situation in some other agencies.

Table IV.–GRANT SUPPORT OF RESEARCH 1965-66

Source	Total (millions of dollars)	Physics (millions of dollars)
NRC	17.22	
All federal sources except NRC, MRC, AECB	5.67	
Foundations	4.75	6.16*
Endowments	0.67	
Individuals	0.47	
Other sources	4.60	
Subtotals	33.38	6.16
AECB	1.60	1.60
MRC	10.29	1.03
Totals	45.27	8.79

* See Section 4.3 (p. 63) for the derivation of this figure.

4.4 LARGE PROJECTS

We have already briefly discussed the topic of facilities that are too expensive to be associated exclusively with one laboratory. Our sixth general recommendation was concerned with such facilities and suggested that they should form the nuclei of joint institutes to which scientists from many laboratories would have easy access.

One may argue that there should be two types of joint institutes, those that are truly national, and those that are primarily regional. However, we suspect that all such institutes would tend to remain primarily regional until transportation facilities greatly improve or until scientists become accustomed to the idea of spending an appreciable fraction of their time away from their homes and their own laboratories. We therefore suggest that only one basic type of joint institute be created, which is by right truly national but which will, we suspect, tend to become regional in its appeal.

The direction of such joint institutes is clearly of great importance and *all* scientists, not merely those from government laboratories, must be involved in the discussions leading to a policy on their organization and administration. *Our first recommendation on large projects is, therefore, that the federal government set up a committee composed of scientists from universities, from industry, and from its own laboratories, to prepare a policy for the organization and operation of joint institutes.* This is a matter of urgency since some large projects may well require the creation of such institutes in the not too distant future. We again call attention to the brief on this subject of joint institutes submitted by Professor H. L. Welsh to the Spinks commission which is reproduced in Appendix E.

It is obvious that such institutes will require a level of support considerably higher than that so far accorded by federal agencies to individual universities or industries. It will even represent a noticeable fraction of the total science budgets that they grant to their own laboratories. However, though the support will be high, it is impossible at this stage to give any very precise indication of its magnitude and breakdown by discipline in the estimates presented in Section 4.3 of Part I; we have therefore not included it.

To arrive at an order of magnitude estimate for this additional support we will try to make a list of the joint institutes that may be required within the next five years. We have restricted our attention to institutes whose primary appeal will be to physicists. We assume that other scientists will use these institutes and that they will, in turn, propose other institutes more specifically oriented towards their own fields which may also have some appeal to physicists.

(i) Institute for astronomy

The construction of a first class optical facility is urgently needed if Canadian astronomers are to continue to play a leading role in their field, and we wish to give this project our enthusiastic support. We feel that it should form the nucleus of a joint institute so that it will be available to all qualified Canadian astronomers. The siting of such an instrument is obviously of paramount importance and must be based on a careful scientific appraisal of the regions of the heavens that will be visible, and of the likely viewing conditions. It is essential to have a facility of this magnitude in a location where it can be used effectively. We note that the total cost of such a telescope and of the development of a possible site is estimated to be about $13 million (see subdivision report number 1, page 87). Some of this has already been spent, and of course more will be needed to operate it after completion. We use for our rough estimate a sum of $4 million per year over the next five years to complete fabrication and to operate this institute.

(ii) Institute for nuclear physics I

Three universities in British Columbia have jointly proposed the construction of a "meson factory" based on a 500 MeV 20 microamp. negative hydrogen ion accelerator. This proposal is described more fully in the subdivision report on nuclear physics (page 225) and we support it in principle. We consider that it is sufficiently large to warrant consideration as the nucleus for a joint institute, even though its appeal will be primarily local. The timing of this project is rather urgent in view of the competition it may receive from ING and from accelerators in other countries, and we therefore urge that approval be given as soon as possible; such approval need not await a decision on its incorporation in an institute or on detailed questions of organization. Rather detailed cost estimates have been published in the document 'TRIUMF proposal and cost estimate'[1], and they suggest an annual expenditure mounting from $4.16 million in 1968-69 to $5.74 million in 1972-73, with an initial expenditure of $0.8 million in 1967. We round these figures out in our summary below.

(iii) Institute for nuclear physics II

The physicists of the Chalk River Nuclear Laboratories have proposed the construction of an intense neutron generator (based on a

[1]Edited by E.W. Vogt and J.J. Burgerjon, Vancouver, 1966

1 GeV 65 milliamp. proton accelerator). If successful this bold and imaginative venture would give Canada a unique facility that would be useful for many different fields of physics research. It is described in more detail in the subdivision report on nuclear physics (page 00). Though the capital expense of about $150 million looks at first sight rather large, it would be spread over a long period and the annual amount would, in fact, be small compared to the total annual budget of the Chalk River project. In view of the impetus it would give to Canadian research and to Canadian engineering technology, we support it in principle.

Nevertheless we feel that more technical development is needed in order to prove the feasibility to the stage where complete approval should be given. We therefore recommend that a one- to two-year development program be financed with an assurance that, if the feasibility of the project is then proved, complete construction approval will be automatically granted.

We feel strongly that this facility should form the nucleus of a joint institute and that, in the discussion of its location, accessibility should be very seriously considered. On the basis that final approval is given before the end of 1968 and that construction then begins immediately and aims at completion in 1974, we suggest that the annual costs of this institute will be approximately as shown in Table V.

(iv) Institutes for materials sciences

With the increasing cost of some of the apparatus used by physicists interested in the materials sciences, it would seem that institutes may be needed to provide preparation and measuring facilities for physicists from many laboratories. Such institutes would differ from those mentioned above in that they would not be centered on a single major facility but would incorporate many medium-sized facilities. They would also be of use to physicists in many fields. This interdisciplinary appeal suggested the use of the expression "materials science" rather than solid state physics, even though the initial major users may associate themselves particularly with this latter field. These institutes will have a strong appeal to scientists from industry as well as from universities and government, and this aspect should be considered in choosing their sites.

Any present estimate for such institutes will necessarily be vague but we do not expect any to be initiated before 1968; they will then probably be reasonably modest in cost, as indicated in Table V.

We would expect two such institutes to start before 1972 and the figures in our table are for the sum of their support.

Table V. – ROUGH ESTIMATES OF THE SUPPORT NECESSARY FOR JOINT INSTITUTES

(millions of dollars)

Institute	1967	1968	1969	1970	1971
Institute for nuclear physics I (TRIUMF)	1	4	5	5	7
Institute for nuclear physics II (ING)	2	12	20	25	26
Institute for astronomy	4	4	4	4	4
Institutes for materials sciences		2	3	5	5
Institute for elementary particle physics				2	3
Totals	7	22	32	41	45

(v) Institute for elementary particle physics

It is clear from the subdivision report on elementary particle physics that no firm proposals are likely to be made during the next three years. It is also clear that some proposal can be expected in the early 1970's; we therefore add amounts for design studies in 1970.

These estimates, which are very rough, are summarized in Table V and show that the expenditure on joint institutes is expected to rise to about $45 million per annum by 1971. This sum is in addition to that indicated in Table III. There is probably some overlap between the "normal" support of Table I and the "institute support" of Table V, and furthermore, part of the cost of ING should be charged to disciplines other than physics. However, since it will be used primarily for physics we have included the full cost here. It should be noted that ING will, after its completion, begin to earn money from the sale of isotopes and from other services, and that its net cost will probably drop substantially after 1974. However, we hazard a guess that something else will then be proposed which will keep the total physics oriented institute expenditure at least constant!

Our second large project recommendation, therefore, is that financial support be available on an increasing scale and up to $45 million per annum by 1971 for the support of joint institutes, and that this support be considered quite separate from the support already discussed in section 4.3 of Part I.

Table V indicates a total cost of $145 million for our suggested institutes over the next five years. This is in addition to our total estimate of about $580 million for the normal support of physics research in university, government, and industrial laboratories over the same five-year period.

Since the $145 million is a new type of expenditure, it should be considered in the light of our general recommendations. To do this we have tried to break down the estimates of Table V into portions primarily benefiting pure physics, those primarily benefiting applied physics and those primarily benefiting other disciplines. This is indicated in Table VI. This breakdown was made in a somewhat arbitrary manner, but in the case of the institutes for nuclear physics was based on information extracted from 'TRIUMF – proposal and Cost Estimate'[1] and from a note entitled 'Benefits of ING'.[2] Though basically guesses, we believe our estimates represent approximately the way in which the benefits of these institutes should be apportioned.

Table VI. – BREAKDOWN OF INSTITUTE COSTS

(millions of dollars)

Institute	Pure physics	Applied physics	Other disciplines
Institute for astronomy	20		
Institute for nuclear physics I (TRIUMF)	12	5	5
Institute for nuclear physics II (ING)	25	40	20
Institute for materials sciences	5	5	5
Institute for elementary particle physics	5		
Totals	67	50	30

[1]E.W. Vogt and J.J. Burgerjon, loc. cit.
[2]T.G. Church, CRNL, 29 Nov. 1966.

They show that about 46% of their cost will ultimately benefit pure physics, about 34% will benefit applied physics, and about 20% will benefit disciplines other than physics. In view of the pioneering nature of these projects we feel that this apportionment is reasonable.

4.5 SUPPORT OF RESEARCH IN THE UNIVERSITIES

1. The principal agency that distributes government funds for research to the universities must be one that understands research on a broad front. It must therefore actually undertake such research. At the moment the National Research Council is the only government agency that satisfies this basic condition, and, in general, we are reasonably satisfied with the way it has operated its granting system. Nevertheless, we think that it should become more familiar with the actual conditions of university research and of the research climate in Canadian industry. We understand that its own operations are kept entirely separate from its granting operations, but we find that not all Canadian physicists believe that this is the case; many, in fact, are convinced that it gives to the universities what it has left over!

Our first university grant recommendation, therefore, is that the National Research Council of Canada continue to be a primary distributing agent of federal government funds for research, with a budget completely and clearly separated from its own operating expenditures.

2. We recognize that other government agencies, with particular interests in special fields, may wish to support university research in these special fields. We welcome this additional support for university research but feel, however, that the NRC should continue to be responsible for the greatest fraction of federal funds allocated for university research. Furthermore, a proper liaison should exist between all the granting agencies in order to provide some uniformity in the amounts and conditions of awards among the different agencies, and to avoid unwarranted multiple applications.

Our second university grant recommendation, therefore, is that other government agencies should continue to give grants to support university research in their special fields of interest, and that a proper exchange of information should be effected between all granting agencies.

We are also pleased to note that provincial agencies are also awarding grants for the support of research in universities. In general, their interests are rather wide, but somewhat oriented toward topics of particular relevance to their economies. We hope that they will maintain and increase this support, and that they will establish a close liaison with the federal granting agencies to provide some uniformity in conditions of award and to avoid excessive multiple awards for single topics.

3. One frequently heard complaint is that there is no procedure by which an applicant can obtain the reasons why his grant was much less than he felt it should have been. We appreciate that such complaints will be difficult to handle, but nevertheless feel that some sort of appeal board should be created which should try to give such explanations.

Our third university grant recommendation, therefore, is that provision be made whereby an applicant, if supported by the head of his department, can obtain an explanation of the reasons for the size of his award.

4. Grants fall into two fundamentally different categories, those to individuals or groups of individuals for their own research, and those for the maintenance and operation of facilities. Grants to individuals have, in the past, been awarded either singly or as block grants to groups of individuals. They have been on an annual basis, on a three-year term basis and more recently on a biennial basis. An insistence on individual one-year grants will, in view of the increasing number of applications, lead to a monumental task for the organization assessing the applications. It will also involve an enormous amount of time and effort in the preparation of the grant applications on the part of an appreciable fraction of the country's physicists. We therefore feel that individual one-year grants should no longer be especially emphasized, and that both block grants and term grants should be encouraged. The difficulty with term grants is that they remain constant unless escalation factors are included or unless the grantee is permitted to reapply for an increase before his term period is complete. We feel that both these possibilities should be allowed.

Our fourth university grant recommendation, therefore, is that block grants and term grants should be reinstated, and that term grants should carry with them a guaranteed annual increment of 10%; grantees of term grants should be able to apply for an increment above the 10% after two years of a three or more year term grant.

5. The second category of university research grant is awarded for the maintenance and operation of facilities. Facilities are assemblies of equipment such as nuclear particle accelerators, telescopes, wind tunnels, high field magnets etc., used in common by a number of

staff members and maintained in operating condition by a staff of technicians.

Grants for the support of these facilities should be relatively easy to assess once the distinction between the research costs and operating costs has been established. We feel that this separation should be made by the applicants, who should apply for individual or block research awards in the manner just described. The operating costs of the facility should then be assessed and budgeted by a visiting committee appointed by the granting organization, and support for the facility made for an extended period. Some provision should be included for normal increased costs and a mechanism created whereby supplements can be applied for before the expiry of the budget period.

Our fifth university grant recommendation, therefore, is that grants for the operation of facilities should be made separately from those to the individuals who will use them, should be assessed by visiting committees, and should be awarded for extended periods with provision for escalation and for supplements on appeal.

6. The "new man" has always been a difficult applicant for granting organizations. He usually has a modest publication record and has not yet proved his abilities. Under their present granting guidelines the best these organizations seem to be able to do for him is to give him a small, almost token, "beginner's grant", in the hope that his university will express its faith in him by using its own funds to get him started on his independent research career. This may be a feasible procedure for a new man in a large university, but a small university may well have great difficulties in raising the necessary funds. The new man may therefore be caught immediately in a vicious cycle; he cannot produce publishable research results without funds and cannot get the necessary funds from grants until he produces publishable results and establishes his reputation.

We are pleased to note that at least one provincial granting organization (Ontario) has been sufficiently concerned with this problem to give special consideration to such applicants. Nevertheless the main responsibility rests with the federal granting agencies and to help resolve their difficulties we offer two suggestions, the first applicable to larger established universities and the second applicable to smaller universities.

In the first we propose a new type of grant called a 'Joint Grant'. This would cover major equipment and supplies needed to start the "new man's" program and would be applied for by him under the patronage of a senior staff member whose field of research is somewhat related to his. The application would be for expenditures over a three-year period with an appreciable fraction being made available for the first year.

At a smaller university without an established research reputation it is unlikely that a suitable "patron" will be available, and in these circumstances we recommend a negotiated "Development Grant" between a senior officer of the university concerned and the granting organization. The application should then be reviewed by a visiting committee whose composition should be restricted to university staff and which should, if possible, include representation from a local larger university. This procedure could be extended, perhaps in a slightly modified form, to the new man starting a new field of research in a larger university.

Our sixth university grant recommendation, therefore, is to introduce "Joint Grants" to be applied for under the patronage of a senior scientist by a "new man" getting started at a larger university, and to introduce negotiated "Development Grants" for "new men" at smaller universities and for new men starting new fields at larger universities.

We see flaws in these two suggestions and in the corresponding sixth recommendation, but discuss them here in the hope that they will initiate a serious discussion of this difficult problem by granting organizations.

7. Finally we mention a problem on which we have failed to find any unanimity on the part of university physicists: should the individual grants be assessed directly by awarding committees who work only from the applications, aided perhaps by the reports of visiting committees, or should the applications be refereed before presentation to the awarding committees?

We feel that there should be a gradual change from the present system toward a referee system, but we know that our opinion is not shared by all physicists. We are also a little concerned about the magnitude of the administration of such a referee system. We are, however, pleased that visiting committees have been used this year in assessing large applications, and hope that this procedure will be further extended.

4.6 SUPPORT OF RESEARCH IN INDUSTRY

In Chapter 3 we have outlined the existing program for the support of research in industry and have suggested that it is inadequate. Our first general recommendation in Section 4.1 of this chapter reiterated our concern for this deficiency and our financial recommendation in Section 4.3 suggested an appropriate level of increase. We now present seven detailed recommendations for the mechanism of of this support:

1. *Our first recommendation for the support of research in industry is that the government substantially increase the number and extent of the fully-funded long-term research programs offered to industry.* Although the main emphasis should be oriented toward applied research, some of these programs should be of a basic nature in order to give industry the opportunity to establish a properly balanced research and development activity.

2. *Our second recommendation is that the present cost-sharing programs be put on a sliding scale with the government-to-industry cost ratio being determined by the basic-research to applied-research content ratio of the program.* This would, we hope, encourage industry to do more research in basic physics and thereby greatly increase the strength of its overall research structure.

3. *Our third recommendation is that aid should be made available to scientists in industry for the support of unsolicited projects.* In this way bright ideas coming from industrial laboratories could be fostered and developed. At the moment there appears to be no way in which scientists in industry can appeal to government support for such new ideas of their own. The exact details of the mechanism of such support will have to be worked out between industry and government granting agencies; it might take the form of a contract between the agency and the industry.

4. The first three recommendations for the support of research in industry have been particularly oriented toward individual projects initiated either by government or by industry itself. We also consider that industry should be given a much greater share of new general research programs than has been customary in the past. *Our fourth recommendation is, therefore, that Canadian industry should be given a substantial research role in any major new programs that may be initiated, particularly if the programs are "mission oriented".* Relegating industry solely to the role of hardware development will ensure that industry will never develop either the caliber of manpower or the interest required for research.

5. It is urgently necessary to encourage management in industry to become more interested in research, and with this in mind, *our fifth recommendation is that, where applicable, each production contract from the government carry with it a closely scrutinized*

grant for research of 2 to 3% of the value of the contract. If the company is not willing to spend such money on research, then it would not be eligible to receive the grant.

6. Existing tax incentives for research and development in industry have been of considerable value. *Our sixth recommendation is that such tax incentives should be continued.*

7. It is important that closer relations be fostered between government and industrial laboratories. With this in mind *our seventh recommendation is that arrangements be made whereby government and university physicists be encouraged to spend one or two years in industrial research laboratories.* In this way they would obtain a better appreciation of the technological climate in industry and hence be better able to undertake the role that government research establishments could play in stimulating the technological development of Canada. Such a program might eventually lead to an exchange of physicists between government and industrial laboratories.

8. The system of postdoctorate fellowships has worked well in the universities and in government laboratories. It has benefited both the laboratories and the fellows themselves, and has helped Canada's relations with the underdeveloped countries from which several of the fellows have come. We feel that a similar scheme could profitably be started in industrial laboratories and that it would further strengthen research in industry. It would also provide an excellent link between industry and universities if some of the fellows, after postdoctorate study in industry, take up academic careers.

Our eighth recommendation is, therefore, that provision be made for postdoctorate fellowships in industrial research laboratories.

4.7 SUPPORT OF RESEARCH IN GOVERNMENT LABORATORIES

It will have been noted from Section 4.3 that our recommendations greatly favor future support of research in industrial laboratories and in universities over that in government laboratories. Nevertheless we do not wish to give the impression that research in the latter should be stifled. Far from it! The research done in government laboratories has earned international recognition and has attracted many distinguished scientists to Canada. For a long time practically all Canadian research was done, and done well, in such laboratories. The present strength of our university research and the growing strength of our industrial research stems from the earlier work in government laboratories, and still depends to a considerable extent on a continuation of such in-house research.

For many years to come industries will turn mainly to the government laboratories for help with problems beyond their own immediate capabilities. Furthermore, these laboratories will always be the guardians and maintainers of the fundamental standards, which are so necessary in a developing industrial economy.

Far from phasing out government laboratories we have, in section 4.3, recommended a 15% annual increase in their support. This is twice the scientific inflation rate and should continue to keep them strong and competitive. We wish to reiterate this in the following specific manner.

Our recommendation for the support of government laboratories is that it should be adequate to enable them to grow in a manner befitting the developing nature of Canada's economy. We feel that this will be accomplished by a 15% annual increase in the level of support over the next five years.

We nevertheless have become aware of a slight lack of internal coordination between different groups of physicists working on similar subjects within the government, despite the existence of the many committees mentioned in Chapter 3. To a great extent this lends a flexibility to the research undertaken; however, we feel that in some instances a better in-house coordination might be advantageous.

Part II

SUBDIVISION REPORTS

Section 1

ASTRONOMY

J. L. Locke (Chairman), D. A. MacRae and W. H. Wehlau

1.1 DEFINITION OF FIELD

The domain of astronomy is the entire universe. The immediate aim of astronomy is to learn the nature of the objects and the sources of energy within the universe. But its ultimate aim is to understand how the objects were formed, how they arrived at their present state and how they will evolve in the future – indeed, to discover the life history of the universe.

This broad definition of astronomy embraces fields that are usually regarded as separate branches of physics. These fields, such as geophysics, upper atmosphere and space physics, and cosmic ray physics, will not be considered in this report. It should not be surprising, however, to find that the astronomer's interests often overlap the interests of scientists in these other fields. For instance, the studies of the geophysicist are of interest to the astronomer, since they relate to his interpretation of the other planets. Conversely, some astronomical observations yield information of value to the geophysicist. For example, the interpretation of certain terrestrial phenomena is dependent upon observations of conditions in the solar atmosphere. Often, the separation of fields is in terms of techniques rather than of interest. Thus although the techniques of space research are foreign to the astronomer, he sees in them an opportunity to further his own interests and it is becoming obvious that, in the future, astronomical observations will represent a larger part of the effort in space.

Although astronomy is often regarded as an ancient science it was not until the beginning of this century that it could be regarded as a branch of physics. Prior to 1900 the main activity of most of the observatories of the world was the determination of the positions of celestial objects. The observed motions of the planets and their satellites were explained by the laws of classical mechanics. The measurement of stellar motions was restricted to the component of velocity at right angles to the line of sight. In the main, the observatories were government supported because of the practical uses of the positional work, principally in geography and navigation. But with the introduction of the spectroscope began the studies of the space motion of stars and the physical nature of celestial objects. The new astronomy came to be known as "astrophysics", thus emphazing its close relationship to physics.

The universe became a vast laboratory. In this laboratory, the distances are so great and parameters such as temperature and pressure often so extreme that similar conditions cannot be produced in terrestrial laboratories. The interpretation of astronomical observations must, therefore, lean heavily on theory. The universe is the testing ground for theories of extremely weak interactions between particles and fields, and of relativity.

The astronomer studies a wide diversity of objects from interplanetary dust grains of microscopic size to clusters of galaxies, each containing billions of stars. Only the very closest objects can he ever hope to study by direct means. For all other studies he must obtain his data by studying the small amounts of radiation that have travelled the distance between the object and his measuring equipment. Modern astronomy uses a host of tools involving techniques ranging from simple cameras to satellites, from photographic plates to sophisticated electronic techniques, from infrared detectors to gamma-ray detectors. It relies on the data from molecular and atomic physics, elementary particle and nuclear physics, radio physics, plasma physics, and the physics of condensed matter.

More and more, progress in observational astronomy depends upon the detection of very weak signals. The measurements can be carried out only with large instruments – radio and optical telescopes costing large sums of money. Astronomers who do not have access to these large instruments cannot contribute to the frontier problems of the science.

1.2 HISTORY OF ASTRONOMICAL RESEARCH IN CANADA

The early history of astronomy in Canada is associated with the requirement, in a new land, for the determination of accurate lines of latitude and longitude. Records exist of solar eclipses observed by the early Jesuits in Quebec for the determination of longitude. The first astronomical observatory in Canada was founded at Fredericton, N.B., in 1851, for the primary purpose of determining latitude and longitude. Other small observatories followed – at Quebec City in 1854, at Kingston in 1875, and at McGill University in 1879.

(i) Research in government institutions

The participation of the Canadian Government in astronomy dates back to 1885 when the first modern longitude surveys were undertaken to define lands involved in railway construction in British Columbia. This eventually led to the establishment of the Dominion Observatory on its present site in Ottawa in 1905. Because of their practical application, accurate measurements of time and star positions were important functions of the new observatory, but provision was also made for research in the new field of astrophysics. A refracting telescope of 15 inches aperture (a large instrument for those days) and a reflecting solar telescope were provided. Thus began the strong support of astrophysical research in government institutions, which has continued to the present day. From the beginning, the Dominion Observatory also undertook research in geophysics, as it does today, but the Geodetic Survey was separated from the Observatory in 1917.

Although important contributions were made with the 15-inch telescope through the application of spectroscopy, the progress of astronomy was so rapid at that time that it soon became evident that, if the significance of the work by Canadian astronomers was to continue, a much more powerful telescope was required. Impressed by the international reputation which Canadian astronomy had assumed, the Government of Canada established, in 1918, the Dominion Astrophysical Observatory near Victoria, B.C. At the time of completion the west-coast telescope, 72 inches in aperture, was the largest in the world. Equipped with a versatile spectrograph the new observatory very soon made important contributions to the knowledge of stellar motions, double stars, the structure of the galaxy, and the physical and chemical nature of stars. Especially notable were the investigation of the rotation of the galaxy by J.S. Plaskett and J.A. Pearce, the studies of molecular spectra in cool stars and the interstellar medium by A. McKellar, and the determination of luminosities, motions and distribution of early-type stars by R.M. Petrie.

It was not until 1962 that the facilities of the Dominion Astrophysical Observatory were expanded with the addition of a smaller (48-inch aperture) telescope equipped with a powerful spectrograph. In the meantime, the need for a much larger telescope, comparable or superior to those existing in other countries, was being acutely felt. The result was a proposal for the construction in Canada of a 150-inch telescope. Government approval was granted in 1964 for construction of such a telescope to be located on Mt. Kobau in southern central British Columbia. The telescope, to be operated as a facility for all qualified Canadian scientists, is expected to be in complete operation by 1973. It is planned that this new observatory and the associated headquarters on the campus of the University of British Columbia will be the focal point of all optical research in astronomy in Canada.

Following the establishment of the Dominion Astrophysical Observatory in 1918, most of the work in stellar spectroscopy was transferred to Victoria. The Dominion Observatory continued activity in positional astronomy and solar spectroscopy and expanded the time service. Meteor research was begun after World War II and observing stations established in northern Alberta in 1952.

Recognizing the rapid advances being made through the use of radio techniques in furthering astronomical knowledge, the Dominion Observatory established, in 1960, the Dominion Radio Astrophysical Observatory on a quiet site near Penticton, B.C. To extend the studies in galactic structure, which had been so successfully carried forward in Victoria, the first equipment was designed primarily for 21 cm. observations – an 84-foot paraboloid and associated receiver. Two low-frequency telescopes have since been added.

The entry of the National Research Council into astronomical research grew out of the realization that the technical knowledge and equipment that had built up within its laboratories as a result of radar work during World War II could be readily used to obtain radio astronomical data. In 1946 the Radio and Electrical Engineering Division commenced investigations of the radio emission from the sun with a small radio telescope situated near Ottawa. Thus began an uninterrupted series of daily observations of solar flux at 10.7 cm., which has been used throughout the world as a basic index of solar activity. In 1955 a linear array was constructed on the same site to give increased one-dimensional resolution for the study of small active regions above sunspots.

Because of increases in radio interference, the solar program was relocated, in 1962, at the Algonquin Radio Observatory, near Lake Traverse within Algonquin Park. The first phase of a multi-element array for high-resolution studies has been completed there, and observations at longer wavelengths are in progress.

The success in the solar observations spurred interest within the Radio and Electrical Engineering Division in other aspects of radio astronomy. A parabolic radio telescope, 33-ft. in diameter for galactic and extragalactic studies was put in operation at the Algonquin Radio Observatory in 1963, and an impressive new telescope, 150-ft. in diameter, has recently been brought into operation. This new telescope is the finest in the world in terms of performance at centimeter wavelengths. The facilities of the Algonquin Radio Observatory are available to all Canadian scientists and a wide range of research programs has begun.

For reasons similar to those that brought about the beginning of radio astronomy within NRC, the Radio and Electrical Engineering Division began, after World War II, a study of meteors by radar methods. Following the formation of an Upper Atmosphere Research Section in 1955, the Springhill Meteor Observatory was built near Ottawa. Beginning with the IGY, radar observations have been on a continuous basis, supplemented with visual and spectrographic observations. A program of acoustic detection of micrometeorites, using rockets, is also under way.

(ii) Astronomical research in the universities

Interest in astronomical research at the University of Toronto dates back at least to 1892. A separate Department of Astronomy was established in 1904 and this department has been responsible for the training of many Canadian astronomers. The untiring efforts of Prof. C.A. Chant in the promotion of the cause of astronomy culminated in 1932 in the donation by Mrs. Jessie Donalda Dunlap of an observatory to the university in memory of her husband. The principal instrument of this observatory, the David Dunlap Observatory, is a 74-inch telescope, completed in 1935. At present it is the largest optical telescope in Canada. In the early years the prime interest at the Observatory was in radial velocities and the study of variable stars in globular clusters. With the recent increase in graduate students, a more varied program is now undertaken, including photoelectric photometry, determination of stellar luminosities from stellar spectra, and galactic and extragalactic research. With the advent of computing facilities at the university, theoretical studies, particularly of stellar models and stellar evolution, have received growing attention. The University of Toronto is also engaged in radio astronomical research, a cooperative program of the Departments of Astronomy and Electrical Engineering. The University has modest observing facilities at the David Dunlap Observatory.

In 1940, through the efforts of Dr. H.R. Kingston, the University of Western Ontario constructed the Hume Cronyn Memorial Observatory, named in honor of Major Hume Cronyn, M.P., for London, a man who had a great influence on the early history of the National Research Council. The observatory houses a 10-inch refractor and one of the first Schmidt telescopes in North America. A program of photoelectric photometry was initiated in 1955. Following increased activity in spectrographic and theoretical astrophysics, a separate Department of Astronomy was established in 1966. The university's facilities for graduate training and research are at present being expanded with the acquisition of a 48-inch optical telescope to be located off-campus.

There has been an interest in optical astronomy at Queen's University since 1861. A 24-inch telescope and facilities were intalled on campus in 1955. The same year, a radio astronomy research group was formed, combining the interest of staff in the Physics and Electrical Engineering Departments. Observing facilities for radio astronomy have been established on a site near the university campus.

The rapidly growing interest in astronomy and the demands of graduate students prompted activity in other universities. A Department of Astronomy was recently created at the University of Victoria. Research in radio astronomy began at the University of British Columbia in cooperation with the Dominion Radio Astrophysical Observatory in the early sixties.

1.3 MANPOWER AND FISCAL SUPPORT

(i) Manpower

In 1966 there were approximately 80 scientists employed in astronomical research in Canada. Of these, about 60 (or 75%) could be classed as astronomers involved directly in the solution of astronomical problems – either scientists with the Ph.D. degree or persons undertaking work at the Ph.D. level. Not all have degrees in astronomy. This is particularly true in radio astronomy; many of the present workers are graduates in electronics engineering or physics.

The remaining 25% of the professional scientists are employed either as assistants to senior research workers or as professionals involved indirectly in supporting roles. Examples are computer and electronics engineers involved in the design and maintenance of radio astronomical and other equipment.

The rate of growth in manpower over the past five years is shown in Fig. I. For the past few years the growth has been most rapid in radio astronomy and the requirement for radio astronomers is expected to remain high. However, the establishment of the Mt. Kobau Observatory by the Observatories Branch of the Department of Energy, Mines and Resources will bring about a need, in the future, for optical astronomers. The requirements of government institutions will be reflected in the requirements for university professors to take care of the expected increase in graduate students. These are the determining factors in the projections to 1972 shown in Fig. I.

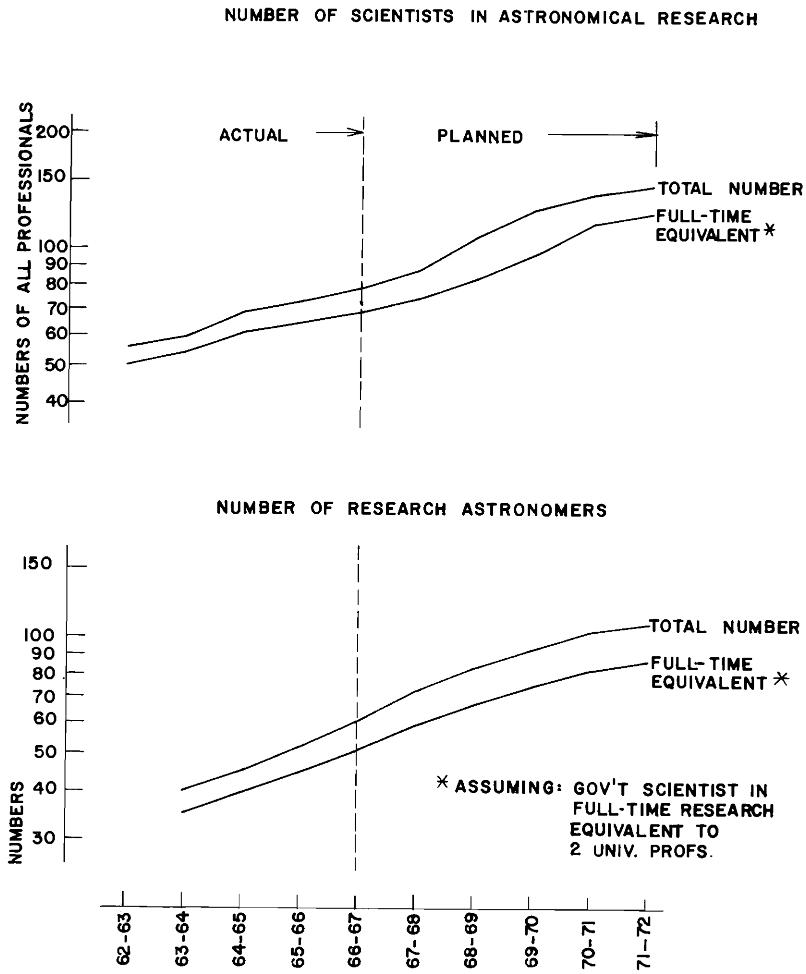

Fig. I Numbers of scientists in astronomical research and number of research astronomers, recent and projected. Vertical scales are logarithmic.

If all existing plans are carried forward, then by 1972 the total number of professionals will approach 150. Of the 90 additional researchers required, approximately 50 should be graduates in astronomy at the Ph.D. level – approximately one third of these in radio astronomy and the remainder in various fields of optical astronomy.

(ii) Operating costs

Total operating costs for research in astronomy for the year 1966-67 are estimated at approximately $3 million. (Fig. II) For the past five years, costs have been rising at the rate of approximately 15% per year and a similar rate is forecast for the next five years. Since university expenditures are a small fraction of government expenditures, this rate of increase is primarily that of government operations.

Operating expenses of universities, by themselves, show a much greater rate of increase – approximately 30% per year over the ten-year period. This higher rate of increase reflects the increasing enrollment of graduate students in the older graduate schools, such as Toronto, Western, and Queen's and the establishment of graduate research programs at other universities such as British Columbia, Waterloo, and Victoria.

In order to calculate the operating cost per scientist, the full-time-equivalent number of scientists has been determined on the assumption that the average university professor spends 50% of his time on research activities. The operating cost per scientist was $42,500 in 1966. Forecasts of staff and operating expenditures indicate the cost per scientist will rise to about $48,000 per year by 1972. This latter figure is surprisingly low. The forecasts of operating costs on which the calculation is based may well be in error, but the increase may in fact be small, since by 1972 the existing facilities will be sustaining a considerably larger number of scientists.

(iii) Capital costs

Capital expenditures for the years 1962 to 1967 and forecasts to 1972 are shown in Fig. III and Table I. During the period 1960-65 expenditures were dominated by the cost of establishing the Algonquin Radio Observatory by NRC – the 150-foot telescope and other facilities. A peak expenditure of about $4 million occurred in 1965-66 resulting from the beginning of the Mt. Kobau project by the Department of Energy, Mines and Resources while NRC expenditures were still large. The forecast for the next five years is dominated by the Mt. Kobau project – the Queen Elizabeth II telescope and ancillary telescopes, and the associated headquarters on the University of British Columbia campus.

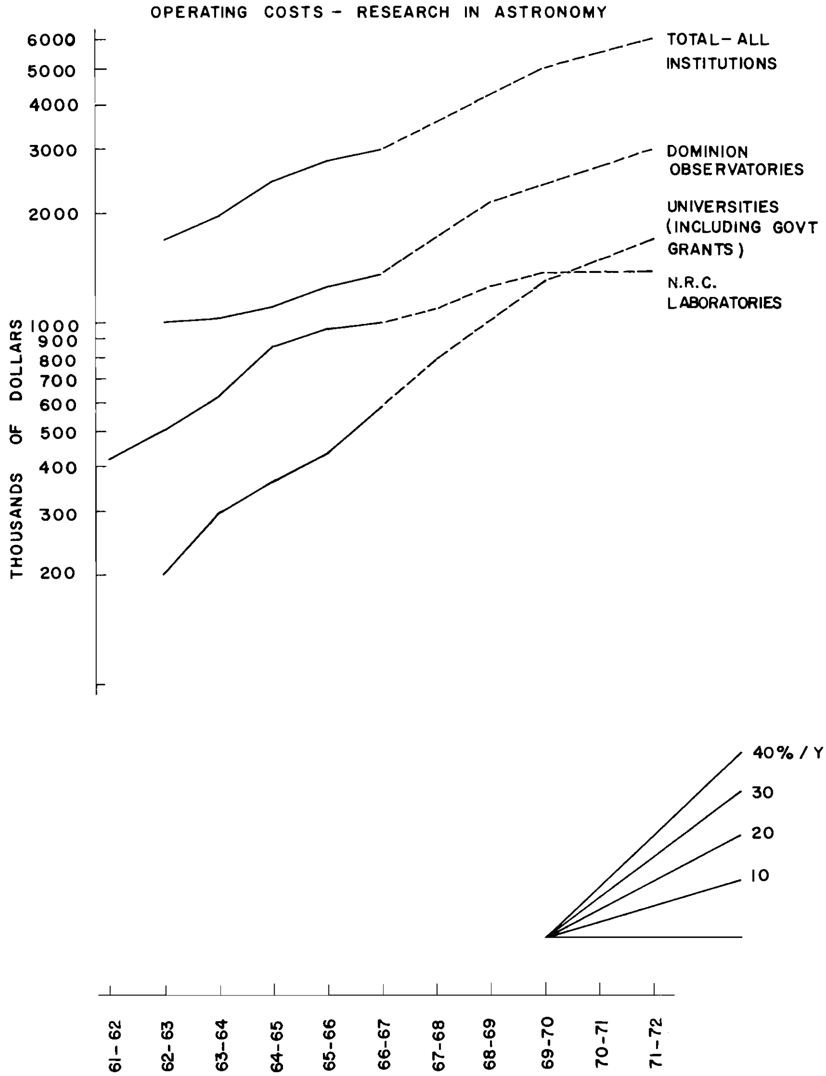

Fig. 11 Operating costs (logarithmic scale) for research in astronomy, recent and projected. The inset shows slopes corresponding to rates of growth of 0, 10, 20, 30 and 40 percent per annum.

CAPITAL COSTS – RESEARCH IN ASTRONOMY

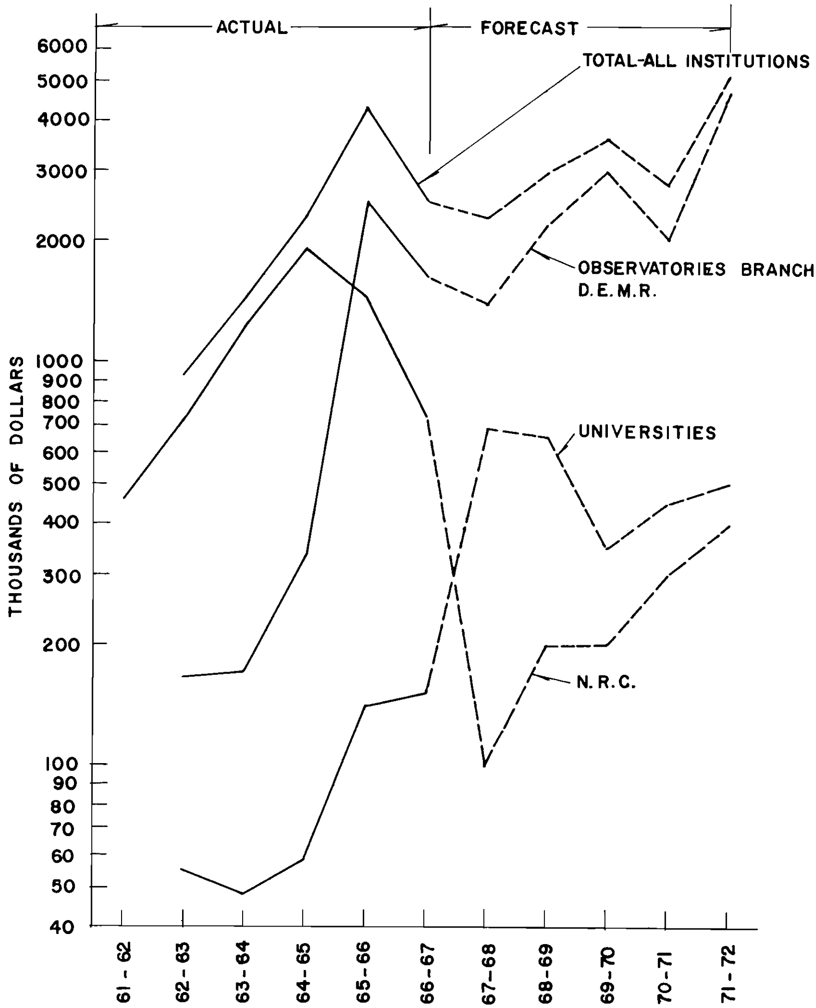

Fig. III Capital costs for research in astronomy, recent and projected. The vertical scale is logarithmic.

TABLE I. Approximate Expenditures for Astronomical Research*

Fiscal Year	Government observatories		Universities†	
	Operating	Capital	Operating	Capital
1962–63	1,500	890	200	55
1963–64	1,650	1,425	300	50
1964–65	2,000	2,250	350	60
1965–66	2,200	4,000	450	140
1966–67	2,350	2,350	600	150
1967–68	2,850	1,500	790	700
1968–69	3,350	2,225	1,020	675
1969–70	3,700	3,250	1,300	350
1970–71	4,000	2,350	1,450	450
1971–72	4,300	5,200	1,700	500

* In thousands of dollars
† Including all grants

Capital expenditures for 1966-67 are estimated at $2.5 million, increasing to about $5 million in 1972 toward the end of construction of the Mt. Kobau project.

It is difficult to forecast capital extenditures beyond 1972. However, the present level of capital costs may well extend beyond 1972. There will be an increasing demand for small telescopes (48-inch aperture or less) to be located at universities. These telescopes will be required for research training at the graduate level since it is uneconomical to use large telescopes at remote locations for this purpose. There will also be a demand for new instrumentation for radio astronomy.

At the present stage in the development of radio astronomy, radio telescopes become obsolete very quickly. In the forecast for the next five years there is no provision for large radio telescopes so that it is likely that by 1973 the need for increased facilities will be urgent.

Because of the rebuilding program in progress, capital costs are at present roughly equal to operating costs, and will remain so until 1972. This contrasts with the situation in the United States where, in 1963, the ratio of capital to operating costs was about 0.6 (Pake Report). However, the situation regarding observing facilities in the United States has been deplored by astronomers there. They have called

TABLE II. Grants to Support Research in Astronomy (in Thousands of Dollars)

Year	University	Toronto	Western Ontario	Queen's	British Columbia	Victoria	Montreal	Calgary	Waterloo
By NRC									
1962–63	O*	46.1	4.5	40.0	–	–	–	–	–
	C*	14.7	–	–	–	–	–	–	–
1963–64	O	46.5	4.5	55.0	–	2.5	–	–	–
	C	2.5	–	–	–	–	–	–	–
1964–65	O	51.2	5.5	63.0	–	3.0	–	–	–
	C	7.5	–	–	–	–	–	–	–
1965–66	O	62.0	12.7	55.0	2.5	3.5	–	–	–
	C	60.0	25.0	–	–	–	–	–	–
1966–67	O	95.5	20.0	57.8	15.5	4.0	1.2	–	–
	C	107.0	75.0	–	10.0	–	–	–	–
By Dept. of Energy, Mines and Resources:									
1965–66		2.5	1.4	–	2.7	–	–	–	–
1966–67		2.9	1.2	–	2.0	–	–	0.5	1.8

*O is operating, C is capital.

for the spending of $224 million over the next ten years for ground-based observing facilities (Ground-based Astronomy – A ten-year program, National Academy of Sciences, 1964).

(iv) Federal grants to universities

Virtually all grants-in-aid of astronomical research in the universities are NRC grants (see Table II). In 1965-66 the Department of Energy, Mines and Resources instituted grants for astronomical and geophysical research. The funds are, however, small – $10,000 in 1965-66 and 1966-67, $25,000 in the estimates for 1967-68 – and are unlikely to increase rapidly since the money must be found in the operating vote of the Department.

The 1966-67 level of operating grants to universities is $200,000 per year. Over the past five years, the level of grants has risen at a rate of approximately 20% per year. However, as shown above, operating expenses of the universities are increasing at a faster rate, 30% per year. The 20% per annum rate of increase in grants (the same as that recommended by the Bladen Commission for the next five years for science in general) will, therefore, not be adequate. The situation is a result of the growing importance of astronomy, as compared with other sciences, in the universities.

Major equipment grants for astronomy have fluctuated widely and no trend can be established. Grants for the acquisition of small optical telescopes and measuring equipment have been made to the University of Toronto and the University of Western Ontario.

1.4 NUMBERS OF DOCTORAL STUDENTS

During the years 1962 to 1966 only about 10 Ph. D. degrees were granted by Canadian universities for research in astronomy, either optical or radio. During the same period, approximately 40 students received M.A. degrees; many of these students proceeded to higher degrees at foreign universities.

The number of students enrolling for graduate studies in astronomy is rapidly increasing. In the present year (1966-67) there are 26 graduate students in astronomy at the University of Toronto alone. The number of Ph. D. degrees granted in astronomy by all Canadian universities in 1967 is likely to be 7, and the number per year will increase to about 12 by 1972. Over the next five years, then, there are likely to be about 45 new Ph. D. graduates.

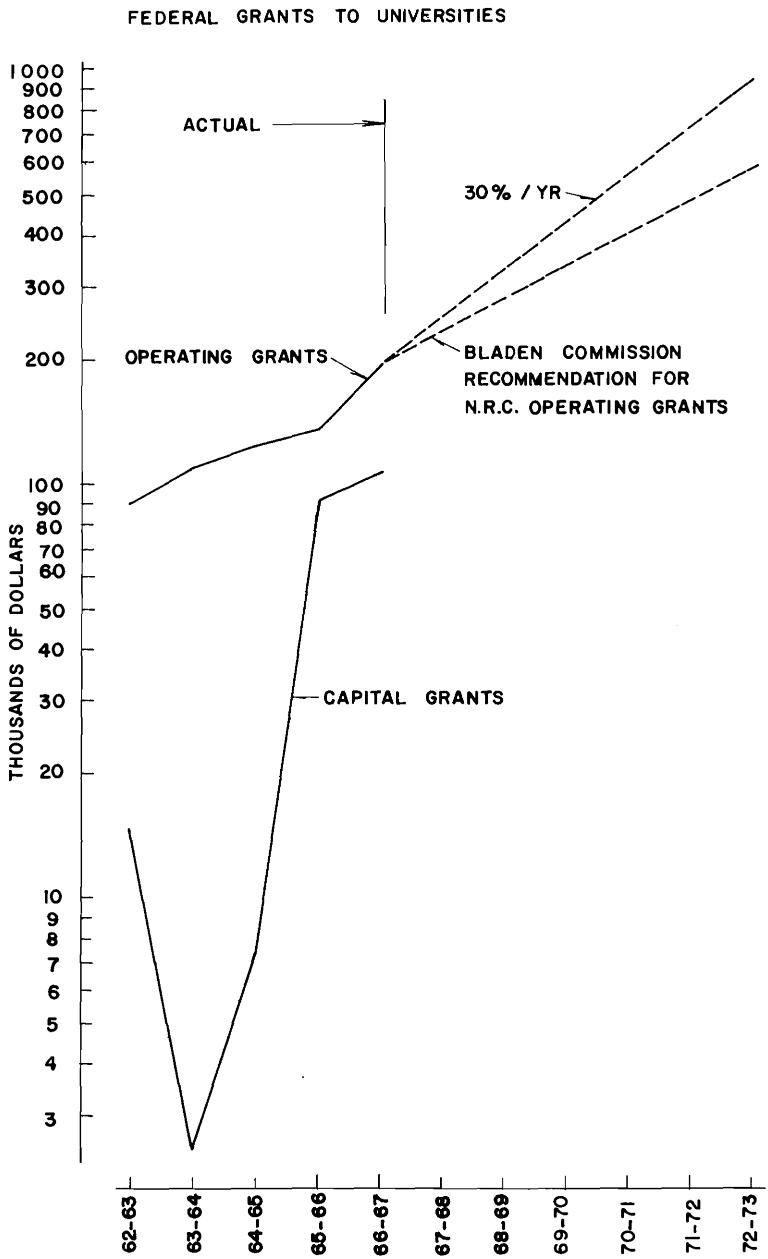

Fig. IV Federal grants to universities for research in astronomy in recent years. For comparison, the operating grants have been projected according to recommendations of the Bladen Commission and also assuming a 30 percent per annum rate of growth. The vertical scale is logarithmic.

If expansion in astronomical research and teaching in Canada proceeds as now planned, this number will be insufficient to fill the needs. When it is realized that some will find employment elsewhere, and that there are unlikely to be graduates specialized in certain fields in which government institutions are active, the number of Ph. D. graduates is likely to fall short of requirement by about a factor two.

1.5 DISTRIBUTION OF ACTIVITY BETWEEN GOVERNMENT AND THE UNIVERSITIES

Since the early days of astronomical research in Canada, by far the major activity in observational astronomy has been concentrated in government observatories. At present, government operating costs for research in astronomy are nearly five times those of the universities. When activity was small this imbalance was not critical. However, with the growth of the science since World War II, the effect of this imbalance has been that the output of astronomers from Canadian universities has been inadequate to fill the needs of government institutions. Specifically, the limited opportunities for graduate research in astronomy at Canadian universities has had the following effects:

(i) government institutions have had to look to foreign countries for staff to meet their requirements.

(ii) in some areas of research it has been necessary for government institutions to hire graduates in other fields of physics and provide in-house training.

(iii) some of the best Canadian graduates have had to leave the country to obtain training in particular fields and many do not return.

The difficulties encountered by government in hiring competent staff are increased by the fact that some areas in which government institutions are active (e.g. positional astronomy and optical solar astronomy) are not now represented in Canadian university research programs. It should also be mentioned, parenthetically, that another factor has been the inadequacy of government research facilities – a situation that is now being corrected with the construction of modern observatories for both optical and radio astronomy.

The situation regarding theoretical astrophysics is different. In recent years, theoretical research at the universities has been increasing but there has been no corresponding increase in the government agencies.

For many years the University of Toronto was the only graduate school in astronomy. Thus it may be said that an imbalance existed among the universities themselves. A number of other universities are now undertaking, or planning, graduate programs. Not all universities, however, should be expected to enter the astronomical research field; it would be preferable to have only a few relatively large centers of excellence.

At present research activities in the universities are increasing slightly more rapidly than those in government. The quickening pace has been brought about by several factors. Not the least of these is the existence or promise of national observing facilities available to all universities. Capital grants, such as the NRC grant for a telescope to the University of Western Ontario, have also had an important effect. But fundamentally the pressure on the universities is external since they must respond to the demands of increasing numbers of graduate students. For a healthy development of astronomy in Canada, university participation must continue to grow rapidly and, in this connection, it is encouraging to note the plans for expansion at such universities at British Columbia, Victoria, and Waterloo.

1.6 SIGNIFICANT UNANSWERED QUESTIONS IN ASTRONOMY

In a subject as complex as astrophysics it is impossible to list all the outstanding problems. We can attempt to outline only representative ones, with the knowledge that the ones selected will not include ones which another group would consider the most urgent.

(i) The solar system

(a) Solar physics

In recent years great progress has been made in understanding the general physical nature of the solar atmosphere. The maintenance of the corona at the high temperature ($10^{6\circ}$K) determined from eclipse observations and by radio methods can now be explained by the existence of shock waves (acoustic, internal gravity, and hydrodynamic) generated in the convective zone. The theory predicts that the corona will expand steadily, producing a corpuscular solar wind which blows out through the solar system, carrying with it the solar magnetic field. The wind has recently been observed from space vehicles, and direct measurements made of its velocity, density, and magnetic field.

The radiation belts around the earth are a result of the solar wind and thus variations in the corona, and hence the solar wind, are of great interest.

Although the general density, temperature, and velocity distribution in the outer atmosphere of the sun can now be explained, the detailed processes are extremely complicated and progress in explaining them is understandably slow. The region where the convection originates is below the photosphere and unobservable. Only the upper layer of the convective zone can be seen as a granular pattern in high resolution photographs of the solar surface. The size distribution of solar granulation and the velocities within the granules are difficult to measure, as are the magnetic fields which must be carried with the convection.

In a complicated and little understood process, the motions interact with the magnetic field to produce effects in the solar atmosphere, collectively referred to as solar activity. The observable features of solar activity are the sunspots, plages, filaments and prominences, and the accompanying changes in the structure of the corona. Since solar activity exhibits an 11-year cycle, observations of these phenomena are only slowly acquired and the investigations often statistical in nature. In the optical region the data consist of brightness measurements and spectrographic observations (line profiles, doppler shifts and Zeeman effect measurements). Changes in the chromosphere and corona can be followed by radio methods – solar flux variations, spectral changes and, more recently, high resolution scanning techniques. Observations from space vehicles are now adding information about the ultraviolet and X-ray regions of the spectrum.

The most violent phenomenon is the solar flare, observed in the optical region as a local brightening of strong spectral lines. As the disturbance propagates through the outer atmosphere there are associated with it bursts of radio noise of various types, and energetic particles which are injected into the solar wind. Theories of the flare phenomenon are, at present, only speculative.

(b) Meteor physics

The methods of observation and many of the results from the study of meteors are astronomical. But, since the meteor process involves the passage of a solid body through the earth's upper atmosphere, many of the results are geophysical. Measurements of deceleration yield data on upper atmosphere densities, and spectroscopic and radar observations give data on the physical reactions involved.

Most, if not all, meteors are found to have elliptical orbits about the sun and, therefore, presumably have an origin in the solar system. From the astronomical point of view, therefore, interest in meteors and meteorites rests on the information they can give about the material in interplanetary space (abundances, isotope ratios, and physical structure) and the evolution of the solar system.

The brightest meteors can be satisfactorily explained by a physical theory assuming solid particles of asteroidal origin, and valuable checks of the theory are now becoming available from experiments with artificial meteors launched from rockets. But the vast majority of faint meteors and shower meteors do not fit this theory. There is photographic evidence that appreciably greater fragmentation occurs along the trails of these meteors, suggesting that the average meteor is a loose conglomerate of material of cometary origin. The precise nature of these particles in interplanetary space and their evolution is, however, uncertain.

No satisfactory explanation has been given for the existence of the auroral green line in the spectra of some fast meteors. Also uncertain is the nature of the long-duration, persistent trains that accompany some meteors. Although spectroscopic data are lacking, the major contributors to the luminosity are the resonance lines of sodium, whose persistence is difficult to explain.

Radar methods give information on meteors of much lower magnitude than do optical methods. Direct observations of meteoric matter of even smaller dimension are now being made by the recording of impacts on acoustic systems flown in rockets. The relation, if any, between micrometeorites and the zodiacal light is still not known.

The astronomical interest in meteorites is in the information they can give on the abundance of the elements, the origin of the solar system, and conditions in interplanetary space. Exposure ages can be determined from measurements of the abundance of isotopes produced by cosmic ray bombardment and hence give some information about the effects of collisions and erosion in space. There are, however, serious doubts about the interpretation of the data. The origin of tektites is still an open question.

The astronomical interest in terrestrial meteorite craters stems from their similarity to lunar features. The importance of meteor impacts in geological interpretation is a much-debated subject. The study has general application to theories of high-energy explosions and the little-understood behavior of material under high temperature and pressure.

(c) Planets

The study of the structure and chemical composition of planetary atmospheres is undergoing rapid progress through the use of balloons and satellites which make available the infrared and ultraviolet regions of the spectrum. Atmospheric temperatures are being obtained by both radio and optical techniques. The existence of radiation belts around Jupiter, trapped by the planetary magnetic field, are inferred from studies of radio bursts. The exact nature of the bursts, and their dependence on solar activity, is a question for further study, as is the apparent dependence on the position of optical features and the position of the planet's satellites. Studies of the circular polarization of the radio emission have been used to determine the tilt of the magnetic axis. Higher and higher powered radars are being used to determine distances and the direction and speed of rotation of the planets. Finally, high-resolution pictures of the planets, and radio studies of the atmospheres, are beginning to be made from space probes.

(d) The moon

For many years there was little interest in lunar research, but the moon is now the object of intense study. This is, in part, because of the project to put a man on the moon. But before this effort began interest was being renewed in some of the outstanding fundamental problems concerning the moon's surface and the origin of the earth-moon system. The origin of the lunar craters is still puzzling; some appear to be meteoric in origin, others volcanic, and the relative importance of the two causes is uncertain. The nature of the surface is now somewhat better known as a result of lunar landings but its precise structure and the manner in which it was formed are in doubt. There are puzzling observations of fluorescent phenomena over restricted regions of the lunar surface. The planned program of lunar landings will undoubtedly provide solutions to many of these questions.

(e) Origin of the solar system

At the present time the origin of the solar system is a matter for theoretical speculation. Additional observational material to guide the theorists has recently been added through radar measurements of the rotation of the planets and studies of the interplanetary material. A reliable theory for the formation of our own planetary system is essential for estimates of the probability of other planetary systems in the galaxy, and hence to the probability of intelligent life elsewhere.

(ii) The stars

The physical study of stars covers a wide range of topics. The basic problems are to understand the physical processes occurring both in the atmospheres and interiors of stars, how the stars were formed, and the way in which they evolve. To solve these problems great quantities of basic data are required. Spectrographic and photometric determinations of color and apparent brightness of a star establish its temperature and variability. Studies of the line spectrum of a star give its intrinsic luminosity, chemical composition, and information about the magnetic fields in its atmosphere. Observations of binary systems establish the masses, radii, and luminosities of stars of different classes. The data – masses, chemical composition, radii, surface temperatures, luminosities, and variability – are the raw material for all studies of stellar structure and evolution.

In order to collect these essential data for a sufficient number of stars of all types and luminosities, long periods of observing with the largest telescopes are required. Although certain critical information (chiefly from the ultraviolet and X-ray regions) will, in future, be obtained using telescopes in space, the bulk of the data required is obtainable with ground-based telescopes of adequate size. Progress has been slow because of the small number of telescopes of adequate size.

Theoretical studies of stellar evolution require large high-speed computers, which are now available, and thus progress has been rapid. In fact, refinement of theories has surpassed the available data necessary to check them. More observations of stellar clusters are needed. Since the members of a star cluster are presumably of the same age, and different clusters have different ages and chemical composition, cluster observations provide checks of the theories of stellar evolution. Observations of variable stars are important since their instabilities are believed to represent major transitions in the life history of the star and should lead to a better understanding of stellar evolution and energy production. Since variable stars exhibit a high degree of individuality, and often differ greatly from one cycle to the next, observations over extended periods of time are required.

(iii) The galaxy

Galactic problems may be grouped under three main headings:

(a) Galactic structure

What is the distribution of material in the galaxy? How are stars of different type distributed and what is the arrangement of star clusters and associations? What is the density, chemical composition, temperature, ionization, and distribution of interstellar gas and dust? What is the nature of the galactic nucleus? What are the systematic and random motions of galactic material and what is the dependence of these motions on distance from the nucleus and height above the galactic plane? What is the strength and distribution of magnetic fields?

(b) Galactic dynamics

What are the forces that hold the galaxy together and determine its present form?

(c) Galactic evolution

What is the age and life history of the galaxy? What is the relation between interstellar material and stars, and what is the process of star formation?

In answering these questions, both optical and radio observations are playing important parts. Information on the distribution and motions of stars depends on large-scale programs of distance determinations – parallax measurements for the nearby stars, and extension to the more distant stars through intrinsic brightness indicators and interstellar absorption measurements. The optical evidence of structure covers only a small fraction of the galaxy because of interstellar absorption, and significant distances are reached only for the intrinsically bright stars. Extension to fainter stars, and hence greater distances, requires the use of the largest telescopes.

Radio methods, which are not restricted by interstellar absorption, enable the entire galaxy to be investigated. The general distribution of atomic hydrogen into arms has been delineated by 21 cm. line studies but there are many uncertainties about their exact form because the distance determinations are affected by unknown departures from the average law of rotation. Studies of the size, distribution, and peculiar velocities of interstellar hydrogen clouds are just beginning and depend on observations with telescopes of high resolution. The recent discovery of the OH line promises to give important clues about physical conditions in different parts of the galaxy but, at present, interpretation of the observations is a perplexing problem. Other atomic and molecular lines in the radio region have been predicted but not yet found. Their detection, although difficult, would provide badly needed additional clues. An outstanding problem is the abundance of molecular hydrogen. Dynamical considerations indicate that its density may be appreciable but it has remained undetected because the hydrogen molecule possesses no spectral lines in observable regions of the spectrum. Infrared observations from satellites might provide the answer soon.

The investigation of ionized hydrogen (H II regions) is an important field for both optical and radio astronomy because of its importance in theories of star formation. Studies of supernova remnants, by both optical and radio means, are required for an understanding of the final explosive stages of certain stars, and the interaction of high speed particles, magnetic fields, and interstellar matter.

The distribution, spectrum, and origin of galactic continuum radiation pose problems that are related to the existence of magnetic fields and high-energy cosmic radiation in the galaxy.

A recently discovered feature of the galaxy is the existence of of X-ray sources, which, to date, have been studied only during the short flight of rockets above the absorbing atmosphere. The most intense source, named Sco XR-1, appears to be associated with a nova-like object; another source has been positively identified with the Crab nebula. Many of the sources appear to be variable but the data are fragmentary. There is no doubt but that X-ray astronomy will become an important line of research in the near future and the data will become more complete and reliable when use is made of artificial satellites as observing platforms.

(iv) External systems and cosmology

The observation of extragalactic objects is a field for only the largest optical and radio telescopes. Thus, optical work in this field in Canada has been restricted and dependent upon observations taken elsewhere. The problems are ones of determining distance, size, shape, luminosity, content, and internal motions and from these quantities to formulate theories of evolution and dynamics. They are the basic data for cosmological theories.

Currently, the most perplexing and interesting problems are those posed by the radio galaxies, the quasi-stellar sources, and blue stellar objects. In the strongest radio galaxies the energy density reaches 10^7 times that of our own galaxy. The quasi-stellar sources have large red-shifts, which, if interpreted as cosmological, indicate immense distances. Yet these objects are believed to have small diameters. If this is so, it is difficult to see how existing theories of energy production can account for their high luminosity. If the sources are not at cosmological distances, it seems impossible to explain their red-shifts. The possibility that these sources may be at extreme distances is exciting because of the potential data they can contribute to the cosmological problem. In any event, the existence of these sources is one of the most exciting and mystifying discoveries in the history of astronomy.

1.7 CANADIAN RESEARCH PROGRAMS

Over the past forty years, Canada has played an important part in the development of optical astronomy. However, in relation to other countries, the importance of the work has steadily declined because of failure to keep pace in the development of modern observing facilities. The situation is now being rectified with the decision to build the Queen Elizabeth II, 150-inch telescope, and proposals for auxiliary instrumentation on Mt. Kobau.

The situation in radio astronomy, a relatively new branch of the science, has improved greatly with the completion of the 150-foot telescope and other observing facilities at the Algonquin Radio Observatory. Radio astronomy is now a vigorous field in Canada and significant contributions can be expected.

(i) Solar physics

Since the early days, the Dominion Observatory has been engaged in solar research, but contributions have been meagre because of the absence of a viable group and the lack of modern instrumentation. The development of a magnetograph for the investigation of small-scale structure of solar magnetic fields has progressed slowly. During the IGY and until quite recently, the major program, partially financed by NASA, has been the routine observation of solar flares in the light of hydrogen-alpha. This work must be regarded primarily as a service, rather than independent research. Nevertheless, the data have been of great value to those involved in the prediction of ionospheric phenomena and optimum conditions for communications and manned space flights.

Solar radio astronomy was pioneered by NRC in 1946 when a program of measurement of the flux at 10 cm. was begun. The measurements have continued to the present and their value as a reliable index of solar activity has been internationnally recognized. The material has been the source of many investigations of solar activity and is sought, on an immediate basis, by agencies responsible for the prediction of phenomena related to solar activity. To give added coverage and some redundancy in the observations, NRC has installed another patrol telescope at the Dominion Radio Astrophysical Observatory, Penticton, which is operated by Observatory personnel. The solar program now includes high resolution studies, also at 10 cm. for which a multi-element array is under construction at the Algonquin Radio Observatory. Research is also undertaken in the spectra of bursts at meter wavelengths.

Information on the very low frequency (0.5 to 1 MHz) spectra of solar bursts is being studied by DRB using data which are a by-product of the Alouette topside sounder program.

(ii) Meteor astronomy

In the field of meteor physics, Canada is a recognized leader. The Dominion Observatory has been active in optical studies of meteors since 1946 and NRC in radar studies for a similar period. The two programs are complementary.

The Dominion Observatory operates observing stations at Meanook and Newbrook, Alberta, each equipped with a Super-Schmidt camera (f/0.65, f.l. 200 mm. 55° field). These stations were established for the accurate triangulation of meteor trajectories and investigations of the upper atmosphere by the measurement of decelerations. This program is now essentially completed and consideration is being given to the transfer of one of these instruments to Mt. Kobau. A variety of meteor cameras are operated at Meanook and the spectra, which are only slowly accumulated, have contributed to an understanding of the meteor phenomenon.

NRC operates several types of radar for the detection of meteors at the Springhill Meteor Observatory near Ottawa. Visual and spectrographic observations are also taken for correlation with the radar data. A vast amount of statistical data on such matters as meteor rates, radiants, and size distribution has been accumulated. A program of acoustical detection of micrometeorites in space is also under way using rockets launched in Canada.

Following the identification in 1952 of the New Quebec (Chubb) Crater as an old meteorite crater, the Dominion Observatory launched a program of identification and study of other circular features visible on aerial photographs. About a dozen features are now suspected to have meteoritic origins and drilling operations in some of them have supported this hypothesis. The investigation of these suspected craters is an active research program of the Dominion Observatory.

It involves primarily the geophysical divisions, engaged in both field and laboratory studies, and its costs have not been included in this report.

(iii) Planetary research

Only a small amount of planetary research is in progress in Canada, essentially all by radio methods. Brightness temperature measurements at centimeter wavelengths are being undertaken by NRC and at millimeter wavelengths by the University of Toronto. There is an interest in Jovian bursts at both NRC and the Dominion Radio Astrophysical Observatory.

(iv) Stellar research

Because of their large telescopes, the Dominion Astrophysical Observatory and the David Dunlap Observatory have for many years been the major centers of stellar research. With the acquisition of a 48-inch telescope, contributions from the University of Western Ontario can be expected to increase and eventually the facilities on Mt. Kobau will enable groups at other universities to participate.

The observational techniques are primarily spectrographic although increasing emphasis is being placed on photo-electric observations. The topics under investigation cover a wide range and all projects cannot be recorded here. The programs include studies of normal stars, peculiar A stars, high-luminosity stars, intrinsically variable stars, spectroscopic binaries, long-period eclipsing systems, and globular clusters.

Theoretical investigations into stellar evolution are being undertaken, primarily at the universities. For checking many points in the theories, observations of very faint stars are required and these are beyond the telescopic power presently available in Canada.

(v) The galaxy

Traditionally, galactic structure is a field in which Canadian optical astronomy has made large contributions. Studies of the motions and distribution of stars in our galaxy, and of interstellar matter, have been major programs of the Dominion Astrophysical Observatory since its beginning. Radial velocity determinations and other galactic investigations have also been a major part of the program of the David Dunlap Observatory. In recent years, this work has diminished in importance because of the lack of a telescope of sufficient light-gathering power to extend the investigations to fainter stars.

It was with the history of Canadian galactic research in mind that the Dominion Radio Astrophysical Observatory was established. The first instruments were designed for the study of neutral interstellar hydrogen – the 84-foot telescope and 21 cm. line receiver. This receiver is at present being modified for multichannel operation with a potential decrease of 100-fold in observing times required for these studies. Receivers are also being provided to cover a wide frequency range (1000 to 4000 MHz) for searching and investigating other spectral lines. Two large low-frequency arrays (22 and 10 MHz) have also been added. These provide maps of the continuum background and, in conjunction with similar surveys at higher frequencies, provide information on the distribution and density of ionized hydrogen clouds (HII regions) in the galaxy.

With its new 150-foot radio telescope NRC is now, able to continue, with higher resolving power, studies of HII regions at centimeter wavelengths begun with its 33-foot telescope. The universities (University of Toronto and Queen's University) are also engaged in observations of specific HII regions using this facility. Programs of investigation of super-nova remnants and planetary nebulae are also under way.

(vi) External systems and cosmology

The optical investigation of galaxies beyond our own stellar system requires the largest telescopes, and virtually all observations in this field are obtained with the large telescopes in the United States. Canada will, however, be able to contribute to this vital branch of astronomy upon completion of the Queen Elizabeth II, 150-inch telescope.

Canadian radio astronomers are, at present, active in this field. The 150-foot telescope of the Algonquin Radio Observatory is admirably suited to studies of extragalactic radio sources and, in particular, the quasi-stellar sources. The complete study of quasi-stellar sources requires a combination of optical and radio observations and it is unfortunate that the corresponding optical observations cannot yet be taken in Canada. Canadian radio astronomers are involved in the determinations of flux densities at a number of frequencies and variations in flux density are being investigated at centimeter wavelengths. An imaginative experiment is being undertaken to investigate the diameters of the quasi-stellar sources. The experiment, in which all radio astronomy groups in Canada are participating, is an attempt to use the large telescopes at the Algonquin Radio Observatory and the Dominion Radio Astrophysical Observatory as the elements of a very long baseline interferometer. If successful, effective resolution of less than 0.01 seconds of arc will be possible, opening up a large field in the investigation of the size and structure of very small radio sources.

Interest in cosmological problems is not restricted solely to astronomers and there is activity in this field among physicists and mathematicians, particularly at the universities.

(vii) Time service, positional astronomy and astrometry

The Time Service of Canada is maintained by the Dominion Observatory. As the name implies, the primary purpose of this activity is not research but to provide, by the observation of star transits, a standard of time for Canada. Accurate time is made available, by radio and other means, to all those requiring it. But with the advent of atomic standards of time, the stellar observations now provide refined information on the vagaries of the earth's rotation. Studies are, therefore, now made in the variations of angular velocity of the earth as well as the wandering of the pole of rotation. The Dominion Observatory at Ottawa uses a special telescope for time determination, a Photographic Zenith Telescope. A second telescope of this type is being established near Calgary, at essentially the same latitude as the Ottawa instrument, to observe the same set of program stars and hence study relative motions of the two sites.

The determination of accurate positions of fundamental stars is classical physics. However, the results are of interest to the astrophysicist since observations over large periods of time provide the data on transverse stellar motions. Since the beginning of the Dominion Observatory, meridian circle observations have been a major activity. A mirror transit telescope, designed and built by the Dominion Observatory, has recently been brought into service. It is hoped that this will reduce the errors of measurement. Because the land on which this instrument is located is required by the Department of Agriculture, it must soon be moved to a new location, possibly on Mt. Kobau.

Astrometry refers to the determination of the positions of stars relative to a fundamental system of stars or galaxies and is normally carried out with specially designed photographic telescopes. The observations are important in studies of the motions and distances of stars and the evolution of stellar associations. No observational work of this kind is, at present, being carried out in Canada but the

Dominion Observatory has plans for the construction of an astrometric telescope, in excess of 60-inches aperture, on Mt. Kobau.

1.8 RELATION OF ASTROPHYSICAL RESEARCH TO OTHER SCIENCES

Except for positional astronomy and some aspects of solar astronomy, the work mentioned in this report must be considered basic science and, as such, is not concerned with practical application. Nevertheless, astronomy has had a profound impact on other fields and its technical requirements have influenced the trend of technology.

As mentioned earlier, astrophysics often involves the behavior of matter under extreme conditions, extending the experiments and theories of atomic, nuclear, and plasma physicists working in the laboratory. With the discovery of increasingly high sources of energy in the universe, it now has a close link with cosmic ray and particle physics. The influence of solar conditions on the earth's upper atmosphere makes the geophysicist and upper-atmosphere physicist dependent upon astronomical observations. The effects of meteorite bombardment have important consequences in geology and in the studies of the behavior of solids under high pressure. The influence of astronomy on the space program is, of course, well known.

The findings of astronomy are a never-ending source of new ideas for mathematicians and physicists in other fields. The explanation of astronomical observations often forces consideration of entirely new concepts, particularly in energy production. An excellent example is the recent discovery of quasi-stellar sources, which has aroused as much interest among physicists in other fields as among astronomers.

The advanced techniques developed for astronomical measurements have found their way into other branches of physics as well as into technology. The need to detect and measure low light levels has brought about advances in photoelectric detectors and photographic emulsions. The advances in design of spectrographs for astronomical purposes have been employed in other branches of physics. In radio astronomy the requirement to detect weak signals has brought about advances in low-noise receivers and techniques for the recovery of of wanted signals from instrumental noise. The design of antennas and the concept of combining the outputs of antennas (for example, the aperature synthesis technique) have found application in communication and radar. Radar studies of meteors have resulted in a practical communication system involving reflection from meteor tracks.

1.9 SPECIAL CONSIDERATIONS

(i) National observing facilities

Large, modern telescopes, both optical and radio, are costly—$4.5 million for NRC's 150-foot radio telescope, and approximately $13 million for the Queen Elizabeth II 150-inch optical telescope and and the development of the Mt. Kobau site. These costs dictate installation at a site where the best possible observing conditions prevail. For large optical telescopes, steady and transparent air, as well as low rainfall and clear skies are essential, conditions that are satisfied only on remote mountain tops. Radio telescopes must be free from man-made interference, a requirement dictating sites remote from centers of population.

These considerations have led, in both the United States and Canada, to the concept of national observing facilities. In Canada these national facilities are being constructed and operated by government. Capital costs for the period studied are dominated by the construction of two major facilities, one for radio observations (the Algonquin Radio Observatory) and one for optical observations (the Mt. Kobau Observatory). Observing time at both these facilities is, or will be, available on an equal basis to all qualified scientists in the country. This subcommittee approves the establishment of facilities of this kind.

Realization of the aims of these facilities is not without difficulties, and it may be of interest to record some of them as an aid to those responsible for administering the facilities. The organization of the operation of these facilities, particularly the Mt. Kobau Observatory, will have a large effect on the development of astronomy in Canada, both in government and at the universities:

(a) The tasks of testing and determination of telescope performance will fall upon the permanent personnel. They will be required also to make changes to equipment required for university-based observing programs and on occasion to assist with the observations. Unless personnel are assigned specifically to deal with the needs of the universities, other permanent personnel will find that their own researches will suffer.

(b) Teaching obligations in Canadian universities make it difficult for professors to use facilities away from the university. This fact must be realized in setting up observing schedules, and recognized by university administrations.

(c) Professors and their graduate students located farther from the facility will incur travelling expenses, which are greater than for those who are located in nearby universities. Some scheme must be worked out to ensure that this situation does not prevent equality in the use of the facility. The merit of the proposed observing program should be the sole factor determining its use.

(d) Despite all precautions, it is inevitable that the facility will have the most profound effect on development of research in the universities closest to it. Thus a strong department is almost certain to develop at the University of British Columbia if, as planned, the headquarters of the Mt. Kobau Observatory is situated on its campus. Plans for the development of astronomical research at this university are welcomed unanimously by the astronomical community. But there is a danger that the establishment of an institute on the campus of the University of British Columbia will weaken the graduate schools in the East, inasmuch as the best research professors and graduate students may be attracted to that university because of its proximity to the institute.

(e) The universities take seriously their responsibility in molding the student. Thus certain universities are loathe to allow their graduate students to spend long periods of time away from the campus even though their research programs may require an extended period of stay at the facility, either observing or using measuring instruments that do not exist at the university. It may also occur that the most capable person to supervise the student's research is on the staff of the facility and not all universities will allow outside supervisors. A solution to this problem and those mentioned in the preceding sections may be found in joint appointments or temporary exchange of university and government personnel, and in generous provision of measuring equipment, computing facilities, and technical assistance at the universities.

(ii) Observing facilities at the universities

It is impossible to train students in any field of experimental physics without modern equipment. This does not mean that the equipment must be the very largest; but it must be readily accessible and sufficiently complex that the student will have no difficulty, when the time comes, in using a major instrument. In astronomy this means that every active graduate department should have fully equipped research instruments located near the university.

A modern telescope near the university has many advantages. The equipment is available for the many astronomical problems not requiring the largest telescopes. Problems requiring close surveillance (variable stars, eclipsing binaries, intrinsic variables, variations in the radio emission from the sun and Jupiter) can best be studied with equipment close at hand. It provides also for the testing of observing programs and equipment to be used later on the large telescopes, thus ensuring the most efficient use of the costly facility.

In the opinion of the members of the committee, optical telescopes larger than about 48 inches aperture should not be installed at university sites. Experience in the United States at, for example, the Case Institute of Technology, the University of Wisconsin, the University of Michigan, and Vanderbilt University, has demonstrated that telescopes of this size can contribute to the progress of observational astronomy. Good telescopes even as small as 16 inches will go a long way in filling the need.

The case for radio telescopes is not so straightforward, partly because of the diversity of types of radio telescopes and the requirement for large physical size to obtain even modest resolving powers. However, many of the present-day problems are those of techniques in receiver and antenna design and these can be tested on modest instruments prior to installation on a large telescope located in a quiet site. A decision on the limiting size of observing instruments at the university must, perforce, be an economic one, having regard to other demands on the source of funds, either federal or university.

(iii) Relation between optical and radio astronomy

In this report, astronomical research has not been subdivided by techniques. Rather, an attempt has been made to show how the various techniques can contribute to the solution of common problems. Nevertheless, it is common to think of astronomical research in terms of techniques, and, in particular, to separate optical astronomy and radio astronomy.

While certain astronomers work solely with either optical or radio techniques and feel no need for direct communication with the other group, undeniably the most exciting discoveries in recent years have been the results of cooperation between the two groups. The prime example is the discovery of the existence of quasi-stellar sources.

The need for cooperation is most strongly felt among the radio astronomers. Perhaps the major barrier preventing effective communication between the groups lies in a lack of understanding of the other's terminology and techniques. There is also a reluctance among some optical astronomers to recognize that radio techniques can make significant contributions to the solution of astronomical problems that gave rise to their own research. Conversely there is a feeling among some radio astronomers that the problems are sufficiently different that communication, except through publications, is unnecessary.

The members of the subcommittee feel that, since the ultimate aims of the two branches of astronomy are the same, efforts in Canada should be directed to effective cooperation between optical and radio astronomers. To this end, administration of federal agencies should be arranged to facilitate exchange of ideas. An exchange of personnel between radio and optical observatories might also be effective in breaking down the communication barriers. Future astronomers should have an understanding of both branches and this can best be achieved where optical and radio research exist side by side in the same university.

(iv) Organization of astronomy in Canada

The majority of the astronomical research in Canada has been done in government observatories and related organizations. Until recently, the University of Toronto was the only university with a developed research program and even this had been restricted considerably by financial limitations. At present, government facilities and activities still exceed those of the universities, but the ratio is changing. The biggest single factor for the future appears to be the development of the Mt. Kobau Observatory and the Queen Elizabeth II telescope, which will be discussed below. The Algonquin Radio Observatory is similarly a major factor at the present time. Other countries show a variety of structures for their astronomical research, but generally the universities seem to play a relatively larger role than they do in Canada.

Before World War II the Dominion Observatory in Ottawa and the Dominion Astrophysical Observatory in Victoria were the only federal astronomical institutions in Canada. The research program of the Dominion Astrophysical Observatory was under the direction of the Dominion Astrophysicist, but administratively both observatories were the responsibility of the Dominion Astronomer in Ottawa.

The situation has changed markedly since that time. The Observatories Branch of the Department of Energy, Mines and Resources has expanded steadily. Its traditional activities have been extended to include meteor physics and radio astronomy, and its growth has culminated in the decision to build the 150-inch Queen Elizabeth II telescope. The astronomical work is now organized into three divisions—the Dominion Astrophysical Observatory, Victoria; the Dominion Radio Astrophysical Observatory, Penticton; and the Astronomy Division at Ottawa. The positions of Dominion Astronomer and Dominion Astrophysicist have been dropped and all divisions report to the Director, Observatories Branch, who is also responsible for the work of three geophysical divisions. The work of coordinating the design studies of the 150-inch telescope has fallen, naturally, on the staff of the Dominion Astrophysical Observatory.

The National Research Council is now also deeply involved in astronomical research. Beginning with the early observations of solar radio emission in 1946, the growth of radio astronomy at NRC has reached the point where its operating expenses are not appreciably less than those for all astronomy in the Observatories Branch of the Department of Energy, Mines and Resources. The research is organized in the Radio Astronomy Section of the Division of Radio and Electrical Engineering. Research in meteor physics is carried out in the Upper Atmosphere Section of the same Division.

The question arises as to whether it would be desirable to combine all these activities under one administration. The Royal Commission on Government Organization (Glassco Report) recommended that all federal astronomical research be consolidated in a national institute of astronomy within NRC, but no action has yet been taken on this recommendation.

From the research worker's point of view a common administration is not a prerequisite for cooperation with other workers in his field. He requires only financial and technical support from sympathetic administrations. An excellent example of cooperation between astronomers under different administrations is the truly joint effort of all radio astronomical groups in Canada in the Very Long Baseline Project. Research groups should not be consolidated merely for the sake of tidy administration unless the research effort will benefit. A single administration for astronomy would, however, have the advantage that there would be one voice to speak for federal astronomers and to state their needs. Within the limitation of federal funds available for all research, the course of astronomical research would be in the hands of the astronomers themselves.

There are a number of types of astronomical research that appear to be best suited to government observatories, in particular, projects requiring many years of concentrated effort. In this class we may list the following:

(a) Projects requiring routine observations extending over many years. Canadian examples are studies of the rotation of the earth associated with observations required for the time service, and radio observations of the sun at 10 cm. as an index of solar activity.

(b) Positional or fundamental astronomy. Transit and meridian circle observations are generally government observatory responsibilities because of their routine nature and the requirement for continuity in maintenance and calibration.

(c) National observatories for the use of all astronomers in the country.

There are, at present, three scientific committees that consider various aspects of astronomical activity in Canada. None of these, however, has the authority to exercise control over the course of astronomical research in all government agencies or to recommend to government policies for university participation. The three committees are:

(a) The National Advisory Committee on Astronomy. This is a committee established to advise the Minister of the Department of Energy, Mines and Resources. It is composed of representatives from government and university, under the chairmanship of the Director of the Observatories Branch. It was created primarily to deal with problems related to the establishment of the Mt. Kobau Observatory, but discusses and advises upon other astronomical matters as well.

(b) The Associate Committee on Radio Science of NRC. This is a typical NRC associate committee with representatives from government and the universities. It serves as the National Committee for the International Scientific Radio Union (ISRU) and in this capacity organizes the work in Canada of Commission V (radio astronomy) of the Union.

(c) National Committee for Canada for the International Astronomical Union. The Department of Energy, Mines and Resources is the adhering organization for Canada and supports, financially, the National Committee for Canada. Its function is to organize the work of the Union in Canada but it has also served as a forum for discussion of matters pertaining to all astronomical research and teaching in Canada, and has organized symposia.

Normally, universities can be expected to carry out a considerable amount of research in astronomy. Examples from other countries indicate that this research can be very fruitful. It is clear that there is a minimum threshold of research activity required for the benefit of graduate students and faculty. In order to educate students adequately in astronomy it is absolutely necessary that they engage in, or be closely involved with, some research work, and also that their professors be familiar with current problems and techniques, through their own research interests. In most universities that are active in astronomy throughout the world, considerably more than this minimum of research work is carried out. The university environment has certain natural advantages for the pursuit of research.

The association of astronomers, physicists, engineers, and others, which can be found at a university, provides an interaction that leads to a rapid development of new knowledge in all the fields. The access that the astronomer has to a wide variety of other scientists at the university is very helpful in the development and investigation of new problems.

Most theoreticians seem to prefer the university environment; as a result the interaction between observational astronomers and theoreticians takes place most effectively in the universities.

The presence of students, particularly graduate students, provides a stimulus to the established astronomers. The association of the faculty and students is beneficial to both, and leads to increased research activity.

For the reasons given above, as well as others mentioned elsewhere in the report, it is clearly desirable that there should be increased research and teaching in astronomy at the universities. An important consideration here is the availability of suitable instruments. Although research can be carried out effectively by using observations that were obtained elsewhere, for a competent and effective program in astronomy it is generally necessary that adequate observational equipment be available at the university. This is required not only by the training and instructional needs of the undergraduate and graduate students, but also to enable the observational astronomers to develop their own programs and equipment. Since most universities are not located near sites of the best quality for observing, the amount and size of equipment installed must be limited by considerations of the cost of installation and operation, in comparison with the important advantage of having the equipment immediately accessible. Very large expensive instruments should, on the other hand, be located at the best available sites. The increased effectiveness of a large telescope at a good site outweighs the expense and inconvenience of transporting astronomers and graduate students to the site. In turn, a graduate student who has learned the necessary techniques on a smaller instrument can take full advantage of his time on the larger one.

The Algonquin Park Radio Observatory is developing into a national observatory. Such a large instrument as the radio telescope there most effectively serves astronomy by being in the best available site. The use of this instrument by university astronomers and others, in addition to NRC personnel, has developed from the natural advantages to all groups of such cooperative operation. The Queen Elizabeth II telescope ought to perform the same function for optical astronomy.

The establishment of a national optical observatory could be a most efficient way of satisfying the needs of government and university astronomers, and graduate students, for observations that can be obtained only with a large instrument. The development of such an installation is essential for the continuing effectiveness of astronomical research in Canada, and should make Canada one of the leading nations in world astronomy.

An excessive concentration of astronomical equipment at one national observatory should be avoided, insofar as possible, because of the danger of a monolithic institution, which would dominate astronomical work in Canada, to the possible detriment of astronomical work throughout the rest of the country.

The location of the national optical observatory is a matter of considerable concern and has received a great deal of attention recently. The advantages of a location for the observatory in the Southern Hemisphere have been pointed out by a number of Canadian and other astronomers. There can be no doubt that a large telescope at a good southern hemisphere site, such as the ones in Chile, would give Canada a pre-eminent position in astronomy. The present lack of large telescopes in the southern hemisphere, together with the many interesting objects that require study there, would give a great advantage to any astronomers in a position to study the southern skies with suitable instruments.

Regardless of whether a southern hemisphere or northern hemisphere site is finally preferred, it is essential that the site be one at which the instrument will be effective and capable of providing for the needs of astronomers all across Canada. The principal questions involved are those of weather, and the size of the image resulting from atmospheric effects. The final decision on the location of the

150-inch telescope should be made only after a complete and careful final evaluation of all weather, seeing, and logistical questions.

The development of astronomy within the universities should proceed in a rational manner. It is clearly impractical for all universities in Canada to have fully developed astronomical programs including research, graduate students, and equipment of intermediate size. The financial support of astronomical research and equipment should provide for a number of universities with fully developed Ph.D. programs, and fairly extensive observational and laboratory equipment, capable of effective research work in a number of fields. Another group of universities should have equipment and programs enabling them to carry out more limited graduate work and effective research in a limited number of fields. Other universities should be encouraged to develop still more limited programs in astronomy, relying primarily on the national facilities and other observatories for the source of observational data for the research interests of their faculty members. Since there is currently comparatively little astronomy in the universities, this rational development of astronomy is not in conflict with any of the existing situations. This provides an excellent opportunity for the universities, in cooperation with bodies granting funds for equipment and research, to arrange for a balanced development of astronomy.

1.10 UNIVERSITY GRANTS

The major complaints heard concerning the administration of grants-in-aid, scholarships, and fellowships were ones of timing—complaints which may be peculiar to astronomy.

University astronomers regard summer observing and other practical experience at the university observatory as essential for the student. Financial support for the summer is imperative as well as financial assistance for the next academic year. The professor must be able to inform the student early in the calendar year if this assistance will be forthcoming. In practice, however, announcements of grants and scholarships are not made until April or later, often after the student has been forced to commit himself to other plans.

Although, in general, grants to individual professors were considered good, since they gave freedom to the professor, there was a feeling by some that block grants were also necessary. For the development of an astronomical program under the head of the department such grants would be most beneficial.

Section 2

UPPER ATMOSPHERE AND SPACE PHYSICS*

P. A. Forsyth (Chairman)

2.1 INTRODUCTION

The field of upper atmosphere and space research in Canada has been the subject of a separate detailed study[1] (Chapman Report). In that study over a hundred briefs were received and hearings were held at all the principal centers at which pertinent research is being carried out. In preparing the present section no attempt was made to repeat the survey. Instead the information relating specifically to physics has been extracted from the Chapman Report and is presented briefly here. In addition, a few people who are closely associated with upper atmosphere and space physics have been given a "second chance" to express opinions or to change the emphasis in the statements made in the previous study. Readers who want more detailed information than is given here should refer to the Chapman Report.

2.2 DEFINITION OF FIELD

Research in upper atmospheric and space physics does not represent a single discipline that can be distinguished clearly from others. Rather it represents the application of several disciplines developed in the laboratory to a set of phenomena that occur in a new and challenging environment. In particular, there are problems of atomic and molecular physics, plasma physics, particle physics, electromagnetic theory, and fluid dynamics, which require solutions in order to further an understanding of the outer reaches of the earth's atmosphere.

*The Appendix on cosmic rays was written by D. C. Rose.

[1] Science Secretariat, Special Study No. 1, Upper Atmosphere and Space Programs in Canada, J. H. Chapman, P. A. Forsyth, P. A. Lapp, G. N. Patterson, Queen's Printer 582-7/1967

For purposes of this study, attention is concentrated on phenomena that occur at distances of more than 50 kilometers from the surface of the earth but at distances less than those of primary interest to the astronomer. No clear-cut division of interest can be made between the space physicist and the meteorologist on the one hand and the astronomer on the other. Indeed, the photochemistry of the atmosphere is continuous across the 50 kilometer level and there is an enormous transport of energy by radiation and by collisional processes in both directions across this level. At the other extreme the physics of the sun and solar-terrestrial interactions are of interest both in space physics and in astronomy.

The methods of investigation used in upper atmospheric studies include direct measurements, using rockets and satellites, and indirect measurements, using balloons and ground-level optical or radio observations. Also included are those laboratory experiments directly related to upper atmoshperic investigations, such as attempts to simulate upper atmospheric phenomena in the laboratory.

In Canada most of the research has been directed toward studies of the mechanical and chemical behavior of the ionosphere; relatively little work has gone into studies of the lower neutral, or higher fully-ionized, regions of the atmosphere. This concentration is due largely to the unique character of the ionosphere over Canada. The northern auroral zone (zone of maximum auroral occurrence) cuts across Canada in an arc that is roughly east-west over Churchill and swings north over Quebec and the Yukon. The presence of the auroral zone results in extremely variable, disturbed conditions in the ionosphere, and for this reason has attracted the attention of scientists from many nations including Canada.

2.3 HISTORY OF CANADIAN INTEREST

The present Canadian interest in upper atmosphere and space research can be traced directly to the scientific expeditions sent by a number of countries into Canada's northland during the first polar year, 1882-83. Although few Canadians were involved in the expeditions, the fact that scientists from other countries were particularly interested in the unique characteristics of some geophysical phenomena as observed from Canada seems to have attracted the attention of many Canadians. From earlier reports carried back to Europe by explorers, it was clear that auroral displays were particularly frequent and intense in Canada, and that unusually strong magnetic disturbances often accompanied the auroral displays. It is now recognized that these characteristics are due to the particular configuration of the earth's magnetic field, which in turn is responsible for the auroral zone described above.

Fifty years after the first polar year another great international year of geophysical study was launched, and this time, in 1932-33, a number of Canadians took part. In particular, observing stations at Meanook and at Chesterfield Inlet were manned by Canadian parties. Spectroscopic and photographic observations of the aurora were made, together with records of the earth currents and magnetic fluctuations that accompanied the auroral displays. Because of the participation in this program of a young professor, Dr. B. W. Currie, a large number of the auroral photographs eventually found their way to the University of Saskatchewan; these photographs provided the raw material for the training of a number of graduate students and stimulated the interest of many more in this fascinating field of study, for which the location of Saskatoon was nearly ideal.

After World War II new optical, radio, and radar instruments became available and were applied at Saskatoon and elsewhere to the study of the auroral phenomena, which occur primarily at heights of 100-200 km above the earth's surface. At about the same time it was recognized that the ionospheric layers over Canada were particularly disturbed, presumably due to the auroral storms. For this reason, a number of agencies were beginning to take up the use of radio techniques for the investigation of the upper reaches of the atmosphere, with a particular emphasis on the ionospheric layers which support long-range radio communications. This research eventually became concentrated in the Defence Research Board at the Defence Research Telecommunications Establishment (DRTE). This establishment operated a network of sites having ionospheric sounding equipment at a number of locations, including several in the far north. As the studies progressed ,it became more and more obvious that a clear understanding of the ionosphere would be achieved only through fundamental studies both of the earth's upper atmosphere and of the interaction of the earth's magnetic field with the streams of particles referred to collectively as the solar wind.

By the time the International Geophysical Year (IGY) commenced in 1957, considerable numbers of Canadian scientists were investigating the properties of the earth's upper atmosphere. Nevertheless, it was a group of American scientists who introduced into Canada the use of rockets for these studies. Primarily at the urging of this group, and through the cooperation of several US military agencies, a rocket range was established at Fort Churchill. During the IGY a number of rockets were fired sucessfully from the range. While the range was intended primarily for the use of the American sponsoring agencies, the facilities were offered to Canadian groups as well. In fact, the Canadian Armament Research and Development Establishment (CARDE) at Valcartier did instrument two rockets for studies of the air-glow in the high atmosphere over Churchill and these rockets were fired sucessfully. At the end of the IGY the Churchill Range was closed down. It was soon realized that the range could fulfill a continuing need for upper atmospheric research and it was reopened in 1959. Stimulated by the existence of this facility a small number of Canadian groups embarked on programs in rocket research. The most active groups were located at DRTE and in the laboratories of the National Research Council (NRC). Fortunately, work already in progress at CARDE eventually led to the development of a family of Canadian research rockets; as these became available Canadian universities began to participate in the program.

Both in Canada and in the US, the initial stimulus to space engineering came as a result of military requirements. In the US, military activities still provide a continuing stimulus to the development of boosters and space vehicles. In contrast, space activities in Canada are becoming oriented more and more toward basic research, or to the fulfillment of civilian requirements. This difference must be considered in any reorganization of space activities in Canada.

While the ground-based observations described above were developing, a parallel development occured in aeronautical research in Canada. This program had its beginning at the University of Toronto during World War I and it continued to grow and flourish; at the beginning of World War II there was a well-established program involving both undergraduate and graduate students, which made use of a wind tunnel and other laboratory facilities. Immediately after World War II, supersonic studies were begun using shock tubes. In the years following, the research program expanded to include the mechanics of rarefied gases, aerospace propulsion, aerodynamic noise, flight dynamics, and plasma dynamics, as well as supersonic and hypersonic flow problems. In order to support this research it was necessary to develop a wide range of laboratory facilities, such as test chambers suitable for reproducing many of the effects encountered in space flight. The Toronto group, now known as the University of Toronto Institute for Aerospace Studies (UTIAS), conducts space research ranging from the complete instrumentation of rocket nose cones, through the necessary laboratory experiments for evaluation of techniques and calibration of instruments, to the more fundamental experiments conducted in the laboratory for the purpose of elucidating upper atmospheric processes. Much of this work is reported specifically in the survey on plasma physics.

With a strong background in ground-based and rocket research, it was natural that DRTE should be ambitious to move into satellite research, as soon as suitable vehicles became available. Scientists at DRB made a proposal to the US National Aeronautics and Space Administration for an ionospheric satellite that would be capable of mapping the distribution of ionization on the topside of the ionosphere over most of the earth's surface. This proposal was accepted. The satellite was built in Canada and launched by a US vehicle on September 29, 1962. This satellite, known as Alouette, was outstandingly sucessful and was followed in 1965 by Alouette II. Both satellites carried, in addition to equipment for ionospheric experiments, an experiment designed and built in the laboratories of NRC for investigating energetic particles impinging upon the topside of the ionosphere. The agreement between Canada and the US has now been extended to cover a complete sequence of ionospheric satellites, the later members of which are to be known as ISIS-A, B, and C. ISIS is an acronym for International Satellite for Ionospheric Studies. Detailed plans have been made for the first two satellites in the series. ISIS-A carries no less than ten Canadian and US experiments, one of which involves a Canadian university team. ISIS-B will carry twelve experiments, three of which will involve Canadian university teams.

Another interesting development which started in 1962 was an engineering research program undertaken at McGill University under the title of High Altitude Research Project (HARP). This program was directed toward the use of large bore guns to launch projectiles into the high atmosphere for research purposes. HARP has been a joint US-Canadian program, with support almost equally divided between the Canadian Government and the US Army. Sucessful high altitude launches have been achieved from Barbados, where McGill University has a research range, from Highwater, Que., and from several ranges in the U.S.

2.4 LEVEL OF PRESENT ACTIVITY

The present level of government expenditure on upper atmospheric and space research in Canada is about $17.7 million per year. Of this amount something more than half is spent in industry for engineering development and engineering support of the program. An additional $2 million is spent in universities for the engineering development involved in the HARP program and in the engineering support for rockets.

Table I.–LEVELS OF ACTIVITY IN PRINCIPAL CENTERS OF SPACE RESEARCH IN CANADA

Location	Annual expenditure (thousands of dollars)	Professional personnel[1]	Graduate students
NRC*			
Internal program	620	17	
Rocket support[2]	1700		
Churchill range[2]	2100	4	
DRTE*			
Upper atmosphere	1240	32	
PARL	520	4	
ISIS program[3]	3800	18	
CARDE*			
Rocket development[3]	1000	5	
Aerodynamic physics	2000	16	
Lower atmosphere	820	9	
RCA Victor Research Lab.	280	7	
Laval Univ.	27	3	8
McGill Univ. – SRI	1150	5	23
Univ. of Toronto – UTIAS	640	12	50
York Univ. – CRESS		10	12
Univ. of Western Ontario	145	12	24
Univ. of Saskatchewan – ISAS	545	9	21
Univ. of Calgary	82	7	12
Univ. of British Columbia-Inst. of Earth Sciences		3	5
Other laboratories[4]	75	13	20

1. No breakdown is available between physicists and engineers.
2. These expenditures must be regarded as operating expenses for the total program.
3. These expenditures must be regarded as "capital" expenditures.
4. Dalhousie Univ., Nova Scotia Tech., Univ. of New Brunswick, Univ. of Montreal, Univ. of Manitoba, Univ. of Alberta, Univ. of Victoria, Royal Roads.

* These figures include substantial contributions to development as well as to research.

Most of the remainder is spent in government laboratories in direct support of ground-based, rocket-borne, and satellite research related to the upper atmosphere. A relatively small amount is being spent in government establishments for applied research in rocket development and communications systems studies. The level of government support of university space research is about $750,000 per year. The US Government expenditures in support of upper atmosphere and space research in Canada amount to about $4.5 million per year. Most of this money goes to support of the Churchill Research Range ($2.2 million) and the HARP project ($1.2 million); university researchers in Canada, excluding those in the McGill Space Research Institute (SRI), derive more than a third of their total support ($0.4 million) from the US Government.

Although there is much activity in industry it is difficult to estimate the precise level of support in terms of either manpower or expenditure for research in physics related to the upper atmosphere. Some companies, notably RCA Victor in Montreal, do maintain competent groups of scientists who undertake basic research under contract. Such research tends to be supported almost equally by Canadian and US agencies, costs about $1 million dollars per year, and involves about 30 scientists. This support is small compared with the total sales of engineering services and devices, which amount to more than $17 million per year, and which are also equally divided between Canada and the US.

The manpower involved in various programs of research is about the same in the universities as in government and industry. The total number of scientists seems to be somewhere between 230 and 250 professionally qualified people. In addition, there are about 100 graduate students, most of whom are enrolled as Ph.D. candidates.

2.5 THE FUTURE TREND

With reference to the future, most government departments estimate that the total expenditures on upper atmospheric research, and the number of people involved, will grow only slowly over the next five years. An exception to this rule is NRC, which estimates that in this area and during this period, its total expenditure on research programs will rise from about $600,000 to $1 million and its professional staff from about 40 to 65. However, the universities estimate that the number of research staff will increase by a factor of about 2.5 over this period and that the required research support will increase by a somewhat larger factor. At the same time the number of students will increase by a factor of at least 5. It is not certain that this is a valid projection. Clearly, so large an increase in the student population implies at the least a comparable increase in the total research activity; such an increase could not be supported properly by the suggested increase in research funds. A further factor of real concern to those who have been involved in this projection is the nature both of the present research and of that projected. At the present time there seems to be a reasonable balance between ground-based research and research that makes use of rocket or satellite vehicles. There may not be an equally suitable balance between vehicle-borne research and the laboratory research needed to provide efficient use of the rockets and satellites. There is a considerable body of opinion to the effect that space-oriented laboratory research should be increased, and that an effort should be made to ensure that all relevant laboratory work is done before a rocket or satellite experiment is undertaken. In the future, a similar imbalance could develop between the ground-based observations and the vehicle-borne observations. Most of the satellite and rocket research is now carried out by scientists employed by government laboratories. The research being carried out at universities is heavily weighted toward ground-based techniques. One important reason for this has been the lack of adequate support to permit full-scale participation in rocket and satellite research; another important reason is that most professors have hesitated to expose their graduate students to the danger of long delay caused by vehicle failure. If the university research program is allowed to grow without changing its character, then the balance between ground-based and vehicle-borne research will be seriously upset. It is necessary that the universities be encouraged to make increasing use of rocket and satellite vehicles. With regard to the reluctance of professors to involve students in the risk of vehicle failure, it may be worth noting that once a university group becomes involved in several rocket firings per year the delay occasioned by a single failure is not likely to be important in a graduate thesis program. Indeed, several university research groups have already passed this threshold and are finding that the demanding discipline imposed by involvement in a rocket or satellite program provides an ideal environment for the training of research scientists.

2.6 UNANSWERED QUESTIONS IN SPACE PHYSICS

The first researchers in upper atmospheric and space physics were attempting to obtain a factual description of physical conditions in the atmosphere out to great distances from the earth and over all reasonable ranges of temporal variation. While much progress has been made in this direction, much work remains to be done, especially in the area of constituent determination in the ionized regions above 100 kilometers. Some of the interest has already shifted to physical descriptions, on both microscopic and macroscopic scales, of the atmospheres of neighboring planets and the sun. In the meantime, it has been found that this vast region, popularly known as space, is the seat of many phenomena, which by themselves offer challenging problems to the physicist.

Most of the current problems in the field of laboratory plasma physics have counterparts in the plasmas of the high atmosphere. In addition, there are many processes that are extremely difficult, if not impossible, to produce within the confines of the laboratory but that appear to occur naturally in the unconfined plasmas of outer space. The compression or extension of magnetic field lines by moving plasmas, the generation of electric fields, the capture and transport of magnetic fields by plasmas, the complex interaction of streams of charged particles with stationary magnetic fields, the electromagnetic acceleration of charged particles, and the propagation of electromagnetic, acoustic and gravity waves in various coupled and uncoupled modes, are all phenomena representative of those being tackled by space physicists. Each year many new such phenomena are anticipated, discovered, or postulated.[1] In such a rapidly expanding field it is natural that each physicist select from a large number of problems those that attract him as being particularly significant and likely of solution within a reasonable time. Probably it will be several years before the results of the far-ranging research projects start to fit together into a pattern from which critical questions can be picked for special consideration. At present many important, perhaps even critical, problems are being by-passed in order to obtain an elementary understanding of each new phenomenon as it is discovered.

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[1] A recent Advertisement for theoretical staff puts it this way: "What are the injection and loss mechanisms for the particles trapped in the radiation belts? What are the complex relations of these particles with electromagnetic disturbances in the magnetosphere, with the solar wind, cosmic rays, and the ionosphere? Do acceleration mechanisms exist? A complicated collection of interactions among atoms, molecules, ions, and strange radicals occurs in the earth's high atmosphere; what is the order associated with these? Do excited quantum states have a role? What is the part played by the sun's radiations? Do solar flares produce cataclysmic changes in this environment? What is the source of the immense flare energies? Do they originate from energy stored in solar magnetic fields? If so, how is the energy transformation brought about in tens and hundreds of seconds over areas thousands of kilometres broad?"

In solar and stellar physics there is a significant area of overlap with astronomy. For stellar physics the only overlap arises from the use of rockets and satellites for studies of stellar sources, and much of the technology used for this purpose is being borrowed from the earlier studies in space physics. On the other hand the study of solar physics represents a true blending of interests of physicists and astronomers. The sun is the source of nearly all the energy that reaches the atmosphere of the earth and sustains life on this planet. One of the most challenging problems of space physics is to gain an understanding of the various mechanisms by which this energy is propagated from the sun to the earth. This study ranges from the mechanism by which radiation of various wavelengths is generated in the atmosphere of the sun, and how the charged particles are accelerated and emitted from the sun, to the study of the interaction of this radiation and these particles with the earth's atmosphere. Out of such studies has come the realization that relatively small changes in the earth's atmosphere can greatly affect the amount of energy that it is capable of absorbing. There are some who believe that the catalytic action of relatively minor constituents in the earth's high atmosphere has a profound effect on the world's weather. If this is so it will be necessary to increase greatly the interaction between space physicists and meteorological physicists before significant understanding is obtained. At the very least, much more should be known about the motions of the neutral atmosphere at heights above 50 kilometers. There is already a growing interest in this field, but new techniques are required to develop it.

2.7 CANADIAN ACTIVITY

While Canadian physicists are interested in the total range of problems outlined in the preceding section, many of them have particular interests which grew out of common questions dictated largely by geography. Presented by nature with frequent visible manifestations of the auroral phenomenon, it is not surprising that Canadians have pursued the mystery, as have other inhabitants of northern latitudes, for thousands of years. "What is the aurora and what are its causes?" Motivated by this basic question and assisted by the presence of the Churchill rocket range, most of the Canadian researchers developed interests related in some way or other to the auroral phenomenon itself or to the region of the atmosphere in which it occurs.

Although the Canadian program is somewhat more limited in scope than, say, that of the US, it too is in a period of rapid expansion, which tends to make the unambiguous identification of critical areas of research difficult. While much progress has been made in establishing some of the basic physical characteristics of the atmosphere in auroral regions, it is only the undisturbed atmosphere that is reasonably well understood. The aurora is a highly variable transient occurrence, characterized by the sudden influx of large quantities of energy into relatively small volumes. Auroral studies are always difficult and definitive results are not quickly achieved. To make matters even more difficult, the principal region of auroral activity lies just above 100 kilometers, a region where satellite investigation is impractical because of the large atmospheric density and consequent rapid decay of satellite orbits. Therefore, the only vehicle available for direct study of this region is the research rocket which, however, permits only a brief period of measurement in each flight.

Auroral research has gone through what might be regarded as a typical evolution. As each new tool was brought into play (such as the fast camera, spectroscope, ionosonde, radar, riometer, magnetometer, and satellite-borne particle counter), the specialists in its use tried to interpret the results obtained in terms of reasonable models of the overall phenomenon. Only after the interpretations and associated models had reached a reasonably sophisticated level was it possible to attempt detailed intercomparisons. In the last two or three years some of these intercomparisons have yielded bewildering incompatibilities. Some researchers feel that the existing models will prove to be adequate, and that the difficulties will be removed when a sufficient number of careful observations have been made. Others are of the opinion that the available observations are adequate to indicate the need for new interpretations. Perhaps some novel and yet undiscovered mechanisms for energy conversion in plasmas are responsible for the incompatibilities; if clearly indicated in the aurora, these mechanisms might subsequently be found in the laboratory.

2.8 SIGNIFICANCE OF SPACE RESEARCH

Early discussions of the value of space research tended to center around the prediction that eventually the new knowledge gained from the research would provide a direct return to society in terms of much improved goods and services. While it is to be hoped that the original predictions turn out to be well-founded, it is nevertheless true that the very substantial social benefits that have already been derived have come not from the research but from the application of the technology generated to support the research. The rapidly growing and potentially profitable use of satellites for long distance communication is the most outstanding example of such an application. Another is the widespread use of weather satellites for the collection of meteorological information for weather forecasting. Still another, which seems not too distant, is the use of satellites for detailed surveys of mineral, water, plant, and animal resources. As was stated earlier, Canadian industry is participating in space technology to the extent of sales amounting to about $17 million per year. This figure is growing rapidly and represents sales that are about equally divided between Canadian and export markets.

Because space science is not a separate discipline, it is reasonable to evaluate its scientific value only in relation to other disciplines. Many space scientists consider themselves individually to be specialists in electromagnetic propagation, plasma physics, particle physics, atomic or molecular spectroscopy, aerodynamics, magnetohydrodynamics, and so on. That they use the techniques of space research in order to advance understanding in these fields is to them incidental. However, it must not be assumed that such people are indifferent to the challenge of space itself. They are well aware that the upper atmosphere of the earth and the regions beyond provide a new laboratory in which experiments of unprecedented scope can be carried out.

The characteristics of space science outlined in the last paragraph make it ideal for the training of graduate students and technical personnel. A vigorous program of space research in the universities, in industry, and in the government laboratories, can lead to a pool of knowledgeable people, competent to work in a wide range of scientific areas and well acquainted with the latest technological techniques and instruments. It has even been argued that such a program provides an ideal way of ensuring a supply of scientifically and technically knowledgeable people who can be called upon to solve specific problems in military science during an emergency.

2.9 SPACE RESEARCH AND THE UNIVERSITY

It has already been pointed out that the amount of space research being done at universities in growing rapidly. Nevertheless, the view is sometimes expressed that space research is not at all suited to the university environment. The suggestion is that while space research is important to the scientific well-being of a nation, it is so expensive, so demanding in terms of deadlines, and so intimately bound up with industrial activities, that it can only be pursued effectively in government laboratories by full-time researchers. In rebuttal the university researchers do not deny that the characteristics cited are incompatable with the traditional university attitude toward research, but they assert that this attitude is changing and ought to change, and that much can be done to improve the response of the university to the demands of space research. While space research is expensive, it is not so expensive in terms of dollars spent per researcher as several other fields in which universities are now active; and while space research is fraught with deadlines, safety regulations, and irrevocable decisions, these are just the characteristics that have become more common in all branches of science. The more a graduate student meets these difficulties in his university days, the better he will be prepared for a career as a professional researcher.

The final criticism, that space research can be done effectively only by full-time scientists, invokes a somewhat wider range of opinion. The most commonly held view in the university is that there is some limitation to research ventures inherent in the performance of undergraduate academic duties. This does, for example, make it impossible for the researcherto guarantee his presence at a rocket launching if the launching is delayed a long time during the academic term. Although it is questionable whether the government-employed scientist has any larger fraction of his time available for research than does the university staff member, it is true that the government researcher finds it easier to organize his non-research activities so that they do not interfere with particular experiments. Much can be done to overcome the difficulty experienced by the university scientist by adequate planning of such items as range usage and launch schedules, bearing in mind the particular limitations of the academic life. It is doubtful that a single university scientist can carry on a vigorous program of space research without occasionally facing the need to compromise between the requirements of his research and his academic duties. However, experience has shown that where groups of researchers are cooperating in a program most of the difficulties disappear. With several people involved, sufficiently flexible arrangements can be maintained to fulfill adequately both the academic and research responsibilities. In fact, there are much more compelling reasons for the formation of groups of researchers at universities. Such groups, organized as graduate departments, research centers, or research institutes, are appearing in several fields at various Canadian universities. In general they have been very sucessfull, not only because they share common expensive facilities, but also because the interaction between colleagues greatly enhances the quality of the research carried out. Examples of the effectiveness of such university groupings are provided by SRI, UTIAS, and ISAS (Institute for Space and Atmospheric Studies at Saskatchewan).

Space research demands collaboration between scientists working in different disciplines. The normal organization of a university for undergraduate teaching does not promote the particular interdisciplinary collaboration appropriate to space research. While many possible collaborations might be effective, it seems particularly essential that a research team provide for adequate cooperation between engineers and physicists. Experience has shown that the major factor limiting the scope of research programs in government laboratories and in the universities is the lack of the engineering and technical support directly available of the scientist. All branches of modern experimental physics would probably benefit from more technical support planning; it is certainly true for space science. Although most universities have active and competent groups of both engineers and physicists, the engineers and physicists are not accustomed to working in close collaboration. In organising a group to carry out space research at a university it would seem wise to provide deliberately for this collaboration. It is worth noting that each of these institutes mentioned in the previous paragraph does in fact provide for this kind of cooperation.

Another kind of collaboration essential to a sucessful space program is that between theoretical and experimental workers. It is not clear whether or not there is an overall shortage of theoretical workers in space physics but certainly there seems to be a shortage of competent theorists who are working sufficiently closely with the experimental teams to provide a continuing interplay between theoretical and experimental developments.

2.10 THE IMMEDIATE FUTURE

Space research is a relatively young field and is growing rapidly. The forecasts discussed here of the activity in government laboratories and in universities have been made against the background of existing support. It is reasonable to suppose that if such forecasts had been made even three years ago the totals would have fallen far below the present level of activity. The Chapman Report, mentioned in the introduction to this report, made several far-reaching recommendations concerning the organization and support of space research in Canada over the next few years. Without knowing the extent to which these recommendations will be implemented, it is quite impossible to predict the total level of activity or even the direction that space research will take in Canada in the next year or two. The forecasts of the expected level of activity given in Section 2.5 would need to be revised sharply upward in the light of any significant response to the recommendations of the Chapman Committee.

Some mention should be made of the possible utilization of the gun-launching technique for upper atmospheric studies. This technique, which is being developed by SRI under the HARP program, is aimed both at providing gun-launched ballistic probes for studies of the lower ionosphere and the development of gun-launched rockets of one or more stages to reach much higher trajectories and ultimately to achieve injection of a payload into orbit. The Institute has itself made effective use of ballistic probes fired from Barbados and elsewhere for investigations of upper atmospheric winds. There is some Canadian interest in the use of probes for this purpose and for similar probing experiments in the lower ionosphere. The extent of this interest is hard to judge because the costs of using the gun-launching technique are not known to the researchers. It seems clear that if a small gun (6-or 7-inch caliber) could be used routinely and economically to lift light payloads to heights of the order of 80 kilometers at Churchill, or at some other site where adequate ground instrumentation exists, there would be considerable interest on the part of a number of scientists. This interest, however, would be restricted to a limited range of experiments. Most researchers believe it would be highly undesirable, if not impossible, to make use of a gun-launched probe to carry out the experiments that they are now conducting with rockets. Moreover, at the present time there seems to be no Canadian interest in the scientific use of satellites that might eventually be orbited by the gun-launching technique. It should be observed here again that there is little immediate likelihood of establishing realistic user cost schedules for the various types of launchings that might be provided through the use of guns. The bringing together of those scientists who might make use of the gun-launching technique, and the operations group who might provide the service, is likely to occur only through some central coordinating agency of the kind recommended by the Chapman Report.

2.11 GRANT PROCEDURE

Despite the universal but understandable complaint regarding the inadequacy of grant support for university staff members, there is no similar unanimous opinion regarding the methods by which grants are disbursed. Some physicists feel that grants should not be the responsibility of an agency like NRC, which also operates its own laboratories. The feeling on this point apparently is that, while the system has worked very well in the past, there will certainly come a time when the large sums of money involved can no longer be effectively administered by the part-time efforts of working scientists.

A much more fundamental question has been raised by some researchers. At present research grants are made to individuals, largely on the basis of their past performance and scientific reputation. This procedure is not consistent with the formation of strong, efficiently organized, research groupings of the kind that are becoming increasingly necessary for the conduct of first-rank research. It is also particularly inappropriate to space research since one grant may commit the granting agency (NRC) to a large, unstated, further expenditure for the necessary rocket or satellite vehicle, as well as launch, engineering, and telemetry costs, whereas another grant may require no such commitment. It would seem that the only equitable solution is to involve the granting agencies in a project evaluation procedure. The superposition of detailed project evaluation on the present system used by NRC in the awarding of grants, if applied to all the individual grants now administered by NRC, would involve an enormous increase in the work load. Clearly such a change in the grant system would require a much wider distribution of the evaluation activity over the scientific community, the consolidation of grants over longer periods, and perhaps other measures as well. In the past few months the NRC Associate Committee on Space Research has moved in this direction by setting up a scientific evaluation panel to study the project proposals of all the Canadian potential users of the Churchill Research Range. This action seems to have gained support among the experimenters, who hope it will bring about a better balance between the various components of the rocket program. In the past it has been felt that it was comparatively easy to gain approval for a research proposal and to obtain the use of an expensive rocket vehicle including the full range support for the firing, but very difficult to obtain a few thousand dollars to build the instrumentation with which to carry out the experiment.

Another factor of importance to researchers who use rocket and satellite vehicles is the very long lead-time necessary for instrumentation planning and development. In the case of satellites this lead-time may be three or four years and such programs are hard to organize on the basis of annual grants to individuals. The consensus seems to be that space research at universities, especially that part which makes use of rockets and satellites, would best be supported by continuing grants to support the facilities and "core structure" of research groups, together with project grants determined by an evaluation procedure making use of expert referees.

APPENDIX – COSMIC RAY PHYSICS IN CANADA

In Section 1 (Part II) of this report cosmic rays were mentioned as being important in astronomy because they represent an important component in the cosmological development of the universe. Many of the elementary particles in physics were first discovered in cosmic rays. These result from nuclear interactions of very energetic cosmic particles with nuclei of the atmospheric gas, or with the nuclei of matter in measuring devices such as nuclear emulsions. Particles in the cosmic ray flux are found with energies one hundred million times higher than those that have been achieved up to the present in man-made accelerators. In the lower energy bands included in the generic term "cosmic rays" there is an extremely variable source in the sun associated with solar flares. The techniques used in studying cosmic rays have been extended to the measurement of particles in the energy region of kilovolts in the Van Allen layers of trapped particles held near the earth by its magnetic field.

Cosmic rays are therefore studied by measurements in rocket space probes, in satellites, in balloons high up in the atmosphere, on mountain tops, and on the surface of the earth.

The real cosmic particles and the energetic particles from the sun can only be observed outside the earth's atmosphere, but secondary particles generated in the atmosphere, some of which reach sea level, can be observed and related to primary particles since the secondary processes are reasonably well known. The flux of cosmic particles outside the solar system is assumed to be constant and isotropic. Variations in intensity within the solar system are found which are related to solar activity and the rotation of the earth in the solar wind. Continuous measurements over the surface of the earth therefore represent an important key in unlocking knowledge about the sun and interplanetary magnetohydrodynamics.

In this regard it is important to have ground observation stations at a variety of latitudes and longitudes. Canada, covering such a large portion of the land surface of the earth, particularly in the north, is a vital area for cosmic ray studies. We have ground stations at Alert and Resolute in the far Arctic, at Inuvik, Churchill, and Goose Bay near the auroral belt, and at Sulphur Mountain, Calgary, Deep

River, and Ottawa. Besides this there are cosmic ray measuring instruments on the satellites Alouette I and II and there will be others on the ISIS series of satellites. Many rockets fired to the outer reaches of the atmosphere at Fort Churchill carry cosmic ray experiments of various sorts.

The major centers carrying out cosmic ray research are at the University of Calgary, the National Research Council's Division of Pure Physics, and the Atomic Energy of Canada's laboratory at Deep River. The stations in the north are jointly operated by NRC and AECL. Foreign visitors often carry out cosmic ray experiments in balloons in northern Canada. We have an extensive system of data exchange with many other countries. Some experiments are being carried out in universities other than those mentioned above.

The total number of scientists of professional rank involved in cosmic ray research in 1966 is:

In government laboratories	9
In universities	13

There is a considerable supporting staff, some of it part-time, at the out stations. Technical help at the out stations is supplied mostly by cooperation on with other government departments.

The expenditure in this field is estimated to be roughly as follows:

In government laboratories	\$350,000
In universities	\$250,000
	\$600,000

These cost estimates include salaries and operational costs but not overheads. University staffs are considered to spend half time on research. These estimates also do not include the cost of rockets or satellites or the launching of either, where rocket or satellite experiments are involved. Since space in rocket and satellite payloads is always shared with other groups carrying out related experiments, the distribution of costs among related subdisciplines is rather meaningless. The expenditure on rocket and satellite construction has been included in the main body of this section.

In estimating growth during the next five years, some of the ground station activities of the government laboratories may be reduced, depending on the results obtained during the next maximum of solar activity about 1969. This will be more than compensated by increased space activity resulting in an estimated increase in goverment activity in the cosmic ray field of about 50% (based on current dollar values), while the university activity should more than double. The latter would be partly because more university groups are becoming concerned with the measurement of energetic particles in space; moreover, as knowledge is increased, more sophisticated experiments become necessary.

An estimate for 1971-72 therefore would be:

In government laboratories:
12 scientists costing $500,000

In universities:
25 scientists costing $1,000,000

Again, this estimate does not include the cost of rocket or satellite vehicles whenever these are used, but only the cosmic ray instruments that may be installed in them.

Section 3

CLASSICAL PHYSICS

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SUMMARY

This report is based on 50 questionnaires that were returned in the survey; of these, 38 were sufficiently complete to be included in all the statistics. The results show a total annual expenditure in this field of nearly $8 million, of which about one third is classed as basic (although it may be mission oriented) and the rest is applied. The federal government supplies about 76% of these funds either through research grants, research contracts, or by operating its own laboratories. Of all the money, 55% was spent in government laboratories, 26% by industry, and 19% by universities.

Of the money spent at the universities less than 9% was spent in physics departments. This and the data on graduates in this field indicate that there is a serious lack of attention being given to classical and applied physics by our universities. (Consider for instance that in the US more than 37% of all physicists are employed in the fields that are represented in this survey). This may have highly deleterious effects on our technology since invention and innovation in the classical fields still form the backbone of modern technology[1]. We therefore urge strongly that, of the greatly increased research funds which practically all studies recommend, the bulk should go to applied research and to basic research oriented toward application to the special problems and needs of our country.

To this end we need a great increase in the proportion of research work done in industry and a greatly increased representation of industry on any panel or agency that has responsibility for the awarding of grants.

[1] Invention and Economic Growth, Jacob Schmookler, Harvard University Press, 1966, p. 69-71.

3.1 FIELD COVERED

Since there is no generally accepted definition for the term classical physics it was considered desirable, for the sake of uniformity, to provide some guidance for those filling out the forms. For this purpose the breakdown of the fields of physics as used by the US National Science Foundation was used and this list, together with code numbers, is included here in Appendix A. This, of course, does not completely overcome the problem, especially since part of the classical physics is covered by other committees, such as those concerned with solid state, plasma, meteorology, etc.

Furthermore, applied physics naturally forms an important part of classical physics, so that an equally difficult problem is that of deciding where applied physics leaves off and engineering begins. This question was raised in the letter that accompanied the questionnaire but no guidance was given in this case,

A total of 180 questionnaires were sent out to universities, industries, and government departments and agencies. Answers were received to 84 of these but 34 institutions merely reported that no research was done in this field. (It is reasonable to assume that the ones who did not reply had nothing to report.) Of the remainder, 12 replies were very limited in usefulness because of failure to fill out vital parts of the form. The remaining 38 laboratories reporting were divided nearly equally among universities, government, and industry.

3.2 HISTORY

Nothing very simple can be written about the history of classical physics research because it varies too much with the subfield and the organization involved. Thus one university reported a cessation of classical physics research in 1966 while another reported no work till now but had plans for major activity starting in 1967. Others ceased classical physics research long before the period covered by this report. In the field of acoustics there was great activity during the war, mainly in underwater sound, but activity then dropped sharply; it is now reasonably active but with a broader base.

Optics (other than spectroscopy) received a major stimulus during the war when the government actually set up a company to design and manufacture optical instruments. As in the case of acoustics it faltered after the war but research in the field continued at

NRC. With the advent of lasers many places showed spontaneous interest and renewed activity although not usually over the whole field of optics.

Electromagnetism also received its biggest impetus during the war with the development of radar. This grew rapidly and spread into every field of physics from molecular physics to astronomy, where the new techniques were used as tools to extend the range of measurements that could be made.

Fluid dynamics on the other hand has received fairly consistent, though not really sufficient, attention.

A noticeable trend is for classical physics at the universities to move out of the departments of physics. In some cases interdisciplinary divisions such as geophysics, engineering physics, biophysics, etc., have taken over the work in classical physics and tend to emphasize the trend toward applied physics, which has, quite naturally, been characteristic of this field.

Most of the provinces have a research organization (organized in most cases since the last war although some were established in the 1920's) whose purpose is usually the commercial exploitation of the natural resources of the province or the provision of technical assistance to its industries. Only one of these, however, reported doing research work that comes under this division, and since it is largely financed by industry it was included under included industrial research.

3.3. PRESENT LEVEL OF ACTIVITY IN CLASSICAL PHYSICS

The most reliable figures on research expenditure are those for 1966; in that year the total spent on classical physics (as specified in Section 3.1) was $7.9 million, of which 55% was spent by government laboratories, 26% by industry, and 19% by universities.

Industrial organizations reported 70 professionals engaged in full-time research work at an average cost of $30,000 per man (compare with $28,000 in the Bonneau Report, (*loc. cit.*), p. 22). The universities spent much less, about $10,000 per man, undoubtedly reflecting the high proportion of graduate students involved and the part-time nature of the research activities of the supervisory staff. The government laboratories spent the substantially higher sum of $40,000 per professional (with some uncertainty in the figure because of different costing procedures). The Bonneau report gives a figure of $32,000 per man for NRC.

The ratio of professional to technical staff also varies greatly among these groups, being about 1.1 in the government, 1.4 in industry, and about 8 in the universities (graduate students were counted as professional staff). We can compare this last figure with the figure of about 5 quoted in the Bonneau Report.

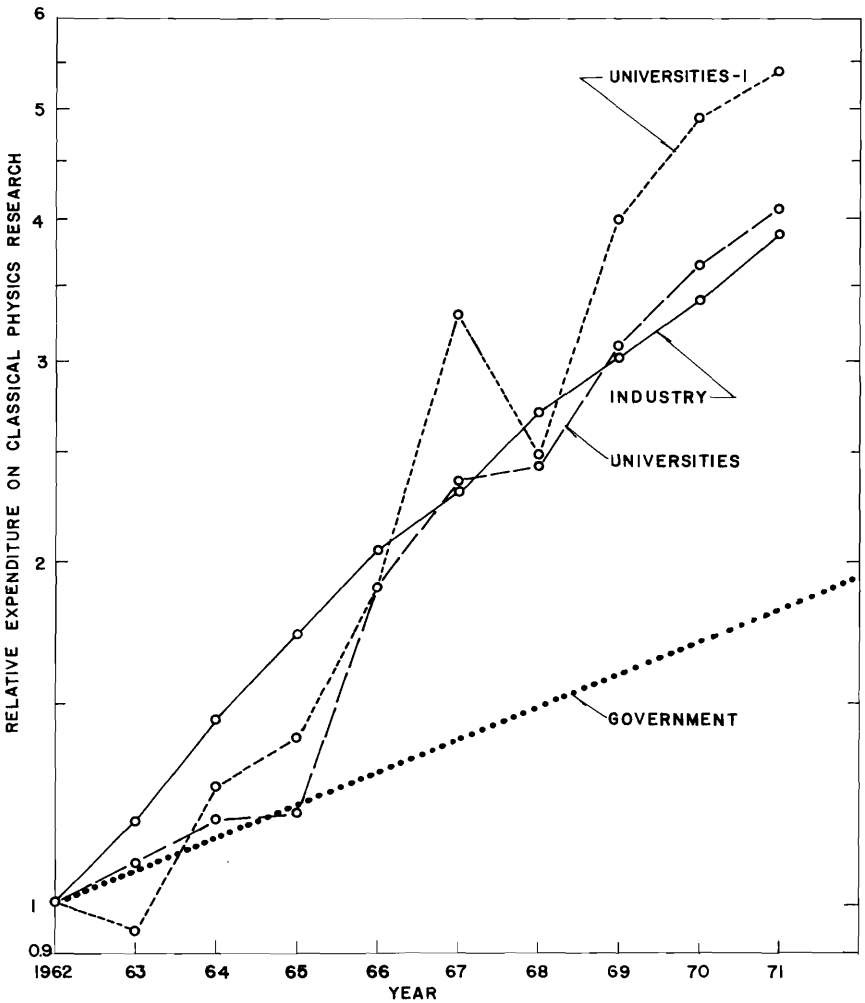

Fig. 1 Recent and projected expenditures (relative scale) on research in classical physics. Separate curves are shown for government, industry and the universities. The curve "universities minus one" is the curve remaining when the one dominant (75%) university is not included.

3.4 CHANGE IN THE LEVEL OF ACTIVITY

The change in activity in classical physics research during the five-year period preceding 1966, as well as an estimate of its future, change, is shown in Fig. I. The solid curve is that for industry while the dashed curve is that for universities. Government research is shown by the dotted line. In each case the year 1962 is taken as the base year and plotted as unity on the ordinate in order to facilitate comparison of growth.

The university research is largely due to one department of one university (75%) and as a matter of interest another curve has been plotted and marked "Universities minus one." This curve fluctuates a bit more and shows a somewhat higher average growth rate (21% per year instead of about 17%), but agrees with the dashed curve in a general way.

Fig. II shows some smoothed data for past and estimated future growth of five individual universities broken down by departments. The universities are labelled A to E with the second letter indicating the department. The two lowest lines are for the physics departments (P) of universities A and B. The budgets are quite low and the rate of growth is low. However, the classical physics research in the mathematics department of University A(A-M) has a much greater growth rate even though its present budget is already much greater.

In the case of University B there are two engineering departments, B-E-1 and B-E-2, which have a much bigger budget as well as higher growth rate than the physics department.

In Universities C and D only the engineering departments do classical physics research and the growth is substantial. The trend for classical physics research to move away from physics departments (as was already mentioned in Section 3.2) is strongly emphasized by this figure. The only exception is University E, which has the highest growth rate. However, it started with such a low budget in the base year that any increase at all meant a high percentage.

The average rate of growth in industry is very similar to that in the universities (see Fig. I), being somewhat over 16% per year. It is, however, more broadly based with the top eight companies spending comparable amounts of money and accounting for about 90% of the total expenditure reported by industry.

Classical physics research (as limited in our terms of reference) in government seems to be pursued mainly in the Applied Physics Division of NRC (55%). Its rate of growth, however, is only about 7%

per year and this, in about 10 years, could cause a very strong shift of balance away from the government laboratories to the universities and industry.

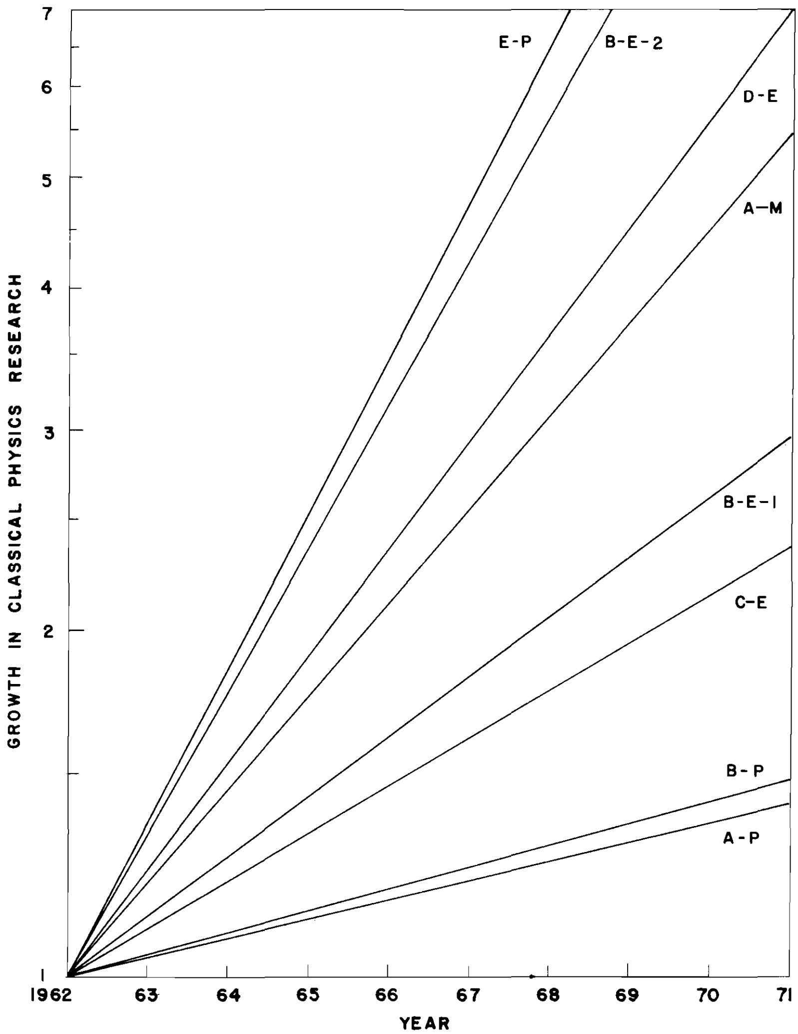

Fig. 11 Recent and projected expenditures (relative scale) on research in classical physics broken down into departments (indicated by the second letter: P for physics, E for engineering, and M for mathematics). The first letters A through E indicate the five universities involved. University B has 2 engineering departments engaged in classical physics research.

Fig. III shows, by means of a histogram, the total expenditure of money on classical physics research for the year 1966 and also a breakdown among government, industry, and universities. The data for the growth rate, both past and future, were obtained from a more limited number of respondents than the values for 1966. However, these were used to estimate the figures for 1962 and 1972, which are also shown. The decreasing proportion, with time, of research in government laboratories is obvious.

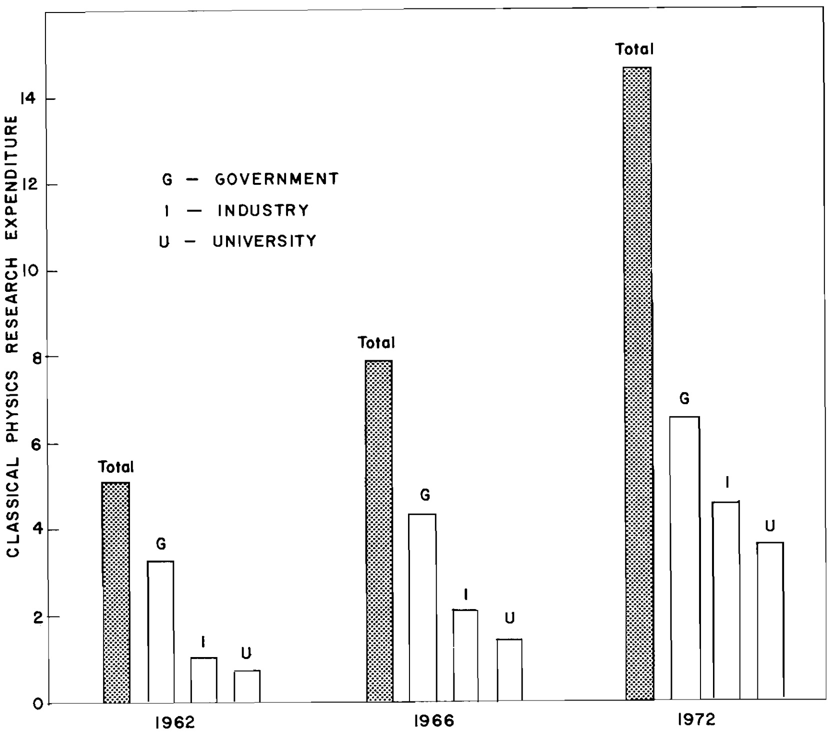

Fig. III Total expenditure on research in classical physics for the years 1962, 1966 and 1972, with a breakdown into government, industrial and university research expenditures.

3.5. MANPOWER

The figures on manpower present only a very hazy picture since the plans of graduating students are unknown. The universities report that an estimated 20 students will get their M.Sc. degree in 1967 in the fields covered here and 9 expect to get a Ph.D. *None of the latter* *and only 3 of the former come from physics departments.* If we consider that the Ph.D. graduates must come from the M.Sc. candidates then we realize that the two figures cannot be added to give the total output. We estimate this total as not more than 20 (assuming no loss to the US). If half of these graduates choose research as a career we have available about 10 new men per year.

If an industrial research growth of 16% per year is equivalent to 13% in constant dollars, then 9 new men will be required each year. Similarly the government will require 7 new men. Replacements for those retiring will add another 5, giving a total of 21 per year or about double the number available.. This does not include the large demand of the universities for their own teaching and research staff.

The estimated hiring by industry in 1967 of M.Sc.'s and Ph.D.'s is, however, only 6, and since the government departments generally declined to make an estimate, their growth rate estimate may be considered largely as wishful thinking.

The sources of manpower in the past are, of course, very relevant here. For industry, these figures show that 70% came from Canada, 23% from the UK, and 4% from the US. If the same proportion holds for government, then a discrepancy between available manpower and estimated growth rate remains, even if we neglect the loss of some of our graduates to other countries.

The total university professional staff (not including 103 graduate students who may be teaching part time) is about 46 in this field. Since their estimated growth rate is the same as that of industry, and their staff requirements were not included above, it is clear that the shortage of manpower is severe. (It should be remembered that universities are in a rather special category since they are consumers as well as producers of manpower).

3.6 SOURCES OF FUNDS

It appears that industry supplies two thirds of the money that it uses for research in classical physics. Government grants and government contracts share equally in supplying the rest.

The universities receive 50% of their research money from government grants, another 20% from government contracts, and the rest is supplied by themselves. A negligible amount (less than 2%) comes from industry.

Government research laboratories, as expected, receive only negligible amounts from other sources.

When all these data are combined with those in Section 3.3 it appears that the government supplies 76% of all research funds in this field while industry contributes about 18%.

3.7 NATURE OF THE RESEARCH CARRIED OUT

Table I shows the distribution of research activity according to whether it is basic, applied, or development. The last mentioned category is not usually classed as research but it is obvious that in an industrial research laboratory there will be development work that cannot readily be isolated from the applied research by normal costing procedures or even conceptually. In any case, for industry the outstanding characteristic is a relatively small amount of basic research; the primary motivation is the solution of technological problems.

TABLE I – Percentage Distribution of Research Between Basic, Applied, and Development

	Basic	Applied	Development
Industry	12	58	30
Universities	24	76	–
Government	46	52	2
Weighted total	33	58	9

Even the universities expend only 24% of their effort on basic research and 76% on applied research in the field of classical physics. (Semantics almost certainly plays an important role here since the one department that dominates the picture in university research rated its work as 10% basic and 90% applied. The figures change to 55% and 45%, respectively, if that one department is excluded). On the other hand the motivation is predominantly the advancement of science and personal interest in the field.

In the government laboratories applied research is still leading fundamental research, but only by a 52 to 46 margin.

TABLE II – Professional Staff Engaged in Different Fields of Classical Research

	Acoustics	Electro-magnetism	Mechanics	Optics	Fluid physics	Thermal physics	Other
Industry	9	11	9.5	16	10	4	10.5
Universities	7.5(15.5)	14(55)	5(12)	6(19)	10(33)	0(3)	3.5(11.5)
Government	12.5	32.5	12.5	19	1.5	13	16.5
Total	29	57.5	27	41	21.5	17	30.0
Percentage	13	26	12	18	10	8	13

The parenthetical figures for universities include graduate students.

TABLE III – Technical Staff Engaged in Different Fields of Classical Research

	Acoustics	Electro-magnetism	Mechanics	Optics	Fluid physics	Thermal physics	Other
Industry	8	12	5	20	2	2	1
Universities	1	6	2	5	3	3	2
Government	9	41.5	5.5	17	1.5	6	19
Total	18	59.5	12.5	42	6.5	11	22
Percentage	10	35	7.3	24.5	3.8	6.5	13

Tables II and III show the distribution of professional and technical staff in the different major fields into which this subject was divided. Electromagnetism and optics are the leading fields and together they use 44% of the professional manpower and about 60% of the technical manpower. The rest is shared almost equally by the other fields.

3.8 A SUMMARY OF RESPONDENTS' OPINIONS

In commenting on the activity in classical physics research in Canada there was almost complete unanimity of opinion that it was low, either absolutely or relative to other countries. About half of those responding believed that it was increasing, but two university staff members believed that it was constant and should remain so.

The average growth rate called for by the industrial group was about 20% per year. The response from universities showed a much greater spread, being anywhere from zero to 110% with a weighted average of about 20%. The high figures were for places where the activity was low and were usually meant to apply only to an initial period; these figures would subsequently taper off. The average growth rate recommended by government laboratories was about 7%.

A somewhat surprising result that emerged was that no more than 70% considered that there was a shortage of manpower in this field.

Hardly anyone in the industry or university group was satisfied with the financing of research. A few wanted merely a substantial increase in the amount of money made available, but the majority were more broadly critical. They felt that the amount of classical physics research done in industry should be substantially increased, and also believed that the universities were not putting enough emphasis on this subject – especially the physics departments.

A SAMPLING OF COMMENTS

(i) Comments made by industry:

1. "Department of Industry funding schemes are attractive in principle but not sufficiently broadly based. Basic research can hardly be shown to have profit potential."
2. "...research associations should be studied and their best features adapted to Canadian conditions."

3. "...Research activity in Canadian universities and government groups should reflect....the needs of Canadian industry for basic knowledge."

4. "There should be more fully paid industrial research contracts." Relatively too "large expenditures in atomic energy and high energy accelerators." "Very little contact between universities and industry."

5. "...Should be more....wholly government-funded programs particularly for research which is directly product or defence-oriented."

6. "Industry needs incentives and aid for pilot plant and development work. Tax incentives need broadening and enlargement."

7. "There are a number of piecemeal programs which only tend to keep the research sub-critical in size."

(ii) Comments from universities:

8. "Not enough in industry – too much in government – too much emphasis on nuclear physics."

9. "Suggest more cooperation between universities and government."

10. "Growing need for work in applied physics in universities."

11. "Expensive fields need revision, good graduate students not readily attracted into classical physics. More industrial research is required."

12. "...disproportionately small percentage of funds available. Consider the devastating effect of a single two hundred million dollar expenditure in one field in one geographical location."

13. Classical physics, both theoretical and experimental, has today no real home in the university."

14. "Universities may be in competition with NRC in-house research, yet the funds are administered by NRC."

15. "Government laboratories are over-represented" in classical physics.

16. "Privileged status of DRB and NRC internal programs is outrageous."

17. "The disproportionate investment in nuclear and particle physics should now be reduced severely."

18. There is a "lack of coordination."

3.9 SPECIFIC EXAMPLES OF PROBLEMS IN CLASSICAL APPLIED PHYSICS

This divisional committee agrees with the general import of the above comments. Because classical and applied physics influence technological development directly, this helps to provide a strong economy as a base of support for all other branches of physics. This should be reflected in university teaching. Since we are emphasizing the applied work it is not possible to mention all the major problems whose solutions are being sought, but some examples of specific problems in this field will be discussed briefly by way of illustration.

(i) Acoustics

The initial development of loudspeakers of reasonable fidelity may be considered to have started around 1925. The important contributors in the period following were well grounded in the classical fundamentals relevant to the subject until the law of diminishing returns set in. An empirical approach then appeared and efforts become very sporadic. But materials development has continued and what was optimum 15 years ago is no longer so now. The whole field of practical electroacoustics, whether loudspeakers or telephone, could benefit greatly if an appropriate number of fundamentally trained specialists in the field were available in Canada. As it is we shall buy knowledge from the US.

With high amplitude mechanical waves the history is different. They were not important 50 years ago because the linearized (and consequently approximate) wave equation was adequate to deal with practically all low-amplitude acoustics. The non-linear wave equation has now become of fundamental importance.

(ii) Electromagnetism

Efforts are being made to improve man's control over the entire electromagnetic spectrum from the ultraviolet through the visible and infrared to microwave and radio wavelengths. Applications of the various spectral regions in the field of communication are being investigated as well as their use for improving methods of electrical power generation and distribution. Electrical engineering, magnetism, electrooptics, and electroacoustics are, of course, related to this field.

(iii) Mechanics

The importance of rheology is shown by the formation of the Society of Rheology, which has grown from 426 members in 1956 to 650 in 1963. The rheology of various structural materials is of importance, as are the dynamic strength properties of these materials, including impact strength. Metal fatigue is by no means understood. Experimental methods of stress analysis of inhomogeneous materials would find ready application to modern structural materials. Properties of various adhesives need detailed study, especially adhesion to some of the new polymers.

(iv) Optics

Problems involving color metamerism (identical color perception arising from different spectral distribution of stimuli) are of considerable importance in this day of colored light sources, dyes, paints, and their specification. There is a need for judging color differences by physical means. Color photometry presents complexities that are reminiscent of general relativity and in fact a metric is being sought for "color space", which involves the measurement of its Gaussian curvature by means of a colorimeter.

Lasers have made it possible to make interferometric measurements of relatively great lengths. This and the development and exploitation of lasers for a great variety of technologies can be of great potential benefit to Canadian industry. In a country such as ours, where communication is important, the development of means of broadband modulation of laser beams could have a major impact on society.

(v) Physics of fluids

Concerning this field, R.G. Fowler has stated:[1] "...although scope, importance, and utility of fluid dynamics in physics have grown spectacularly, teaching of the subject in physics departments has been receiving less and less attention."

The field of plasmas is considered by another division, but of even greater immediate importance are the problems of turbulent flow, boundary layer problems, and shock waves. Shock waves originating from supersonic transports will be a practical problem long before the need for hydrogen fusion energy becomes critical; in some forms, such as tidal waves, this field is already of great concern.

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[1] Current Problems in Fluid Dynamics, Physics Today, June, 1966, p. 37.

(vi) Thermal physics

Heat transfer has remained an important technical problem at low and intermediate, as well as at high temperatures. Even the measurement of temperature continues to present difficulties at low and high temperatures.. The strength of materials, especially metals, and the measurement of other parameters at high temperatures is of importance to many industries.

(vii) Fundamental physical standards and basic constants of physics

The extension of scientific knowledge is directly dependent on ability to make measurements. Thus, research to improve our ability to make measurements with ever higher accuracy and precision is of basic importance. Linked directly with this is the need to upgrade continually the precision and accuracy of our knowledge of natural physical constants, such as the velocity of light, the acceleration due to gravity, the gyromagnetic ratio of the proton, etc. Research in measurement and its related fields is particularly vital to a country such as Canada that must develop industries based on science. Although such research work will depend upon a variety of phenomena in many fields of physics, it is very deeply rooted in those fields of physics considered as classical for the purposes of this report.

3.10 DIVISIONAL COMMITTEE COMMENTS

It is obvious that neither the comments quoted above nor those made in this section can be considered to represent the opinion of the majority of physicists. The workers in this field (as in any other field of physics) are in it by choice and hence represent a biased group. Nor can this bias be removed by an averaging process since this will automatically give weight to the most popular field. What is needed is reasoned argument from fundamental criteria that are independent of the individuals' personal preferences. Such criteria can be derived only from clearly stated objectives of the country's research activity, but these appear not to be part of the terms of reference of the CAP committee. We shall assume, therefore, that for the country (although not necessarily for the individual researcher) *the primary objective is the optimum stimulus to technological development and economic growth.* (There are other good reasons for research activity, such as national prestige and inherent cultural value, which derive from important contributions to scientific knowledge. However these will be considered here as secondary objectives.)

Frederick Seitz of the US National Academy of Science wrote:[1] "There are occasions when all of us involved in science and public policy find it convenient to take the view that the development of science is the principal ingredient needed to achieve technological advancement....On the other hand, it is easy to be convinced that one can go very far by borrowing pure science from other nations and putting it to work. Our own country did not really pull abreast of Western Europe in creative science until the second quarter of this century, by which time it was technically advanced by any standard. Its level of living was among the highest in the world *well before it challenged Western Europe in competition for Nobel awards.*"

One could easily argue that Dr. Seitz is stating the case modestly. The standard of living in the US was more than "*among* the highest" long before 1935. Yet in the first 35 years of Nobel awards (which began in 1901) the US received only three in the field of physics (Michelson, Millikan, and Compton); since then it has been collecting about 50% of the awards. The picture in chemistry is similar though not so striking. Before 1930 there was only one award in the US. From 1932 to 1965 there were 10.

Even in physiology and medicine the trend is the same. There were no awards before 1930 in the US but 15 in the following 35 years.

In the relation between science and technology it appears much more reasonable to consider technology as a greater stimulus to science than vice versa. The fundamental work on electricity and its impact on technology is often cited as proof to the contrary. But for each such case an opposite can be found. James Watt's invention of the steam engine and its subsequent development sparked the industrial revolution and occurred many years before the Carnot cycle provided a proper scientific basis and an accurate understanding of its limitations.

Generalizations from a small number of case histories are highly unreliable and are not usually considered the foundation of the scientific approach. Many students of economics have attempted more systematic studies of the causes of economic growth and have come to conclusions that cast serious doubt on the above popular thesis of pure scientists.

In the last 10 years economists dealing with production functions have occupied themselves with the "Residual", which arose

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[1] Science, Vol. 151 (1966), p. 1039.

out of a paper by Abramowitz[1], who introduced this element because the input of physical capital stock and services of labor was unable, by far, to account for the net per capita production. In commenting on it he writes (p.11) "... the indicated importance of this element may be taken to be some sort of measure of our ignorance about the causes of economic growth in the United States...." In view of such statements by economists it would be rash of scientists to maintain glibly that economic progress can be explained by increased fundamental science research, and to use this as a basis for recommending accelerated expenditures in these fields without regard for the specific needs of applied physics research.

Jacob Schmookler, in a study of patent statistics and a detailed study of 900 of the most important inventions in about the last 100 years[2], lists the order of importance of three elements in economic growth as follows:

1. "The production of inventions that are sought because *problems and opportunities have been initially identified.*"
2. "Insight yielding accidents and discoveries *within industrial research operations.*"
3. "Individual discoveries in pure science."

He goes on to caution "...not that science is unimportant to invention but merely that its role is often misconceived. Most inventions, including most of the important ones, are made by men more attuned to events in the workaday world than to the latest issue of the Physical Review.... In short, vital though it is, scientific discovery is far more a *permissive* than an *active* factor in the inventive process."

Even the boundary set by the "permissive" factor is downgraded further on. "To state the issue as I see it:

(1) If some omniscient being were to list all the inventions that could have been made.... on the basis of the scientific discoveries made in the nineteenth (century) his list would greatly exceed the list of inventions actually made in this century....

(2) If somehow we were able to eradicate from history a scientific discovery required for some invention then perhaps more often than not some other invention would have been made,

[1] Papers and Proceedings of the American Economic Association, Vol. 46, May, 1956, p. 5-23.

[2] Invention and Economic Growth, loc. cit.

or taken off the shelf and used, to do roughly the same thing....

It seems an error to suppose that the course of technological and economic progress could, in principle, be predicted from the progress of science."

It might be assumed that invention, product development, and innovation will automatically follow if the "permissive" boundaries of science are widened, but an increase of a factor of three in research expenditure in the drug industry between 1955 and 1962 resulted in only an increase of somewhat over 20% in new drugs marketed. In the general patent field an increase of about 5% in the US patents filed resulted from an increase of more than a factor of two in research expenditure by industry[1].

In view of the above statements, the sampling of opinions expressed in Section 3.8 by people working in classical physics research loses its apparently biased character. Though differing in detail there seems to be a consensus on the need for more stress by universities on the teaching of classical physics as well as for support by the government of classical and applied physics research. Furthermore, the need for a closer relation between the research carried out on the one hand, and industrial problems and Canadian needs on the other, should be emphasized. In other words the emphasis should be on *applied* research.

The latter part of this century is characterized by an enormous store of largely unexploited scientific knowledge, which is now so great that information retrieval is presenting problems almost as great as those of its accumulation. Those who try to use this store are not usually those most familiar with it. (A new business is growing up rapidly – that of making literature searches for a price). This can easily lead to a low ratio of actual to potential utility of this knowledge. The greater the acceleration of the rate at which this accumulation takes place, the lower will be the utility ratio unless positive steps are taken to overcome this difficulty. In physics such interdisciplinary fields as biophysics, medical physics, chemical physics, etc., do much to close the utility gap. But we need many more such bridges (especially in the field of industry, transportation, and environment control) and we must realize that "the national research and development enterprise is an organic whole...."[2]

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[1] Eighth Annual Meeting of the National Research Council, Washington, D.C. 1965; Breaking the Innovation Barrier, by C.E. Barnes.

[2] Ibid. Effects of Current Trends on the Support of Research, H. Brooks.

The main producers of the wealth of this country are now too isolated from a basic knowledge in physics. The fact that this has never been the case in the field of chemistry may well be one of the reasons why chemistry plays a so much more important role in our economy than does physics. Industry is often blamed for not knowing how to use physicists, but it is up to the physicists to show how this can be done. We need more "hyphenated" physicists!

Comparison with other countries has so far been deliberately avoided in order to attempt, as far as possible, to deduce from more basic considerations an appropriate perspective in which to regard our research. If we do make such comparisons the salient feature that is immediately obvious is the much smaller fraction of the GNP that is spent on research in Canada than in similar western nations. Even if we take into account the substantially lower per capita income relative to that in the US (and the normally nonlinear relation between it and research expenditure) a very appreciable increase in government support for research is indicated. However *most of this increase should go into applied physics,* especially in industry, in order to redress a serious imbalance that shows up particularly strongly when a comparison is made with the distribution of funds in the US.

Another fact of great interest is that in the US more than 37% of all physicists are employed in the field covered here and labelled "classical physics." Unfortunately the figures for Canada are not available but it suggests strongly that a change in emphasis in university teaching is desirable.

3.11 RECOMMENDATIONS ON GRANT SUPPORT MECHANISM

Our main concern should be with specifically Canadian problems, and it is important to state again what was said in Section 3.10, that we have assumed that the *primary objective of this country's research activities is the optimum stimulus to technological development and economic growth*; an important prerequisite to success in this objective is to ensure that our national "...problems and opportunities have been initially identified."[1] This objective cannot be attained in an atmosphere where applied research or technology is regarded as intellectually or socially inferior. Yet this atmosphere is

[1] Invention and Economic Growth, loc. cit.

altogether too prevalent at our universities today. (This was not always so, and it is interesting to note that in the first 30 years of its existence only 40% of the research of the Fellows of the Royal Society was in so-called pure science[1]). A realistic grant support mechanism must take account of these facts and do so without unduly interfering with the traditional and highly prized freedom of the universities.

We believe that a biased grant system, which is slanted toward specific national problems, can overcome some of the reluctance of students to work in the fields not surrounded by auras of glamour and might even help to shift the aura. Such bias does not necessarily represent interference with freedom of the universities but rather makes it compatible with the freedom of society to spend its money as it sees fit. If society is to be denied that freedom then the word ceases to have much meaning. (The growth of the technical universities in Europe, Britain, and the US, and certain relevant comments in the Robbins Report[2] must be regarded as significant for Canada in the present context.)

We consider research as a product that one part of the community wishes to sell to the rest of the country. Scientists may offer research A at $20,000, research B at $40,000, or C at $100,000 per man-year. Society as a whole, through its representatives, must decide on how much of each it wishes, or can afford, to buy with due regard to the effect on the country, both technologically and culturally. If one branch of research is more expensive than another, then it should be shown to be that much more useful in reaching our objectives.

We therefore suggest that the distribution of grants be in the hands of a panel *constituted of representatives approximately equally distributed between government, universities, and industry.* It is especially emphasized that the latter have no less than one-third representation so that industry will have a voice, not only in the amount of support that their research will get, but *also in the support that the universities will get and how it will be distributed in different research areas.* This panel should also be the one to prepare the case regarding the total amount of money that should be made available for research support, since they will have fairly detailed knowledge of projects and relative costs. How, and through what body, this case is presented is of secondary importance.

[1] Education and the Technological Revolution, G. Walters, Tonbridge Printers Ltd. (1964), p. 7.

[2] Higher Education: Report of the Committee under the Chairmanship of Lord Robbins, Cmnd. 2154 (H.M.S.O. 1963).

The present system of having one body providing grants for defence-oriented research, another for development in industry, another for research in industry, etc., has the serious fault that coordination is lacking. To centralize the responsibility for all grant distribution in one body would assure a broader viewpoint, while a strengthened representation of industry would ensure that there is due regard for the fact that we can afford to import science (in fact it is distributed free), *but we cannot afford to continue forever to import our technology.*

3.12 FUTURE SURVEYS

It is strongly urged that surveys be carried out periodically (e.g. every five years) in the future to ensure that up-to-date information is available. However, these surveys should be made in a uniform manner in the different fields (not just of physics but all other sciences) and provide a thorough coverage. To this end a small group, representing different fields, should be set up to work in cooperation with the Dominion Bureau of Statistics or the Department of Manpower and Immigration to draw up an appropriate form that will elicit the desired information from those circularized. Once adopted, these forms would be sent out in a routine manner by this agency and the data processed by them. This might be done in conjunction with the general manpower survey.

Section 4

PHYSICS OF THE EARTH

R. D. Russell (Chairman), J. H. Hodgson, A. D. Misener, and K. Whitham

> We travel together, passengers on a little space ship, dependent on its vulnerable reserves of air and soil; all committed for our safety to its security and peace; preserved from annihilation only by the care, the work, and I will say, the love we give our fragile craft.
>
> Adlai Stevenson
> Geneva July 9, 1965

4.1 INTRODUCTION

(i) Definition of the field

Any person with no interest in his surroundings would be extraordinary. The air we breathe, the water we drink, the ores we mine, and the fuels we burn are of such importance that they could hardly escape attention. *Earth physics or geophysics,* is a study of the physical processes occurring in the earth and is a study of the earth by physical means. These fields are normally considered to include the scientific study of the interactions of the earth with its immediate surroundings. Thus earth physics usually includes meteorology, physics of the upper atmosphere, and the effect at the earth's surface of such distant phenomena as solar disturbances. In order to make the present study manageable, meteorology and aeronomy are being handled as separate disciplines, and therefore our interests here terminate at the earth's surface. Because most of this surface is water covered, physical oceanography and the physical limnology of large lakes are included as part of earth physics.

The techniques of geophysics are those of physics, mathematics, and chemistry, and the field is therefore closely dependent on these subjects. It interacts strongly with research in other disciplines. The interpretation of geophysical processes may contribute significantly to geological understanding as, for example, in mining and oil exploration. Geophysical findings may relate to geography and certain branches of engineering. Physics of the earth is thus seen to be a rather broad subject, meeting a number of distinct disciplines at diffuse and ill-defined boundaries.

In organizing this report, rather arbitrary decisions have had to be made in order to choose the material to be included. The most difficult decisions occur at the boundary with geology, where distinctions are particularly difficult to make, and at the boundary between research and development, for in geophysics the boundary between academic and economic problems is constantly changing. We have included in our discussions a number of studies, such as the nature of the earth's crust, which could equally well be considered geology.

In such cases we have based our decision on the fact that the scientists primarily responsible for carrying out the work are trained as geophysicists and that the techniques used are primarily based on physics. In considering industrial geophysics, we have interpreted the term "research" rather broadly to include many practical studies which, although not fundamental, are not routine.

(ii) Method of collecting information

The members of this subcommittee have a reasonably broad personal knowledge of geophysical research in the universities and in government in Canada. The geophysical activity with which these groups are involved is reported annually and fully in the Canadian Geophysical Bulletin, edited by Prof. G. D. Garland and published by the Associate Committee of Geodesy and Geophysics of NRC. No attempt will be made in this report to catalogue these activities, and the reader more interested in this aspect of the study is advised to turn to this publication. In addition to this source, additional information was sought by sending questionnaires to those universities known to us to be active in geophysics. The questionnaires were intended to serve two purposes not served by the Geophysical Bulletin. It was necessary to obtain statistical information concerning financial and manpower aspects of present geophysical activities in the universities, and it was desirable to get some personal impressions of current progress and the rights and wrongs of present procedures.

Documentary information on geophysical activities in the Canadian government was obtained through various officials. In this regard everyone has been most helpful; names of certain individuals who have contributed generously to the material for this report are acknowledged at the end.

The activities in the geophysics industry form an important part of geophysics in Canada, and it is fortunate that the industry is also well organized to provide information of the type we require. In particular, we were able to obtain formal briefs from three associations, the Canadian Society of Exploration Geophysicists, the Well Logging Association of Canada, and the KEGS (mining geophysicists), all providing us with valuable material for this report.

Additional statistical data were obtained from reports published by the National Research Council of Canada and the Dominion Bureau of Statistics.

In the time available for the preparation of this report it was not possible to discuss all research areas adequately. Glaciology, groundwater hydrology, and seismic studies of lake-bottom sediments should be included, but are not. The impetus recently given to research in marine geophysics, particularly by the discovery that ocean floors are imprinted magnetically, is not adequately described, and incomplete references to oceanographic research do not do justice to that subject. It is not intended that these inadequacies in this report should reflect on the importance of the subjects concerned.

(iii) Development of Canadian geophysics

Geophysics is a subject in which Canadian activity has been substantial and profitable. In some cases the source of Canadian interest can best be described as a happy accident. Thus it happens that the first geological age determinations, which were based on radioactive decay, were carried out in 1905 at McGill University by Rutherford and his associates. The subsequent work by H. V. Ellsworth of of the Canadian Geological Survey, published in 1932, is a classic of its time. With this type of beginning it is not surprising that this particular field has flourished in Canada. It is fortunate that a number of Canada's distinguished physicists have, over the years, turned their attention to problems in geophysical exploration. In this regard one thinks of such persons as Eve, Keyes, Gilchrist, and others. It was because of their interest that Canadian geophysics came to be founded on a strong *physical* base, a factor that has proved to be an important source of its strength.

The earliest geophysical work to be carried out in Canada was the measurement of the magnetic declination by the navigators and explorers of the 16th century. By the early 1600's, magnetic inclination was also measured. Many of these observations survive, and are useful today in studies of the magnetic secular change. The first expedition to Canada with the primary purpose of magnetic surveying was that of Sir John Ross, which resulted in the discovery of the north magnetic dip pole on Boothia Peninsula in 1831. An outstanding example of the many magnetic surveys of this period was carried out by J. H. Lefroy, who observed at over 300 stations extending from Montreal to York Factory on Hudson Bay, and down the MacKenzie River as far as Fort Good Hope, in 1843-44. In 1883 Lefroy published remarkably complete and detailed magnetic charts of British North America south of the Arctic Circle, based on measurements at some 600 stations.

The Toronto Magnetic Observatory holds an important place in the history of geomagnetic research. It was established by the British government in 1840 under Captain E. Sabine, and taken over by the province in 1853. Professor G. T. Kingston of University College directed its operation until 1872, when it was transferred to the Meteorological Service. In 1936 the Canadian magnetic observatories were transferred to the Dominion Observatory. The Toronto magnetic observations form the longest continuous record in the western hemisphere, and one of the longest anywhere in the world. Important early discoveries made from the Toronto records were Sabine's recognition, in 1851, of the correlation between magnetic disturbance and sunspot variation, and his discovery of the lunar daily magnetic variation in 1853.

The same Captain Sabine apparently made the first measurements of gravity in Canada when, as the astronomer and scientific observer on the second voyage of Parry (1819-20), he swung pendulums at Winter Harbour on Melville Island.

Other highlights in the history of gravity observations are the measurement of gravity in the basement of the physics building of McGill University (1894) by Commandant Defforges of the Geophysics Service of the Geographical Service of the French Army; this was part of a series of observations aimed at testing the theory of isostasy in North America. The first absolute measurement of gravity in Canada was made in the basement of the School of Practical Science, University of Toronto, by A. M. Scott in 1896.

Seismological observations also date from the 19th century. There is a reference to a seismometer operated by a Dr. Smallwood of McGill University in 1871, although nothing is known about it. Government interest in seismology dates from 1897 when the British Association for the Advancement of Science asked observatories throughout the empire to purchase and operate seismographs of a standard design.

In Canada it was the meteorological observatories that responded; one seismograph was installed at Toronto, another at Victoria. Shortly after, the newly formed Dominion Observatory became interested in the study of the earth as the only available planet. Dr. O. Klotz, the assistant director, purchased the most up-to-date seismographs, comparative pendulums and a magnetometer, and hired young physicists to specialize in these three fields under his direction. From this beginning sprang the present three geophysics divisions of the Observatories Branch. With the reorganization of government departments in 1936 the Observatory took over the seismic and magnetic responsibilities and assets of the Meteorological Branch.

Initially, government interest in geophysics lay in its application to the larger problems of planet earth, but it became obvious very soon that it had possibilities in the search for minerals. In 1928 a group of Geological Survey geologists and university professors investigated and reported on the various methods of geophysical prospecting. Their report, which forms the substance of Memoirs 165 and 170 of the Geological Survey, demonstrated that the rather spectacular claims of the early exploration geophysicists were based on sound scientific principles. From that day there has been a strong and growing geophysical exploration industry that has many interactions with university and government geophysics. It is our belief that the spirit of cooperation among university, government, and industry provides an important contribution to the strength of the subject. Each year government and university geophysicists join forces to carry out field programs to determine new information about the structure of the North American continent. At times industry, too, becomes involved with these essentially academic problems. For example, during the International Geophysical Year commercial well-logging experiments were augmented to add basic information about the electric currents passing through the sediments forming the Canadian prairies. From time to time large explosions, originating usually from experiments by DRB, are monitored not only by university scientists but also by oil company geophysicists who contribute at such times not only valuable instrumentation capabilities, but also their substantial experience. At a seminar recently held at a western university, oil company geologists and geophysicists were to be seen comparing notes with university geophysicists and geologists on seismic measurements on the structure off our western shores. From the point of view of university geophysicists, one of the most important interactions with industry is the need by industry for university graduates trained in this field. To anticipate a discussion that will come later in this report, the demand for geophysics graduates exceeds the supply at all levels.

Physics of the earth has human values as well as scientific and economic significance. The Dominion Observatory, within the Department of Energy, Mines and Resources, operates one of the finest seismic networks in the world. As well as enabling Canada to fulfill international commitments, the background information provided as a routine service makes it possible to calculate the statistical probabilities of earthquake tremors in different parts of the country, which is an important factor in determining building codes. Through geophysical activities, particularly in the Department of Energy, Mines and Resources, any interested citizen can acquire maps showing the magnetic and gravity fields for almost any part of Canada. The scientific study of the Great Lakes and of our coastal waters contributes to the important questions of pollution and navigation, recreational facilities, and fisheries.

Canada has a number of international commitments related to geophysics. Oceanographic data are supplied to scientists around the world. Canadian seismic and magnetic networks contribute to international data centers. Our responsibilities in such work are proportional to the area of our country, rather than to our population or our economic wealth and we can take pride in the fact that we are meeting these responsibilities. However, because of the limitation of Canadian funds some special projects have been conceived and directed by non-Canadian funding bodies. For example, recent extensive experiments to determine crustal structure under Canada are receiving major support from the US. Canada has international obligations, too, in the area of atomic explosion detection, which it is meeting with its medium aperture array at Yellowknife and its excellent seismic network.

The importance of Canada's contributions to international earth science is attested by the positions of importance Canadians occupy in international scientific unions and associations. The organization representing geophysics is the International Union of Geodesy and Geophysics. During the period 1954-57 Professor J. T. Wilson was vice-president of this organization and during the following three years he was president. Since 1960, Dr. G. D. Garland has been secretary-general of this important international organization and Dr. M. Caputo, the deputy secretary-general. Dr. J. H. Hodgson is president of the International Association of Seismology and Physics of the Earth's Interior and M. L. Godson is secretary of the International Association of Meteorology and Atmospheric Physics. Dr. J. M. Harrison has been the first president of the International Union of Geological Sciences and is now president of the International Council of Scientific Unions. Many other Canadian scientists have important positions on commissions and working groups. These appointments not only recognize the Canadian individuals involved, but also attest to the high regard in which Canadian earth scientists are held by the international community.

4.2 PRESENT LEVEL OF ACTIVITY

(i) Manpower

It is pertinent to inquire about the number of Canadian geophysicists who, through their employment, contribute to scientific understanding and to the Canadian nation. In order to answer these questions it will be necessary to consider activities of industry, government, and the universities.

The gross distribution of personnel among the physical sciences can be obtained from the census figures reported by the Dominion Bureau of Statistics; the figures for the 1961 census have just become available.[1] These show that approximately 11,000 Canadians are employed as physical scientists. Of these, more than half are chemists and about a quarter are geologists. Approximately 400 professional scientists, other than geologists, are shown to be occupied in industries related to exploration for minerals and for oil.

More detailed estimates were obtained from the industry itself.[2] In petroleum geophysics the numbers are:

B.Sc. –	440
M.Sc. –	50
Ph.D. –	10
Total	500

Well-logging is an aspect of geophysical exploration that is important in industry. At present the well-logging service companies employ about 170 professional personnel. It is estimated that there are 75 geophysicists engaged in mining exploration in Canada. In addition, a significant number are working for Canadian companies on overseas programs.

The Department of Energy, Mines and Resources employs the following geophysicists:

[1] 1961 Census of Canada, Bulletin S1-2 *Labour Force*, Dominion Bureau of Statistics, June 30, 1966.

[2] Submissions by the Canadian Society of Exploration Geophysicists, Calgary, the Well Logging Association of Canada and the KEGS, Toronto.

	Ph. D.	M. Sc.	B. Sc.	Technician
Geophysics Division[1]	13	10	12	23
Geophysics Section[2]	4	3	2	10
Seismology Division[3]	11	6	8	14
Geomagnetic Division[3]	3	6	22	2
Gravity Division[3]	4	7	11	3
Physical Oceanography (About 30 professionals, distribution not known)				

[1]Geological Survey of Canada. [2]Marine Sciences Branch [3]Dominion Observatory.

We have not obtained specific information about provincial government activities, but the numbers of geophysicists involved are small.

The above table shows that the ratio of technicians to professionals is quite variable. It is widely agreed that the ratio should approach one to one, if professional personnel are to be used most efficiently. This is also the desirable ratio for university research.

In the universities the number of geophysics faculty members is between 35 and 40; in addition there are about 15 working in physical oceanography and large lake limnology. The uncertainty in these figures arises principally from the uncertainty in defining the boundaries of solid earth geophysics and physical oceanography. For example, Prof. G. L. Pickard estimates that in January 1966 there were 130 working in oceanographic research, of whom one half to two thirds, that is 65 to 80, are in physical oceanography. This estimate contrasts with the total of 54 for the figures presented here.

The universities are supervising the studies of about 40 graduate students in solid earth geophysics and 25-30 in physical oceanography. These estimates are subject to the same uncertainties mentioned above.

The universities graduate about 30 students per year in solid earth geophysics and award about 22 master's degrees and 11 doctorates in the same field. These figures result from a survey that included only the eight universities most active in geophysics. We do not have such detailed figures for physical oceanography, but a total of 25-30 students proceeding towards graduate degrees is a reasonable estimate.

(ii) Cost

In 1965, geophysical activity in Western Canada included 756 seismic crew-months, 45 gravity crew-months, and some 100,000 miles of airborne magnetometer coverage. The greatest cost is involved in the seismic exploration activities, which require an expenditure of $35,000 per crew-month for operation in the plains and about $75,000 per crew-month for operation in bush areas. The industry estimates that in 1966 the cost for obtaining and processing seismic data will be at least $52 million. An additional expenditure of about $1 million for airborne magnetometer work and $250,000 for gravity-meter surveys will bring the total for 1966 for exploration to approximately $54 million. To this should be added the costs of well-logging, which are expected to reach $11 million in 1966.

The detailed figures provided by the Canadian Society of Exploration Geophysicists throw an interesting light on the changing nature of the work involved. In the years 1949 to 1952 the number of seismic crew-months spent in Western Canada increased from 750 to 1,850, and then between 1952 and 1959 the number declined steadily to about 670 crew-months. From 1959 to 1966 the number has risen slowly to about 830. Therefore in the last 17 years this measure of geophysical activity has fluctuated by about a factor of two. On the other hand, the number of Canadian members of the Society of Exploration Geophysicists rose from 95 in 1949 to about 430 in 1957. After this it declined almost uniformly between 1957 and 1966 to the present figure of 370. It is noticeable that the peak membership lagged the peak in activity by five years and that the factor of two decrease in activity following the peak results in only a 20% decrease in the society membership. Spokesmen for the industry confirm our inference that the geophysicist is doing more sophisticated work in the last ten years than he was doing previously and, in particular, that a much greater proportion of his effort is directed towards the processing and interpretation of data rather than its collection.

We have not been able to obtain any estimate of the money expended in mining geophysics.

The more basic research in earth physics tends to be carried out in Canada by universities and by government laboratories. Here, too, there are ambiguities in distinguishing research in earth physics from research in other branches of physics, and from engineering and geology. It is difficult to proportion costs between education and research.

Table I shows expenditures in the Department of Energy, Mines and Resources for geophysics for the years 1964 to 1967, contrasted with the year 1954-55. A forecast for the year 1967-68 is included.

Table 1.–DEPARTMENT OF ENERGY, MINES AND RESOURCES EXPENDITURES ON GEOPHYSICS IN THOUSANDS OF DOLLARS*

	1954-55	1964-65	1965-66	1966-67	1967-68
Dominion Observatory					
Salaries	212	539	697	746	986
Operating	86	566	676	725	868
Capital	60	524	500	548	606
Total	358	1,629	1,873	2,019	2,460
Geological Survey of Canada					
Salaries	152	326	349	403	458
Operating	98	1,520	1,428	1,447	1,584
Capital	37	51	132	150	346
Total	287	1,897	1,909	2,000	2,388
Marine Sciences Branch (solid earth)					
Salaries		42	69	78	156
Operating		43	47	51	86
Capital		151	145	159	130
Engineering assistance		40	60	40	30
Ship operation		364	352	684	80
Total without ship time		276	321	328	402
Total with ship time		640	673	1,012	482

Geodetic Survey					
Salaries	4	102	75	93	84
Operating	1	122	64	159	128
Capital		10	7	9	10
Total	5	234	146	261	222
Department Total for Geophysics	650	4,400	4,601	5,292	5,552

*This table does not include Physical Oceanography, which involves additional expenses comparable with Marine Science.

The figures for expenditure within the survey include the following amounts paid to industry for carrying out the Federal/Provincial Aeromagnetic Survey:

1964-65	$1,343,400	
1965-66	$1,067,800	
1967-68	$1,100,000	(proposed)

The expenditures listed in Table I include items that make comparison with university costs difficult. The observatory capital vote from 1964 onward includes the cost of constructing seismograph vaults throughout Canada. These must be included because they constitute part of the data-collecting system. The Observatory operating vote includes substantial sums for diamond drilling, to study meteor craters or to permit measurement of heat flow. Again, this is a necessary part of the data-gathering technique. Many projects, in several branches, involve large sums of money for the charter of aircraft. Sometimes the instruments are mounted in the aircraft and a physicist might then recognize it as a laboratory; more often it is a means of transportation in the remote areas where data are collected. The Marine Sciences Branch conducts geophysical operations from ships that are floating laboratories. In Table I we have listed this cost separately. The smaller figure for 1967-68 is due to the fact that no major geophysical cruises are planned for that year. Note that this table includes salaries, which account for more than 40% of the total.

We do not have comparable figures for government expenditure on physical oceanography or large lake limnology. On the basis of relative staff numbers, we judge that the expenditures will be comparable with the geophysics costs of the Marine Science Branch (Table I).

The Defence Research Board is also very active in earth and marine physics. Table II summarizes its 1966–67 activities in the area of basic marine sciences. In addition, in the same year it awarded about $137,000 in grants to universities for research in earth sciences, of which we judge about three quarters to be research falling within the scope of this division. DRB also awards contracts for research in universities, which totalled about $200,000 in 1966–67.

It is more difficult to obtain realistic costs for university research. One measure of activity is the money given to universities by NRC in the form of operating grants. We have tried to select from the 1966–67 operating grant figures, those that seem to be directed toward geophysical studies. In this way we obtain a total of about $450,000 for the fiscal year 1966–67, with an uncertainty of probably not more than about 15%.

Table II. – DEFENCE RESEARCH BOARD EFFORT IN BASIC MARINE SCIENCE

1. DRB's effort in basic marine science has been focussed on underwater or under ice acoustics because of the clear applicability of such fundamental knowledge to the defence problem of submarine detection. This work has been carried out primarily at NRE and PNL.

2. The following list of projects, manpower, and money considered to be basic marine research as distinct from applied research or direct service oriented research is given for each establishment:

NRE

Project title	Manpower allocated	Money allocated 1966/67
Underwater acoustics research.	17.0 scientists	$400,000
Signal processing (distortion of sonic signals caused by medium and target).	6.0 "	105,000

PNL

Project title	Manpower allocated	Money allocated 1966/67
Deep ocean acoustics	5.5 scientists	170,000
Under ice acoustics	4.0 "	140,000
Creation and detection of turbulence in the ocean	6.0 "	160,000
Long period electromagnetic phenomena	4.6 "	210,000

Fig. I shows the growth of this support during the past several years. Also plotted are the numbers of individuals specifically named in the published summaries of awards. The curves are essentially parallel and show a mean support of about $6,000 ± 10% per individual, not including major equipement grants. The budgeting procedures in NRC are based on a proportional increase (recently about 20%) to established scientists plus a modest allotment ($3,500 during the period covered by the graph, recently increased to $5,000) for new applications. Because the number of new applications in earth physics is very large, the overall result has been to keep the average support per individual approximately stationary.

Oceanography and large lake limnology are supported by three additional major grants totalling $335,000 in 1965–66. This supports all branches of oceanography and we do not know the proportion devoted to physical studies.

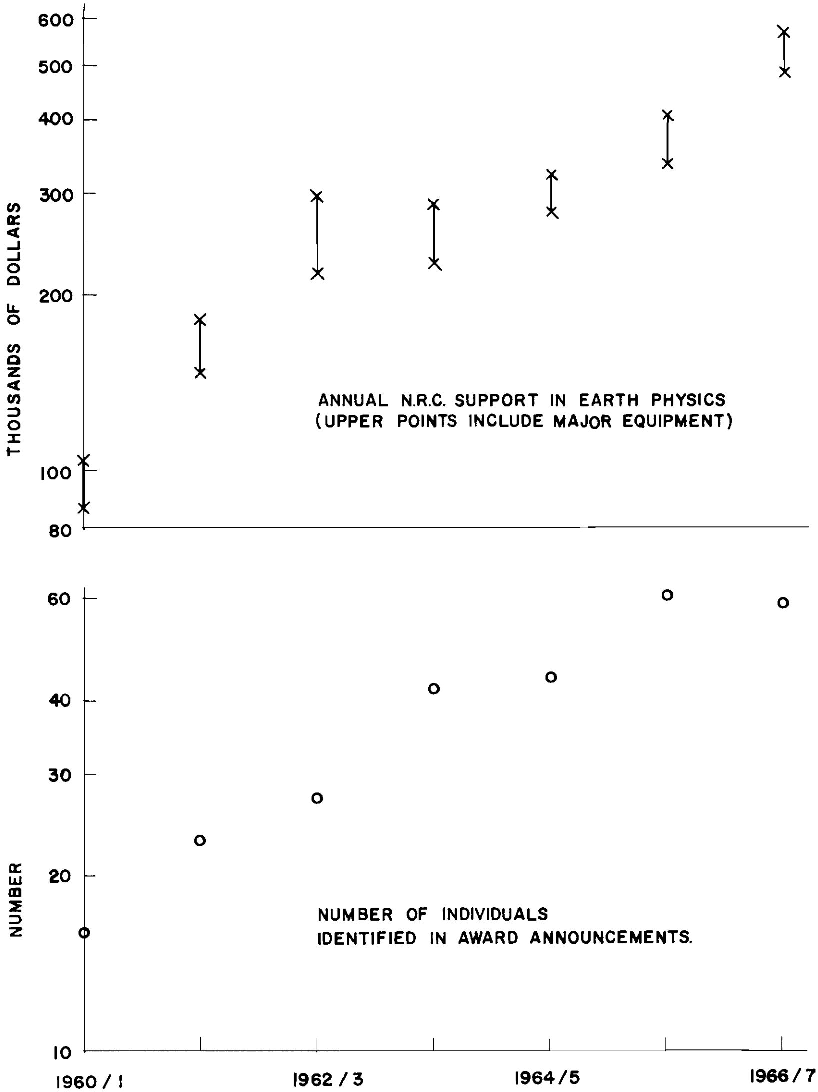

Fig. 1 Annual NRC support in earth physics in thousands of dollars (upper), and number of grantees (lower), versus time in years.

While NRC is the largest single source of operating funds, it is by no means the only significant source. We have attempted to obtain reasonable estimates for other research support directly from the universities. We have figures from eight universities that together represent the bulk of university geophysical research. The NRC support reported by these university laboratories totals about $320,000. The amount we have missed in this way is accounted for by geophysical research carried out in smaller geophysics departments, and in engineering departments. The check is reasonably satisfactory, and we have scaled the figures for other support upwards by the same amount to obtain overall estimates. The support to Canadian universities in solid earth geophysics in the year 1966, so estimated, is approximately:

NRC	$450,000
Other federal sources in Canada	90,000
Local and provincial support	280,000
Support from US sources	100,000
Support from industry	10,000

These figures based on questionnaires are apt to be particularly imprecise. For example, the US Air Force contributed $87,000 to Canadian universities for the single seismic experiment Early Rise. In view of this the above estimate for US support may not be realistic. It is also likely that the support from industry has also been underestimated.

It is important to notice the expenses that are not included in the above figures. In the fiscal year 1965-66, NRC contributed about $75,000 for capital expenditures for research equipment in earth physics. This is not included in the amount listed above from this source, although the amounts listed from the other sources may include capital expenditures. Faculty and some supporting salaries are also not included; they would add at least another $700,000 to the total.

(iii) Output

How can one judge the value of this geophysical effort? It has been true for many years that no oil is found without the help of geophysics. It is more and more true that geophysical methods are used as a primary tool in almost every mining exploration program. The most widely known, but certainly not the only, successes for geophysical techniques in the last few years have been the several ore bodies located at Matagami, Que., and the recent discovery made by Texas Gulf Sulphur Company near Timmins, Ont. Numerous ore zones have been located in the New Area and the recent exploration boom in the Pine Point Area is based entirely on the use of geophysical techniques to find zones of subsurface mineralization. New methods have also been instrumental in locating the zones of disseminated mineralization that have recently become so important in the Gaspé Area of Quebec, and in British Columbia.

The range of activities of university and government scientists can be indicated by listing the names of the subcommittees of the Associate Committee on Geodesy and Geophysics of NRC. These are as follows:

- Aeronomy
- Canadian Committee on Oceanography
- Exploration Geophysics
- Geodesy
- Geomagnetism
- Glaciers
- Gravity
- Hydrology
- International Year of Quiet Sun
- Isotope Studies and Geochronology
- Meteorology
- Scientific Committee for Upper Mantle Project
- Seismology
- Volcanology

Activity in the above fields is quite unequal but in each there is a significant volume of geophysical research. The issue of the Canadian Geophysical Bulletin published in 1966 lists in its bibliography a total of 388 scientific papers, not including those in aeronomy or meteorology.

Results of economic importance are not limited to industry. The gravity and magnetic maps issued by the Dominion Observatory are in constant demand, and ever since systematic aeromagnetic surveys were started by the Geological Survey in 1947 it has been observed that prospecting activity increased in areas where aeromagnetic maps were published. Gravity surveys of the Dominion Observatory over the continental shelves of the Atlantic, Pacific, and Arctic ocean basins and and over Hudson Bay have proved invaluable to the exploration industries in their search for petroleum. Present interest in prospecting Hudson Bay for petroleum is directly attributable to a shipboard magnetometer survey carried out by the Marine Sciences Branch (then the Division of Oceanographic Research) in 1961, and to Geological Survey of Canada aeromagnetic surveys in the area.

In 1949, the discovery of the Marmora, Ont., iron mine resulted directly from a government aeromagnetic survey. Since that time about

$70 million worth of pellets have been shipped from Marmora. The important nickel mine at Thompson, Man., lies on the northern flank of a large regional gravity anomaly discovered by the Dominion Observatory in 1949. The extension and development of the nickel range has resulted from active exploration of the gravity disturbance. The Kapuskasing structure between Chapleau and James Bay in Northern Ontario was first discovered through regional gravity surveys in 1949, and the recent renewal of active exploration in 1964 was prompted by a map published by the Geological Survey of Canada showing a magnetic anomaly associated with the structure. The discovery of the whole New Brunswick base metal camp in 1953 was indirectly attributable to federal/provincial aeromagnetic surveys.

Another matter of practical importance concerns seismic risks in Canada. As a result of pressure from the Dominion Observatory, certain cities are requiring seismic provisions in their building codes. These add greatly (5% to 10%) to building costs. If an earthquake occurs the added cost is more than justified, but any money spent on defining areas of low risk will more than pay for itself in saved construction costs.

4.3 FUTURE OF CANADIAN GEOPHYSICS

(i) Special nature of geophysical research

There are two distinct sides to geophysical research, the observation of physical phenomena with which the earth is associated, and the execution in the laboratory of experiments designed to clarify the interpretation of field measurements. The laboratory experiments have much in common with other types of physical measurements. They may or may not be expensive or involve expensive equipment. They may refer to specific earth material or phenomena, or they may be involved with the clarification of fundamental understanding. It is the field experiments that present a problem in the organization and support of geophysical research.

The geophysicist often has to set up his experiments at the site where the phenomena are observable; he cannot ordinarily bring the phenomena into his own laboratory. In addition, and unlike much research in other branches of physics, he may be quite unable to do a controlled experiment in the area of his interest, since the physical system with which he is concerned may not be controllable in any laboratory sense. The consequences are that the geophysicist is often required to carry out relatively sophisticated scientific experiments under field conditions, and he may be required to make a very large number of scientific observations before he obtains the ones that are required for his experiment.

On one extreme the field laboratory may be large, expensive, complex, and have many of the characteristics of the usual physics laboratory. For example, it may be a ship costing millions of dollars and fitted out especially for the purpose of making marine observations. Other measurements involve the construction of buildings or roads, or the provision of air transport, all in addition to the normal research facilities required. In the case of remote sites, even simple considerations present formidable difficulties.

For some applications the main requirement of the geophysical apparatus is portability. It must be battery-operated, and small and light enough to be transported quickly from place to place by ground vehicles or by aircraft. The net result of such requirements is almost invariably that apparatus for field work is more elaborate and expensive than that which can be tolerated in the laboratory. Airborne methods are particularly suited to Canada because of her vast area and lack of roads in the north. The fact that successful exploration is being based more and more on specialized quantitative data, much of which requires complex geophysical and analytical instruments, suggests a marrying of this equipment with either fixed-wing or helicopter transportation.

The necessity of collecting vast amounts of data also provides important practical problems. In the past much of the geophysical data was collected in a form that made adequate editing and processing virtually impossible. Attention is sometimes called to the fact that some of the data collected in the second polar year in 1932 is still not processed. The reason for this is that, until very recently, the only recording methods involved graphical representation on paper sheets. With ingenuity, geophysicists have learned to pack information onto such sheets very compactly, as in the case of the familiar helical record written by a station seismograph. The only practical way of handling such data is hand editing by human operators. In a highly developed society like Canada's, there are simply not enough competent people available for such tasks, and hand reduction of data has to be avoided wherever possible.

Even early tape recording mechanisms could approximate the fidelity of the paper record and formed a useful basis for storing and handling the equivalent data. More sophisticated modulation techniques have resulted in systems that have far better storage capabilities than the paper records they replaced. We have arrived at a situation where field operations depending on paper records are considered rather primitive and impractical. The change is expensive, however. The chart paper recorder, which may have cost $1,500 or $2,000, is replaced by devices costing ten times that amount. This can be an economy, if the data are important, for data recorded on magnetic tape are more easily recoverable and much more likely to be put to useful purposes. For preliminary analysis few machines can hope to compete with a human operator, but once this stage of processing has been accomplished, the data will very likely be processed by a high speed digital computer. Such a computer is available to almost any geophysicist in Canada. The point at which data should be converted from an analog form to a digital form, which a computer can manage, is a decision that involves many subtle factors. In some cases it seems efficient to make the conversion at the point of the measurement and to record on digital magnetic tape; in other cases it seems preferable to maintain the analog record and to provide facilities for converting analog records to digital after preliminary editing. There is no single answer for such questions, but the important fact is that the conversion of data to a computer-manageable form is likely to be required at some stage of any experiment and that this too is a costly procedure.

A new generation of instruments, spawned in large measure by space research, such as optically-pumped high-sensitivity magnetometers, infrared scanners, X-ray fluorescent analyzers, gamma ray spectrometers, and high-sensitivity electromagnetic detectors should be adapted and applied to mineral exploration. The point is that the needs are often unpredictable and the rate of obsolescence high.

(ii) Relative roles of industry, university and government

What are the proper roles for industry, government, and universities in geophysics, and what balance should be struck between them? As a beginning we may recognize that there are certain services that can be provided only by the federal government and some responsibilities that only it should assume.

(a) Nation-wide surveys demanding nation-wide standards – magnetic and gravity surveys, earthquake maps.

(b) Regional surveys, still demanding nation-wide standards and providing basic data to broad segments of industry – the aeromagnetic coverage of the Canadian Shield.

(c) Continuous operation of national networks – seismic and magnetic, for example, the preliminary reduction of the observations and the forwarding to regional centers; very long-term programs such as the heat flow survey of Canada.

(d) Matters related to public safety or national policy – seismic regionalization, magnetic charts, monitoring of nuclear explosions.

(e) Evaluation of techniques or the development and testing of instruments where such evaluation or testing is beyond the resource or immediate interest of industry or universities.

The above functions can sometimes be filled in cooperation with industry or with the universities. The aeromagnetic survey of the Canadian Shield, organized and supervised by the Geological Survey, provides an example of cooperation with industry. Several universities are making heat flow measurements which are coordinated with the longer term interests of the heat flow section of the Observatory. If industry or universities are to help, however, they must meet the same standards as the central agency.

Government scientific organizations cannot divorce the functions listed above from research. Only if they are using the data they collect as research material will they be able to maintain their high standards. Unless they are involved in the design of techniques and instruments they will not be aware of advances in these fields and will always be trailing behind other nations in their application; and only if they are distinguished research organizations will they be able to attract and hold the bright young scientists they need in all aspects of their work.

If it is admitted that government must maintain a strong research interest, what areas of research should it pursue? Many of these will derive from its service responsibilities. Instrumental development, data processing techniques, and interpretative developments derive from the particular discipline involved. But within any group there must be room for development of new ideas and it is important that these be directed toward the solution of problems important to Canada. Managerial direction is obviously necessary in selecting these problems.

University research in geophysics has provided a good balance to that of government and should continue to do so. The necessity to provide suitable thesis problems demands that the interest of university geophysics departments should tend to be "pure" rather than applied, local or regional rather than national, and short- rather than long-term. A sequence of theses is normally planned to lead to the solution of a major problem, but the possibility of separating the major problem into parts, each suitable for a thesis, must always be borne in mind.

Where research problems involve complex and expensive combined operations of several university groups, or of university and government groups, government geophysicists should probably undertake the organization, and possibly the financing, of such projects. Large crustal "shoots" are a case in point. In studying the crust large charges of dynamite must be exploded under controlled conditions and this is usually the most expensive part of the operation. Obviously, the more recording positions that can be occupied for each shot the more efficient the operation. In 1965 such a combined operation was organized by the Bedford Institute of Oceanography and the Geophysics Division of the Geological Survey. Nine universities and government seismological parties, as well as all the newly equipped seismological net stations of the Dominion Observatory participated, with ship time and navigation assistance being provided by the Bedford Institute of Oceanography. Including the cost of aircraft transportation for the seismological parties, as well as the cost of ships and explosives, the total bill for the operation was of the order of $200,000, not including overhead. Resulting from this are new concepts of the earth's crust underlying Canada. At least seven scientific papers of import to international science have resulted, as well as three M.Sc. and one Ph.D. theses.

A desirable extension of government–university cooperation might be envisaged in the use of expensive instruments. Universities need expensive field equipment but they can use it for only limited periods. More efficient use of government funds could result if expensive equipment purchased by government agencies were made available to university groups on a mutually agreed basis. It would be essential of course that an adequate technical staff be provided to maintain the equipment in good order to handle preparation and shipping, and possibly to act as operators of highly specialized equipment. Similarly, very expensive government laboratories might be made available to competent university people. Specialized palaeomagnetic instruments, oceanographic vessels, or certain hybrid computer operations are cases in point. It is estimated that on the east coast alone universities receive without charge the equivalent of $200,000 worth of ship time each year.

Despite the fact that the current standard for the state of the art of mining exploration geophysics is set by Canadian industry, there is no group, nor even one individual, working full-time in research. The mining companies and the contract survey firms do small amounts of research, but this is mostly of an applied nature. The mining industry as a whole appears to be unwilling to finance much pure research. Many of the petroleum companies may refer their problems to parent companies in the US, with the result that only one has a major research laboratory in Canada.

We believe that these policies are short-sighted. The highly trained men required by these industries can be held only if a proportion of the work, say 10%, is sufficiently fundamental to be stimulating. Moreover, it is agreed that more interaction is desirable between universities and industry; this interaction will take place most naturally in the area of pure research. Despite the advantages of fundamental research within the industry it is unlikely to develop without the aid of tax concessions significantly better than those existing in the US.

4.4 ACKNOWLEDGEMENTS

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4.5 RECOMMENDATIONS

In consideration of the above discussion of Canadian geophysics, the subcommittee makes the following recommendations and comments. Most of them reflect our opinion that the present situation is, on the whole, satisfactory, and that continued growth at a steady rate is desirable.

Particular attention is called to (vii), the only recommendation that does involve a change in policy.

(i) The strength of Canadian geophysics is due in no small measure to the healthy interaction of government, university and industry, particularly as fostered by the strong associate committee on geodesy and geophysics, and its subcommittees. Efforts to reduce the size or effectiveness of this body, and particularly to make any change that might result in its becoming less accessible to young Canadian scientists, should be strongly resisted.

(ii) Industrial research in geophysics, while comparing favorably with other branches of physics, still leaves much room for improvement. Strong government incentives are required to encourage more industrial research of a fundamental nature; such research is required by industry to retain top scientists and to facilitate communication with university scientists.

(iii) Canada's large area and economic interests related to natural resources, as well as its international obligations, require a geophysical activity disproportionate with its economic wealth. All branches of research (as outlined, for example, in "Solid Earth Geophysics, Survey and Outlook" Publication 1231, National Academy of Sciences – National Research Council, US, 1964) are at present represented and all should be encouraged to develop as a major part of Canadian science. The activity in various fields of geophysics is, and should remain, unequal since areas in which we have exceptional competence, or in which our scientists are particularly interested, should be emphasized.

(iv) No major redistribution of activities between universities, government, and industry is deemed necessary. As research in geophysics expands, scientists will have to guard against overworking fields that are popular at the moment, although present balance seems reasonable. Both the number of government laboratories active in geophysics and the number of universities engaged in geophysics research seem about right for the present.

(v) Recent major cooperative field projects between government and university demonstrate that satisfactory means for joint planning, financing, and sharing of equipment and supplies can be worked out, particularly where government laboratories are involved. There is, however, a mechanism needed for planning and financing joint university projects in which government is not involved; this would avoid pressuring of government laboratories by universities requiring support for pet projects, and help preserve the autonomy of university scientists. In general, universities should avoid projects aimed at large-scale data acquisition, since government should be able to do this more effectively.

(vi) Present levels of noncapital research financing are about adequate for university and government, but will need to be increased regularly in the future as has been the case in the recent past. For universities the rate is about 20% per year for established scientists plus provision for the support of new appointments at a modest level. Estimates for the Department of Energy, Mines and Resources are more difficult because of the large, more or less fixed costs of the operation of major networks. Our intention is that the research activities within the department should grow parallel to those in the universities. We are unable to comment on DRB, which has special interests in maintaining the defence capabilities of Canada.

(vii) In the universities, the lack of building space and facilities is widely apparent and, in many cases, acute. Priorities for such needs are often and unwisely based on the population of introductory courses rather than on contribution to Canadian science and technology. Direct federal support in this area would seem to be indicated.

(viii) The committee notes and accepts the statements from mining and petroleum industries that there is a severe shortage of geophysicists. We recommend that this can best be met by a moderate, healthy growth of student classes particularly at the bachelor level. The industry itself will have to find ways to make its work interesting and challenging to geophysics graduates, who now have a wide range of employment opportunities open to them.

(ix) Since a shortage of professional geophysicists now exists and is likely to continue for five years, it is particularly important to provide adequate technical support so that they can occupy their time most efficiently. A ratio approaching one technician to one professional is suggested. The existence of university support from the National Advisory Committee on Geological Sciences, the Dominion Observatory and DRB, are useful safeguards but NRC should remain the principal granting agency.

(x) It is generally agreed that the screening mechanisms for usual operating and capital grants from NRC are fair and workable. A more careful screening mechanism for the very large grants seems indicated. The present mechanism for awarding postdoctorate fellowships to the universities seems inefficient and wasteful since there is no assurance that acceptable candidates will be found. Consideration of the merit of both the applicant and the proposed fellow would be preferable.

(xi) Canadian government must be aware of the substantial US contribution to our university research in geophysics. Should this terminate at any time, it will have to be replaced by Canadian support.

Section 5

METEOROLOGY AND THE ATMOSPHERIC ENVIRONMENTAL SCIENCES

A.W. Brewer (Chairman), B.W. Boville, and W.L. Godson

5.1 INTRODUCTION

(i) Definition

For the purpose of this survey meteorology is defined as the study of physical phenomena occurring in the atmosphere below a height of 50 km. The upper limit is taken as dividing meteorology from aeronomy and space research.

(ii) History

Meteorological research began in Canada in 1840 when the Toronto observatory, which was in the grounds of the University of Toronto, began operation. The observatory was established by the British Government primarily with geomagnetic problems in mind, but it was also a first-class meteorological observatory.

It was first manned by serving officers, Lt. (later General Sir) John Henry Lefroy being the best known. Lefroy was an enthusiastic meteorologist. He was twice president of the (Royal) Canadian Institute.

In 1853, the observatory was handed to the University of Toronto "to hold in trust for the people of Canada" and in 1855 G.T. Kingston was appointed Professor of Meteorology and Director of the Observatory. In this way Toronto came to be the first university in the British Commonwealth to have a professor of meteorology. When Professor Kingston retired in 1870 no successor was appointed by the university, but C. Carpmael, M.A., F.R.S.C. was appointed director of the observatory and director of the Meteorological Service of Canada. Since then, and for these historical reasons, the headquarters of the Meteorological Service of Canada has been located on the campus of the University of Toronto. At Montreal, McGill University appointed Dr. Charles

Smallwood Professor of Meteorology in 1856 and the McGill observatory was established in 1862.

Until about 1946 almost all Canadian meteorological research was carried out in the Meteorological Service. The amount done was small but the Canadian climate made climatological analysis and some applied research essential.

In 1946, in a reorganization, the Meteorological Service of Canada, known formally as the "Meteorological Branch, Department of Transport", established a research and training division. Since then there has been a steady growth of research within the Meteorological Service, which now has an annual research budget of $3 million, or perhaps more, since it is often difficult to separate research and operations.

At about the same time (1946) J.S. Marshall at McGill University established an atmospheric physics research group and from this a large and healthy school has developed. The University of British Columbia began a program on the atmospheric aspects of air-sea interaction in 1960 and this group too, is now a significant contributor to meteorology. Since 1962 there has been a considerable quickening of the pace of university development, and active groups are now to be found at universities from Acadia to British Columbia. Expenditure in the universities (grant and contract money only) is now about $430,000 per annum.

In this same period, roughly since the war, there has also been a growing sense of the importance of meteorology in many fields of Canadian life: agriculture, forestry, water resources, hydroelectric power generation, air pollution, and building development to mention the most obvious. Meteorological research effort is now being expanded in these directions. It would be difficult to overstate the importance of these subjects to Canadian life and to the Canadian economy, but present research expenditure in these directions is relatively small, probably about $1 million per year. This question will be discussed in detail later.

5.2 THE OVERALL PICTURE

(i) Nature of meteorological research

Meteorological research can be viewed from two apparently different directions.

First, meteorology may be regarded as a complex set of challenging physical problems. They are mainly problems of classical physics that were by-passed by 19th century physicists. The challenge they offer is sufficient justification for tackling them, but their intractable nature is a discouragement.

Second, since the atmosphere is an essential part of our environment, meteorology may also be regarded as the prime environmental science and, because we are then concerned with application to real problems, there is a danger of regarding this as engineering. This is not so. It is not a question of applying well-understood principles to familiar problems; we are unfortunately still wallowing in fundamentals.

We may perhaps list here the main branches of the environmental sciences, with which we shall be more concerned later.

(a) Weather forecasting – required for decision making in all weather-sensitive situations. Forecasts are required for varying lengths of time according to the operations concerned, and can range from a few hours (for short period operations) to a few days, or even to climatological periods of a decade. (Will the dust bowl conditions of the prairies, which occurred in the 1930's, return?)

(b) Agrometeorology and climatology, including microclimatology – this includes the influence of the atmosphere on agriculture, including domestic animals, on forests and sylviculture, and also on wildlife, the natural ecology, and on buildings.

(c) Water resources.

(d) Air pollution.

(e) Weather and climate modification.

We cannot easily assess the economic importance of these areas in simple terms of money. Except for weather and climate modification, which remain in the future, the annual sums involved in each of the above areas is of the order of $1 billion. If improved knowledge brings only a very small fractional increase in benefit, it would justify expenditures on research many times greater than are at present available. Weather modification and water resources have political significance, which makes proper understanding of these subjects imperative. Since the US wants water now and in the future will need it urgently, it may wish to divert rivers or remove the water from moist air as it travels toward Canada. We must not be caught unprepared.

The urgent needs of the community have caused workers from other disciplines to move into atmospheric research, largely because some areas have, to a considerable extent, been abdicated by the physicists, with whom they are unfashionable. As a result studies of these subjects are often heavily loaded with empirical approaches, which give results of greater or less value, while the fundamentals remain unknown, and progress is needlessly slow. It is imperative that physicists accept their responsibilities and take a proper interest in fundamental studies of the environmental sciences, even though the field is essentially classical. It is also important that government, at its different levels, should make funds available to support research in these sciences to demonstrate that their importance is recognized.

(ii) The organization of research

In meteorology, as in other branches of science, research is carried out in the public, industrial, and academic sectors. The proportion in these different sectors in unusual. In Canada approximately $3 million per annum[1] is spent on research by the Meteorological Service of Canada, and about $250,000 per annum is spent by the provinces.

In the universities, research grants totalling about $310,000 per annum are received from the federal government and less than $100,000 per annum is received in contracts, making a total about 10 times smaller than the Meteorological Service "in house" expenditure.

Meteorological research in industry, whether government supported or not, appears to be very small; we were not able to get any figures at all.

It would seem that there is room for change. For reasons to be discussed later the university effort should be greatly increased, and industrial participation should not be so low as it appears to be. Unfortunately industrial meteorological research tends to be confused with "rainmaking". This latter activity is rightly regarded with suspicion.

(iii) Financing

A total of about $5 million is expended annually on meteorological research; this is to be compared with an annual value of meteorologically sensitive areas of the Canadian economy amounting to more than $10 billion. This comparison alone suggests gross unbalance, a condition that may be emphasized by comparison with meteorological research expenditures in the US. It is understood that the

[1]Almost all figures of moneys spent are very approximate. In the government service (the largest items) we were almost always compelled to use next (1967-68) year's estimates. No overheads are included. Data of university research grants are available but academic salaries are not included and must be estimated; again, no overheads are included. In industry, overheads are usually generous but this does not arise as a problem here since no industrial expenditure is reported.

US federal estimates for the year 1967–68, include provision for "research and development" in the atmospheric sciences to the extent of $278 million, an increase from $221 million for the current (1966–67) year.[1] This ratio of about 50–1 between US and Canadian expenditure is typical of the funds available to support meteorological research of any kind. By comparison with his US colleague the Canadian researcher is severely handicapped.

University research funds come as annual research grants from the Meteorological Branch, Department of Transport ($120,000 plus contracts for $65,000), National Research Council ($140,000), other federal departments ($57,000), and provincial funds ($46,000). The grants are made, following Canadian tradition, to university staff members. Funds from US sources in support of Canadian university research totalling $110,000 came to our notice.

These moneys are insufficient to ensure adequate growth of university meteorology. The total should be increased to at least $600,000 immediately and considerable growth over the years should be planned.

(iv) Manpower

We located about 32 physicists in universities and provincial research councils carrying out research in meteorology. In the Meteorological Branch there are 275 "meteorologists" who hold a higher degree. Of this number 140 are employed in operational forecasting duties, and 54 in the administration of operations. Sixty-four carry out research or research administration and 13 are employed in training.

Thus, of about 315 persons capable of carrying out full-time meteorological research we have an actual research manpower of close to 100; some few of the remainder, of course, undertake part-time research. The number employed in operational forecasting could perhaps be reduced somewhat. It is a policy of the Meteorological Branch to do this wherever possible, but this potential source of research scientists is not large, partly because the very skilled manpower is needed at some level in forecasting and partly because many of the people concerned are not particularly interested in research.

Although only a fraction of these meteorologists are engaged in research, these scientists are nevertheless a very valuable body of people. Eighty-four of them are over 50 years of age, and losses by death and retirement during the next five years must be expected to

[1]Science 155, p. 434, January 27, 1967.

average about 10 per annum. The present average intake into the Meteorological Service is no more than this.

The available manpower is therefore too small. Having regard to the projected loss, the difficulties of obtaining a net increase will be considerable. The position can be improved only by attracting young people, and this will be done only if the prestige of the subject is enhanced in the universities. *It is for this reason that we urge substantial increases in the funds available to support university research.*

5.3 THE ORGANIZATION OF METEOROLOGICAL RESEARCH IN CANADA

(i) Research in the atmospheric sciences in the Government of Canada

As may be expected, research in the Government of Canada is mainly carried out within the Meteorological Service, but the departments of Agriculture; Forestry; Energy, Mines and Natural Resources; Health and Welfare; the Defence Research Board; the National Research Council; and Atomic Energy of Canada Ltd., are also involved.

Pure research in the Meteorological Service is mainly carried out within the Research and Training Branch, though its work is by no means entirely pure. The Central Analysis Office, located at Dorval, Que., undertakes research in numerical prediction and numerical models, and the climatology division also conducts research, especially for specific applications, including water resources and limnology. The total budget of the Meteorological Service is about $30 million, of which $3 million is used specifically for research. Much of the remainder goes into maintaining forecast services with no research value, although a considerable sum is consumed in making and storing valuable meteorological observations.

(ii) The Research Section, Meteorological Branch, DOT

This section has an expenditure of approximately $2 million per annum, and was established in 1946. It has a research staff of 26, 15 of whom have Ph.D. degrees.

The research section has no requirements for major facilities. There is a meteorological research station near Toronto, which is shared with other divisions. Active research is proceeding on forecasting topics, mesometeorology[1], radiation, atmospheric ozone,

[1]Meso, or intermediate scale, meteorology is the study of events that occur on too large a scale to be observable by one observer on the ground, but are too small to appear on a normal weather map. This, of course, includes "local" weather effects.

turbulent diffusion especially in relation to air pollution, upper atmosphere structure, cloud physics, wind-water-wave relations, and other topics. Members of the division play an active part in international meteorological affairs.

Primarily, the purpose of the section is to conduct pure research, but applied research is also carried out. Both are required to meet the present and future commitments of the Meteorological Service. It is planned to increase the research personnel of the division by 50% in the next five years. This would require 13 additional scientists of Ph.D. caliber. Having regard to other requirements it will not be easy to find these people from Canadian sources.

(iii) The Central Analysis Office

This office has an annual expenditure of $1.8 million approximately 1/3 of which may be regarded as for research. It was established in 1952 after a two year period as a pilot project.

This unit provides numerical weather prediction for the Meteorological Service of Canada. The justification for the research is that an operational unit of this kind needs the support of a research organization. Its computer is its major facility. The present machine costs about $0.5 million per annum and it will be replaced next year with a faster and larger unit (IBM 360–65).

Numerical analysis and prediction is one of the most promising areas of meteorological research, since there is evidence that useful forecasts for periods up to (perhaps) 10 days may eventually be obtainable by these means. Because of this it is highly competitive, and because there appears to be no limit to the size and speed of the computer that can be employed usefully it is very expensive. Canada's position should be cooperative rather than competitive in this exciting but extravagant race. Nothing is gained by duplicating research, but there is considerable scope for special studies for application to smaller areas to meet particular Canadian problems.

The 5-year plan of the Central Analysis Office proposes an increase of 5 or 6 first-class research personnel, which is probably more than the supply of such people will permit. At present there are 20 meteorologists in the unit, 8 of whom are classed as doing research.

When the art of numerical prediction develops to the degree expected, it will almost certainly be found that hemispheric, or even global, calculations are necessary. This is a proper subject for international cooperation, which indeed is now taking shape in the form of "World Weather Watch". The Central Analysis Office must retain full competence in this field so that Canada will be in a position to take advantage of the promised advance. Excellent work is being done but future developments should emphasize small-scale, Canadian problems rather than global analysis.

(iv) Climatology division

This division has an annual expenditure of $1.4 million, nearly half of which is spent on research, the remainder on data handling.

The climatological work of this division of the Meteorological Service is older than Canada; most of its work is the patient accumulation of meteorological data, which is now handled by mechanical methods. Though not classed as research for the purpose of this report, this store of data is a necessary part of research and it is essential to many of the environmental studies that will be discussed later. The research effort of this division, which involves about eight research scientists, is in these applied fields and this is the major Canadian contribution to them. Also included on its staff (and in its budget) are five meteorologists who are seconded to various government agencies and who work in the fields of agriculture, forestry, building science, water resources, and conservation. The contribution made by this division is invaluable but it is hardly equal to the tremendous economic importance of the problems.

(v) Other government agencies

Other branches of the Government of Canada carry out meteorological research, the total internal expenditure being apparently of the order of $300,000. (Substantial expenditure by DRB at the Canadian Armament Research and Development Establishment is not included here since it has been reported to the Chapman committee). The attempts by the departments concerned to carry out meteorological research are handicapped by their inability to obtain suitable staff. The Civil Service Commission reports that in the Government of Canada there are at present about 30 vacancies for meteorologists or for physicists to carry out meteorological research. The vacancies are in the departments of Transport; Agriculture; Forestry; and Energy, Mines and Resources.

(vi) The universities

The total expenditure of the universities in 1966 was about $537,000, plus academic salaries and overheads, which are provided by the universities.

Prior to 1960 McGill was the only university that had a significant meteorological research program. In the early part of the century climatological research was carried out there, but the modern program began after World War II when J.S. Marshall and K.M. Hare came to the physics and geography departments, respectively. Their work became a major enterprise when US support was received in 1950, so that by 1960 McGill had an internationally known group with five or six staff members, though it was still dependent upon US support. This support is now effectively ended. Its termination has presented McGill with problems. The subjects studied by this group are cloud physics, radar meteorology, climatology, particularly of the Arctic, and upper air dynamics. Hail studies have been pursued since 1956. McGill now has ten staff members in an independent Department of Meteorology. It trains students for the Department of Transport.

In 1960 there was new impetus: the University of British Columbia began a program of air-sea interaction studies, the University of Alberta at Edmonton (Department of Geography) acquired a senior staff member for meteorology, and interest was appearing in radar studies of turbulence at the University of Western Ontario.

The University of Toronto has been in a special position since 1934. It has run a graduate course leading to an M.A. degree in meteorology since that date, but all the meteorological teaching had been done by Department of Transport personnel. In 1962 it acquired a staff member in meteorology, succeeding Professor Kingston who died in 1872(!). The university now has three staff members in meteorology.

At present, expansion is rapid; however, it is not all occurring in the physics departments, but often in other departments who see the need for the studies or who cannot proceed in their own discipline without first solving meteorological problems. We may mention the following universities and departments: Alberta, Calgary, McMaster, McGill, Laval, Simon Fraser (Geography); Western, Waterloo, New Brunswick (Engineering); Guelph (Soil Science); Manitoba and New Brunswick (Botany); and Montreal (Hygiene). In these, at least, research is proceeding or planned; much of it would, however, be done more efficiently or more properly by meteorologists with a strong training in physical science.

A serious gap in this progress is apparent in the universities that train French-speaking students. There is too little in these universities that would enable a student to be attracted to, or to be trained in, the atmospheric or environmental sciences. The problems of weather and climate, especially in relation to agriculture, forestry, and water resources, clearly bear heavily on Quebec. It is vitally important that an effort be made to establish a very active group in at least one of the universities concerned. The physicists should be willing to play their part, but if there is not sufficient interest among the physicists then it will be better to establish such a group where it will thrive. The Agriculture Department at Laval University, we understand, would be a willing host.

5.4 THE DIVISIONS OF ATMOSPHERIC AND ENVIRONMENTAL SCIENCE

(i) Pure atmospheric sciences

This involves about 20 research workers and about $1.1 million annual support.

Research into purely meteorological topics is proceeding in the Department of Transport, at McGill University, and at the University of Toronto. The studies include atmospheric dynamics and energetics, radiation, atmospheric transport, ozone, and cloud physics. In addition to the scientific interest of the problems, the justification for encouraging these groups is as follows:

(a) The schools of meteorology which Canada needs will not be viable without fundamental work.

(b) Some of the problems may be vital in weather modification; these will be discussed later.

(c) Progress in most of these problems will, directly or indirectly, improve the accuracy of weather forecasting and assist in many other applied areas.

(ii) Applied meteorology

(a) Weather forecasting

This involves about 12 research workers and about $800,000 annual support.

Weather forecasting is developing rapidly at present, on a highly technical basis. The benefit to Canada of a properly disseminated supply of accurate forecasts is large. For example, in the construction industry the total value of new work started in 1966 exceeded $10 billion. About 1/3 of this is for outdoor, weather-sensitive operations. An improvement in efficiency of only 1% in this area would give a saving of $30 million. Similar arguments can easily be applied, say, to farming and many other operations of everyday life. Only aviation now seems to get a real service because here the benefit is entirely obvious.

It will not be easy to increase the effort available, and so its direction will require careful planning. During the coming years we may expect the major world weather centrals to use very large computers to make global analyses and forecasts. As mentioned in connection with the work of the Central Analysis Office, Canada should not compete in this field. Rather it must develop the competence to work within the framework of global forecasting and produce detailed local forecasts of high accuracy. This involves the solution of the complex mathematical equations of atmospheric motion in very great detail, and requires the inclusion of local (meso-scale) effects. Then, when the numerical solutions are obtained, further meteorological understanding is needed to interpret these in terms of the weather. Meteorological competence of the highest order will be necessary and the computer requirements will still be very great, but the forecasts produced should be of a sufficient accuracy to command popular respect and permit the realization of the economic potential of useful forecasts.

We cannot afford to stay out of this field, and we must prepare ourselves to meet the challenge. Work at the Central Analysis Office must be promoted with this in mind, and the training in this field being given to students at McGill University and the University of Toronto should be encouraged.

(b) Agrometeorology, climatology, and microclimatology

This involves about 25 research meteorologists and about $382,000 annual support.

As agriculture, forestry, and other biological sciences develop, it is becoming clear that the influence of the actual conditions under which a plant (or animal) grows is very great. The results of research in laboratory-controlled environment cannot easily be transferred to the real outdoor world, and even studies of such basic processes as photosynthesis cannot be made without accurate knowledge of the atmospheric processes around the plant, which transport heat, water, and carbon dioxide. As a result, large numbers of scientists from other disciplines (including those in geography, since they are concerned with the economic consequences), are finding themselves involved in many matters that are essentially physics. In dealing with these problems they are handicapped by the difficulties of both measurement and interpretation.

Many of the relevant physical processes as they occur in nature are not understood, but we cannot reject these problems as of no concern to physics. The economic importance of forests (total value of products about $1.8 billion per annum) agriculture (total value of products about $2.4 billion per annum) and animals, whether domestic or wild, will not be disputed.

We may perhaps give one more example. Forest fires caused actual losses (damage plus fire-fighting costs), averaged for the years 1953 to 63, of $19.3 million per annum. In 1963, which was a good year with losses of only $9 million, 31% of all the fires were attributed to lightning. Forest fires occur because of flammability resulting from drying winds and absence of rain. We do not know, for example, how the wind penetrates through the canopy into the forest to dry the litter on the forest floor.

The following areas have been suggested to us as being of urgent importance:

(1) The transport and balance of heat, momentum, water vapor, carbon dioxide, and other material such as fungus spores or noxious pollution to and from, and in and around, the crop (whether trees or other plants). Meteorological processes under the crop are important; they control weeds, or in the case of forests, regeneration and fire risk. Events on the leaf surface control growth, and also often control infection and damage by pollution. The overall water balance determines the need for irrigation, and the surplus water available as a resource.

(2) The radiation conditions (i.e. the energy of the illumination and its spectral quality) on and under the crop.

(3) The influence of topography and soil on local climatology. This is required in order to relate standard climatological data to a potential agricultural or forest site some distance away, and of very different topography. (For example high-quality fruit-growing land is disappearing very rapidly. Can we find more?)

It may be mentioned that in any studies of transport, as discussed in (1) above, the measurements required present severe problems of instrument design.

All these are very formidable problems indeed. To make a start on them scientists concerned with the International Biological Program are seeking meteorological assistance which, for manpower reasons, is not available.

(4) The requirements of the construction industry for fundamental meteorological knowledge may be mentioned here. These were given as:

(i) Heat exchange at land and water surfaces. These studies are required for frazil ice which damages hydroelectric generators, for predicting ice thickness and ice pressures against structures, for highway management and design, and for foundation design.

(ii) Wind structure: knowledge is required of the structure of strong winds for predicting static and dynamic loads on large buildings, bridges, and towers. New and very large cooling towers have recently been destroyed by resonant wind forces both in the UK and the US. This clearly involves heavy loss, but so does needless over-construction which may be necessary if failure is to be avoided when we do not understand the nature of the wind. A facility consisting of a large (8 x 8 sq. ft. cross-section) turbulent wind tunnel has recently been established at the University of Western Ontario to study the effects of the wind on buildings. In 14 months it has attracted over $120,000 in grants, all from the US.

(iii) Influence of wind in redistributing snow.

(c) Water resources

This involves about 10 research meteorologists with a support of about $220,000 per annum.

With growing populations there will be increasing demands for water, both for irrigation and for industrial purposes; water will therefore be the subject of intense political pressures during the coming years. There is already a plan, North American Water and Power Alliance, being discussed elsewhere, to redistribute water among three nations, including 7 provinces of Canada, 35 states of the US, and 3 states of Mexico.

The power production value of the water resources of Canada is given by the Dominion Bureau of Statistics as 20 million kw developed hydroelectric power and 22 million kw available undeveloped water power. If this is valued at 1 mil per kwh, this gives an annual value of the resource of $400 million.

Water comes from the atmosphere as rain or snow, and most of it evaporates again. The remainder is available in the rivers, but unfortunately much is lost because it cannot be stored at times of flood, or at the spring runoff. Understanding of all the processes would permit much more efficient utilization of the water with very considerable benefit to the economy.

The following major meteorological problems are involved and solutions are required:

(1) Quantitative precipitation forecasting, for areas about 20 or 30 miles square, required for irrigation and flood control.

(2) Is weather modification possible? (This will be discussed later).

(3) The nature and efficiency of storms. Knowledge of this will permit absolute maximum flow of rivers to be predicted, which is required for storage and spillway design, and flood control.

(4) The influence of topography on precipitation, snow accumulation and evaporation.

(5) The relation between radar echoes and rainfall.

(6) Can climates be modified (for example by the heat transported by diverted rivers or, say, by closing the Belle Isle Straits)?

These problems are not only associated with water resources studies. They are meteorological problems of great depth.

(d) Air pollution

This involves about six research meteorologists with support of $400,000 per annum.

Estimates of the total annual cost of air pollution to the citizens of Canada vary between $400 million and $1 billion. The prime solution to this problem will depend upon reducing the flow of pollutants into the atmosphere, but a complete cessation of atmospheric pollution is unlikely. We must therefore make the best use we can of the disposal qualities of the atmosphere. This is a meteorological problem.

Research is being undertaken by the Meteorological Service in Toronto, Ottawa, and at the Suffield Experimental Station; by Atomic Energy of Canada Ltd., at Chalk River and Whiteshell; and by the University of Waterloo (Faculty of Engineering); University of Toronto (Faculty of Engineering), and the University of Montreal. However, air pollution studies require the cooperation of a number of different scientific disciplines. The total Canadian effort suffers from a lack of coordination. In addition, scientific attention to many of the regions where pollution occurs is impeded by jurisdictional problems since health research is the concern of the provincial government; these restrictions interfere with the most effective use of the scientific manpower. For example, so far as we could ascertain no meteorological investigation has been made of the Sudbury area.

Thus, more knowledge is required concerning:

(1) The dispersive properties of the atmosphere under all possible weather conditions, for pollutants that are either gaseous, with or without thermal radiative properties, or particulate, not merely for a single chimney but also for a modern megalopolis.

(2) The effects of topography, including the influence of lakes, which can be warm in winter or cold in summer, and of nonuniform surfaces (e.g. downwash behind buildings).

(3) The effect of the heat generated in cities.

(4) The dispersal of hot gases, perhaps with a high exit velocity from a chimney.

(5) The transport properties of the atmosphere in the immediate vicinity of surfaces; these convey pollutants to the surface where they cause dirt or damage.

(6) Photochemical studies of polluted air.

(e) Weather and climate modification

Hail research and cloud physics research involve about 13 meteorologists, and about $400,000 per annum support.

Except for hail research programs, which might be interpreted as relevant, little research is being done in Canada on weather or climate modification. At present there is no proved way of changing either weather or climate significantly[1].

In the US great effort is being expended on research; and the chance that it may prove possible to affect the Canadian climate adversely in order to secure benefits elsewhere, must be borne in mind.

However, Canada has very severe and very obvious problems in the environmental sciences that will require most of our attention, so that we cannot compete in this league. The exception is in hail research. The problems of hail are being tackled by fundamental studies at McGill University and the University of Toronto, and there is a substantial field program organized jointly by McGill University, the Alberta Research Council, NRC, and the Meteorological Service of Canada. The cost of the program is about $300,000 per annum. It is a valuable contribution, and Canada deservedly has high international prestige in this subject. Hail insurance payments in Alberta

[1]This matter is still in dispute; there is some responsible opinion that orographic rain can be increased by silver iodide seeding.

alone amounted to $3 million in 1966, but real loss is estimated at about $30 million since most farmers do not insure. The program is therefore relevant.

(iii) Other fields of meteorological research

(a) Air–sea interaction

This involves seven research scientists, with support of about $213,000 per annum.

The atmosphere receives from the oceans most of its water vapor, which later falls as rain, and also most of its heat, in the form of latent heat. On the other hand the sea receives all its momentum from the atmosphere, for all the ocean currents are wind-driven, and most water waves are wind-produced. The interaction of the sea and the air is therefore important. This subject is receiving attention by groups at the University of British Columbia, at the Bedford Institute of Oceanography, and recently at the Great Lakes Institute, University of Toronto, and in the Meteorological Service. These groups are contributing to fundamental studies and should be encouraged.

(b) Arctic research

This involves about two research scientists, with support of $15,000 per annum.

Canada claims sovereignty over a substantial part of the arctic regions of the world. Arctic research is being carried out by McGill University, and some contributions can be expected from the Department of Transport Arctic Forecasting Unit at Alberta and the Sea Ice Unit at Halifax. There is, of course, an extensive observing network in arctic regions. At first sight it would seem that Canada should be making substantial contributions in this field, but most of the problems do not seem very pressing compared with those of the populated parts of Canada. The natural growth of these studies seems to be all that can be afforded.

(c) Measurements of atmospheric properties between 30 and 50 km

Measurements of most atmospheric parameters can be made with reasonable ease up to levels of about 30 km, using instruments carried aloft by balloons. Meteorologists generally use small rubber balloons which are relatively cheap and easy to launch. If measurements are required at greater heights balloons become increasingly expensive and unreliable. At present 35 or 40 km can be reached by balloons only at a cost of $50 or more per flight; to reach 50 km, rockets or ballistic missiles are necessary. These can, of course, reach greater heights and "meteorological" rockets are small rockets of relatively low cost, which are usually capable of attaining an apogee of 70 or 80 km with a payload of about 10 pounds.

There is a substantial history of rocket measurements in Canada, and this has been discussed in the Chapman Report. The Meteorological Service of Canada plans to spend about $200,000 per annum, commencing in 1968–69 on a program of meteorological measurements made by instruments dropped from rockets. The initial planning of this venture has been delayed by lack of suitable personnel but some progress is now being made.

(d) International cooperation and data gathering

The effort has not been evaluated since its contribution to research is indirect.

Canada has a responsibility to world meteorology to provide proper measurement of atmospheric events that occur over Canada. The global pattern of these observations is the subject of recommendations by the World Meteorological Organization (WMO) in which Canada traditionally plays an important part. The effort is being intensified under the terms of World Weather Watch, and research programs are being established by the scientific organizations. Canada at present fulfulls its obligations under WMO rules and may be expected to cooperate in World Weather Watch.

5.5 SUMMARY AND CONCLUSIONS

(1) Research in meteorology or in atmospheric parts of the environmental sciences is being carried out in some 10 universities, and in the departments of Transport; Agriculture; Forestry; Defence; Energy, Mines and Natural Resources; the National Research Council; and Atomic Energy of Canada Ltd. As may be expected, the greatest effort is in the Research Division of the Meteorological Branch of the Department of Transport. There is some meteorological research by the provincial governments of Alberta, Quebec, and Saskatchewan.

(2) There is need to clarify the question of responsibility for the meteorological parts of the environmental sciences. The Department of Transport is primarily concerned with transport alone, while other departments feel that all meteorology is the responsibility of

the Meteorological Branch of the Department of Transport, since this is properly regarded as the Meteorological Service of Canada. Also, there is no other significant source of meteorological competence. This problem not only arises between departments of the federal government but also where provincial governments are involved.

(3) The total effort involves about 100 research scientists, about 70 of whom have a first degree in physics, and 30 of whom are not meteorologists but carry out meteorological research because it is essential to the furtherance of their own discipline.

(4) The funds involved are about $4.3 million per annum. About $3.8 million is spent by government agencies, and research grants totalling about $0.5 million are given to the universities.

(5) Research in meteorology can be justified by its scientific interest alone, but for Canada the importance of weather and climate makes the environmental sciences of overbearing significance. The annual value of meteorologically sensitive parts of the Canadian economy is greater than $10 billion.

(6) The effort in either manpower or money expended on research does not match this importance of the environmental sciences.

(7) We found in most cases that the effort was limited by a shortage of manpower rather than by a lack of financial support. It also seems to us that most plans to increase research will be frustrated by this lack of manpower.

(8) A determined effort should be made to increase the scientific manpower that contributes to meteorology and the environmental sciences. This will require that young people be attracted to the subject and that facilities be available to train them. For this purpose Canada needs two or three major schools of meteorology, each capable of giving a first-class training over the whole spectrum of the fundamental atmospheric sciences. McGill University in cooperation with the Central Analysis Office, and the University of Toronto in cooperation with Headquarters Meteorological Service of Canada both come near to this. They should be strengthened to meet the need. The University of Alberta, which cooperates with the Arctic Forecast Unit, shows promise of developing a strong school of climatological studies. In other universities there are specialist groups devoting their attention to various facets of meteorological science. They will contribute to the overall program, and also serve to attract the attention of young people to atmospheric physics, only if they are fully viable. These objectives would be promoted if:

(i) Selected universities were encouraged to appoint meteorologists to their staffs.

(ii) The funds available to support university research in meteorology were increased somewhat, given a high rate of growth, and funding methods simplified. It would appear that about $0.6 million would have been just adequate in 1967-68 (about $0.5 million was actually available). A growth of at least 25% per annum will be necessary during the next five years. Funding through the Meteorological Service of Canada would have the advantage of separating it from exotic and expensive projects of other sciences which, though elegant, are not relevant to the Canadian problems of environmental science.

(iii) Special efforts were made to establish at least one significant unit contributing to the environmental sciences in Quebec.

Table I,–RESEARCH IN METEOROLOGY – MANPOWER AND FINANCES

		Professional staff[1]				Students				Operating Expenses (thousands of dollars)		Capital Expenditures (thousands of dollars)
		Ph.D	Without Ph.D.	Total	Estimated f^2	PdF	M.Sc.[3]	Ph.D.	Total	Total	Staff salaries	
Current	Universities	27	1	28	0.4	4	42	35	81	936	400	nil
	Government	15	50	65	0.9	2	–	–	2	3,750	not determined	nil
	Industry	–	–	–	–	–	–	–	–	–	–	–
Prediction 1971-72	Universities	45	–	45	0.5	10	60	60	130	2,100	700	300
	Government	30	60	90	0.9	6	–	–	6	6,000	not estimated	500
	Industry	3	–			–	–	–	–	100	50	–

[1] Does not include postdoctorate fellows, students, or technicians but does include senior staff administering research.

[2] f is the fraction of time spent on research.

[3] The Department of Transport has a program to train about 20 students per annum in two-year courses at McGill University and the Universities of Alberta and Toronto. The number given here includes 22 students supported in this way; many of these will proceed to operational meteorology.

Table II. Expenditure on Research in the Meteorological and Atmospheric Environmental Sciences 1966-1967*

Money spent by \ Research field	Climatology	Dynamic and upper air	Forecasting and synoptic studies	Mesometeorology	Micrometeorology including air pollution	Air-sea interaction	Radiation	Agrometeorology including forestry, ecology, and building applications	Cloud and precipitation physics	Hydrometeorology	Totals
Meteorological Service of Canada	150	950	800	300	282	50	50	200	200	200	3,182
Other federal departments	–	–	–	–	30	80	–	190	50	–	350
Provincial governments	20	–	–	–	–	–	–	50	75	72	217
Universities (grants and contracts only)	62	67	–	–	70	83	18	50	178	8	536
Totals	232	1,017	800	300	382	213	68	490	503	280	4,285

*The figures given are in thousands of dollars, and are very approximate.

Table III. – SOURCES OF UNIVERSITY RESEARCH FUNDS 1966–1967*

Research field / Money provided by	Climatology	Dynamic and upper air	Forecasting and synoptic studies	Mesometeorology	Micrometeorology including air pollution	Air-sea interaction	Radiation	Agrometeorology including forestry, ecology, and building applications	Cloud and Precipitation physics	Hydrometeorology	Totals
Meteorological Branch	10	8		–	25	12	18	11	45[1],48	2	183
NRC	28	33		–	–	20	–	31	22	5	139
Other federal governments	5	2		–	10	20	–	–	20	–	57
Provincial governments	19	–		–	–	–	–	8	17	1	45
US	–	24		–	31	31	–	–	24	–	110
Totals	62	67		–	70	83	18	50	176	8	534

*The figures given are in thousands of dollars, and are very approximate.

[1] Contract.

Section 6

ATOMIC AND MOLECULAR PHYSICS

L. Kerwin (Chairman), G. Cloutier and A. E. Douglas

6.1 GENERAL

Atomic and molecular physics is one of the oldest, yet one of the youngest, branches of science. It shares with astronomy an origin that can be traced back thousands of years. All books concerned with the history of science make much of Democritus; and the atomic physicist can lace his texts with examples plucked from all ages. The modern era in atomic and molecular physics coincides with the modern era of science *tout court;* the subject is particularly rich in association with and interdependence on other branches of physics. Certain of its aspects have become recognized subdivisions of physics in themselves, e.g. spectroscopy, plasma physics, and solid state physics. Other subdivisions draw heavily on its methods and personnel, e.g. astrophysics and nuclear physics. Thus it seems to represent, in a particularly attractive and complete way, the Holy Grail of physicists: the ultimate description, the detailed analysis – the *atomos.*

Atomic and molecular physics has known several golden ages. The atomic explanation of the laws of physical chemistry still makes the epoch of Lavoisier, Dalton, Avogadro, and Proust outstanding in the historical context. The period extending roughly from 1880 to 1920 was also dominated by atomic physics, as spectroscopy was honed to its state as physics' most precise tool. Half of the first 25 Nobel prizes were awarded in atomic and molecular physics – a fact that reflects the importance of this field. For the next few decades – until just after World War II – the upsurge of activity in nuclear physics and electronics (a close cousin of atomic physics) attracted most of the attention. In the last decade, however, atomic and molecular physics has been enjoying a veritable renaissance. New techniques (particularly in atomic and electronic collisions), new species (various excited, resonant, and autoionizing states), and new applications (in astrophysics and biology in particular) as well as new technology (lasers, clocks) have made it an avant-garde field once again. It is still a favorite haunt of the quantum mechanics theorists. This year the Nobel prize once again went to atomic physics.

The many unanswered and important questions in this field indicate that the renaissance will continue for some time.

6.2 DEFINITION OF SUBJECT

Atomic and molecular physics is concerned with understanding the nature of the atom and the molecule *per se*, and with observing and understanding processes involving a very small number (one, two or three) of atoms or molecules. The atoms or molecules may or may not be charged. It is the emphasis on the small number of particles that distinguishes atomic and molecular physics from solid state physics, from statistical mechanics and thermodynamics, and from plasma physics. However, since all the branches of physics that deal with many particles involve in some degree the properties of the individual particles, atomic and molecular physics has very nebulous boundaries with many branches of physics, chemistry, and astronomy.

The ultimate object of atomic and molecular physics is to establish the physical laws that govern the observed atomic and molecular processes. In one sense this task appears complete. Within the limits set by our imperfect knowledge, it appears that all known phenomena are compatible with the laws of quantum mechanics. It is, however, an unfortunate fact that even with the best available computing techniques, the equations of quantum mechanics can be solved for only a few of the most simple situations. These equations have proved of little value in determining quantities such as the probability of transfer of energy in a collision, or the stability of the first excited state of BH_3, or the frequency of the line of the CH molecule which the radio astronomers hope to find. Also, quantum mechanics cannot readily guide scientists to the many important devices that are based on atomic and molecular physics, e.g., the atomic clock, magnetometers, the masers and lasers, etc. Thus a knowledge of fundamental theory in the form of quantum mechanics leaves unsolved most of the problems of atomic and molecular physics, and many of these can be solved only by establishing semi-empirical laws based on observations. The measurement of a wide range of constants relating to atomic and molecular processes, the establishment of empirical rules, and finally the process of relating these rules to the more fundamental laws of quantum mechanics – this is the field of atomic and molecular physics.

6.3 DEVELOPMENT IN CANADA

Before World War II Canada did not have very many major centers of physics research, but work in atomic and molecular physics figured prominently in them. The work of McLennan at the University of Toronto toward the turn of the century gave that laboratory a rank as one of the main sources of precise spectroscopic terms. This department has developed steadily, maintained its reputation, and is one of the best-balanced atomic and molecular physics centers in the country. Foster's work at McGill University on the Stark effect is a very bright spot in Canadian scientific history. Lang engaged in spectroscopic work at the University of Alberta back in the 1920's, doing much research on hyperfine structure. The University of Saskatchewan was the scene of Herzberg's early work in Canada. About eight physics departments now have atomic and molecular groups whose work goes back 20 years or more. Together they have provided Canada with recognized status as a leader for work in atomic spectroscopy, molecular spectroscopy, electron impact, and atomic and ionic collisions.

Most of the laboratories are of more recent establishment (one third of those reporting are five years old or less) and their lasting contributions have yet to be assessed. In any event there appear to be few aspects of atomic and molecular physics that are not being vigorously pursued somewhere in the country, and the sharply increased activity corresponds with the state of increased activity in atomic physics in the world as a whole. Canada's influence on developments in the field is certainly respectable. The Chairman of IUPAP's Atomic and Molecular Physics Commission is a Canadian, and several of the major international conferences on the subject have recently been held in Canada or are being planned here.

Atomic and molecular science is also the legitimate field of chemistry departments, and many in Canada have been engaged in it for some time. Development in chemistry departments is more recent, however, since only four major laboratories have been significantly engaged in the work for 15 years or more. About a third have launched programs only since 1960.

Government and industrial laboratories in the field go back, generally speaking, only about 10 years. The National Research Council's prestigious spectroscopy division began in 1949, but most laboratories appear to date from after 1958.

On the whole, Canada has a well-established experience in the field of atomic and molecular physics and enjoys a remarkable reputation throughout the world for its contributions in this field of research. Nevertheless the present level of financial support to universities (e.g. as measured in terms of dollars per researcher) for research in this area is below that given to the physicists working in the same field in the US.

If Canadian physicists are not given the required increased support by the government for improving research facilities and for attracting top grade research physicists, the quality of the research work will undoubtedly greatly suffer, and the reputation of Canada in this area will quickly deteriorate. It is important to emphasize here that the level of excellence of the research work carried out in universities will directly reflect on the quality of the research graduates emerging from these institutions.

6.4 THE SURVEY

A questionnaire was prepared in accordance with the instructions of the Steering Committee, together with a covering letter and a report schema. These were sent out to 105 Canadian institutions: 46 physics departments in universities, 49 chemistry departments, and 10 other institutions.

Of the 46 physics departments canvassed, 37 replied. Of these, 20 filed detailed replies and 17 filed nil reports. An examination of 9 not replying indicates that it is improbable that any carry on a significant amount of work in atomic and molecular research. Therefore, to a first approximation, the 20 detailed replies probably cover all the work carried on in physics departments.

Forty-nine chemistry departments were canvassed. Of these, 23 filed detailed reports, 22 filed nil reports, and 4 did not reply. Remarks made above concerning physics departments apply here as well.

Ten other institutions were canvassed. All replied, 4 filing nil reports. For the most part the other 6 filed partial reports, and the relatively large groups involved (AECL, CARDE) make cost analysis difficult. The figures for this group are probably the least reliable.

(i) Personnel

Two hundred and fifty professional staff are reported to be working on research in atomic and molecular science: 120 in physics departments (P), 80 in chemistry departments (C) and 50 in other institutions (X). The 200 university staff members represent about 7% of the Canadian university research personnel reported by the NRC Forecasting Committee (Bonneau Report). This is an average of 5 per laboratory (P,6; C,3.5; X,8). The corresponding figure of 750 physicists in the US reported by the Pake Committee appears startlingly low. We note that an APS survey for 1962 gave over 1,000 as the figure for the number of physicists engaged in atomic work. This seems to compare more reasonably with our figure of 120 university physicists in Canada in 1966. The university scientists do other things besides research, however, and the number of equivalent full-time atomic research physicists in Canadian universities is probably closer to 50 than to 120.

They are assisted by 100 technicians (P,39; C,29; X,32), an average of 0.4 technician per staff member (P,0.33; C,0.33; X,0.66). The Bonneau Report gives an average of 0.69 for all university research. Nineteen administrative personnel are involved, mostly stenographers (P,8; C,8; X,3). This is one per 13 staff members (P,15; C,10; X,16).

There are 373 graduate students (about 6% of the science and engineering enrollment in Canada, according to the Bonneau Report) involved in this work (P,198; C,175) – an average of about 8 per institution (P,10; C,8) and about 2 per staff member. Few institutions report refusing graduate students for lack of research support. The 9 that do (P,2; C,7) say that they turn down 77 per year. Assumingthat a student spends 5 years in graduate school on the average, this corresponds to 75 atomic scientists per year being placed on the market (P,40; C,35). Of these, 48 are Ph.D.'s (P,21; C,27). The Pake Committee reported 200 Ph.D.'s per year in atomic and molecular science for the US in 1964. The 6 "other" institutions hire only 5 per year. The assumption that the other 70 are absorbed by the universities, or emigrate, obviously does not tell the whole story.

(ii) Financial support

The annual expenditure reported is \$2.8 million (P, 1.2; C,1.0; X,0.6). The \$2.2 million reported by the universities is about 4% of total university research support, according to the Bonneau report, indicating that our figures do not include much "indirect" support. Of the \$1.2 million reported by physics departments, \$0.5 million was granted by NRC.

Financial support averages $11,000 per staff member (P,$10,000; C,$12,000; X,$12,000). The Bonneau Report states a figure of $16,000 per faculty member, averaged over all sciences, and $32,000 per equivalent full-time faculty member. The Pake Report estimates about $70,000 per faculty investigator. The Bonneau Report also gives $32,000 per scientist in industry and NRC; this appears to confirm the unreliability of our support figures for "other" institutions. University support corresponds to $5,900 per graduate student (P,$6,000; C,$5,700).

Forecasts of future needs are indicated in Fig. I. Physics departments estimate that support must rise from the present $1.2 million per year to $4.3 million per year in 1971. Few cared to estimate total investment from 1971 to 1976, but the 10 who did indicated a need for a further, slower, increase to $4.9 million. All figures are normalized to the 20 institutions reporting for 1966. This factor of 4 increase over the next five years followed by a further 20% increase in the following five-year period indicates a hesitancy to make long-term estimates. We may compare the factor of 2.2 (calculated from the Bonneau Report, p. 21) for capital grants for the next five years with the subsequent slower rise of 11% per year predicted for the period from 1971 to 1976.

The $1.2 million spent by Canadian physics departments is about 7% of the $17 million spent by US physicists in 1964 (Pake Report). If the $4.3 million estimated need by 1971 is obtained, it will represent about 8.5% of the $51 million estimated from the Pake Report as being necessary in the US. At this point the US will be placing 3.5% of its physics funds in atomic and molecular physics; this figure is obviously artificially lowered by the heavy US commitment to nuclear and space research.

While there is some justification for comparing support figures arrived at in similar ways, some care is necessary in interpreting the absolute values (e.g. $11,000 per staff member per year). Our figures do not include salaries, nor do they usually include building depreciation, shop services, etc. The US support figures, on the other hand, often include such expenditures.

Chemistry departments express stronger views than do physics departments. They estimate their needs as increasing from the present $1 million per year to $7.9 million in 1971, with a slower increase to $8.8 million by 1976. Here the total increase is a factor of 8. Other laboratories indicate an annual increase of about 15%.

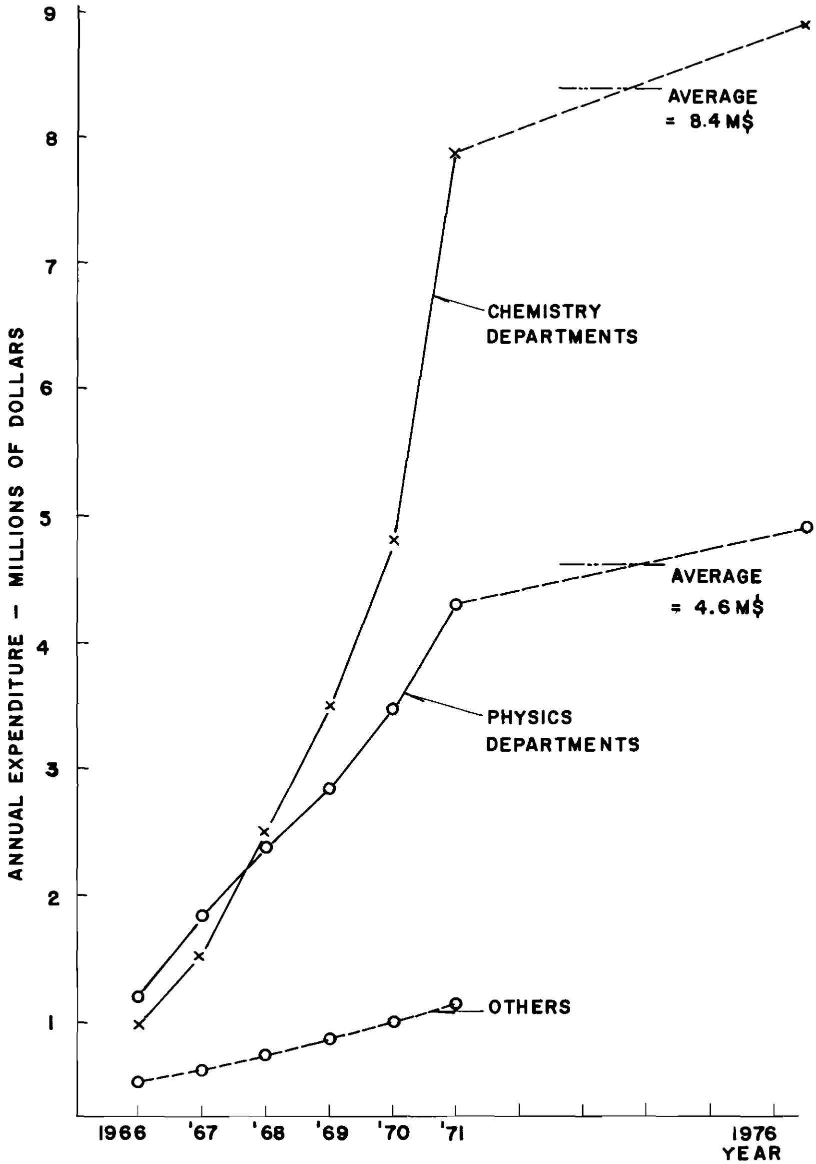

Fig. 1 Projected annual expenditures for research in atomic and molecular physics in university chemistry departments, in university physics departments, and in other institutions contributing to the field.

(iii) Equipment

There is a remarkable degree of agreement that the half-life of equipment used for atomic and molecular research is about five years.

Much has been made of the tenet that atomic and molecular physics is one of the low-cost areas of physics; several replies took this line. The members of this Subdivision Committee tend to disagree. Compared with elementary particle physics, it *is* inexpensive, but compared with the average of all physics subdivisions, it is not a low-cost area. The emphasis on the low-cost and small-laboratory aspect of this field could limit Canada to only second-class work in the future. Just as nuclear physicists and elementary particle physicists need electronic technicians, large computers, and expensive specialized apparatus, so do those working in atomic and molecular physics. Research spectrographs alone may cost over $200,000; moreover, the source of radiation that will dominate the short wavelength range in the future will be the emission from 100 MeV electrons in a storage ring; the very long wavelength regions are being studied by interferometric devices that require large and expensive computers; theoretical work in the field is limited by the fact that the largest computers are too small and too slow; crossed beam experiments and electron diffraction require large vacuum systems as well as large computers. While it is true that a single physicist can set up a small piece of apparatus at a small university and claim to be involved in atomic and molecular physics, seldom will his contribution to the field be significant. Significant progress requires a number of competent physicists working in closely related aspects of a field, each with the best of modern equipment—an arrangement that may be called by various names but that is in fact an institute.

(iv) Policy

University physicists were almost unanimous in stating that research in atomic and molecular science should be pursued in Canada. Several considered that it should be given preferential treatment. Only one (a high-energy physicist) thought it should be assigned reduced importance.

The present policy for awarding grants was given a very even spectrum of support, ranging smoothly from harsh criticism through moderate disapproval and approval to warm commendation. Specific suggestions (coming particularly from older institutions and established laboratories) indicated concern for new institutions and new men. These will be summarized in another section.

(v) Fields of research

The various types of projects under way in the laboratories are summarized in Table I. Although the number of laboratories involved in a given type of work is always small (about 5) most areas of atomic and molecular research are getting some attention in Canada. It was not possible to estimate the relative expenditure involved in each type of project, other than by assuming that all were equally expensive (or cheap), in which case the support is simply proportional to the number of laboratories involved. Most of the projects are of the "continuing type" and have been going for some years. Only 2 of about 40 projects are in the final stage, and only 12 are in their initial stage.

TABLE I. – PERCENTAGE OF INSTITUTIONS ENGAGED IN SUBFIELDS OF ATOMIC AND MOLECULAR SCIENCE.

Subfield of research	Physics departments (20 reporting)	Chemistry departments (23 reporting)	Other institutions (6 reporting)
Infrared spectroscopy	30%	35%	33%
Visible spectroscopy	55	30	66
Ultraviolet spectroscopy	30	23	33
Microwave spectroscopy	20	2	33
Beam spectroscopy	30	40	66
Electron impact	25	2	16
Paramagnetic resonance	10	30	0
Lasers	10	0	33
Theory	15	18	16
Other	55	47	100

6.3 FINANCING POLICY

The scientists at the institutions canvassed were asked if they were satisfied with the present system of research financing. Of the 40 replying to this question, 13 were very unhappy, 5 moderately disgruntled, 2 indifferent, 10 relatively pleased and 10 quite happy. In the opinion of the members of this subdivision, views tended to be somewhat less aggressive than a decade ago, no doubt reflecting the influence of the numerous books and reports on the financing of research that have been published recently, and that reveal it to be a difficult and complex operation. A general view seemed to be that distribution of research funds in Canada (apart from the overall level) was done as competently as possible; improvements would be welcomed, but no one knew how this could be achieved.

Some specific and valuable suggestions nevertheless were made, and have been incorporated in the following recommendations:

(i) The first question that arises is how much should be spent. We maintain that not enough is being spent now, and that ten years is a reasonable time in which to bring ourselves to a proper spending level[1].

The various estimates of the percentage of Canada's gross national product (GNP) being spent on research and development cluster around 0.8%. Technologically advanced countries are spending amounts that tend to be about 3% of their GNP. This has been increasing over the years, and in ten years' time will no doubt be at least 4%. From these considerations we recommend that the percentage of Canada's GNP spent on research and development should increase by a factor of 5 in the next 10 years. The Economic Council of Canada estimates that our GNP should increase by 7% per year—a figure which, we are told, has recently been realistic. In ten years' time then, our GNP will be twice its 1967 figure.

We thus arrive at a factor of 5 x 2 = 10 in the level of spending on R & D for which Canada should aim by 1977. *This means a steady increase in spending of 26% per year.*

(ii) The second question that arises is how should the money be spent. To a first approximation, the present granting and contracting agencies should continue their current policies. However, there are two areas requiring special attention. One is the financing of new staff members. We suggest that 10% of each new budget be allocated to this purpose. In the case of university research, this could be given to the universities as a block grant, to be distributed locally. The best judges of new researchers and their projects would probably be a committee of local grantees. New men could be supported in this way for three years, after which they would apply for grants in the normal fashion.

The other special problem is that of financing new institutions. We suggest that a further 10% of each new budget be placed in a new-institution pool, thus avoiding the problems of recognition and year-averaging, which have been solved in analogous cases by techniques

[1]The figures given are illustrative, but probably as good as any.

of varying success. Eighty per cent of the budget would then remain to finance established laboratories and projects.

(iii) There is no doubt that several physicists working together as a group in a given field, and having frequent contact and discussions, guarantees significant progress in research. The allocation of operating grants to research groups at the department level should be restored. Such a policy was abandoned by NRC some years ago at the request of academic representatives on the Council. There have been second thoughts on this subject, however, and we now recommend a return to block grants. This would reduce the administrative load and ensure a better utilization of technicians. It facilitates the acquisition of common equipment, and reduces the number of grant requests that have to be processed. However, grants should not be made to departments, except for supporting new men–see (ii) but to groups of specified individuals who wish to work in this way.

(iv) To ensure both continuity and control, the term grant is useful, but the amounts granted outright could be 1/2, 1/3 and 1/6 of the total in each of the three succeeding years. For the second year, if the project is deemed to be going well, the 1/3 amount could be increased appropriately, and 66% and 33% of this allocated for for two succeeding years. If the project falters, its support would be phased out in two years, thus avoiding sharp dislocation of personnel.

(v) The "Visiting Committee" technique, recently employed by NRC and AECB in connection with applications for major equipment grants, is a great improvement over the present method of refereeing these applications. It should be extended as much as feasible, although certain limitations are apparent: the number of man-days consumed by such committee work is very large, and is justified only if large projects are involved.

(vi) Canadian scientists have greater distances to travel than most scientists, and it should be more widely recognized that travel is a necessary and productive research tool. Since this is usually a very sensitive item–and also subject to abuse–both public education on the subject and great responsibility on the part of scientists is necessary.

(vii) A difficult problem facing Canada is the low level of industrial research. This is a complex problem and will probably require a variety of measures for even partial solution. One contribution toward a solution would be the acquisition, by federal or provincial agencies, of large tracts of suitable land that could be developed into research complexes of the Sheridan Park variety. This should minimize land speculation and provide inducements (such as subsidized land and certain services) to industry to participate in R & D establishments.

The awarding of operating grants to industrial scientists working on fundamental research would be another excellent way of increasing the productivity of industrially based laboratories and of promoting the spirit and atmosphere of research in these organizations. This suggestion raises problems whose solutions may not be easy to find; but of course this is no reason for not searching for them.

Section 7

NUCLEAR PHYSICS

A. E. Litherland (Chairman), G. M. Griffiths, and R. J. A. Lévesque

7.1 SUMMARY AND RECOMMENDATIONS

Pure nuclear physics is concerned with the structure and behavior of nuclei in their normal and excited configurations and with their interactions with other nuclei, photons, nucleons, and the subnuclear particles. It is one of the branches of physics at present on the frontiers of human knowledge, and the intellectual challenge it presents is expected to continue for many years to come. Research in experimental nuclear physics is an excellent way for a graduate student at a university to obtain advanced training, since he becomes acquainted with many aspects of modern technology besides the theory of nuclear structure and nuclear reactions.

The applied nuclear physics and nuclear engineering research and development groups at the laboratories of the Atomic Energy of Canada and in industry, have produced nuclear electric power stations competitive with fossil fuel power stations. This has stimulated the growth of a nuclear electric power industry in Canada; nuclear electric capacity is expected to rise from the present value of 200 MegaWatts to 2,600 MegaWatts in 1975.

Pure nuclear physics research is now well established in Canada, both in Government Laboratories and at universities, and the research is acquiring a favorable international reputation. Research at Canadian universities particularly has grown rapidly in recent years. In 1961-62 the annual federal capital expenditure at Canadian universities was about $100,000, whereas the annual expenditure during the last three years has been over $1 million. Federal operating grants for nuclear physics at Canadian universities have risen from about $0.6 million in 1961-62 to $2.4 million in 1966-67. The details of federal expenditures over the years at Canadian universities are given in Table V. Provincial expenditures have roughly equalled the federal expenditures. In 1966-67 the provincial contribution was estimated to be approximately $1.85 million. During the last five years major capital expenditures on nuclear physics research at universities were approximately $6.4 million by the federal government and $10.4 million by the provincial governments.

It can be estimated that in 1966-67, the operating costs of the pure nuclear physics facilities at the Chalk River Nuclear Laboratories (CRNL) of Atomic Energy of Canada Limited (AECL) were about $1.75 million, all federal funds, and that during the last five years major capital expenditures on nuclear physics research at the CRNL were about $7 million.

By 1971-72 the investment of federal funds on operating grants for existing facilities for nuclear physics at universities, as given in Table V, is projected to be about $5 million per year, increasing thereafter by about 10% per year to keep the facilities up to date. Before 1971, however, it is expected that additional major (and minor) nuclear physics facilities will be needed to supplement those already in existence and to replace the older obsolescent equipment. The projections given in Table V are therefore for a minimum requirement.

There are at present 81 experimental nuclear physics staff in the universities supervising about 180 candidates for higher degrees, and an estimated 160 technical staff and other assistants supported by the federal operating grants. There are also 27 theoretical nuclear physics staff supervising about 39 candidates for higher degrees in theoretical physics and 26 postdoctorate fellows in experimental and theoretical nuclear physics combined. The data on enrollment of candidates for higher degrees at Canadian universities as a function of time are given in Table IV.

There are 16 experimental and 2 theoretical nuclear physics staff at CRNL engaged in full-time research. These are supported directly by about 36 technical personnel. There are also 7 postdoctorate fellows in both experimental and theoretical physics. Additional significant support is given by the research and development oriented staff at CRNL. This support has not been estimated.

The number of staff engaged in applied nuclear physics at CRNL is estimated to be 102. In addition, there are 5 postdoctorate fellows and 10 attached staff. Supporting technical personnel have not been estimated.

The total operating cost for nuclear physics at Canadian universities in 1966-67 was estimated to be $4.25 million (federal plus provincial sources) supporting a total experimental nuclear physics staff of 81. If university staff are counted as part-time research workers, and a factor of one-half is used, the support for each effective staff member becomes roughly $100,000 each year. At the CRNL the total operating cost of pure nuclear physics was about $1.75 million to support a staff of 16, or about $110,000 per staff member.

During the last five years the total major capital expenditure on nuclear physics at universities by both federal and provincial governments was about $16.8 million which is to be compared with the estimated expenditure at CRNL of $7 million. Again the expenditure per effective staff member turns out to be very similar and is roughly $420,000 per staff member for five years. However, as discussed in the report, these similarities are deceptive.

The total number of nuclear physics graduate students receiving doctorates in the last five years was 86. Of a sample of 65, 23 are now university staff, 10 are in industry, 17 are in federal government laboratories, and 15 are carrying out postdoctorate studies.

The distribution of research activity in nuclear physics between government laboratories, industrial laboratories, and university laboratories is peculiar to Canada; compared with, for example, the UK and the USA, little applied nuclear physics research, in contrast to engineering research and development, is carried out in industry. The majority of the applied nuclear physics research in Canada is carried out at CRNL itself. A small but increasing amount of research, however, is being carried out in industry with the encouragement of AECL.

The following recommendations are made in this report:

(i) After 1969-70, the federal expenditure on nuclear physics research at universities should increase at about 10% per annum. This expenditure, which does not include possible escalation due to rising costs, is considered to be the bare minimum that will allow university staff to keep existing facilities up to date.

(ii) Additional *minor* nuclear physics facilities should be approved as required during the next ten years. These will be required for two main purposes. The first is to increase the facilities available for graduate student training, and the second is to provide a local facility for university staff and students who will be carrying out their major nuclear physics research at a government or a university regional laboratory. The total expenditure involved in such "minor" facilities could well be $5 million in capital funds and $7.5 million in operating funds, possibly spread over ten years. Roughly half of the capital and operating funds would be from federal and half from provincial sources. A contribution from industrial sources might also be possible.

(iii) New *major* facilities should be provided during the next ten years to ensure that nuclear physics continues to develop as a vital field of fundamental research in Canada. The first proposal for a major nuclear physics facility, which will be shared among four universities, is the TRIUMF proposal from the Universities of British Columbia and Alberta. By 1972-73 this facility could involve $25.7 million (dollars escalated at 4% per annum). In addition, a joint facility of a very different kind is being considered in Southern Ontario, for which no projected cost is available. These expensive shared facilities for nuclear and high energy physics research can be compared with the proposal of AECL for an Intense Neutron Generator (ING), which is expected to cost $140 million (dollars escalated at 4% per annum), before 1975. Although ING will be of great importance for pure nuclear physics research, it is a project of even greater relevance to applied nuclear physics and in this respect it should be compared with, for example, the NRU reactor at CRNL.

We strongly support the effort to develop ING and the principle of large shared facilities such as TRIUMF at or near universities, and we recommend that each of the large shared facilities be considered in detail by the Science Council.

7.2 DEFINITION OF THE FIELD

Nuclear physics is concerned with the structure and behavior of nuclei, in their normal and excited configurations, and with their strong, electromagnetic, and weak interactions with other nuclei, photons, nucleons, and the subnuclear particles such as mu-mesons. Phenomena associated with the interaction of single nucleons with photons and the subnuclear particles are considered in the report on high energy physics. The study of nuclear physics with accelerators in the 100 MeV to 1 GeV energy range has recently been called intermediate energy physics and treated separately from nuclear physics and high energy physics.[1] In this report those parts of intermediate energy physics that fit into the definition given above will be considered as nuclear physics.

Nuclear physics can be conveniently divided into two areas of endeavor.

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[1]Physics: Survey and Outlook, loc. cit.

(a) Pure nuclear physics is concerned primarily with the attempt to understand the nature of the nuclear forces, nuclear reactions, and the structure of nuclei, as well as the weak force involved in the nuclear beta decay process. Besides generating discoveries that have important practical applications, such as induced radioactivity and fission, pure nuclear physics has an intrinsic intellectual value. This makes it highly suitable for graduate student training at universities. This report will be concerned mainly with pure nuclear physics.

(b) Applied nuclear physics is concerned primarily with the attempt to find practical applications of nuclear phenomena such as fission, spallation, or radioactivity. A very good example is provided by the development of a nuclear-electric power reactor competitive with a fossil fuel electric power station. This activity is typical of applied science in general in which a completely new situation is postulated and then one tries to realize it. For this reason, applied science in general and applied nuclear physics in particular are eminently creative fields. It is not the amount of creativity but its direction that distinguishes it from pure nuclear physics.[1] A recent important development in applied nuclear physics is the idea that the spallation phenomenon should be exploited to make an intense neutron generator. This development is discussed further in Appendix 7.B.

7.3 GROWTH OF NUCLEAR PHYSICS RESEARCH IN CANADA

Nuclear physics research in Canada began in 1898. In that year, the Curies announced the discovery of the new radioactive elements polonium and radium, and Rutherford came from the Cavendish Laboratory to McGill University in Montreal, where he stayed for nine years. Together with Soddy, he worked out the basic steps in natural radioactive decay. Rutherford correctly concluded that radioactive decay resulted in the transmutation of the elements with an energy release a million times greater than that available from any chemical reaction. Many Canadian students, who were later to play a significant role in the development of nuclear physics research in Canada, were trained in Rutherford's laboratories at McGill, Manchester, and Cambridge.

In 1939, the first major price of equipment for nuclear physics research in Canada, a cyclotron, was started at McGill but it was not completed until after World War II. The cyclotron is still in productive operation today at McGill.

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[1] "The Role of Applied Science" E. Teller, March 1966, Bulletin of the Atomic Scientists.

The discovery of fission in 1939, and the realization that the release of energy stored in the nucleus was possible, played a key role in speeding up the development of both pure and applied nuclear physics in Canada. In 1940, G.C. Laurence, working in the radioactivity and radiology section of the Physics Division at NRC began work on the possibility of making a fission chain reaction using natural uranium. He was later joined by B.W. Sargent of Queen's University who had also studied at Rutherford's Cavendish Laboratory. In 1942, a joint United Kingdom-Canadian atomic energy research project was started in Montreal. The deciding consideration of the Canadian Government at that time was the thought that "when peace was restored, atomic energy was bound to have consequences and economic significance far beyond the possibilities of imagination and prediction.[1]

The joint United Kingdom-Canadian atomic energy project later became a purely Canadian project and at its present site near Chalk River, Ont., it is now known as the Atomic Energy of Canada Limited (AECL), a Crown Company with responsibility for the development of atomic energy in Canada.

The first reactor outside the United States, a zero energy experimental pile (ZEEP), went critical at the Chalk River Nuclear Laboratories in September, 1945, and provided useful data for the development of the 20 MegaWatt NRX reactor, which went critical in 1947, and reached the full design power in January, 1949. This reactor produced the highest neutron flux for research purposes in the world, and by 1954 the power was increased to 40 MegaWatts. Later, in 1957, this was followed by an even more powerful reactor, NRU. The construction and use of the reactors at the CRNL have established a worldwide reputation for both pure and applied nuclear physics in Canada. The neutrons from the NRX reactor have been used for a series of pioneering experiments on the radiative capture of neutrons by many different elements, the study of solids by neutron diffraction, and on the physics of the fission process. The radioactive decay of the reactor neutrons was also observed and the half-life of the neutron measured to be about 15 minutes. In addition, the experience gained with research reactors led to the development of the first Canadian reactor used for generating electricity, the Nuclear Power Demonstration Reactor or NPD. The success of NPD, which has been for some years supplying about 20 MegaWatts of electricity into the transmission lines of the Ontario Hydro-Electric Commission, has led to the construction of other major Canadian designed nuclear-electric power stations in Ontario as well as in India and Pakistan.

[1] Physics in Canada *22* (1966) 9 "The Montreal Laboratory" by G.C. Laurence.

Pure nuclear physics research at the CRNL has flourished in other areas besides that of neutron physics. An early design of a Van de Graaff positive ion accelerator was put into operation at Chalk River in 1952. The use of this machine led to the discovery of rotational bands in light nuclei, which provided a new stimulus to the theoretical study of the nuclear many-body problem. This accelerator was later replaced by the first large tandem accelerator, which was built for AECL by the High Voltage Engineering Company of Burlington, Massachusetts. The tandem first operated at Chalk River in 1959 and was so successful in its research potential that it led to the 50 or more tandems now in operation in the world. The highly successful experiments with a variety of swift heavy ions such as carbon, oxygen, and even bromine, led to the recent installation of a higher current tandem twice the size at the CRNL. This new tandem is expected to be in full operation in the spring of 1967.

In 1958, a large iron-free beta-ray spectrometer was put into operation at the CRNL. This device makes possible the detailed study of the electrons associated with radioactive decay and it is the most precise device of its kind in the world.

The growth of pure nuclear physics research after World War II at universities in Canada was necessarily slower than at AECL, partly because of the part-time nature of such research at universities, and partly because of more complex funding problems. However, as can be seen from the major facilities listed in Table I, several major facilities came into operation shortly after World War II and these facilities and their staffs have played a major role in the development of nuclear physics in Canada. For example, the betatron at the University of Saskatchewan in Saskatoon, was used for some of the pioneering measurements on the photonuclear reaction. The success of this work led to the installation of the powerful 150-MeV electron linear accelerator that is now in operation at Saskatoon.

There have been few major developments in the application of nuclear physics at Canadian universities, a notable exception being the initial development of the cobalt-60 radiation therapy unit simultaneously at the University of Saskatchewan and at NRC.

The rapid growth of pure nuclear physics research at universities occured, however, after 1960 with the installation of several modern pieces of equipment. An early success with one of these new facilities occured when the proton-proton bremsstrahlung phenomenon was observed in 1965 at the University of Manitoba with the 40 MeV protons from the new cyclotron there. Also, the phenomenon of delayed proton emission following beta decay was observed for the first time at

McGill in 1963 with the help of the high energy protons from the 100-MeV cyclotron. Pure nuclear physics research at Canadian universities has now grown to a level where the majority of published papers in Canada on nuclear physics are produced by university personnel.

Table I.–MAJOR NUCLEAR PHYSICS RESEARCH FACILITIES IN CANADA

Institution	Facility	Date Operational
Chalk River Nuclear Laboratories, AECL, Ontario	Nuclear Reactor ZEEP	1945
Chalk River Nuclear Laboratories, AECL, Ontario	Nuclear Reactor NRX	1947
McGill University, Quebec	Cyclotron (100 MeV protons)	1949
University of British Columbia	Van de Graaff (3MeV)	1951
Queen's University, Ontario	Synchrotron (70 MeV electrons) (no longer used)	1950-1966
University of Saskatchewan	Betatron (22 MeV electrons) (no longer used)	1952-1965
Chalk River Nuclear Laboratories, AECL, Ontario	Van de Graaff (3MeV) (no longer used)	1952-1961
Princess Margaret Hospital and University of Toronto Ontario	Van de Graaff (3MeV) (to be moved to McMaster)	1957-1968
	Betatron (22 MeV electrons) (no longer used for nuclear physics)	1957-1965
Chalk River Nuclear Laboratories, AECL, Ontario	Nuclear Reactor NRU	1957
University of Montreal	Cockcroft-Walton (500kv)	1957-1967
Chalk River Nuclear Laboratories, AECL, Ontario	Tandem (6MeV) (now at the University of Montreal)	1959-1966

TABLE I (Continued)

Institution	Facility	Date Operational
McMaster University, Ontario	Nuclear Reactor	1959
Chalk River Nuclear Laboratories, AECL, Ontario	Large Beta-Ray Spectrograph	1958
University of Alberta	Van de Graaff (5.5 MeV)	1962
Laval, Quebec	Van de Graaff (5.5 MeV)	1964
University of Manitoba	Cyclotron (40 MeV protons)	1965
University of Saskatchewan	Linac (150 MeV electrons)	1966
University of Toronto, Ontario	Linac (35 MeV electrons)	1967
Chalk River Nuclear Laboratories, AECL, Ontario	Tandem (10MeV)	1967
Queen's University, Ontario	Van de Graaff (3MeV)	1967
University of Ottawa, Ontario	Dynamitron (3MeV)	1967
University of Montreal, Quebec	Tandem (6MeV) Dynamitron (4MeV)	1967
McMaster University, Ontario	Tandem (7.5 MeV) Van de Graaff (3MeV) (to be moved from Toronto)	1968 1968

7.4 LEVEL OF THE PRESENT NUCLEAR PHYSICS ACTIVITY IN CANADA

The numbers of nuclear physics staff, graduate students, and postdoctorate fellows engaged in pure nuclear physics research are given in Table II for both Canadian universities and for CRNL. In Table III, the estimated 1966-67 operating funds for pure nuclear physics are given, together with estimates of the total major capital funds during the last five years.

Table II.–PURE NUCLEAR PHYSICS MANPOWER 1966/67

	Staff		Graduate Students		Postdoctorates
	Exper.	Theor.	Exper.	Theor.	
University	81	27	180	39	26
AECL	16	2	–	–	7

Table III.–ESTIMATED RECENT EXPENDITURES ON PURE NUCLEAR PHYSICS

(millions of dollars)

	Operating Funds 1966-67		Major Capital Funds During the last Five Years	
	Federal	Provincial	Federal	Provincial
University	\$2.4	\$1.85[1]	\$6.4[2]	\$10.4[2]
AECL	\$1.75[3]	–	\$7[4]	–

1 Includes 30% of Federal operating funds as overhead charges and 50% of university staff salaries.

2 Includes \$1.54 million Federal and \$1.70 million Provincial contribution towards the FN Tandem at McMaster University.

3 Includes 30% overhead charges.

4 The total cost of the MP Tandem was given as \$5 million.

In order to compare the support for staff at universities and at the CRNL it is necessary to make allowance for the part-time nature of nuclear physics research at universities. The fraction of time available for research has been subject to much discussion. A figure of 50% has been suggested in the Vogt Report[1] even though some estimates are as high as 66%. This committee prefers the figure of 50%. A university professor inevitably spends part of his research time on the important task of training graduate students to do research. This time is not expended at a government laboratory where the staff and postdoctorate fellows, who are usually recently trained graduate students from a university, can spend nearly full time on research. In addition, the fragmented research time of a university professor implies that though 50% of the academic year may be available for research, it cannot be used as efficiently as the same time spent uninterrupted at

[1] A Statistical Report on Canadian Physicists. E.W. Vogt, L. Katz and P.A. Forsyth. Physics in Canada 21, No. 3, 1965, page 44.

a government laboratory. The university professor's research time is, however, amplified by the good senior graduate students so that in comparing figures for a government laboratory with a university the figure of 50% may be realistic.

Assuming that effectively 50% of the time of a university professor is devoted to research, the comparisons between the figures in Table III become quite interesting. It can be seen that the average operating expenditure per effective experimental staff member is $105,000 at universities and roughly $109,000 per staff member at the CRNL.[1] These figures are subject to two main errors. The first is that the operating funds at the CRNL may be somewhat underestimated as the number is basically an educated guess. The second is that for university support, an estimate of the effective number of staff members must be used. The average five-year major capital expenditure per effective experimental staff member is about $415,000 at universities and roughly $440,000 per staff member at CRNL.

In both cases, these numbers seem to suggest that the average university staff member is now supported at roughly the same level as the average CRNL staff member in pure experimental nuclear physics.

The number of technical staff and assistants employed by the nuclear physics staff at universities with the help of their grants was roughly 160 in 1966-67. The number of technical staff assumed in the estimate of the AECL expenditure on nuclear physics was 36. In both cases it is difficult to estimate the numbers of additional supporting staff who are frequently shared between a large number of people. In order to get a very rough estimate of the cost of these extra staff, overhead charges of 30% were added to the estimated AECL operating funds. The university operating funds provided by the provinces also contain 30% of the funds provided by the federal government as overhead charges.

The number of staff engaged in applied nuclear physics with the AECL is estimated[2] to be 102. In addition, there are 5 postdoctorate fellows and 10 attached staff.

The quality of the supporting staff at the CRNL and university nuclear physics laboratories is hard to compare, but there is no doubt in our minds that this is basically where the figures on relative support given above are misleading. The quality of the administrative and technical staff support at a research and development oriented project

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[1] These numbers include the cost of supporting staff and in the case of universities part of the cost of graduate students.

[2] "A Brief on Applied Physics" complied by J. Mullin AECL Report PD-323, 1966

like the CRNL is undoubtedly superior to that available at universities and is one reason for the suggestion by Welsh[1] that joint institutes for (nuclear physics) research be established. This suggestion is also mentioned in Section 7.9.

7.5 DISTRIBUTION OF NUCLEAR PHYSICS ACTIVITY BETWEEN INDUSTRIAL, GOVERNMENT, AND UNIVERSITY LABORATORIES

The distribution of nuclear physics research activity in Canada between industrial, government, and university laboratories is strongly influenced by our proximity to the US, and the existence of a crown company, Atomic Energy of Canada Ltd., charged with the responsibility for the development of atomic energy. Our proximity to the US implies that Canadian subsidiaries of large US companies are unlikely to carry out pure or applied nuclear physics research in Canada, even though their parent companies do so, unless there is some special advantage to them. The creation of AECL by the Canadian Government has ensured that industry in Canada has become deeply involved in the development of nuclear-electric power stations both for use in Canada and for export. Without the encouragement and support given by AECL it is unlikely that any significant research or development relevant to the applications of nuclear physics would have been carried out in Canada either by Canadian-owned companies or by Canadian subsidiaries of foreign companies. It is reasonable to expect that the growth of activities in industry related to nuclear physics will continue to be encouraged by AECL, and that the assembly of competent research, development, and design teams in industry will result in their assuming greater responsibilities in the future. We have made no estimate of the present level of applied nuclear physics activity in industry.

In our opinion, the majority of research in pure nuclear physics should be carried out in conjunction with the training of graduate students and postdoctorate fellows. At present, this training is carried out largely at universities. Research in pure nuclear physics is considered to be an excellent way of obtaining an advanced physics training for a graduate student at a university, or for postdoctorate training. This is because a graduate student or postdoctorate fellow doing experimental nuclear physics becomes acquainted with many aspects

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[1] "Memorandum on Joint Institutes for University Research" brief submitted by H.L. Welsh, University of Toronto, to the Commission to study the Graduate Programmes in Ontario Universities. Appendix D. Toronto, 1966.

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of modern technology besides the theory of nuclear structure and nuclear reactions.

One of the main reasons for stressing the university role in pure nuclear physics research is that there is really no need at present for a crash program to obtain a detailed understanding of nuclear forces and nuclear structure. Consequently, this understanding can be obtained over an extended period of time and involve the training of graduate students and postdoctorate fellows.

There is a definite place for high quality research in pure nuclear physics in government laboratories such as the CRNL, because such research attracts able staff members and ensures that some new developments in technique are exploited as soon as possible. A recent good example of this was the development of Ge(Li) high resolution gamma ray spectrometers. Such devices are of great value to the pure nuclear physicist but their development at the CRNL, in collaboration with the RCA Victor Company in Montreal, was rapidly exploited for ruptured fuel location in nuclear reactors. In addition, some university staff in Canada were able to exploit this breakthrough and make their own Ge(Li) counters, usually with some help from the CRNL staff.

It is to be hoped that federal government scientists will continue this tradition of pioneering new techniques in the study of nuclear physics and that there will be extensive interaction between them and university staff and students.

In addition to interacting with government scientists, university staff should continue to interact with scientists at industrial laboratories. The facilities at universities are often of the kind that would be impractical for an industrial laboratory in Canada. They could, however, be used occasionally by scientists from industry and it is not out of the question for particular industries to support part of the research at a university nuclear physics facility. The Bell Telephone Laboratories in New Jersey, for instance, supports some of the research on the tandem accelerator at Rutgers University and even has several of its staff associated with the accelerator. In this way, at a minimum cost to itself it can ensure that it has part time access to nuclear physics research equipment.

7.6 SIGNIFICANCE AND IMPORTANCE OF NUCLEAR PHYSICS IN CANADA

The development of nuclear physics has profoundly affected many branches of knowledge and the applications of nuclear physics have had a dramatic impact on human affairs.

Nuclear forces play a central role in the production of energy from stars such as the sun, and in the storage of electrical energy in, for example, the uranium nucleus. In the first case, energy is released during the formation of heavier elements from hydrogen by the transformation of mass into energy according to Einstein's well-known relation $E=mc^2$. In the second case the disruptive effects of the repul-electrical forces are just counter-balanced by the attractive non-electrical strong nuclear forces. In the case of the Uranium–235 nucleus the absorption of a single slow neutron is enough to release the stored electrical energy in the nucleus. The energy released appears in the form of the kinetic energy of the fission fragments. This energy can be released either in a controlled manner inside a nuclear reactor or in the form of the powerful explosion of a nuclear weapon.

The phenomenon of the radioactivity of many nuclei has been of great importance to many branches of knowledge. The dating of geological and archaeological materials has revolutionized our knowledge of the past, and the use of radioactive tracers to unravel complex physical, chemical, and biological phenomena will continue to increase the understanding of our environment.

All these developments have been possible without a detailed understanding of the strong nuclear forces or of the much weaker forces responsible for nuclear beta-decay. It is probably true to say that such an understanding is not, strictly speaking, necessary for the further development of, for example, nuclear-electric power or of the applications of radioactivity to scientific and industrial problems. As a consequence, even though a fundamental understanding of nuclear forces or nuclear structure is far from complete, applied nuclear physics is a pursuit of great importance.

In Canada, the development of pure and applied nuclear physics have been intimately connected since 1942 and it is quite likely that this situation will continue for the forseeable future. It is difficult to envisage the scale of the present Canadian activity in pure nuclear physics occurring without the existence of strong support by the federal government for activities in applied nuclear physics. Because of this connection it is not possible to discuss the importance of nuclear physics in Canada for other branches of physics, for science in general, and for technology, without discussing both pure and applied nuclear physics.

Applied nuclear physics has been, since 1942, of great importance to Canada and has been one of the essential ingredients in the creation of a nuclear-electric power industry. If the nuclear-electric capacity of Canada increases as forecasted[1] the capacity will be 2,600 MegaWatts by 1975, which implies an expenditure of some 650 million dollars. By 1985, the forecast is for 14,500 MegaWatts of nuclear-electricity, which can be compared with the total installed electrical capacity in Canada in 1966 of 29,000 MegaWatts.

In addition to the nuclear electricity program, applied nuclear physicists[2] have been concerned with the commercial uses of radioisotopes, which now include:

- application of radioactive tracers to process control, for example, in the pulp and paper industry,
- sterilization of medical sutures,
- treatment of foods to enhance storage-life.

Part of the activity of applied nuclear physicists during the next decade may involve the development of an intense neutron generator or ING, which is described in more detail in Appendix 7.B. This intense neutron source is unlike those presently available at CRNL. which are produced by fission chain reactions in Uranium–235, in that it is based upon the phenomenon of spallation of heavy elements such as lead or bismuth by accelerator-produced high energy protons. The discovery of spallation was a consequence of pure nuclear physics research because the high-energy proton cyclotrons used were built mainly to study nuclear forces.

Pure nuclear physics research is important in Canada for several reasons:

(i) It is one of the branches of physics at present near the frontiers of human knowledge, which makes it highly suitable for graduate student training in physics at universities.

(ii) The applications of basic discoveries in pure nuclear physics, such as fission and possibly spallation, can be of great importance to the future of Canada.

(iii) The training received in pure nuclear physics research at a university or government laboratory can be of great subsequent value for students or postdoctorate fellows interested in careers in applied physics and especially applied nuclear physics. This is because a graduate student or fellow becomes acquainted with many aspects of

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[1] "World and Canadian Energy Today and Tomorrow" Part 1 by H.B. Merlin. AECL-2390

[2] A more detailed account is given in "A Brief on Applied Physics" compiled by J. Mullin, AECL Report PD-323.

modern technology, such as the use of computers, high vacuum technology etc., in the process of advancing our knowledge of nuclear forces and nuclear structure.

There is general agreement on these reasons for the support of pure nuclear physics research at universities in Canada. However, in the "Brief on Applied Physics"[1], which refers to the largely applied-nuclear-physics oriented activities of AECL, it is pointed out that "the supply of graduate students who are oriented towards applied physics by their academic training is very small. One consequence of this is that the needs for staff for research in reactor physics[2], and for the design and operation of nuclear reactors, are being met at present by the hiring of graduates from foreign universities." Section E of the AECL brief on applied physics concludes: "It seems to us most unfortunate that the universities throughout Canada do not offer more facilities for graduate studies in the applied sciences. Perhaps this situation might be remedied somewhat by the bringing about of closer cooperation between universities and companies such as AECL, after the fashion of the ties between CRNL and some nuclear physics groups in the country."

These conclusions of the AECL brief on applied physics apply only partly to the nuclear physics groups at Canadian universities as the graduate students from nuclear physics groups do not all enter applied nuclear physics or applied physics. From a sample of 65 of the 85 doctorates in nuclear physics in the last five years, 23 are now on university staff, 10 are in industry, 17 are in federal government laboratories, and 15 are carrying out postdoctorate studies. It appears that somewhat less than one half of the doctorates in nuclear physics are headed towards careers in applied physics or applied nuclear physics. Assuming that one third of the candidates for a higher degree obtain a doctorate after 4 years of study there should be about 200 doctorates in experimental nuclear physics during the next five years. If a larger fraction of these students are to be headed towards careers in applied physics or applied nuclear physics, and if more facilities for graduate studies in the applied sciences are to be provided, then the suggestion of "closer cooperation between universities and companies such as AECL" should be seriously considered.

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[1] "A Brief on Applied Physics", compiled by J. Mullin. AECL Report PD-232, 1966.

[2] Reactor physicists require a considerable background in nuclear physics and many reactor physicists have had their training in nuclear physics.

7.7 PRESENT AND PROJECTED GROWTH RATE OF CANDIDATES FOR A HIGHER DEGREE IN EXPERIMENTAL NUCLEAR PHYSICS

The growth rates of candidates for all types of higher degrees[1], and for higher degrees in experimental nuclear physics, have been roughly constant for the past nine years at about 21% per annum. The data together with the projections at 21% and at 10% per annum after 1971/72 are given in Table IV.

Table IV.–CANDIDATES FOR HIGHER DEGREES

Year	All Candidates[1]		Experimental Nuclear Physics Candidates	
1957-58	1,710		29	
58-59	2,040		36	
59-60	2,510		54	
60-61	2,920		60	
61-62	3,360		69	
62-63	4,020		89	
63-64	5,000		95	
64-65	6,010		114	
65-66	7,400		158	
66-67	8,910	8,910	180	
67-68	10,800	10,570	219	213
68-69	13,100	12,270	263	247
69-70	15,880	13,950	320	281
70-71	19,200	15,680	386	316
71-72	23,250	17,250	470	348
72-73	28,200	19,000	566	383
73-74	34,200	20,900	690	421
74-75	41,400	23,000	830	464
75-76	50,200	25,300	1,000	510

Projections to 1975-76 are shown below the solid lines.

The first and third projection columns are for steady growth rates of 21% per annum and the second and fourth columns are for growth rates declining to 10% per annum after 1971-72.

[1] NRC 9196 (1966) Table III. The numbers are Science and Engineering Candidates.

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[1] In Science and Engineering.

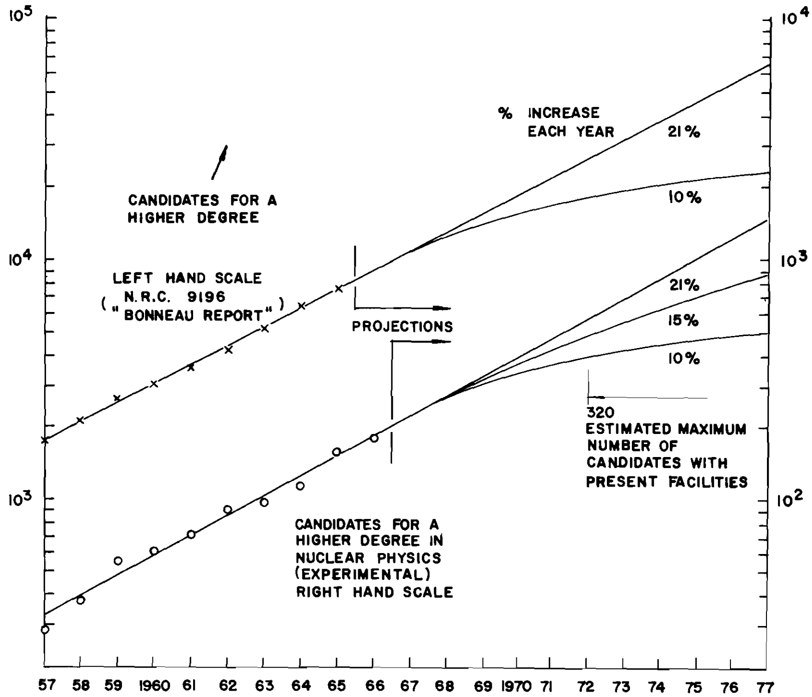

Fig. 1 Number of candidates for a higher degree (logarithmic scale) versus time in years. The left hand scale and upper curves refer to the total number of candidates for a higher degree, as extracted from the Bonneau Report. The right hand scale and lower curves give the number of candidates for a higher degree in experimental nuclear physics. Beyond 1967 projections have been made according to several assumed levels of percentage increase.

The similar rate of growth of the two groups of candidates for higher degrees is surprising and no definite explanation seems possible. The roughly exponential growth of the number of candidates for higher degrees in experimental nuclear physics summed over all Canadian universities is made up of several non-exponential growth curves, which approximate roughly the familiar S-shaped growth curves typical of many biological processes. Such growth curves, first of all, show an exponential rise followed by saturation. If no more new experimental nuclear physics facilities are constructed in Canada then it can be estimated that the number of candidates that can be accepted will saturate at about 320. The date of saturation or near saturation is very uncertain.

Table IV shows two simple projections. The first is for a continued 21% per annum growth rate, which is highly unlikely. The main difficulty with such a growth rate would probably be the provision of experienced university staff and technical personnel for a comparable growth rate. The second projection is for a growth rate of 21% per annum declining to 10% per annum after 1971–72. The projected number of candidates for experimental nuclear physics with the growth rate of 10% per annum after 1971–72 implies near saturation at present experimental nuclear physics facilities in 1970–71.

7.8 GRANT SUPPORT MECHANISMS FOR PURE NUCLEAR PHYSICS RESEARCH AT CANADIAN UNIVERSITIES

It is generally agreed that the recent innovation by NRC and AECL of a Visiting Subcommittee for major nuclear physics installations is an important step forward. Early this year, a joint AECB–NRC subcommittee visited six cities in Canada and discussed the nuclear physics research programs[1] and grant applications of eight major groups of nuclear physicists. The subcommittee consisted of some members of the main grant selection committee for nuclear physics, which meets annually in early February. The improved contact with the granting bodies, particularly NRC, was considered by the applicants for major grants to be an important improvement.

The situation is somewhat different for the applications by individual university staff members to NRC for operating grants in that it is conceivable that there could be no contact with the individual other than his application for a grant. In Canada, this is not yet a problem that requires special attention in the field of nuclear physics because the number of individuals applying for individual operating grants is quite small. The number of applications for individual operating grants for nuclear physics in 1967–68 was only 39 and of these 20 were directly involved in discussions with the visiting subcommittee. It is possible that new procedures for processing individual operating grants may be needed in future but at present the problem is a very minor one and no changes are recommended.

A criticism that has been made, of the support for major nuclear physics projects by NRC, is that after a project has been approved and a large capital grant made available, adequate funds for operating the project are sometimes slow to appear. This problem arises, for example, when university staff want to hire supervisory and operating

[1] High energy physics programs were also discussed. The cities visited in January, 1967, were: Winnipeg, Saskatoon, Edmonton, Ottawa, Montreal, and Toronto.

personnel for training purposes before the actual operation of the project. It has been suggested that large capital grants should always be coupled with a grant for expediting the operation of the project. The operating grant would recognize that the many commitments and expenditures connected with operating a project, such as an accelerator, have to be made as soon as capital expenditures start.

In the replies to the questionnaires there was support for both block grants for group projects and for individual grants. Supporters of block grants pointed out that, as much of the major equipment is shared, it should be part of the project and not the property of an individual. Supporters of the individual grants pointed out that the local division of minor operating funds from a block grant was often on a percentage basis so that everybody got the same percentage of their requested funds. This can have the effect of supporting the less able and energetic members of a group at a level far in excess of what they might get if they applied for an individual operating grant on their own record of past achievement.

A solution to this problem is to have the individual operating grants, for travel, minor equipment, graduate students and postdoctorate support, considered separately from the major operating grant for an accelerator. This would remove the objection to the present system stated above and remove the minor operating funds from local politics. For a large nuclear physics group, these funds can add up to as much as $100,000.

There is general agreement that the present grant support mechanisms for pure experimental nuclear physics are adequate though the size of the awarded grants is frequently disappointing to individuals and groups of individuals.

The upper limit of $6,000 for postdoctorate fellowships from NRC funds has been frequently criticized as inadequate. There is widespread feeling that the upper limit should be increased to $7,500 in the near future.

7.9 TEN-YEAR PROJECTION FOR NUCLEAR PHYSICS RESEARCH IN CANADA

9a. Pure nuclear physics research in Canada

Nuclear physics research has a continuing vitality, which makes it highly suitable for advanced training in physics at universities and government sponsored laboratories. This vitality can be traced to the very many only partially answered questions in nuclear physics and to the rapid advances in the experimental techniques used for answering them.

A good example was provided by the recent development of the lithium-drifted germanium Ge(Li) gamma ray spectrometer. The greatly improved resolution, which can be more than a factor of 20, of the Ge(Li) counter has revealed an incredible amount of new detail in nuclear gamma ray spectra. In addition, measurements of nuclear lifetimes from 10^{-10} seconds to 10^{-14} seconds can now be made by studying the details of the spectrum line shapes of gamma rays following nuclear reactions.

This single development, pioneered largely at CRNL and at the RCA Victor laboratories in Montreal, has revitalized the study of the gamma rays associated with radioactivity and with low-energy nuclear reactions. Even with no further improvements in Ge(Li) detectors, it will take at least a decade of work to exploit adequately this single advance. In common with other advances in nuclear physics, the development of a new detector or accelerator is inevitably followed by applications that exceed the boundaries of pure nuclear physics. The new Ge(Li) counters have already been used in attempts to locate ruptured fuel in nuclear reactors and their wide application in the activation analysis of materials is inevitable.

We can conclude from the example of the Ge(Li) counter and other similar examples that, with each advance in technique or with each new facility that is brought into operation, better answers to some of the basic questions asked by nuclear physicists are produced. We can expect this process to continue for at least several decades. Some of these basic questions have been discussed at length in the Pake Report (loc. cit.) to the National Academy of Sciences and so only a summary will be given here.

(i) The nucleon-nucleon interaction

The nucleon-nucleon interaction (the forces between pairs of protons, neutrons, or a proton and a neutron) is basic to our understanding of the strong forces that hold nuclei together. These non-electrical forces are very much more complicated than the forces that hold atoms and molecules together, and their elucidation has occupied the attention of nuclear physicists on and off for the last 30 years. The principal difficulty was encountered at a very early date when it was discovered that the nuclear two-body system, known as the deuteron, had only one bound state. This is in contrast to the atomic two-body system, the hydrogen atom, which has an infinite number of bound states. Partly as a result of this difference, much more complicated experiments must be performed to determine the properties of nuclear forces, and the analysis of these experiments is mathematically much more difficult.

In order to carry out a detailed study of the nucleon-nucleon interaction it has been necessary to develop new techniques and invent new devices. It has been necessary to develop accelerators that can produce nucleons in the energy range from zero to many hundreds of MeV in order to unravel the complicated details of the nuclear forces. Above about 270 MeV energy the problem is further complicated by the emission of the first of the quanta of the nuclear force field. These are the pi-mesons or pions. At still higher energies other quanta such as the kaons appear with strange new properties.

In addition to the development of new accelerators, the study of the complicated spin dependence of nuclear forces has badly needed the development of beams and targets of polarized nucleons. These developments are still taking place. However, rather than wait for the completion of such developments, nuclear physicists have resorted, with some success, to complex and time-consuming triple-scattering experiments.

Up to the present, the only major Canadian contribution to the study of nucleon-nucleon interaction has been the study of the so-called proton-proton bremsstrahlung with the 40 MeV protons from the cyclotron at the University of Manitoba. These measurements were made at roughly the same time as measurements at different proton energies at Harvard and Rochester. The proton-proton bremsstrahlung phenomenon provides additional information on the interaction to that provided by the study of elastic proton-proton scattering because the emission of the bremsstrahlung photon allows the energy of intersection to be different in the initial and final states of the system. Such interactions, without the emission of photons, are common in nuclei where there are many nucleons close together. The experimental results on proton-proton bremsstrahlung are now in reasonable agreement with theory. Further experiments on this phenomenon are in progress.

It is reasonable to expect that the coming years will produce a better understanding of the nucleon-nucleon interaction and it is quite likely that, with some of the existing or projected new accelerators such as TRIUMF or ING[1], Canadian nuclear physicists will make their contributions towards this understanding.

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[1] Discussed in more detail in Appendices 7.A and 7.B

(ii) Nuclear spectroscopy

In contrast to the two nucleon system the many nucleon system shows a very large number of bound states. These bound states have been extensively studied in the past and very much still remains to be done. A large fraction of the pure nuclear physics research in Canada is in the field of the nuclear spectroscopy of bound and nearly bound nuclear states.

Nuclear spectroscopy, like atomic and molecular spectroscopy, involves the study of the electromagnetic excitation and decay of nuclear energy levels and the high resolution study of the charged and uncharged particles from nuclear and atomic interactions. In addition, an entirely new non-electromagnetic and non-nuclear interaction appears in the study of nuclei. This is the so-called weak interaction responsible for the beta decay of nuclei, and its study is of great interest to both nuclear and elementary particle physicists.

The study of nuclear spectroscopy has required the development of precision devices for detecting electrons, protons, neutrons, and gamma rays, as well as the development of accelerators producing protons, electrons, and secondary neutrons with many millions of electron volts of energy. Without such accelerators and their buildings, which constitute a large fraction of the capital cost of nuclear physics, it would be possible to study only the ground states of stable nuclei or the limited number of excited states excited by naturally occurring radioactive nuclei.

The study of nuclear spectra has also required the development of techniques for determining the properties of excited nuclear states. In atomic spectroscopy the anomalous Zeeman effect provides a wealth of information on atomic energy states. However, partly because of the very small nuclear magnetic moments, the anomalous Zeeman effect is not observable in nuclear spectra and new techniques have had to be devised in its place. In addition, the study of nuclear electromagnetic transitions has required the development of a whole range of new devices such as the Ge(Li) gamma ray counter and the multichannel pulse analyzer, which in turn required the invention of the transistor and the development of solid state physics.

It is, therefore, hardly surprising that the study of nuclear spectra has been slow in developing, and not surprising that there is still very much to be done. In spite of the handicaps the study of nuclear spectra has progressed steadily from the early 1920's when Ellis realized that nuclei, like atoms, had a spectrum of excited states.

The study of nuclear spectra and the properties of the excited states of nuclei is an important activity in nuclear physics for a variety of reasons.

1. It is a source of information on the nucleon-nucleon interaction additional to the study of nucleon-nucleon scattering. The charge independence of nuclear forces is supported strongly by nuclear spectroscopic studies.

2. It is a source of information on the weak interaction responsible for beta decay. The non-conservation of parity in weak interactions was first observed by studying the beta decay of Cobalt-60.

3. The properties of individual nuclear energy states can be of importance to other branches of physics such as astrophysics. For example, nuclear spectroscopic studies of the 7.65-MeV level in Carbon-12 have shown it to have just the right properties for the formation of Carbon-12 during the "burning" of Helium-4 inside certains kinds of stars.

4. An understanding of some of the properties of nuclei in terms of nuclear models can be used to predict the properties of nuclei which are very difficult to observe. For example, the observed abundance of the different types of nuclei on the earth gives information on the astrophysical processes that occurred before the earth was formed. These processes undoubtedly involved the temporary formation of highly unstable nuclei which are at present very difficult to study directly. An interesting prediction, which may be verified during the next decade, comes from the shell model of the nucleus. The nuclear shell model predicts that nuclei of mass 310, with 126 protons and 184 neutrons, should be more stable than neighboring nuclei, and also that they should be stable against spontaneous fission. This increases the possibility that they might be observed. Nuclei with as many as 104 protons have been observed to date.

Some of the past successes of nuclear spectroscopy in Canada have been as follows:

1. The extensive investigation of neutron capture gamma rays at the CRNL demonstrated the importance of electric dipole radiation in nuclear electromagnetic transitions.
2. The first strong evidence for rotational levels in light nuclei was obtained at the CRNL for the Aluminium-25 nucleus. This discovery had led to a better understanding of the nuclear many-body problem.

3. Delayed protons following nuclear beta decay were first observed[1] at McGill University. The measurement of the properties of the proton-rich precursers of the delayed proton emitters is of importance to the study of nuclear matter.

The facilities recently installed in Canada, together with the older equipment, could, if supported in the future at the minimum level given in Table V, ensure the continued modest development of nuclear spectroscopy. However, major new facilities will be needed during the next ten years if Canadian nuclear physicists are to keep up with the developments in the rest of the world.

(iii) Nuclear reactions

Since the discovery of nuclear reactions of disintegrations, by Rutherford, their study has been pursued vigorously. The development of accelerators such as the cyclotron, the betatron, and the direct current electrostatic machine, has allowed detailed investigations to be made of a wide variety of nuclear reactions. Canadian nuclear physicists have played a small but valuable role in the study of nuclear reactions. Extensive early studies of the photonuclear reaction were carried out at the University of Saskatchewan. Some of the early studies of the so-called direct nuclear reaction mechanism with 14-MeV neutrons were carried out at the CRNL. Also, early detailed studies of the nuclear spallation phenomenon were made with protons from the cyclotron at McGill University, and with cosmic ray protons by Chalk River scientists. This early work has been extended and made more precise by recent work carried out on the spallation phenomenon in connection with ING.

The basic problem in past Canadian studies of nuclear reactions has been the lack of suitable equipment for making the studies. This fault has now been largely rectified with the installation of modern electron linear accelerators, a modern cyclotron, and large electrostatic accelerators. A large Canadian contribution to the study of nuclear reactions can be expected during the next ten years.

It will be essential for the further development of nuclear physics in Canada to plan the installation of more modern laboratories during the next decade. This is discussed in the next two sections.

9b. New facilities for pure nuclear physics research

If the present growth rate of candidates for a higher degree in nuclear physics, given in Table IV, continues, then saturation of the

[1] Contemporary observations on heavy nuclei, in the Soviet Union, also provided evidence for delayed proton emission.

present facilities listed in Table I will take place in 1969-70. It is estimated that about 320 graduate students in nuclear physics could use the facilities at present available at universities. The present growth rate of 21% per annum for nuclear physics graduate students must presumably decline during the next few years, and the projections from the Bonneau Report (NRC 9196) for the total number of candidates for higher degrees shows a drop from the present 21% per annum to less than 10% per annum in five years time. In Table IV we have assumed that the present growth rate of 21% per annum will decline to 10% per annum after 1971-72.

The response to the saturation of experimental nuclear physics facilities in Canada early in the 1970's can be of three main kinds.

(1) A decision could be made that no new nuclear physics facilities be constructed at universities, and that further development of nuclear physics should take place by the use of shared major facilities situated in various parts of Canada.

(2) During the development of the major shared facilities, new minor facilities, described in more detail below, could be installed as required.

(3) New major and minor facilities could be constructed as needed at universities in Canada.

This subcommittee, together with the majority of nuclear physicist in Canada, favors the second course of action. The main argument in favor of the second and not the third course of action is the realization that some of the next generation of nuclear physics facilities could be large and expensive to build and operate. An example of such a shared facility proposed in Canada is given in Appendix 7.A. Appendix D of the Spinks Report (loc. cit.) describes the growth of different kinds of joint institutes for nuclear research, and makes particular reference to nuclear and high energy physics research projects. There will be further discussion of this in Section 7.9 (subsection 4).

For the remainder of this 10-year projection, it will be assumed that the rate of increase in the number of graduate students wanting to take a higher degree in nuclear physics will fall gradually from the present value of 21% per annum to a value of about 10% per annum in 1971-72. These projections are given in Table IV. The projected rate of increase of 10% implies a need for roughly a 50% increase of the nuclear physics facilities in 10 years. In addition to increasing the number of nuclear physics facilities to some extent, it will also be necessary to improve the quality of the existing facilities and to make sure that the new facilities contain some of the most up-to-date equipment.

9c. Suggestions for increasing the number of the present facilities

In Table V, the projected expenditures on operating grants and major capital expenditures are given. The numbers in Table V are for a projection assuming no new facilities beyond those available at present. The rise in operating expenditure does not include an escalation factor of about 4% for the increase in operating costs and the 10% per year is for increased usage of facilities and increased operating costs due to the updating of the existing equipment using the projected major capital expenditures. The rise in major capital expenditures after 1970 includes the cost of updating existing equipment. The numbers in Table V probably imply a decline of nuclear physics activity relative to the rest of physics during the next 10 years.

Table V.–FEDERAL EXPENDITURES ON UNIVERSITY NUCLEAR PHYSICS
(millions of dollars)

Date	Operating Grants	Major Capital Grants
1959-60	0.51	0.150
60-61	0.58	0.100
61-62	0.57	0.115
62-63	0.65	0.500
63-64	0.73	0.910
64-65	1.05	1.27
65-66	1.47	1.50
66-67	2.18	1.41
67-68	3.00	1.26
68-69	3.50	0.85
69-70	4.00	0.80
70-71	4.40	0.80
71-72	4.84	0.85
72-73	5.32	0.90

Projections to 1972-73 are shown below the central line. After 1973-73 the projections are for an increase of 10% per annum. The projections are in 1967$.

In a number of replies to the questionnaires it was suggested that there should be further non-major nuclear physics facilities located at universities. Nuclear physics facilities costing say $0.5 million in total capital funds (federal plus provincial) can hardly be considered major, when projects costing over $3 million have been approved or proposed at universities. Consequently, we will in this report regard nuclear physics facilities costing less than about $0.5 million in total capital funds as minor nuclear physics facilities.

Even minor facilities can play an important role in nuclear physics research and in the training of candidates for higher degrees in nuclear physics. As pointed out in the answers to some of the questionnaires, and in private discussions, the trend of opinion towards large major shared nuclear physics facilities makes sense to the smaller universities, provided there is also some local minor facility. It is also clear from the plans of the University of Montreal and McMaster University that minor facilities in conjunction with major facilities are considered to be a powerful combination.

It should be possible to increase the capacity for graduate student training of the present facilities by 50% at an expenditure of roughly $5 million in capital funds (roughly half federal and half provincial) and $7.5 million (roughly half federal and half provincial) in operating funds on minor facilities. These sums of money could be spread over the next 10 years, more or less, depending upon the graduate students growth rate. For example, 10 projects similar to the recent installation at Queen's University of a 3MeV electrostatic accelerator could cost these sums of money. It some of these projects were undertaken at laboratories now having one major facility, there would accrue a double advantage. First of all, graduate students in their first and may be second years could use the minor facility for early training, thereby reducing the demand for time on the major accelerator or facility. This would then provide more time for the nuclear physics research of senior graduate students, postdoctorate fellows, and university staff, on the major facility. A second advantage would accrue from the presence in the laboratory, housing a major accelerator or other facility, of sophisticated equipment such as an on-line computer, which can easily be justified for a major facility. This would allow a limited number of advanced projects to be undertaken with the minor facility, which would be otherwise impossible. This approach has already been adopted in two somewhat different arrangements at the University of Montreal and also at McMaster University, in collaboration with the University of Toronto. In two years time there should be some useful experience from these laboratories on this point.

In addition to projects at already existing laboratories, some of the new projects should be initiated at universities now without any nuclear physics facility. There is a strong opinion among nuclear physicists at universities in Canada and elsewhere that, if future major nuclear physics facilities are to be shared between several universities, some sort of minor nuclear physics facility at the home university will also be necessary.

If the cost of the 50% increase in facilities described above takes place over the next ten years then it represents a very modest growth of expenditure on nuclear physics at universities in Canada.

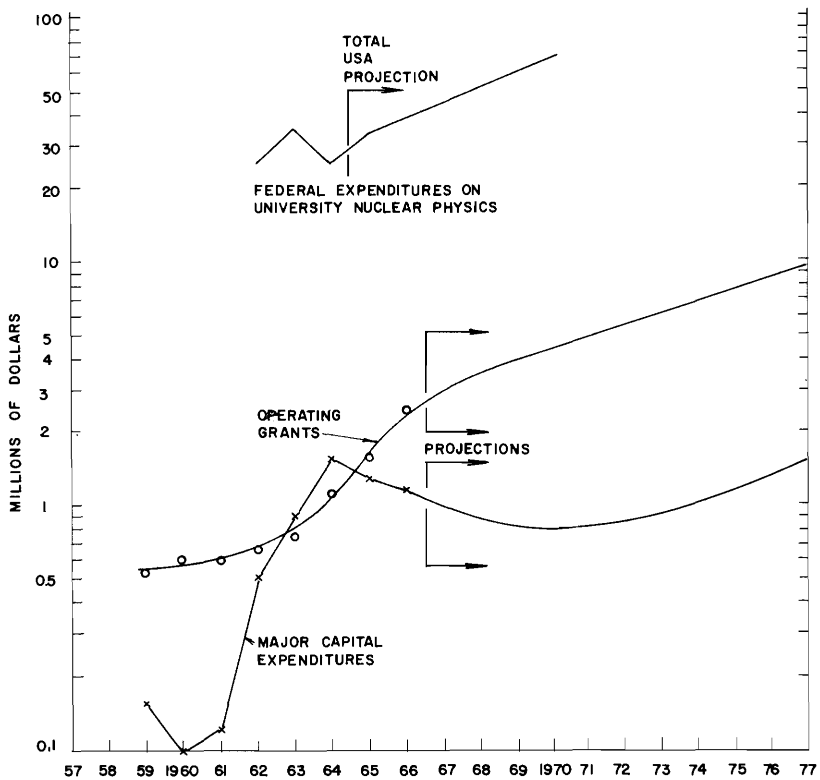

Fig. II Federal expenditures on nuclear physics (logarithmic scale) in the universities versus time in years. The lower curves show the growth and fluctuations in the operating grants and in expenditures for major capital equipment for the period 1959-1966. The projections have been made on the basis of arguments made in the text. The upper curve shows the total US expenditure on nuclear physics for the past few years.

9 d. Suggestions for improving the quality of nuclear research facilities

To ensure that nuclear physics continues to develop as a vital field of fundamental research in Canada it will be necessary to initiate new and imaginative projects during the next five to ten years. These projects, limited in number because of their size and cost,[1] will probably be shared among several universities and government laboratories. Such a project, proposed recently by a group[2] of universities, is the meson producing cyclotron known as TRIUMF (Tri-University Meson Facility). This project will cost about $26 million, in dollars escalated at 4% per annum, which is similar to the sum of all the other Canadian university nuclear physics facilities put together. The project is discussed in more detail in Appendix 7.A. If approved, it is expected to serve about 33 university staff and 71 graduate students in nuclear physics, and similar numbers in chemistry, starting late in 1972. It is worth noting that the increase in the number of graduate students in nuclear physics in the two years, 1972 and 1973, is projected to be about 70 if the 10% per annum growth is fulfilled.

Another advanced and highly imaginative project proposed in Canada is the Intense Neutron Generator (ING)[3] of the Atomic Energy of Canada. This project, described in more detail in Appendix 7.B, involves the acceleration of at least 65 milliamperes of protons to 1 GeV in a proton linear accelerator. These protons could then be used to generate an intense flux of neutrons by bombardment of a liquid lead-bismuth alloy. This project, if approved and successful, would provide a unique facility for physics. Although originally conceived as an intense source of neutrons superior to any proposed uranium reactor, ING could also be used for a variety of nuclear physics experiments. The estimated cost of the facility is about $140 million, in dollars escalated at 4% per annum, and it is not expected to be operational before 1974. It is also expected that university staff and graduate students will be able to carry out experiments with some of the beams produced by the facility. However, the total number of university nuclear physics users is projected to be similar to those using TRIUMF, which implies that TRIUMF and ING cannot be the only new nuclear physics facilities constructed during the next ten years unless the number of graduate students saturates at the 1974-75 value, 464, given in Table IV and none of the present facilities becomes obsolescent.

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[1] Cheap imaginative projects will be done anyway and they require much less fiscal foresight than expensive imaginative projects.

[2] At present the Universities of British Columbia, Victoria, Alberta, and also Simon Fraser University.

[3] AECL-2600 (1966) Atomic Energy of Canada Report

This seems unlikely. It is, therefore, quite likely that other nuclear physics projects will have to be started during the next ten years and an appropriate combination of major and minor facilities would seem to be ideal. Additional major facilities might contain, for example, advanced large tandem accelerators or a cyclotron for precision nuclear studies with fast nucleons and not mesons as in the case of TRIUMF or ING.

There has been some discussion between the University of Toronto and McMaster University on the possibility of a regional laboratory, to be located in Southern Ontario, that would concentrate on the development of large direct-current electrostatic machines of the tandem type for nuclear physics research. The workshop and computer facilities of this laboratory would also be of great interest to an emerging high energy physics group at the University of Toronto, which could use the laboratory as a base for its operations at the high energy machines in the US.

Large direct-current accelerators of the tandem type are of interest to the ING project and it has been proposed[1] that a high power tandem accelerator be used as an injector to the ING. An AECL contract for the development of an "axial magnetic generator" has been awarded to the Electrical Engineering Department of the University of Toronto and if the development is successful this generator may be incorporated in a high power tandem accelerator of advanced design.

It is expected by the staff at McMaster University and the University of Toronto that the development of a regional laboratory in Ontario will be evolutionary rather than revolutionary as in the case of the TRIUMF proposal discussed in Appendix 7.A. This difference in approach is due to the adequate facilities for nuclear physics research in most parts of Southern Ontario at present. No reliable cost estimates for development of a regional laboratory in Ontario can be made at present but such a development is likely to take place during the next ten years. The idea of regional laboratories, or joint institutes as they have been called, has been developing for some years (See Appendix E of this Report).

The creation in Quebec universities of large nuclear physics facilities has resulted in a sudden increase in the number of students interested in nuclear physics and, because of the present low number[2] of French-speaking nuclear physicists per French Canadian, every

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[1]AECL-2600 (1966) Section SV B Page 2.

[2]Physics in Canada 21 (1965) No. 3. Page 37.

effort should be made to provide additional facilities as soon as they are needed. However, as both the Université de Montréal and the Université Laval have relatively new major nuclear physics facilities, a few years will elapse before there is any need for a regional laboratory. The physicists at Laval and at Montreal are convinced that further major developments in nuclear physics in Quebec will be done on a regional basis and, in order to prepare for it, have already started to collaborate on research projects.

In the opinion of the nuclear physics subcommittee, shared projects, sometimes called "centers of excellence" or "regional laboratories", which are constructed during the next decade should ideally be interdisciplinary and not be confined to nuclear physics. Both ING and TRIUMF have this property to some extent. The ING will serve nuclear physicists, some high energy physicists, solid state physicists, reactor physicists and engineers, metallurgists, and chemists, and will produce radioactive isotopes for commercial purposes. Also ING will, if situated at the Chalk River Laboratories of AECL, be near two powerful research and development reactors, a large tandem accelerator, and other facilities for research and development. CRNL is already a "center of excellence" in nuclear physics and a successful ING project located there would continue and enhance this tradition.

The TRIUMF project will be used also by several disciplines, nuclear physics, chemistry, and solid state physics, for example. Combined with an active plasma physics group and low energy nuclear physics groups at the universities of British Columbia and Alberta, the TRIUMF project could form the beginning of one of the "centers of excellence" needed during the next decade.

Ideally a "center of excellence" in which nuclear physics plays a role should be diverse enough to ensure that there is always something of great current interest happening at the center, and sufficiently small so that there is adequate interaction between the disciplines. Nuclear physicists can profitably interact with physicists and engineers in a number of neighboring disciplines.

(i) plasma physics

The formation of plasmas from intense beams of excited neutral atoms uses many techniques similar to those used by nuclear physicists. For example, advanced versions of intense sources of ions are used in such devices and ion sources are of great importance to the nuclear physicists who use accelerators.

(ii) atomic physics

The accelerators used by nuclear physicists are being used increasingly for basic atomic physics measurements. This is because high energy ion beams represent a source of atoms in unusual states of excitation and ionization. For example, the Lamb shift in the hydrogen-like atom Li^{++} has been measured using 1.68-MeV lithium ions from a small electrostatic machine. The lack of contact between atomic physicists and nuclear physicists is partly responsible for the late introduction of better negative ion sources for use with tandem accelerators. The substitution of potassium as an electron donor for negative helium production instead of hydrogen has improved ion beams by about a factor of 100. The principle upon which this improvement is based was known to atomic physicists for many years.

(iii) electrical engineering

The interaction of electrical engineering and nuclear physics is still potentially fruitful as it was when the first Cockcroft-Walton accelerator was constructed over 30 years ago and many of the problems of modern accelerators are of great interest to present electrical engineers. For example, the radio frequency system for the Intense Neutron Generator must have as high an efficiency as possible for turning 60 Hertz power into 200 and 800 Mega Hertz power. High voltage insulation problems are of interest to nuclear physicists in connection with accelerators, and to electrical engineers in connection with direct current power transmission. In both cases, the interest is centered on more compact or less costly larger equipment. Electron microscope technology has connections with nuclear physics and electrical engineering as microscopes with voltages 1 MeV are being used and ones with up to 5 MeV are being contemplated. The use of techniques developed in high energy physics and nuclear physics has been advocated to improve electron microscopy[1].

(iv) elementary particle physics

Many of the techniques used in elementary particle physics are also used in nuclear physics. At a Canadian "center of excellence" involving nuclear physicists it has been suggested that there be an active elementary particle physics group who use the resources of the center, such as the workshops, to develop apparatus that would be used largely at the very large high energy accelerators in the US. A computer at such a center could also be used for the extensive analysis

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[1] Scientific Research, 1 (1966) 31. A New Approach to Electron Microscope Design.

of bubble chamber data. A very expensive high energy machine for particle physics is not being seriously considered in Canada at present but several groups are interested in carrying out experiments in the US from a Canadian base. The presence of an active elementary particle physics group at a "center of excellence" containing an active nuclear physics group would be mutually beneficial.

In conclusion, it would also be desirable in future to locate "centers of excellence" near large universities so that there can also be interaction between the disciplines actively pursued at the center and others in the universities.

Appendix 7.A

THE TRI-UNIVERSITIES MESON FACILITY

(i) Introduction

During the period from 1951 to the present, a productive nuclear physics group has been in existence at the University of British Columbia. This group is well known for its early studies with low energy accelerators of the direct radiative capture process and other nuclear reactions of interest to astrophysics. A total of 27 Ph.D.'s in nuclear physics have been awarded up to 1966-67. The other two universities in British Columbia involved in the TRIUMF project are Simon Fraser University and the University of Victoria. These universities have not yet awarded a doctorate in nuclear physics or a related subject though they expect to do so at an early date. Recently, the three British Columbia universities have been joined in the TRIUMF project by the well-established and productive nuclear physics group at the University of Alberta.

The Tri-Universities Meson Facility has been discussed in considerable detail in a report[1] issued in November, 1966. The project originated in March, 1965, after much deliberation on the future of nuclear and high energy physics[2] in British Columbia.

The TRIUMF proposal basically is for a variable energy 200-500 MeV negative hydrogen-ion cyclotron of advanced design, which will

[1] "TRIUMF Proposal and Cost Estimate", edited by E.W. Vogt and J.J. Burgerjon, November, 1966.

[2] A memorandum on a 7 GeV proton synchrotron is described in Physics in Canada, *15* (1959) 52.

produce beams of pi-mesons (pions) and mu-mesons (muons) as secondary particles. These unstable secondary particles, which can be created only by high energy ion beams from an accelerator, can then be used for a variety of important studies in nuclear physics.

There have been several similar proposals in recent years and so far only two have received tentative approval.[1] The first proposal to receive tentative approval was for a 510-MeV proton ring cyclotron at ETH, Zurich, and the second proposal was for an 800-MeV proton linear accelerator at the Los Alamos Laboratories. The Zurich machine is a similar but less flexible machine than that proposed for TRIUMF, whereas the Los Alamos Meson Physics Facility (LAMPF) is a more powerful machine with 10 to 100 times the proton ion beam intensity. However, the lower macroscopic duty cycle (6% to 12%) of the LAMPF accelerator reduces this advantage by a factor of ten for a number of important experiments.

The accelerator in the TRIUMF proposal is a modified version of a design for a high intensity meson factory, produced at the University of California in Los Angeles (UCLA). Because of restricted budgets, the United States Atomic Energy Commission has given approval to only one meson factory, the LAMPF project at the Los Alamos Scientific Laboratory.

There is great interest in these machines for producing mesons in large quantities and successive study groups on the US have urged that they be built[2].

(ii) Research scope of TRIUMF

The main research scope[3] of the TRIUMF project lies in the field of intermediate energy physics, in the nuclear chemistry associated with this field, and in the neutron experiments that are made possible as a by-product with any machine for intermediate energy physics. More specifically:

For intermediate energy nuclear physics, TRIUMF would provide several tens of microamperes of primary proton beams from 200 to 500 MeV with an energy resolution of 1.5 MeV total energy spread. These

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[1] The conversion of the Dubna synchrocyclotron in the USSR to a high meson intensity facility has apparently started already. Physics Today *19* (1960) 31

[2] "Report of the Ad Hoc Panel on Meson Factories to the office of Science and Technology" — H.A. Bethe et al, March, 1964.

[3] Described in detail in "TRIUMF Proposal and Cost Estimate", edited by E.W. Vogt and J.J. Burgerjon, November, 1966.

proton beams can be used to make more precise studies of the nucleon-nucleon interaction than have been possible up to now. Also, very important studies of meson production in nucleon-nucleon collisions will provide information about off-the-energy shell interactions. With the addition of further energy analysis it should also be possible to carry out a variety of nuclear structure studies.

For nuclear physics studies with pions and muons, TRIUMF would provide meson beams 100 to 1,000 times as intense as those available from present synchrocyclotrons. Negative muons captured by nuclei will provide much information on the electric charge distribution in the nucleus as well as other effects not at present accessible to detailed study.

For nuclear chemistry, TRIUMF would produce radioactive species not now readily available in the neutron-poor and transuranic regions of the mass table.

For solid state physics, TRIUMF would provide beams of thermal neutrons which, with neutron scattering and diffraction techniques, permit the study of crystal and molecular structure.

Several of the activities described above will be possible simultaneously with the proton beam from TRIUMF. For example, the thermal neutron production facility is located at the proton beam dump of the accelerator and the neutrons are generated in tantalum metal by the spallation process. In addition, experiments with pion and muon beams will be possible, using a fraction of the proton beam before it reaches the beam dump.

(iii) Significance of TRIUMF for nuclear physics in Canada

The TRIUMF is by far the most ambitious proposal put forward by a group of universities[1] for a nuclear physics facility in Canada. Projected expenditures on TRIUMF, including a 4% per annum escalation of costs, are given in Table VI. There is no doubt in our minds that a TRIUMF, put into operation on the target date of 1972-73 would be a world leading facility of its kind.[2] Only other similar facilities are being constructed at present and they have some disadvantages compared with the chosen design for TRIUMF. A successful TRIUMF would undoubtedly put Canadian intermediate energy nuclear physics on the map.

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[1] The TRIUMF study has been supported so far by the Atomic Energy Control Board.

[2] With the possible exception of the Dubna, Moscow USSR facility. Physics Today, *19* (1966) 36

Table VI.–ESTIMATED EXPENDITURES ON TRIUMF
(millions of dollars)

Year	Construction Cost	Initial Research Equipment	Recurring Cost
1967-68	.800		
68-69	4.160		
69-70	4.328		
70-71	4.500	.450	
71-72	4.680	1.053	
72-73	2.694	1.217	1.825
	21.162	2.720	1.825
	Total to 1972-73	25.71[1]	

[1]Includes a 4% per annum escalation. Taken from the "TRIUMF Proposal and Cost Estimate".

In addition to intermediate energy physics studies, it will be possible to utilize the thermal neutron flux at the proton beam dump of TRIUMF. The scientists who propose to use this not-so-intense neutron generator[1] apparently "constitute a substantial body of support for the TRIUMF project as a whole."[2] It is estimated that the total cost of the neutron facility will be about $354,000 including the components required in any case for an ordinary beam dump. This is apparently cheaper than an equivalent nuclear reactor, provided an appropriate fraction of the cost of the accelerator is not included.

The builders of TRIUMF aim to spend as much as possible of the cost of TRIUMF in Canada. This could naturally have some short-term beneficial effects on industry, but the main impact of a successful TRIUMF would seem to be the highly trained nuclear physicists, chemists, and solid state physicists that the project would produce.

If both TRIUMF and ING are funded, and if both are successful, then Canada will have two projects capable of making contributions to the potentially important field of intermediate energy nuclear physics. However, the question, "Does Canada need to start two expensive intermediate energy physics projects at this time?" requires an answer. It can be argued that the accelerators of the two projects are quite different and this difference makes the research aims of the two projects

[1] See Appendix B on "The Intense Neutron Generator".

[2] TRIUMF Proposal, loc. cit.

complementary rather than competitive. We can also as nuclear physicists argue that, even if the two projects are competitive, the field of intermediate energy nuclear physics will be sufficiently important to justify support for both projects in Canada. However, we believe that an answer to the question posed above can be given only in the context of the overall scientific development of Canada, which is the responsibility of the Science Council.

Appendix 7.B

THE INTENSE NEUTRON GENERATOR

(i) Introduction

In view of the past achievements at the Chalk River Nuclear Laboratories, it is not surprising to hear that there are ambitious plans for the future. Some of these plans, described in great detail in the AECL Report Number 2600, are for an intense neutron generator, ING, based upon a 1 GeV high current proton linear accelerator. The idea dates back to about 1952 when W.B. Lewis of CRNL realized the significance of certain experiments[1] carried out with high energy protons from the 184 inch cyclotron at Berkeley. The experiments implied that from thick targets of heavy elements, such as bismuth, many neutrons were generated by each proton. This phenomenon has been called the spallation of heavy elements by protons. It was also realized that a proton accelerator, which converted electrical energy efficiently into proton kinetic energy and then into neutrons by spallation, could generate fissionable material by neutron capture in fertile, but non-fissionable, material such as thorium. If "burned" in a reactor the U-233 produced from thorium could result in more electrical energy being generated than was used originally to accelerate the protons.[2] This process has been called the electrical breeding of fissionable material and is potentially as important for the future as thermonuclear fusion and fast reactor technology.

As a result of these highly imaginative ideas, and because of the secrecy that surrounded spallation research for a time, the yield

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[1] "The Significance of the Yield of Neutrons from Heavy Nuclei Excited to High Energies", by W.B. Lewis. DR-24(1952) AECL Report.

[2] "The Nuclear Power Implications of ING", by C.H. Millar. AECL-2177 (1965) AECL Report.

of neutrons from high energy proton bombardment was measured by Chalk River scientists using cosmic rays as the source of high energy protons. At proton energies lower than 100 MeV the spallation phenomenon was studied in detail by McGill scientists using the McGill cyclotron. It was concluded that it should be possible to produce fissile material efficiently from the neutrons produced by high energy proton bombardment of heavy elements such as lead and bismuth. Finally the extensive work from the Livermore laboratory in the US was declassified and it became apparent that the same idea had been considered in detail there and had been shown to be feasible.

From 1952 to 1963, however, nuclear reactors utilizing the fission of U-235 dominated the scene as neutron sources and as fissile material producers, and the spallation process was shelved.

In 1963, one of a series of seven groups at AECL studying a variety of projects for a Future Systems Committee, produced a report[1] which recommended that the spallation process be exploited by AECL to produce a high flux thermal neutron facility some sixty times as intense as that then available at the NRU reactor. The facility, which was first based upon a type of cyclotron (SOC – separated orbit cyclotron) and is at present based upon a proton linear accelerator, came to be known as the Intense Neutron Generator or ING.

The AECL proposal for a generator of intense neutron fluxes for research and development purposes represents one of the logical steps in the extension of the present work at the CRNL. High neutron flux facilities based upon reactors have been and are being built, or have been proposed in the US and the UK.[2] There is also interest at the Oak Ridge National Laboratory, and in the UK, in the application of the high-energy proton accelerator to the generation of intense neutron fluxes.

The AECL Report Number 2600 describes in detail the research scope of ING, which is broader than neutron physics.

(ii) Research scope of ING[3]

The Intense Neutron Generator (ING) provides an opportunity for major new advances in many fields of research and technology. The areas of fundamental research that would derive greatest benefit are

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[1] "High Flux Neutron Facility Based upon a Proton Accelerator" FSD/64-3 AECL Report. April, 1964.

[2] Report to the "Study Group on High-Intensity Sources of Thermal Neutrons" TNSG/14 (1965). UK AEA report.

[3] Part of the Introduction of AECL-2600

solid state physics, nuclear physics, and nuclear chemistry. In applied science ING would provide powerful tools for materials research and would provide many useful radioactive isotopes. Of potentially great significance in the long range power outlook, ING would open the door to methods of electrical breeding of fissile material and, with development of efficient accelerators and associated technology, promises a radical new approach to economic nuclear power. More specifically:

For solid state physics, ING would provide very intense beams of thermal neutrons which with neutron scattering techniques, permit major steps forward in studies of the structure and of dynamic processes in solids and liquids.

For nuclear physics, intense beams of thermal neutrons, and pulsed beams of resonance and fast neutrons, would become available. In addition, powerful new tools for the examination of nuclear structure would be provided by the very intense beams of mesons. (Mesons have, as yet, little use as nuclear probes). Further opportunities for fundamental research in nuclear physics result from the strong beams of intermediate energy protons and neutrons and the intense fluxes of neutrinos.

For nuclear chemistry, ING would produce radioactive species not now readily available in the neutron-poor and transuranic regions of the mass table.

In materials science, ING could be a major research tool for studies of liquid metals and structural materials bombarded by high fluxes of energetic neutrons and other particles.

In the industrial area, ING could produce many new high-grade radioactive materials of commercial value, and stimulate the development of many new components and techniques required for accelerator development and maintenance as well as for other purposes.

For research in the electro-nuclear power area, ING would provide initially only a zero-energy facility but the general experience with that facility should contribute much needed information for larger future programs.

In addition to the nuclear physics and related research possible with ING, the advances in accelerator technology stimulated by the building of ING should provide nuclear physicists with the opportunity to build and use more advanced forms of particle accelerators than are available today. Particle accelerators from the early direct current and cyclotron types to the highly developed versions of today have played an important role in nuclear physics and it is expected that they will continue to do so.

(iii) Cost of ING

ING is a very expensive project compared with TRIUMF and technically much more difficult, though this is compensated in part by the past experience of the CRNL staff. This experience includes the building – and repairing – of large high-power nuclear reactors. The estimated cost to the completion date of 1974-75, for the present reference design based on a proton linear accelerator, is about $140 million. This includes a 4% per annum escalation of costs. As pointed out by Lewis[1], it will be necessary to introduce some 40 projects as expensive as ING during the next ten years if Canada is to approach a possible target of 3% of the gross national product (GNP) for research and development expenditure.

Another interesting way of viewing the expenditure on the ING is to compare the total cost with the projected budget of AECL integrated over the years of design and construction.[2] The 1966-67 budget of AECL was about $60 million, which if the present rate of increase of 12.6% per annum is kept constant, will become about $160 million in 1974-75. The integration from 1966-67 to 1974-75 yields $880 million which can be compared with the $140 million expenditure in that period on ING. This emphasizes that ING would be only a part, albeit an important part, of the total projected future activity of AECL.

The total federal government research and development expenditure in 1966-67 was about 1% of the GNP compared with about 3% for the US and the UK. If a national goal of 2% of the GNP for federal research and development expenditures was set for 1974-75 then the present expenditures would have to increase by about 17% per annum, which is considerably greater than the present increase of 12.6% per annum of the AECL budget.

(iv) Significance of ING for nuclear physics in Canada

Unlike the TRIUMF project, ING is not primarily oriented towards pure nuclear physics research. It is basically a highly imaginative suggestion for exploiting the spallation phenomenon to generate neutron fluxes at least ten times higher than any competitive device. The intense neutron fluxes from ING can be used for the wide variety of purposes outlined earlier.

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[1] "A Perspective in Canada for the Intense Neutron Generator" by W.B. Lewis, DM-89 (1966) AECL Document

[2] "A Perspective in Canada for the Intense Neutron Generator" by W.B. Lewis, DM-89 (1966) AECL Document

A successful ING put into operation on its target date of 1974-75 could have a great impact on pure nuclear physics research as well as on the growth of advanced technologies in Canada. This impact was discussed earlier under Subsection (ii) of this appendix and we refer the reader to other detailed discussions[1] of the possible impact of a successful ING on Canadian technology.

In addition to providing intense fluxes of thermal neutrons, intense beams of neutrons, protons, muons, and pions would be available as nuclear probes and for a number of elementary particle studies. In this field of intermediate energy nuclear physics ING will compete with the proposed TRIUMF. However, we do not consider this competition to be a problem as far as nuclear physics is concerned because we are of the opinion that the field of intermediate energy nuclear physics will be important enough to justify support for both projects in Canada.[2] In addition, the pure nuclear physics research potential of both projects is not the sole reason for supporting them. As pointed out by Lewis[3], "Any project that is large enough to represent a considerable national investment should be judged not only on the merits of its own objectives, but also for the quality of the occupations called up. The relevant occupations are not in the main those of the sponsor or of the scientists, but of all those employed and developing special skills whose efforts constitute the "expenditure". Without 'expenditure', there can be only subsistence farming and a small total population in the world. At this time it is desirable to select inspiring activities that upgrade the nation's industrial capabilities." In our opinion, TRIUMF and particularly ING, are "inspiring activities." The ING proposal is at present being studied by the Science Council.

(vi) Site for ING

There has been some discussion on possible locations for the Intense Neutron Generator. Sites near major cities have been proposed and the difficulty of travelling to an ING located at Chalk River from centers of population has been discussed widely. In our opinion, though the present difficulties of travelling to Chalk River have been somewhat overrated, serious consideration should be given to improving the accessibility of Chalk River, especially if ING is located there.

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[1] "The Future of Nuclear Energy", W.B. Lewis. AECL Report DL-69 (1966). See also, "The AECL Symposium on the Generation of Intense Neutron Fluxes", AECL Report 2177 (1965).

[2] See also concluding paragraphs of Appendix 7.A.

[3] 'Inspiration and Aims for Advanced Projects in Canada" by W.B. Lewis. DM-71 (1963) AECL Document.

A more important consideration for the future than site accessibility is that about 28% of Canadians are French speaking. It is obvious from past experience at the Chalk River Nuclear Laboratories that if the ING is situated there, which is in an area where no French schools or culture exists, then one can conclude without any doubt that it will attract very few French-speaking scientists and engineers. On the other hand, if for scientific, technical, and financial reasons it becomes apparent that ING should be situated at CRNL, a serious study should be made of the requirements necessary to transform the Chalk River area into a place where French Canadians can feel at home, and where they can raise their children in surroundings that are in harmony with their culture.

SECTION 8

ELEMENTARY PARTICLE PHYSICS

W. T. Sharp (Chairman), C. K. Hargrove
and D. G. Stairs

8.1 INTRODUCTION

Elementary particle physics has been recognized as a separate field of physics for only twenty years. Most of the activity in this field in Canada has occurred over the last five years. Therefore the elementary particle physics divisional committee has devoted most of its effort to a consideration of the problems of future growth.

The general plan of this report is as follows. In Section 8.2 we discuss our definition of the field of elementary particle physics and its relation to the work of other divisional committees. In Section 8.3, after a brief historical survey, we describe and assess the present state of elementary particle physics in Canada and present statistics showing the money and manpower now devoted to the field. In Section 8.4 we try to present answers to the general question: Why study elementary particle physics in Canada? We conclude that there are very strong reasons for Canadian activity in the field.

Section 8.5 deals with four controversial matters that have arisen in submissions to us. These are: the construction of a Canadian high energy accelerator; active collaboration with the United States on the 200 GeV accelerator; a national or regional laboratory for elementary particle physics; and the role of the "small" university in elementary particle physics research.

In Section 8.6 we present our recommendations for the development of particle physics for the period 1967 to 1972. There is little that can be said at this time about 1972 to 1977 but some general remarks about the outlook for those years are included. In Section 8.7 we discuss the mechanism of support for research. Finally, in Section 8.8 we make a few general comments pertinent to the questions put to us by the steering committee.

8.2 WHAT IS ELEMENTARY PARTICLE PHYSICS?

One of the great historic aims of physics is to understand the properties of macroscopic matter in terms of the properties of its ultimate constituents. In the last hundred years or so the "ultimate" constituents have in turn been atoms, nuclei, and electrons, and now "elementary" particles. For the atomic physicist the atom is usually viewed as a nucleus surrounded by electrons and for the nuclear physicist the nucleus is a many-body system of neutrons and protons. The elementary particle physicist seeks to understand the structure of the nucleons themselves (i.e. the neutrons and protons). As nucleons have been accelerated to higher energies a broad spectrum of new and interesting particles has been produced. All the evidence now suggests that to understand the internucleon force we must understand many of the properties of these new particles. Already the results of elementary particle physics have profoundly influenced our conceptions of the basic force laws and the symmetries of nature.

We do not distinguish experimental and theoretical elementary particle physics as separate fields. Experimenters and theorists may use different tools but they are interested in the same problems and continued progress in particle physics depends on close collaboration between them.

The fields of physics are often classified according to energy regions; thus high energy physics is greater than 1 GeV, intermediate energy physics between 1 GeV and 100 MeV, and nuclear physics below 100 MeV. Although high energy physics does overlap both of these fields, we have understood it to mean greater than 1 GeV for the purposes of this report. For the most part, we shall use particle physics as synonymous with high energy physics (the work on muonic X-rays is an exception). Thus ING and TRIUMF, both intermediate energy facilities, have some interest for the elementary particle physicist, but are mainly within the scope of the nuclear physics divisional committee. Work done by theorists in particle physics is included in this report, as is research on the particle aspects of cosmic ray measurements.

8.3 ELEMENTARY PARTICLE PHYSICS IN CANADA

(i) Historical background

The history of elementary particle physics in Canada is easy to survey. Before 1947, one could hardly distinguish it from nuclear physics and there was little Canadian activity in what we would now call elementary particle physics, apart from field theory. In the period 1947 to 1962 Canadian contributions to experimental elementary particle physics were mostly dividends from the Chalk River nuclear program. The earliest Canadian work in this field was that by Pontecorvo and Hincks on the muon, by Robson on the lifetime of the neutron, and by Pickup, Voyvodic, and McDiarmid on cosmic ray interactions.

Since 1962 three groups of workers in experimental particle physics have become established in Canada; these groups work in collaboration with United States groups on experiments carried out at United States accelerator laboratories. The first group to be established was at NRC in Ottawa and is now based upon collaboration between NRC and Carleton University. The NRC group is active in muonic X-ray work in collaboration with physicists at the University of Chigago and in a proton-proton scattering experiment at the Argonne National Laboratory (ANL).

The two university groups in experimental particle physics, one a joint effort between the University of Toronto and Trent University, and one at McGill, were established only in 1964. The Toronto-Trent group analyzes and interprets bubble chamber pictures taken at ANL in collaboration with investigators from the University of Wisconsin and ANL. The development of the bubble chamber work has depended to an unusual extent on financial support from the University of Toronto. At McGill one physicist works in collaboration with a group from Harvard, Cornell, and Stanford universities in experiments at Brookhaven National Laboratory (BNL). There is also activity on a smaller scale in experimental particle physics at the universities of Ottawa and Manitoba. There has been, of course, some work in elementary particle theory for many years in Canada—to survey it in more detail seems unnecessary. Only in the last four years have there been at single institutions (e.g. McGill, Carleton, and Toronto) genuine groups of workers in elementary particle theory.

(ii) Present manpower

In discussing manpower, it is convenient to separate experiment and theory. In experimental particle physics during the winter 1966-1967 there were 14 physicists (all on university staffs except for 3 at NRC) with continuing positions, 3 postdoctorate fellows, and 4 students (2 Ph.D., 2 M.Sc., all at Toronto). The typical elementary particle physicist in Canada believes that he spends 2/3 of his time on research (including working with graduate students). Taking this figure into account and making allowance for some special circumstances, we arrive at a figure of 10 equivalent full-time research physicists with continuing positions, and 3 full-time postdoctorates. In theoretical particle physics there are 20 physicists on university staffs (say 12 full-time equivalents), 9 postdoctorate fellows, and roughly a dozen Ph.D. students. We would estimate a total of about a dozen M.Sc. students. Since graduate work in experimental particle physics has only recently become available in Canada (no Canadian university has yet awarded a Ph.D. degree in experimental particle physics) and students wishing to work in this field have traditionally been forced to leave the country, there is every reason to expect the number of graduate students in particle physics to increase rapidly. In summary, there are at present the equivalent of about 20 full-time research physicists on staff in Canada, about half experimental and half theoretical, and 12 postdoctorates, mostly in theory. These figures are to be compared with the conclusion of the Vogt Report[1] that in 1964-1965 there were 15 Canadian Ph.D. physicists in elementary particle physics and almost no graduate students.

(iii) Financial support

Our data on the cost of elementary particle physics in Canada are summarized in Table I. Experiment and theory are considered together. In order to avoid presenting figures for particular institutions all institutions (government and university) are taken together. Excluded, however, are all costs related to ING and TRIUMF; these are considered in the nuclear physics report and not easily allocated between different fields of physics. Thus NRC is the only government institution whose internal costs are considered in our table.

Table I.–FINANCIAL COST OF ELEMENTARY PARTICLE PHYSICS IN CANADA
(thousands of dollars)

Year	Government Cost	University Cost	Total Cost
1962-1963	90	70	160
1963-1964	100	80	180
1964-1965	190	130	320
1965-1966	240	260	500
1966-1967	450	370	820

[1] A Statistical Report on Canadian Physics. E.W. Vogt, L. Katz and P.A. Forsyth. Physics in Canada *21*, No. 3, 1965.

The first column of the table refers to NRC fiscal years. The second column (Government Cost) includes NRC grants to universities for research in elementary particle physics and our own estimates, necessarily rough, of the costs of NRC internal elementary particle physics research. It includes also the portion of computer costs for particle physics research paid by NRC. NRC internal costs accounted for most of the government cost in 1962-1963 but only about 40% in 1966-1967. The third column (University Cost) includes direct university support of research projects including salaries of staff and university-supported postdoctorate fellows. The salary figures are reduced to take account of time devoted to teaching and administration, not properly regarded as a cost of research, but increased to make some allowance for overhead. The final column is the sum of the preceding two. The figures quoted should be regarded as rough estimates, unlikely to be correct in detail. They represent, however, our best guesses as to the total cost to the country of elementary particle physics research and its distribution between federal government and the universities. As is also found in the Pake Report, the size of the university contribution is noteworthy.

In this paragraph we discuss in somewhat more detail some of the ingredients of the table above. Computer costs seem to be a significant fraction of the total cost at only two institutions. For these institutions we have taken the number of hours of machine time devoted to elementary particle physics, multiplied by a cost per hour according to a figure supplied by a staff member of the institution concerned, and allocated the cost between the second and third columns according to estimates given by the same individual. This procedure, of course, treats rather lightly some tricky accounting questions; we claim only that this procedure gives a better approximation than if computer costs were ignored entirely. In computing the entries in the third column we did not wish to accumulate data on individual salaries. University contributions to salary and overhead are estimated on the basis of $10,000 per year per full-time staff member. By "full-time" in the last sentence we mean full-time in elementary particle physics, not full-time in research. Thus the $10,000 figure is supposed to take into account total salary paid, time devoted to research, and overhead costs. It is only a very rough approximation and surely underestimates the university contribution to overhead costs for experimental physics. The United States government currently reimburses universities for overhead costs amounting to 30% to 70% of the direct cost of a grant-supported research project. The $10,000 formula was not used in estimating NRC costs. It represents only a naive approximation to a very complex problem.

There are a number of more general remarks that must be made in connection with the above table. To the best of our knowledge, there is no activity in elementary particle physics in Canadian industry. Both "capital" and "operating" costs are included in the table. In the context of the programs of the present Canadian users groups, the traditional distinction between capital and operating expense seems largely arbitrary. Not included in our figures are NRC scholarships, studentships etc., or university scholarships awarded to students working in elementary particle physics, or special travel grants, or summer supplements to staff members. In principle, perhaps, these expenses should be taken into account but we lack the data required to do so and we doubt if their inclusion would change our totals significantly. It is important to emphasize that Canadian users of US accelerators (in common with other users) make no financial contribution toward the capital and operating costs of the accelerators. This accounts for the relatively low cost of elementary particle physics in Canada at the present time—no large capital investment has so far been necessary and a large fraction of the cost of experiments has been borne by our US collaborators.

(iv) Present status

In assessing the status of Canada's efforts in this field in the spring of 1967 one can cite first of all that a small but increasing number of high energy physicists are working in Canadian universities and at NRC. The grant support per staff member is beginning to approach the level that the United States has found necessary in this field. But because of the formidable size and complexity of experiments in particle physics, each group will need many more staff members before independent strength can be achieved. Every effort is being made to attract new members of staff with recognized ability and experience. The universities for their part have given full support to the development and expansion of particle physics research within their respective departments. The future development depends on continued increases in support per staff member, particularly for capital items such as measuring machines, both conventional and automatic.

8.4 WHY ELEMENTARY PARTICLE PHYSICS IN CANADA?

The plan of this section is as follows: First we consider briefly why elementary particle physics is important and worth study in general. Second, we consider more specifically why elementary particle physics is worth study in Canada. Granted that the Canadian physics research program should include particle physics, how should we allocate limited resources between elementary particle physics and other fields, in particular nuclear physics?

(i) Why particle physics?

There are perhaps two basic motivations for the study of physics. One is almost aesthetic: we seek to comprehend and understand the physical universe around us. The other is practical: through understanding we seek to control our environment and to lay a firm foundation for technological advance. It is remarkable in the history of physics how closely linked these apparently disparate aims have been.

Purely theoretical advances have led to unforeseen technological progress (for example, quantum mechanics led to modern quantum electronics and Einstein's principle of the equivalence of mass and energy led to the development of nuclear power). Moreover, it appears that technological and industrial development occur most readily in association with a vigorous, pure science research program. The spectacular achievements of contemporary particle physics required the technological achievements of those who build accelerators, design bubble chambers, or develop automatic data reduction systems. Thus it is essential to maintain balance between fundamental physics and technology.

Particle physics is concerned with such questions as the following. Which, if any, of the stable and unstable particles are truly elementary? What are the forces that act between them: in particular what are their symmetry properties? What basic laws describe the interactions of these particles and predict their properties? We do not even know yet what are the proper questions to ask. To quote from the Pake Report, "It is certain, however, that particle physics is at one of the frontiers of science and is one of the great creative intellectual efforts of our time."

It would be wrong, however, to think that the case for elementary particle physics stands entirely on the intellectual appeal of the subject. While it is premature to describe or to predict what specific technological advances may follow, it seems to us not presumptuous to claim that particle physics will continue to lead to technological advances and even, perhaps, to a technological revolution. One is reminded of the view sometimes expressed in the late nineteenth century, that physics was essentially complete with only a few details remaining to be filled in. Unexpected properties of the fundamental particles may lead to entirely new macroscopic consequences. Alternatively, we may be driven to new ways of formulating questions in particle physics and these new ways may have vital implications for other parts of physics. Thus the methods of the quantum theory of fields, developed for use in elementary particle physics, have seen significant application in solid state and nuclear physics. While we cannot predict exactly what form these implications will take, we have no doubt that advances in particle physics will have significant implication for other fields of physics as well as for technology.

Often new techniques must be developed to solve the special problems of particle physics. These techniques are then directly applicable to commercial problems. This explains why centers of research are often surrounded by large manufacturing complexes as in the Boston and San Francisco Bay areas in the United States.

Finally particle physics provides good training for graduate students. For reasons that may be connected with the second preceding paragraph, particle physics has a special appeal for graduate students, particularly for the best graduate students. The United States experience is that about half the students who obtain Ph.D. degrees in elementary particle physics find employment in other fields of physics. To conclude from this that research in elementary particle physics is overemphasized seems unsound. A Ph.D. is not bound to work for the rest of his career in the field in which he takes his degree. In the unlikely event that research in particle physics were abandoned on a world-wide scale, many of these students would probably not pursue graduate work in physics at all, but the special appeal to young minds of particle physics seems to us an additional reason why work must be done in the field.

We conclude that elementary particle physics warrants study because of its fundamental contributions to our view of nature, because of its innate intellectual appeal, particularly to graduate students, and because it shows promise of significant implications for other fields of physics and technology.

(ii) Why particle physics in Canada?

We ask now the more particular question: Is it essential to study particle physics in Canada? Since our neighbors to the south have a record of excellence in this field, why not leave it to them? Is it sensible to support the work of Canadian groups on United States accelerators: if Canadian participation were withdrawn would not the experiments continue in any case? We shall not meet these questions by arguing (as one can argue with justification) that Canada should do elementary particle physics because nearly all other developed nations do it or because of the scale of the United States effort in the field. Instead we shall try to present positive reasons why elementary particle physics should be studied in Canada.

The arguments of the preceding section all seem to us to apply to elementary particle physics in Canada. If one accepts that particle physics is one of the great creative intellectual efforts of our era, no serious department of physics should ignore the field entirely. One would hope then that in each department there would be at least one staff member, perhaps a theoretician or a nuclear physicist, with at least a casual interest in particle physics, sufficient perhaps for undergraduate instruction. In at least one or two Canadian graduate departments of physics there should be at least enough research activity in particle physics to provide training for graduate students. Since students who wish to study particle physics, including a high proportion of the outstanding undergraduate students of physics, will leave the country if we do not provide first-class facilities for them here, we must provide first-class graduate programs in particle physics in Canada.

If one accepts the conclusions of the previous paragraphs, one is led to ask: how much activity in particle physics is required to meet the minimum needs of the country and what kinds of activity should be pursued? Here the financial aspect must be considered. The cheapest particle physics program would surely be one consisting of theoretical research exclusively. The undesirable effects on the staff physicists participating in enforced isolation from experiment could possibly be minimized by generous provision of travel expenses. However, we consider that a purely theoretical environment would be bad for the graduate students and in no sense lead to a first-class research atmosphere or balanced Canadian program. There must be significant research activity in experimental particle physics in universities in Canada. The cheapest way of maintaining such activity is to maintain supporting groups which do experiments, usually in collaboration with others, on United States accelerators. Such groups can obtain machine time only if their experiments are at least competitive with others. We conclude that a policy for the support of experimental particle physics in Canada should be based on users' groups at a level adequate to maintain their competitive position with respect to US groups.

8.5 FOUR PROBLEMS

(i) A particle accelerator for Canada?

We believe that at the present time in experimental particle physics, Canadian efforts should be concentrated on experiments with foreign accelerators. Perhaps over the next five years there will be a study proposal for a high energy accelerator that has general support among the particle physics community. In that case money should be made available for the study. Since a design study for a large accelerator may take years, we doubt if the decision as to whether or not to build an accelerator in Canada will be needed before 1971. We do not wish to forecast conditions beyond that date.

(ii) Participation in the 200-GeV accelerator?

In the United States it is now planned to build at Weston, Illinois, a 200-GeV proton accelerator at a total cost approaching $240 million. A new organization, University Research Association, has been formed to manage the laboratory.

In elementary particle physics there is a clear trend toward international cooperation. CERN in Geneva has been an outstandingly successful international laboratory. In France, a large bubble chamber is being moved to the 70-GeV accelerator at Serpukhov in the USSR. A US-USSR group is building an experiment at Brookhaven to be done at Serpukhov, and CERN-US collaborations are very common. Under these circumstances some physicists have asked if it might be possible for Canada to participate as a full partner in the construction of the 200-GeV machine. This is an imaginative and attractive proposal. The 200-GeV machine will be unique and is readily accessible from Canada. A practical proposal with widespread support should be considered very seriously.

Two other possible forms of participation in the 200-GeV machine should be mentioned. It would be possible for Canadian particle physicists to unite to build some piece of ancillary equipment for the accelerator, perhaps a bubble chamber or an experimental hall. This would be a useful project. The other form of participation is that one or more Canadian universities might become members of University Research Association (URA). This possibility is already under study.

(iii) A national or regional laboratory for particle physics?

For the last three years there has been some discussion among Canadian particle physicists of the possibility of setting up a national laboratory for particle physics. Such a laboratory could be run by an organization of cooperating universities, and have a small staff, but many research associates and university visitors. It could serve as a home base for the assembly of experiments for a common Canadian users' group and as a center for accelerator design studies. The objection to such a proposal is that at the present time little could be done at the laboratory that could not be done at the individual universities, particularly so since the scientific interest of the various Canadian groups seem to be moving in different directions. We conclude that immediate establishment of a national laboratory for particle physics would serve no useful purpose. In the long run, of course, if any high energy accelerator is built in Canada it should be located at such a laboratory, and it may well be desirable to set up the laboratory long before an accelerator is approved. National policies should be such as to support such a laboratory if it is desired by the groups active in particle physics. There may be some economy in doing some things centrally rather than at several campuses. It is important from the national point of view that the different groups in particle physics should cooperate with each other, and sometimes actively collaborate. Particle physics is too expensive to allow us the luxury of completely uncoordinated experimental research.

There is a somewhat different situation in Southern Ontario. Trent and Toronto are at present collaborating in a program of bubble chamber film analysis. There is a fair chance that other universities in the area may wish to join the program. If so, it might be sensible to establish a regional laboratory, under joint control, to become a center for automatic measuring. It would be easier perhaps for the smaller universities to participate in a new research center than in a centralized operation on any one campus. Again, it would be premature to speak of details. If a proposal for establishment of a regional laboratory is made by a group of universities, it should be given very serious consideration.

(iv) Particle physics in small universities?

In considering particle experimental physics in small universities, one is on the horns of a dilemma. On the one hand it is important to discourage proliferation. The minimum size of an effective users' group is about six. To support many scattered small groups is wasteful and may prevent the development of effective graduate programs in any one place. On the other hand, new universities must have a chance to allow their staff to participate in research. Since particle physics is one of the most exciting fields and only a few Canadian universities are at present active in the field, what is more natural than that some of the new universities should wish to work in particle physics? We do not wish to restrict particle physics to a few established universities.

Our solution to this dilemma is clear. Formation of new groups should not be discouraged when there is evidence that they will be able to achieve threshold size. It will, in any case, be difficult for new universities to hire staff of established competence in experimental particle physics. On the other hand, new universities should be encouraged to participate in established programs in collaboration with others as part of a group. Thus particle physics at Trent should be regarded not as a new group but as part of a Trent-Toronto collaborative group. It remains important, of course, to apply the usual tests of scientific competence and reputation. We consider it important that institutions should not be prevented from participating in one of the most exciting fields of physics. At the same time their participation should not result in new ineffective groups but must be in collaboration with others. Establishment of regional laboratories will facilitate useful research in these universities.

8.6 RECOMMENDATIONS FOR 1967-1971

(i) Experimental particle physics

The first priority must be to give support to users' groups that participate in experiments on US accelerators. "Adequate" here means adequate to remain competitive. At present this probably requires about $60,000 per year per staff physicist (operating and capital). By 1972, adequate is likely to mean $100,000 per year per staff physicist. This figure takes account of inflation, the increasing complexity of apparatus, and routine computer costs. It does not include the capital cost of a computer for automatic measuring. At present we have three potential experimental groups. If we assume that after a fair trial all are judged first-class, that a new group elsewhere is formed, and that each group is allowed to grow to the threshold size of about six staff physicists, we find in 1972 about 25 physicists needing annual support of about $2.5 million. We recommend that funds allocated for support of users' groups (NRC included) rise linearly from the present level of about $0.5 million to $2.5 million in 1971-72.

(ii) Theoretical particle physics

The existing situation in theoretical particle physics is healthy, and present grants mechanisms adequate. One can expect steady growth in established groups and the formation of new ones. By 1972 one might expect 40 theoretical staff and 40 post-doctorals, requiring grant support of about $640,000 per year.

(iii) Accelerators, regional and national laboratories

In the next five years scientifically sensible proposals for particle accelerators in Canada may be made. If so, study funds should be available. Proposals from groups of universities for joint research laboratories for particle physics should also be considered on their merits.

There is also a possibility of other major proposals in the next five years, not in the accelerator class but nevertheless requiring much more money than the support for users' groups proposed in (i). These should also be considered on their merits in the whole context of national scientific development. Proposals from within or without the government service should be treated in the same way. One guess would be that no such major proposals are likely to emerge in particle physics before 1972.

(iv) Outlook for 1971 to 1977.

We make no numerical predictions for this period. Several Canadian users' groups should be firmly established. During this period, construction of a Canadian accelerator may be sensible or, alternatively, construction of major facilities for a foreign machine, or participation in a great international cooperation. By the end of the period Canadian particle physics should have reached a state of maturity, with a steady output of graduate students. Whether particle physics in Canada will have achieved a real international reputation by 1977 depends on the efforts of physicists in the field.

8.7 GRANT MECHANISMS

We have the impression that the members of grant committees do a conscientious job under difficult conditions. The changes made by NRC in the last six months go a long way toward eliminating earlier dissatisfactions within the scientific community. NRC is to be commended for the introduction of negotiated development grants, which seem to provide a very flexible means of support.

In conclusion, we think that the 1967 procedure was on the whole satisfactory. In future we recommend that particle physics have a greater representation on the appropriate grant committee. Some membership from theoretical particle physics is very desirable.

In theoretical particle physics the grant mechanism seems to work well. Greater flexibility about travel expense is needed, however. Travel for theoreticians is a relatively large share of their small research grants and travel expenses are needed for postdoctorals as well as grantees.

8.8 CONCLUDING COMMENTS

In 1967 we expect no Ph.D. degrees to be awarded in experimental particle physics, about three in theoretical particle physics.

There is a satisfactory distribution of effort between government, industry, and universities. It is reasonable that there should be no industrial effort in the field, and under present arrangements between NRC and the universities, it is not meaningful, for graduate instruction purposes, to separate NRC from the universities.

Canadian physicists are active in most of the central areas of particle physics. In our present state of ignorance we do not know if the attack on, for example, the strong interaction has just begun or is nearing and end. We do not even know if we are asking the proper questions, let alone whether we are close to answers.

Particle physics is international. It has special relevance to Canada only insofar as Canada, as a part of human civilization, wishes to participate in one of the great intellectual frontiers of our era. Many distinguished particle physicists have been born in Canada; nearly all have had to leave and the country is poorer for their loss.

Particle physics has immediate applications to nuclear physics, astrophysics, and perhaps atomic and molecular physics (at least one Canadian chemist is looking for quarks). The conceptual changes it may bring about will have profound influence on all of science. It is unlikely to have immediate technological importance; for the long range it would be rash to so predict.

In experimental particle physics the need is for a few first-class research groups with adequate support by US standards.

Section 9

SOLID STATE PHYSICS

R.R. Haering (Chairman), M.H. Jericho, and R.J. McIntyre

FOREWORD

In the following pages, we attempt to present a comprehensive study of the present status of solid state physics in Canada and to make specific recommendations regarding the future of this activity. During the course of its deliberations, the committee received 44 written briefs from solid state groups in university, government, and industrial laboratories. In addition, members of the committee visited 20 different solid state groups throughout Canada. The number of solid state physicists who have in some way contributed to our task is nearly 100, and the members of the committee wish to thank all those who have helped us during the course of this study.

9.1 DESCRIPTION OF THE FIELD

Solid state physics deals with the understanding and control of the properties of all solid matter. Until 50 years ago, man's understanding of solids was entirely empirical and descriptive, and indeed recognition of solid state physics as a separate branch of physics did not come until about 1945. Even today, the field has no universally accepted definition and solid state physics overlaps many other branches of physics, chemistry, and metallurgy.

In the solid state, the individual atoms which constitute matter are sufficiently close together that their mutual interaction cannot be disregarded. Indeed, it is this mutual interaction that is responsible for the rich variety of properties of the solid state. For example, an array of carbon atoms in the solid state may be nearly metallic in nature (graphite) or it may be an insulator (diamond). Solid state physics is concerned with the elucidation of observed properties of solids in terms of atoms, of electrons, and of the interaction between these constituents. At present, we think that our understanding of these constituents and their interaction is, in principle, adequate to account for all of the observed properties of solids. We do not believe that major new concepts are needed in solid state physics, in the sense that such concepts are, for instance, needed in high energy physics. Nevertheless, the description of the solid state presents a

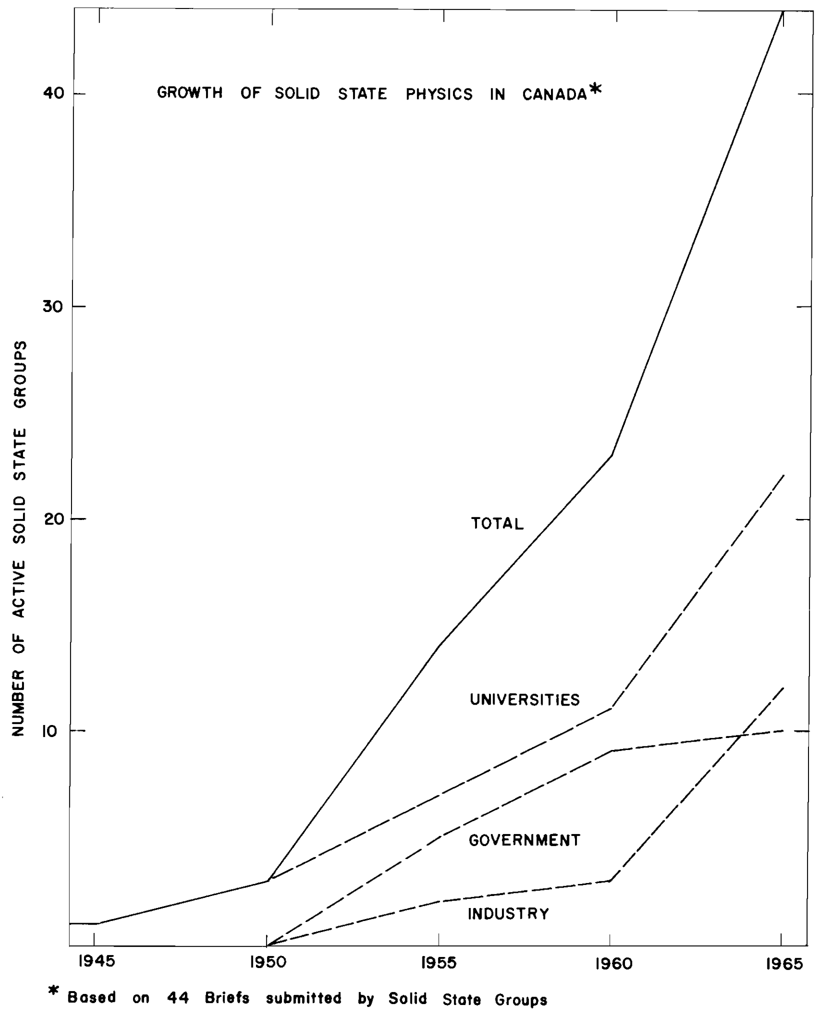

Fig. 1 Growth of solid state physics in Canada; the increase in the number of active groups between 1945 and 1965.

considerable intellectual challenge, because of the complexity of the many particle aspects. Indeed, it has proved quite impossible to provide a description of solids that contains all of these features simultaneously. For this reason, solid state physics must resort to the use of physical "models." Such models focus attention on those aspects of the situation that are thought to dominate the phenomenon to be described, and disregard other aspects believed to play no essential role. The construction of successful models requires a considerable facility for abstraction. Often the required insight is obtained only after examination of relevant experimental data. Much of solid state theory is therefore descriptive and explanatory after the fact, rather than predictive.

9.2 HISTORY OF SOLID STATE PHYSICS IN CANADA

The origin of solid state physics in Canada may be traced to the University of Toronto, where liquid helium was successfully produced on January 10, 1923. This important achievement resulted in the establishment of the world's second low temperature laboratory at the University of Toronto, and paved the way for a number of pioneering solid state investigations during the twenties and thirties. However, solid state physics did not emerge as a recognized field of physics until after the second world war; its subsequent growth in Canada is shown in Fig. I. The data in Fig. I were taken from 44 briefs submitted to the committee by solid state groups in university, government, and industrial laboratories. In spite of its rapid growth in Canada, this field of physics accounts for only 8.2% of Canadian physicists, whereas over 25% of US physicists fall in this category.

The rapid advance of solid state physics in Canada after 1945 can be attributed mainly to the major developments that have occurred in this field in the past 20 years, and that have had a profound influence on science and technology. The most important event was undoubtedly the development of the transistor in 1948, but there have been many other more recent advances and the full benefits of these have yet to be reaped.

A second factor, which has contributed to the growth of solid state physics in the universities, is the suitability of this subject for research projects that are of modest size in terms of manpower and expenditures. The realization that meaningful research groups in this field could be quite small (involving perhaps 3 or 4 staff members) led many of our newer institutions to establish solid state groups. There is every indication that this factor will continue to contribute to the growth of solid state physics in Canada.

The growth of solid state research in Canadian industry has lagged considerably behind the development of this subject in university laboratories. Some semiconductor research was initiated at Northern Electric and at Marconi in the early 1950's, but no major expansion in industrial solid state research occurred before 1960. Even today the amount of such research is absurdly small and is badly out of balance with the size of the university effort.

Solid state physics research in government laboratories began in the early 1950's and enjoyed a period of substantial growth during the following decade. Indeed, much of Canada's reputation in solid state research during this period was derived from work done in government laboratories. However, during recent years such research in government laboratories has not grown adequately. Further comments regarding this situation are made in Section 9.5.

Solid state physics is an exciting subject in its own right and occupies a very special position with respect to the development of science and technology in Canada because of the intimate link between it and Canada's mineral resources, and because of the many contributions that this field has made to other disciplines. Many of the advances in computer technology, space technology, communications, chemistry, biology, nuclear physics, astrophysics, and medical physics, simply would not exist without contributions from solid state research. It is certain that this trend will continue for many years to come.

9.3 ESTIMATE OF PRESENT LEVEL OF ACTIVITY IN TERMS OF MANPOWER AND DOLLARS

(i) Manpower

The most recent data pertaining to manpower and expenditures in physics in Canada are provided by the Vogt Report.[1] We have made extensive use of these data, but we urge the reader to use caution in their interpretation (see Section 9.4, particularly that part dealing with the distribution of activity among the universities). The chief difficulty regarding any data on solid state physics originates in the large amount of overlap between this and other fields of physics

[1] Statistical Report on Canadian Physicists, loc. cit.

(e.g. atomic and molecular physics, electromagnetic theory). A similar difficulty was encountered in the US survey[1] with the result that it was not possible to give the number of Ph. D.'s working in solid state physics to an accuracy of greater than 50%. In spite of this difficulty we shall here rely heavily on the results of the Vogt Report. We are convinced that the criticisms that can be raised about this survey apply equally well to any other attempt to produce precise figures for a field which itself lacks a precise definition.

The distribution of the 147 Canadian solid state physicists identified in the Vogt Report is given in Tables I and IV. A more liberal interpretation of solid state physics would increase the manpower estimates, particularly in the universities (see Table IV), but would not significantly alter the percentage distribution among the various subfields (see Table I).

(ii) Expenditures

Present research expenditures in solid state physics are summarized in Table II, where the total expenditure per physicist is given for each type of laboratory. In 1966-67 the average university physicist received about $8,500 in research support from sources other than his university. This figure is based on 22 briefs submitted by university groups during the course of the present study. It is largely made up of NRC operating and major equipment grants, but it also includes all other support from federal and provincial agencies. (A figure of $5,300 is given for physics in the Vogt Report for 1963-64, but this includes only NRC and AECL support). In addition, many universities make a direct contribution to the cost of research. In many of the newer universities particularly, this contribution is comparable to that from federal granting agencies and even in the older institutions it is not a negligible factor, largely because of a tendency for universities to "match" major equipment grants. On the average, this direct university contribution amounts to $2,000 per scientist per annum. Finally, the universities make an indirect contribution through salaries of faculty, students, and technicians, as well as through overhead and capital expenditures. It is difficult to arrive at an accurate figure for this indirect support. If 1/3 of the faculty member's salary is charged to research we estimate the university's total indirect contribution to be about equal to the support from granting agencies. A similar estimate has been used in an earlier study by Spinks.[2] Adding these various contributions, we estimate the present level of support at

[1] Physics Survey and Outlook, National Academy of Sciences, Washington, D.C. Vols. 1 and 2 (1966) NAS–NRC Publications 1295 and 1295A.

[2] J.W.T. Spinks, Trans. Roy. Soc. Can. *IV*, 2, 13 (1964).

$19,000 per university solid state physicist per annum. This figure should be compared with $36,000 per annum for a physicist in the same field at a US university.*

Table I.–DISTRIBUTION OF SOLID STATE PHYSICISTS BY SPECIALIZATION.

	Specialization[1]	Number[2]	Percentage
8801	Ceramics	2	1.4
8802	Cooperative phenomena	0.5	0.3
8867	Crystallography	6	4.1
8803	Dielectrics (incl. fluids)	2.5	1.7
8804	Dislocations and plasticity	4	2.7
8805	Dynamics of crystal lattices	10	6.8
8806	Electrical properties of surfaces and junctions	5.5	3.7
8807	Electron emission	3	2.0
8808	Ferromagnetism	2	1.4
8810	High polymers and glasses	2	1.4
8811	Internal friction	2	1.4
8812	Lattice effects and diffusion	6	4.1
8813	Luminescence	3	2.0
8814	Optical properties	9.5	6.5
8815	Para- and diamagnetism phenomena	8	5.4
8816	Photoconductivity and related phenomena	5	3.4
8817	Photoelectric phenomena	1	0.7
8818	Piezo and ferro-electricity	3	2.0
8819	Quantum mechanics of solids	7	4.8
8820	Radiation damage	5	3.4
8821	Resonance phenomena	10	6.8
8822	Semiconductors	25	19.0
8823	Superconductivity	7	4.8
8824	Surface structure and kinetics	–	–
8825	Thermal conduction in solid state	3	2.0
8826	Thin films	6	4.1
8809	Other (specify)	9	6.1
	Totals	147	100.0

[1] Numbers refer to those used in the specialties list for the Vogt Report, loc. cit.

[2] Fractional numbers arise because physicists who have indicated more than one area of specialization have been counted (fractionally) in each indicated area.

* Physics Survey and Outlook, loc. cit.

Table II.–AVERAGE ANNUAL SUPPORT PER SOLID STATE PHYSICIST.

Institution	Canada ($ Can.)	US ($US)
Universities		
Total federal and provincial grants (1966)	8,500	–
Direct university contribution	2,000	–
Indirect university contribution	8,500	–
Total research support	19,000	36,000
Government laboratories	43,000	83,000
Industrial laboratories	37,000	57,000

An estimate of the average annual level of support in government laboratories may be obtained by dividing the NRC operating budget for 1965-66 ($30 million) by the total number of professional staff (approximately 700); this yields $43,000 per scientist per annum. This figure is not directly interpretable as the level of solid state physics support, but it has not proved possible to extract more specific information in a reliable fashion from the present study. The equivalent US figure is $83,000 per scientist per year.[1]

The present level of research support in industry was estimated from data supplied to us by 12 industrial solid state groups. The average level of support per scientist per year is approximately $37,000. In many cases, a large portion of this support comes from government research grants (these are discussed in Section 9.11). The corresponding US figure is $57,000.[1]

The above figures indicate a large discrepancy between the Canadian and US support levels in each of the three types of laboratories. This discrepancy becomes even larger when one takes into account the higher efficiency of the large US laboratories, which is attained through more effective use of expensive backup facilities. Finally, there is the exchange rate for the Canadian dollar, which constitutes a further disadvantage to Canadian scientists. In all, present support of solid state research must at least double in each of the three types of laboratories before it can be considered adequate by US standards.

[1] Physics Survey and Outlook, loc. cit.

9.4 NUMBER OF PH.D.'S GRANTED

The Vogt Report identified 27 solid state Ph.D. students at Canadian universities who expected to graduate in 1965. This number represents 13% of all Ph.D. students in this category. Briefs submitted by Canadian universities during the course of the present study indicate that 30 Ph.D. students graduated in 1966. Several universities have mentioned that their solid state programs are undergoing rapid expansion, and it is estimated that 40 Ph.D. students in solid state physics will graduate, beginning in 1968. A similar increase may be inferred from the Vogt Report. These data are summarized in Table III.

Table III.–NUMBER OF Ph.D's GRADUATED IN SOLID STATE PHYSICS.

Year	Total physics	Solid state physics	% Solid State physics
1965[1]	207 (735)	27 (199)	13 (27)
1966[2]	–	30	–
1968[3]	–	40	–

[1] Based on Vogt Report (loc. cit.). Numbers in parentheses are US figures for 1962 and were taken from the Pake Report (loc. cit.).

[2] Based on present study.

[3] Projection based on present study.

9.5 DISTRIBUTION OF MANPOWER AMONG INDUSTRIAL, UNIVERSITY, AND GOVERNMENT LABORATORIES

There are really two aspects to the complex question of the proper distribution of manpower, namely:

(1) the question of a proper balance between the efforts of industry, government, and the universities, and

(2) the question of an effective distribution of activities among each of the three types of laboratories, particularly among the universities and government laboratories.

Obviously, an attempt to answer the first of these questions depends on one's views as to the role of research in university, industrial, and government laboratories. Before attempting to provide at least a partial answer to the above questions, we shall for this reason set forth our views regarding the function of research in each type of laboratory.

(i) Research in university laboratories

Universities are educational institutions and research at a university inevitably has the education and training of students as one of its primary objectives. This does not mean, of course, that there are no technological implications to university research. However, these implications have traditionally been long-term rather than short-term; in fact, the university is the ideal place for long-term research since it is the kind of activity that flourishes best in an atmosphere free from the financial pressures of industry. The distinction between research projects with long or short-term technological implications is one that is easily made in many areas of physics. In solid state physics, however, the distinction is less useful, since it is often only a matter of three to six years before a new concept or discovery in this area is used in a commercial product. It is perfectly reasonable, and indeed desirable, that some university research have immediate technological implications. Some university research should therefore be *applied*, but the university *approach* should always be *fundamental* and should not be directed towards device production. Once an area of research ceases to be of fundamental interest, it should not be pursued further in university research laboratories. Some fundamental research should, of course, also be pursued in the larger and more enlightened industrial laboratories, presenting ideally a smooth transition between the two types of research. We feel that this situation is perfectly proper and will result in effective liaison between university and industrial laboratories.

(ii) Research in industry

The primary function of research in industry is obviously to support the products of the company. Such research is therefore oriented towards the development of a marketable device or a commercially usable process and this goal is normally a short-term one. If a company is sufficiently large, it should also support research of a more fundamental nature in fields that are likely to lead to new applications. Such fundamental research programs are necessary to keep the company informed of the latest developments in the field, and to facilitate the hiring of new staff from the universities. The latter benefit is one that has been exploited to great advantage by many US industries but that has not yet received wide recognition in Canada.

(iii) Research in government laboratories

The primary function of government research laboratories (federal and provincial) is to provide a comprehensive reference of standards and technical information for matters of national or regional importance. This definition of the function of government laboratories does not imply that they are merely reference libraries. Indeed, if the above task is to be done well, it will require that government laboratories engage active research groups in each area of national interest, and that these groups be of a size appropriate to the task expected of them.

In addition to the primary function defined above, government laboratories should support national defence and should be concerned with large-scale, long-range research related to major national objectives. An example of the latter kind of activity is the crystal dynamics and lattice vibrations program at AECL. This work resulted from the availability of neutron beams at the NRX and NRU reactors, and has contributed significantly to Canada's reputation in solid state physics.

(iv) Distribution of manpower among industry, government and universities

The distribution of manpower in solid state physics is shown in Table IV. A glance at the figures in this table will suffice to indicate the weakness of the effort of Canadian industry. In the US, 55% of all Ph.D.'s in solid state physics are employed in industry; in Canada the corresponding number is 18%, despite recent attempts by the Canadian government to promote industrial research. The prospects for Canadian technology will not improve unless this figure can be altered significantly.

Table IV. – DISTRIBUTION OF MANPOWER IN SOLID STATE PHYSICS[1]

	Total Manpower		Ph.D. Manpower	
	Number	Percentage	Number	Percentage
Universities	75	51	35[2]	48 (34)
Industry	43	29	13	18 (55)
Government	29	20	25	34 (11)
Combined	147	100	73	100 (100)

[1] Based on the Vogt Report (loc. cit.); figures in parentheses in last column are for the US and are taken from the Pake Report (loc. cit.)

[2] See text.

(v) Distribution of activity among the universities

A total of 22 briefs were submitted to the present committee by solid state groups at universities. The average group consists of 5 staff members, most of whom have Ph.D. degrees. The present study, therefore, identifies about 100 Ph.D. solid state physicists at the universities. This is many more than the 35 Ph.D.'s identified by the Vogt Report[1] in 1965 (see Table IV). The discrepancy is in part due to the rapid expansion of this field in the universities. However, most of the difference arises from the difficulty of identifying a solid state physicist in a questionnaire such as that used in the Vogt Report because of the overlap with many other specialities. Examples of overlapping specialities are: electromagnetism (code 82), which included magnetism and quantum electronics; atomic and molecular physics (code 81), which included magnetic resonance; optics (code 86), which included lasers; and thermal physics (code 8B), which included low temperature physics. In the submission made to the present committee, the universities chose to include such activities as part of their effort in solid state physics. In view of the difficulty of obtaining a universally acceptable definition of the field extreme care must be taken in the interpretation of statistical information. Nevertheless, we feel justified in drawing some general conclusions regarding the distribution of activity in solid state physics.

The average size of solid state groups in Canada is too small. It is true that some projects in this area of endeavor can still be mounted by small groups of scientists working in comparative isolation. However, research at the forefront of the field often requires careful sample preparation and sample evaluation facilities. Thus a typical experiment may require crystal growing facilities such as vacuum furnaces and radio-frequency generators, sample evaluation facilities such as X-ray diffraction apparatus, mass spectrometers, spin resonance apparatus, infrared spectrometers, low temperature apparatus, electron microscopes, and a host of other sophisticated and expensive physical, chemical, and metallurgical apparatus. Modern solid state physics has, in fact, evolved into materials science.

It is obvious that the elaborate equipment required cannot be justified for small research groups consisting of half a dozen scientists working part time on their research projects. It is equally obvious that all of the existing solid state groups cannot and should not grow into

[1] The Vogt Report gives 35 Ph.D.'s if one takes the replies that listed solid state physics (code number 88) as the main speciality in question 15, that listed the type of employment as university or college (code number 18) in question 10, and that listed the highest degree as Ph.D. (code number 3) in question 7.

large-scale research centers. Nevertheless, solid state physics in Canada can evolve in a satisfactory fashion only if a number of such research centers are established and receive adequate operating support.

The requirement of expensive backup facilities is not the only factor that dictates the establishment of large centers of research. A research effort generally becomes more productive when a scientific group exceeds a certain critical size. In such a group the output can be considerably greater than the output of the same people working in isolation. This critical number theory of solid state research is widely accepted throughout Canada and has also been discussed in the US context in the Pake Report.[1] The latter report suggests that the critical size lies somewhere between 7 and 10 scientists at or above the assistant professor level, plus a comparable number of research staff. The report further suggests that the basic group should contain 2 or 3 theorists and 5 to 8 experimentalists. In Canada, where the number of non-teaching research staff has been traditionally much smaller than in the US, the size of the basic group will need to be increased. It is suggested that the critical size is reached when a group contains 9 to 12 scientists at or above the assistant professor level. Twenty-five to thirty percent of these scientists should be theoreticians. In addition to graduate students, such a group should normally contain 4 to 6 post-doctorate fellows and 2 or 3 full-time research technicians.

(vi) Distribution of activity among the government laboratories

Ten briefs were submitted to the present committee by solid state groups in government laboratories. Generally speaking, the government effort in solid state physics is far too fragmented, the various groups are too small, and liaison between them is too infrequent. In some cases, the size and prestige of groups has steadily declined during the last few years, to a point where national objectives cannot possibly be met.

It has been suggested on a number of occasions that the various solid state groups now existing in federal government laboratories be united in a single materials research institute. This proposal seems to us to have a good deal of merit, and should be considered seriously, in spite of the formidable administrative obstacles that will be encountered in amalgamating the different branches of government activity. It is suggested that such an institute focus its attention on materials research, particularly on the properties of metals and their alloys. A comprehensive study of such materials is obviously closely related to

[1] Physics Survey and Outlook, loc. cit.

Canada's mineral wealth and is the first step toward the proper and complete exploitation of our natural resources. The size of such an institute might well be comparable to that of AECL. Indeed, if our resources of uranium were ample justification for the latter effort, surely our resources of over 20 other metals are adequate justification for the former.

It is obvious that Canada cannot aspire to be best in every branch of science and technology. It is our view, however, that such an aspiration is perfectly proper in the area of materials science and this aim should be the primary goal of the proposed federal institute. As secondary goals, such a facility should:

1. provide sample preparation and evaluation facilities for research groups in industries and universities that are too small to have these facilities themselves.
2. provide for the frequent exchange of personnel with industry and university groups in order to bring about an exchange of ideas.
3. provide a large pool of capable scientific personnel who would be available for consultation in connection with the evaluation of proposed research and development projects submitted by outside groups.
4. encourage the development of new technological products comparable to the development of reactors by AECL. An example of a possible activity of this sort might be the development of a 1 MeV electron microscope.

(vii) Distribution of activity among industrial laboratories

A total of 12 briefs were submitted to the present committee by solid state groups in industrial laboratories. The present size of the industrial effort is much too small and is often too closely related to production. If Canada is to reap the full benefits of the impact of advanced technology on productivity and growth, its performance in industrial research must improve drastically. It is estimated that Canadian industry reinvests about ½% per dollar of sales in research. Britain spends 3 times, Sweden 4 times, the US 6 times this amount.

The basic factors that prevent the rapid growth of research in industry are not the quality of research personnel in industry nor the shortage of graduates from the universities. The trouble lies partly with senior management in industry, which has little or no conception of the value of research. What is required here is a management training program similar to programs in the US. In this context, it has been estimated that the impact of the Harvard School of Business Management on US science has been at least as great as that of the Massachusetts Institute of Technology. A further difficulty arises from the foreign ownership of much of Canadian industry. Canadian subsidiaries of foreign companies *do* support research; however, most of this research is done outside of Canada. A subsidiary that wishes to support research in Canada must normally use funds over and above those that go to the parent company and are used to support laboratories outside Canada. It is unlikely that this difficulty can be resolved without legislative action.

At present there exists a vast gulf between university research on the one hand and industrial research on the other. If some of our best university graduates are to be attracted into Canadian industrial research laboratories, this gap must be narrowed – not by beginning development work in the universities, but rather by industry engaging in a modest amount of pure research. Such research in industry is justified because it increases the interaction with the university and government laboratories, because it helps the company to stay abreast of the latest developments, and because it opens the doors to a supply of first-rate manpower that cannot be tapped in any other fashion.

9.6 UNANSWERED QUESTIONS IN SOLID STATE PHYSICS

Solid state physics is the study of materials. The range of phenomena and properties investigated by physicists in this field is so wide that it is not possible to list a small number of major questions that dominate present investigations. Indeed, it has become characteristic of solid state research that unforeseen effects are discovered regularly. These discoveries have contributed to our understanding of solids and have led to new technological developments. We shall list a number of specific examples in Section 9.8. In this section we shall list those areas of solid state research in which a major amount of activity is anticipated, either because of the availability of new tools or because of increased theoretical or technological interest.

(i) Solid and liquid state spectroscopy

New laser techniques permit the study of elementary exicitations via their interaction with light (inelastic light scattering). These experiments will complement similar experiments with neutrons (inelastic neutron scattering).

(ii) Critical point phenomena

Light scattering techniques similar to those used in (i) yield information about the nature of phase transitions.

(iii) Ultralow temperature experiments

New techniques for the attainment of ultralow temperatures will permit the extension of many measurements to lower temperatures.

(iv) Size effects in metals

The attainment of very pure single crystals of certain metals has resulted in electron mean free paths of macroscopic dimensions (approximately 1 cm). This allows investigation of a large number of size effects, which yield information about the Fermi surface.

(v) Superconductivity

Most of the activity will be in the area of type II superconductors, whose properties are still imperfectly understood, and in the area of weakly coupled superconductors (Josephson junctions).

(vi) Transition metals and compounds

Emphasis will be on magnetic materials and on materials displaying interesting electrical properties (e.g. metal-semiconductor phase transitions).

(vii) Nonlinear optics

The availability of high power lasers will permit the systematic study of a variety of nonlinear optical effects.

(viii) Ultrasonic phenomena

Ultrasonic measurements of all sorts will receive an impetus from the experiments under (i). Ultrasonic amplification studies and phonon maser experiments will increase our understanding of the electron-phonon interaction and of phonon drag.

(ix) Thin film and surface studies

Emphasis will be on crystalline layer structures and on highly crystalline films. Device possibilities will give this field the needed impetus. Emphasis should be on fundamental studies, particularly theoretical work.

(x) Experiments in large magnetic fields

The ready availability of large magnetic fields from superconducting solenoids will give impetus to galvanomagnetic studies and Fermi surface studies.

(xi) Optical properties of solids

The increasing technological importance of electroluminescent displays will encourage further work in this field, particularly in the area of recombination phenomena.

(xii) Defects in solids

High voltage electron microscopes will yield new information about crystal structure.

The above list is undoubtedly incomplete and will require frequent modification as new and unanticipated phenomena appear. It is these that make solid state physics one of the most exciting branches of science.

9.7 QUESTIONS BEING ANSWERED BY CANADIAN PHYSICISTS

It is beyond the scope of this survey to give even a brief description of each of the several hundred solid state research projects now under way in Canada. Detailed information of this sort is available in a number of government publications. Furthermore, we have already indicated in Section 9.6 that the situation cannot be described by saying that a small number of key questions justify and motivate solid state research. All of the topics listed in Section 9.6 are being pursued by one or more Canadian research groups. A further indication of the present distribution of Canadian solid state research may be obtained from Table I (see above). We shall therefore conclude this section by simply giving examples of a few very general questions, to which Canadians are helping to provide answers.

1. What is the ground state energy of a given (homogeneous) substance?
2. What is the nature of the elementary excitations in the substance?
3. What are the residual interactions between these excitations?
4. How do these excitations interact with external fields?
5. What is the nature of an isolated imperfection in the substance?

6. What is the nature of the interaction between elementary excitations and imperfections?
7. What fundamental factors determine the performance of a given solid state device?
8. How can these factors be optimized to improve device performance?

9.8 SIGNIFICANCE OF SOLID STATE PHYSICS

(i) Importance of solid state physics to other areas of science

Although solid state physics has made a number of conceptual contributions to other areas of science, its main contributions have been technological. The following is a partial list of examples.

Nuclear physics

The theory of superconductivity has been applied to nuclei to account for certain energy gaps in the excitation spectra. Resonance techniques have been used to measure magnetic dipole moments and electric quadrupole moments. Mössbauer studies have been used to study nuclear decay schemes. Lithium drifted solid state detectors have revolutionized low energy nuclear spectroscopy.

Plasma physics

The theory of plasma excitations and electron screening has benefited greatly from related solid state theories. Characteristic plasma effects such as the pinch effect, helicons and Alfven waves have been confirmed in electronhole plasmas in semiconductors and semimetals. Superconducting magnets are being used to confine plasmas. Laser techniques are being used as diagnostic procedures to measure plasma temperatures.

Space physics

Solar cells are being used to energize electronic equipment in satellites and space probes. Solid state radiation monitors and lightweight miniature solid state instrumentation is essential in nearly all space research.

Radio astronomy

Travelling wave amplifiers are used at the inputs of radio telescopes.

Chemistry

The theory of diamagnetism has been applied to benzene ring structures. The theory of electric susceptibility is widely used to measure dipole moments. Vibrational and rotational spectra are used to identify structures. Crystal field theory is used to study inorganic complexes. Nuclear magnetic resonance and electron spin resonance techniques are widely used in physical chemistry. Lasers promise wide application in photochemistry and may allow efficient photochemical separation of isotopes. A wide variety of solid state instruments are used, particularly in physical and nuclear chemistry.

Biology

Semiconductor concepts have been used in theories of photosynthesis. Electron spin resonance techniques are used to study organic materials.

Medical science

Lasers have been used for reattaching detached retinas and for microsurgery. The hearing aid, the heart pacer, and the artificial larynx are all solid state devices, as are temperature sensors and pressure transducers. Fluoroscopes and oscilloscopes use solid state phosphors. Miniaturized solid state detectors are used in catheters.

Computer Science

All modem high-speed computers use solid state devices in their logic circuitry and in their memory and storage units.

The above list is far from complete. In addition to specific examples, such as those given above, solid state physics has greatly affected instrumentation in all branches of science and technology.

(ii) Importance of solid state physics to Canadian technology

It is in the area of technology that solid state physics has had its greatest impact. Much of this impact is the result of the development of the transistor. This and other semiconduction devices have revolutionized communication, instrumentation, and control. It has become a characteristic of this field of physics that a newly discovered effect is frequently transformed into a marketable device in five years or less. We give some recent examples.

Tunnel diodes

The discovery of electron tunneling in degenerately doped p-n junctions by Esaki resulted in the development of the tunnel diode, a high speed bistable element that can be used for logic or storage applications.

Gunn effect

The recent discovery of current instabilities in certain semiconductors by Gunn converts DC power directly and efficiently to microwave power. The device, presently in the development stage, may revolutionize microwave sources.

Ultrasonic amplifiers

The discovery of ultrasonic amplification in CdS by Hutson, McFee, and White provides a "booster" for ultrasonic delay lines. Recent further developments yield an extremely monochromatic source of ultrasonic waves.

Superconducting magnets

The discovery of hard superconductors has resulted in the development of high field magnets, and has placed such magnets within the range of any moderately large research group. Such magnets may revolutionize plasma research and high voltage electron microscopy.

Lasers

The wide range of lasers that are already available is expanding daily. These devices are now operating over a wide range of the electromagnetic spectrum and will find uses in many branches of science.

Solid state physics has become a pacesetter for modern technology. Canadian technology is already heavily dependent on new discoveries in this field of physics, although this dependence presently occurs largely through goods imported from the US. As our technology grows our dependence on the US will also grow unless Canadian solid state research, particularly industrial research, becomes an integral part of our plans for technological advancement. In this connection, we point out that the development of all of the aforementioned devices is within the range of Canadian capability, both technically and financially.

9.9 ADDITIONAL COMMENTS

In this section, we offer a number of additional comments that are not easily included in any of the foregoing sections.

(i) Tariff barriers

The key national characteristic determining the Canadian economy is the proximity of the US. At present goods manufactured in Canada do not flow freely into the US *and it is these trade barriers, more than any other factor, that have prevented the development of applied research in Canadian industry,* in spite of the considerable volume of Canadian "know-how". There are those who worry about the effects that any free trade agreement with the US would have on our national identity. It is our opinion that this fear is unfounded and that economic domination is more likely in a climate that prevents development of Canadian industry. If steps are not taken to assure the rapid growth of industrial research in Canada, the present imbalance in the Canadian research effort will become even larger in the future.

(ii) Communication problem in industry

The task of keeping up to date with the latest scientific advances, and with the most recent requirements of various contracting agencies, presents a tremendous problem for the industrial scientist, particularly if he is located at one of the smaller laboratories. The acquisition of pertinent information is completely beyond the capabilities of any small company and steps may soon have to be taken at a national level to ensure a more effective distribution of information.

(iii) Cooperation between different laboratories

It is perfectly clear that each of our laboratories cannot expect to have all of the facilities required for modern solid state research. In future years, the amount of interaction between different laboratories will have to increase greatly if our research programs are to be as effective as possible. Whereas it is true that cooperation has not been discouraged in the past, it is also true that it has not been effectively encouraged. For instance, most university scientists are not aware of the procedure to be followed in order to work at a government laboratory during the summer. They need to know what their position will be regarding use of equipment, technicians, workshops, parts, and supplies, etc. Such information should be widely circulated by government laboratories as well as by other institutions.

The granting agencies could also encourage cooperation through travel grants and through favorable consideration of inter-institutional research projects. It must be recognized that some personal inconvenience is nearly always involved in such inter-institutional projects and that such projects must be generously encouraged if they are to become more widespread.

(iv) Depletion of our natural resources

Canada is emerging from a period during which its wealth was largely derived from export of raw materials. During the next 25 years Canada must learn how to compete in world markets with economies that are far more advanced than our own. Many of our natural resources are being gradually depleted, and an alternate means of survival must be provided before this depletion is substantial. It appears to us to be perfectly reasonable to expect those industries that are depleting our resources to make a particularly heavy contribution to research, either by establishing major research centers of their own, or by contributing substantially to research programs in our university laboratories.

9.10 FUTURE REQUIREMENTS

(i) Manpower requirements for the next five years

Universities

The rate of growth of our universities has been traditionally determined by the rate of growth of the undergraduate student population, with the graduate student population being approximately 10% of the undergraduate enrolment. (In 1961–62, this percentage was 6.3% for the University of British Columbia, 10.7% for the University of Toronto, 6.6% for the University of Manitoba, 10.9% for McGill University, and 8.4% for Queen's University). We do not foresee a change in this pattern during the next five years and we shall therefore base our projections for the universities on the rate of growth of the student population.

For the period 1967 to 1972 it is estimated[1] that the student population of our universities will increase by about 50%. This increase is in part due to population growth and in part to the increasing percentage of students seeking higher education. The growth of solid state physics at our universities will be considerably greater than this, since much of the expected growth will occur in our younger universities where this kind of research is already favored. Furthermore, it must be remembered that a shortage of solid state physicists exists in our universities even today. We therefore estimate that the number of solid state physicists at Canadian universities will double

[1] J.B. Macdonald, Higher Education in British Columbia, University of British Columbia (1962).

by 1972. About 100 Ph.D.'s were identified in this category by the present survey and our average annual production of new Ph.D.'s over the next five years was estimated to be about 40. The universities themselves will therefore require about one half of the total output of new Ph.D.'s in this field.

Government laboratories

The estimated number of solid state physics Ph.D.'s in government laboratories is presently 25 to 35. The low level of solid state activity in these laboratories has been discussed elsewhere in this report. This activity should at least be doubled by 1972, and if a national materials science center is formed it should be tripled. The number of new Ph.D.'s required is thus between 30 and 60, or 6 to 12 per annum for five years.

Industrial laboratories

We have already indicated that the flow of Ph.D.'s from the universities to industry has been minimal in the past. In our opinion, it will remain so until industry takes a more enlightened attitude towards research. Canadian industry *ought* to be able to use the new Ph.D.'s produced by the universities. If the size of our industrial effort were to be in balance with that of the universities by 1972, there should be about 200 solid state Ph.D.'s working in industry by that time. This figure implies a rate of growth that in unrealistically high. Nevertheless, every effort should be made to secure a rate of growth of industry exceeding that of the universities; otherwise the present imbalance will become even more severe. The minimum acceptable expansion rate for industry is a tripling over a five-year period. This will require about 50 Ph.D.'s, or 10 Ph.D.'s per year for 5 years. In addition, industry will, of course, require a large number of new people with lower qualifications. We have not documented these additional needs here.

The above remarks make it clear that our universities will be training new Ph.D.'s in solid state physics in numbers that are marginally adequate for Canada's needs, if one assumes that our loss to the US is compensated by a corresponding gain from Europe. We have been unable to find reliable data that would prove or disprove this assumption.

(ii) Financial requirements for the next five years

In Table II we presented a summary of the present level of research support for the average solid state physicist in the university, government, and industrial laboratories. It is our view that these levels of support are inadequate and that they should immediately increase by 50% and then grow at a rate of 10% per annum for the next 4 years. The projected figures for 1967 to 1972, calculated in this fashion, are given in Table V.

Table V.–PROJECTED ANNUAL SUPPORT PER SOLID STATE PHYSICIST.

Institution	Year				
	'67-68	'68-69	'69-70	'70-71	'71-72
	(thousands of dollars)				
Universities					
Total federal and provincial grants	12.8	14.1	15.5	17.1	18.8
Direct university contribution	3	3.3	3.6	4.0	4.4
Indirect university contribution	12.8	14.1	15.5	17.1	18.8
Total research support	28.6	31.5	34.6	38.2	42.0
Government laboratories	64.5	71.0	78.1	85.9	94.5
Industrial laboratories	55.5	61.0	67.1	73.8	81.2

It should be mentioned that the projected rates in Table V imply a *total rate of increase* of research expenditures that is much greater because of the anticipated increase in manpower. This difficulty has consistently plagued Canadian scientists in all fields. Our rate of growth of manpower has been so large that available funds have not permitted an acceptable rate of growth in the support *per scientist*.

The projected rates in Table V will bring the level of support of Canadian solid state physicists in universities and government laboratories up to the 1965 US level by 1970-71, (see Table II). The rate will, however, close the gap in the support level for the two countries only slightly since an annual growth rate of *7% per scientist* is recommended for solid state physics in the US.[1]

(iii) Projection for 1972 to 1977

The rate of growth during this period will depend greatly on our accomplishments in the next five years. We foresee a reduced rate of growth of solid state physics in the universities and government laboratories and an increased rate of growth in industry.

[1] Physics Survey and Outlook, loc. cit.

9.11 GRANT SUPPORT MECHANISMS

(i) Industrial research and development programs

In recent years, the federal government has recognized the importance of science and technology to Canada's economy and has introduced a number of programs designed to stimulate research and development in Canadian industry. At present five such programs are in effect. One of these, GIRD (General Incentive for Research and Development) is incorporated in the Income Tax Act and allows for a benefit of 25% of all capital research expenditures as well as a benefit of 25% of the amount by which current research expenditures exceed the average for the preceding three years.

These allowances are in addition to the 100% tax deduction allowed for all research and development costs. The remaining four programs provide for direct financial assistance for research and development projects. These programs are the following:

1. Program for the Advancement of Industrial Technology
2. Industrial Research Assistance Program
3. Defense Industrial Research Program
4. Defense Export Program.

On the whole, Canadian industry has made good use of these programs and seems well satisfied with them. For instance, over 50 DIR contracts for solid state research and development were in force in July 1966. The committee recommends a continuance of all the above programs during the next five years. We feel, however, that the desired rate of expansion of industrial research will not be achieved unless other measures are also taken. Most of these have been discussed elsewhere in our report, but we summarize our recommendations below.

1. Some measures (legislative if necessary) to assure more research activity in Canadian subsidiaries of foreign-owned companies.
2. Some measures (legislative if necessary) to assure more research activity from industries that are depleting our natural resources.
3. An organized education program for Canadian industrial management.
4. Initiation of a new program for the support of *pure* research in industry.

5. More insistence that Canadian developments that are financed totally or partly with government funds include systems developed and produced in Canada.

(ii) University research programs

Some criticism of the present support mechanism was voiced by nearly all of the solid state groups that contributed to the present study. Most of the support for university solid state research comes from NRC and most of the criticism was directed at NRC policies. Our findings and recommendations are detailed below.

NRC operating grants

The major portion of support for solid state research is now provided through NRC operating grants, awarded to individual staff members. These awards are made through the vehicle of a selection committee, which may examine the several hundred applications over a period of a few days. Emphasis is placed on the reputation of the applicant, the policy being to support the "good man". We agree that this criterion is a good one. However, much depends on the members of the selection committee, and, as the number of applications increases, there comes a point when the committee members cannot possibly know—even by reputation—every applicant in the broad category that the committee covers. Certainly the present system is unfair to the young scientist who tends to the dealt with on a formula basis, regardless of his ability.

We suggest that the number of selection committees dealing with solid state applications be increased in order to avoid "formula financing". Alternatively, consideration might be given to a referee system, in which each application is evaluated by three referees whose competence is in the applicant's field of research. Consideration should also be given to "initiation" grants for young scientists. The latter might, for instance, be handled through a grant to the department in which the scientist holds a position. An amount equal to 10% of the total departmental operating grant is suggested.

Major equipment grants

For a number of years NRC has recognized the need for large and expensive pieces of research equipment, through its major equipment grants program. If Canada is to reap the maximum possible benefit from solid state research in the universities, it is essential that a proper balance be achieved between operating and major equipment grants. Without adequate equipment, spending from operating grants will be ineffective, and elaborate facilities without proper operating support are equally wasteful. Up to the present there has been a scarcity of major equipment grants in solid state physics and it is recommended that the number of such grants be increased until the expenditures equal 2/3 of the operating grants. Consideration should also be given to allowing major equipment grants to be block grants. Many of the items in question will, in fact, be used by more than one person, and it is often artificial to submit the application over the signature of one scientist.

Major installation grants

Up to the present, there have been no major installation grants in solid state physics, and this fact has prevented the coherent development of many areas of this branch of physics at the universities. In the opinion of the committee, the time has now come to establish a number of large scale, solid state centers. The factors that dictate the establishment of such centers have already been discussed in Section 9.5.

It is suggested that such centers *not* be established on a "first-come first-served" basis. Instead, a national committee should be chosen to assess the suitability of prospective locations in order to ensure an orderly development. In this connection, we point out that such a center need not necessarily belong to a single university. Upon completion of its study, the committee might *invite* applications from potential host institutions. Care should be taken, however, that research in the laboratories be established on a broad base, rather than in one narrow specialty area. Solid state physics does not lend itself to such departmentalization and the basic facilities of one such center will be quite similar to those of another, although the research projects themselves may differ widely.

Postdoctorate fellowships

The present level of support for postdoctorate fellows seems to us to be inadequate. It should always be possible for a scientist to engage a postdoctorate fellow using funds from his operating grant—as indeed is the case at present. However, until the level of the operating grants is raised substantially, it is unrealistic to consider this provision to be a solution to the problem. It is suggested that each department be given a grant for support of postdoctorate fellows, based on a percentage (approximately 15%) of its total NRC grants.

Section 10

PLASMA PHYSICS

M.P. Bachynski (Chairman), S.A. Ramsden and H.M. Skarsgard

10.1 DEFINITION OF FIELD

A plasma can be defined as matter composed of a collection of free charged particles (there may be neutral particles as well) such that the net uncompensated charge is small compared to the charge of either sign, but whose properties are markedly affected by the presence of the free charged particles. The result is that a plasma exhibits strong collective behavior due to space charge effects, is a good electrical conductor, and can exhibit complicated dynamic behavior in the presence of electro-magnetic fields, both external and self-induced. These properties make a plasma intrinsically different from the other states of matter (solids, liquids, gases). The characteristics of a number of plasmas of importance are shown in Fig. I.

10.2 SIGNIFICANCE OF FIELD

Until recently the people most interested in plasmas were the astrophysicists. This is not surprising since more than 99.9% of the matter in the universe is comprised of plasma. Recent developments giving a strong impetus to plasma research were: (a) the possibility of generating energy by the fusion of nuclei of the light elements, and (b) the capability of propelling vehicles at high velocities and into outer space. The current motivations for plasma research are:

(i) Space exploration
(ii) Thermonuclear fusion
(iii) Electrical generation and propulsion techniques
(iv) Defence associated with re-entry phenomena
(v) Plasma devices
(vi) Knowledge of the structure of matter

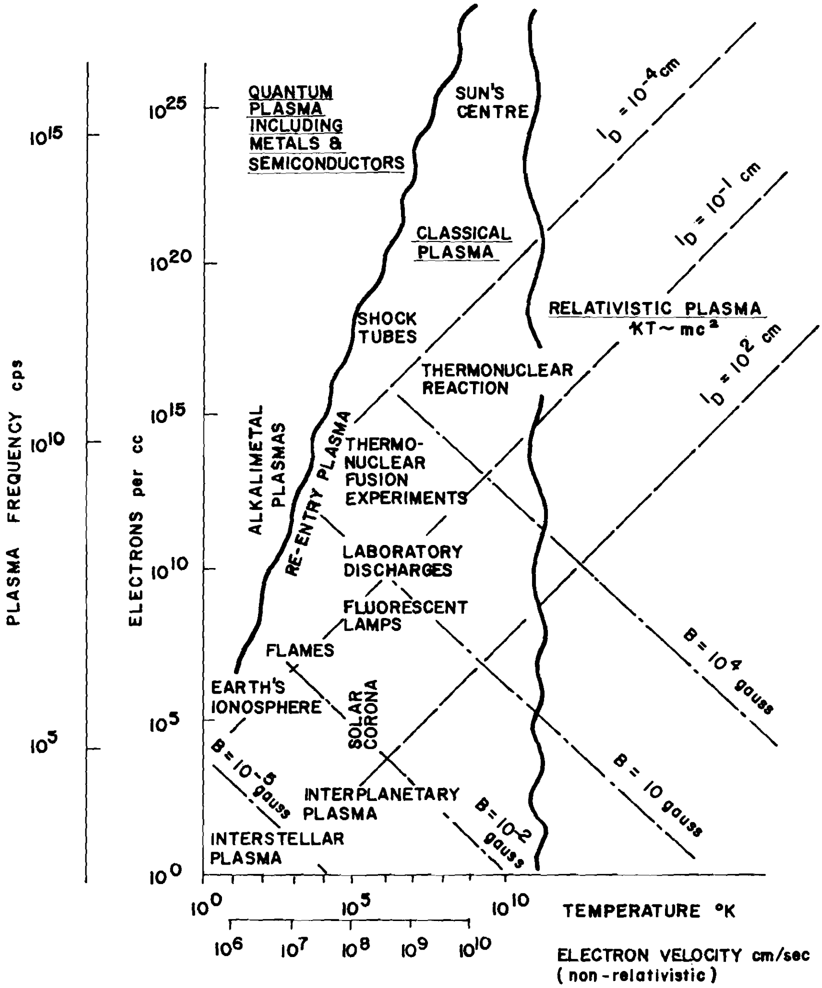

Fig. I Regions of interest in plasma physics. Regions can be conveniently delineated on a plot of electron density versus temperature (or equivalently, plasma frequency versus electron velocity). The figure illustrates the large number of rather distinct physical phenomena encompassed by the field of plasma physics.

10.3 SCOPE OF THIS SURVEY

The intention of the plasma physics survey is to include research being conducted in Canada on fundamental plasma physics, plasma theory, plasma diagnostics, high temperature plasmas, space and geophysical plasma phenomena studied in the laboratory, applied plasma physics, magnetohydrodynamics, aerodynamic plasmas, etc.

Associated fields closely allied to plasma physics, such as astrophysics, ionospheric physics, solid state plasmas, and certain phenomena related to hypervelocity flow are not included specifically. These are to be found in the reports of other subdivisions in this survey.

10.4 HISTORY OF PLASMA PHYSICS IN CANADA

An approximate chronology of plasma physics research in Canada is as follows:

Year	*Organization*	*Interests*
1958	CARDE	Ballistic missile defence
1958	RCA Victor	electromagnetic wave-plasma interaction
1959	Univ. of Saskatchewan	hot plasmas
1959	Univ. of Toronto (UTIAS)	high speed aerodynamics
1960	Univ. of British Columbia	pinch plasmas
1961	NRC/Mech.Eng.	high speed aerodynamics
1962	NRC/Pure Physics	laser studies of plasmas
1963 ↓ present	Several universities and AECL	chiefly arising from training with above groups as either former staff members or students.

10.5 CURRENT ACTIVITY IN CANADA (1966)

Institute	Division or Department	Year plasma activity started	Staff (1966) Profes-sionals	PdF	Techni-cians
Universities[1] – A					
Alberta	Elect. Eng.	1965	2	1	2
British Columbia	Physics	1960	6	1	2
Montreal	Physics	1963	4	1	3
Saskatchewan	Physics	1959	2	1	1
Toronto	Aerospace	1959	3	2	3
York	Space Sciences	1966	2	3	0
			19	9	11
Universities[1] – B					
British Columbia	Elect. Eng.	1964	1	0	1
Carleton	Engineering	1964	1	0	0
Lakehead	Physics	1966	1	0	0
Manitoba	Elect. Eng.	1966	1	0	0
Toronto	Elect. Eng.	1960	2	0	0
Toronto	Mech. Eng..	1962	1	0	1
Trent	Physics	1966	1	0	0
Western Ontario	Physics	1963	1	0	0
Western Ontario	Mathematics	1960	2	0	0
Windsor	Mathematics	1965	1	0	0
			12	0	2
Government					
AECL	Applid Physics	1964	1	0	1
CARDE	Aerophysics	1958	3	0	4
NRC	Mech. Eng.	1961	4	0	3
NRC	Pure Physics	1962	2	4	6
			10	4	14
Industry					
RCA Victor	Research	1958	15	0	5

[1] Universities – A have staff greater than 2; universities – B have staff of 2 or less.

The trend to do work in plasma physics has arisen in two ways:

A. Interest of individuals in plasma physics, e.g. RCA Victor, Univ. of Saskatchewan.

B. Technology had progressed so as to achieve conditions where plasma phenomena had to be contended with e.g. CARDE, NRC/Mech. Eng., UTIAS, AECL, etc.

10.6 STUDENT TRAINING AND MANPOWER

A. Graduates and students

Graduates:	1962 to 1966 –	M.Sc.[1]	43
		Ph.D.	27
	1966 –	M.Sc.[1]	17
		Ph.D.	10

Graduate Students:	1966–	Physics	43
		Applied Sciences	22
			65
	1971[2]–	Physics	72
		Applied Sciences	41
			113

This amounts to 20 to 30 graduates annually. Considering the loss to the United States, there would seem to be no problem placing these numbers of graduates in university, government, and industrial positions in Canada in the next few years.

B. Manpower obtained from and lost to other countries

Staff obtained	UK	20
	Other	14
	US	2
		36
Staff lost	UK	5
	Other	2
	US	27
		34

[1] A number of the MSc. students proceed to their Ph.D.

[2] A linear, projected increase from 1966 - 1971 probable gives a reasonably estimate of the lower limit.

(i) It appears that loss to the US is approximately equal to gain from the UK and other countries.

(ii) Although statistics on graduate students are poor it appears that approximately 40% go to the US.

10.7 SCIENTIFIC PROGRAMS AND PROGRESS

A. Publications in recognized journals

Institute	1960	'61	'62	'63	'64	'65	'66
Universities	–	5	8	22	4	16	9
Government[1]	–	–	1	–	5	4	6
Industry[1]	4	9	8	11	14	12	11
Total	4	14	17	33	23	32	26

B. Scientific programs

A number of very diverse projects exist including the following general areas[2]:

(i) Theoretical plasma physics
(ii) Laboratory studies of space and geophysical plasmas
(iii) Optical and spectroscopic studies of plasmas
(iv) Ionization phenomena in gases
(v) High temperature plasmas
(vi) Ionized gas dynamics

C. Short summary of the Canadian achievements and scientific programs in plasma physics

(i) Theoretical plasma physics

In basic plasma theory the derivation of kinetic equations from the Liouville equation and analyses based on the derived equations has been considered by a number of groups, notably at the Universities of British Columbia. New Brunswick, Carleton, and Toronto (UTIAS). Important contributions were also made by a now defunct theoretical physics group at NRC.

[1] does not include classified reports.

[2] see "Report on Plasma Physics in Canada" NRC Associate Committee on Plasma Physics (1966).

Calculations of plasma transport co-efficients have been made at the RCA Victor Research Laboratories in Montreal, extending the existing analyses to a state of considerable generality. The basis of this work is formed by the Boltzmann and Fokker-Planck equations. Researchers at RCA Victor, NRC, and Carleton University have considered plasma kinetic theory from the standpoint of the collisionless (Vlasov) model.

Waves and oscillations in plasma have been studied at RCA Victor from the point of view of kinetic theory. The influence of negative ions on wave propagation has been investigated at the University of Montreal; NRC workers have considered boundary effects, and DRB scientists have been concerned with plasma cavities and the resonances resulting therefrom. Instabilities resulting in wave growth and runaway electrons have been examined at RCA Victor and the University of Saskatchewan. Wave-wave interactions have been considered at the University of Alberta.

Wave scattering and fluctuations have been the subject of investigation at RCA Victor, the University of Toronto, DRB, and other laboratories. Radiation from antennas immersed in plasma has been studied in a significant way at NRC and at the University of Toronto.

The theoretical basis of continuum plasma flow (magnetohydrodynamics) has received some attention at the UTIAS with an eye on possible applications to power generation. The gross motion of plasmas in thermonuclear machines has been considered at the University of British Columbia, while the Applied Mathematics Department at the University of Western Ontario has dealt with the hydromagnetics of interfaces. (Within the context of basic plasma theory should be mentioned the work on solid state plasma at McGill University, University of Toronto, and RCA Victor).

In the theoretical work related to specific applications, mention should be made of the adaptation of the analysis of plasma transport theory made at RCA Victor to special gases and its verification. This work, carried out at NRC, will be referred to elsewhere. Much of the work on plasma theory adapted to applications has had its origin in magnetospheric and ionospheric studies generated by the noteworthy Canadian effort in rocket and satellite physics. DRB, RCA Victor, and various universities have been particularly active in this field. In connection with a number of experimental projects, the theory pertaining to diagnostic methods of plasma studies has been actively pursued at RCA Victor, NRC, and the universities of Montreal, Toronto, and British Columbia. Much attention has been devoted to Langmuir and conductivity probes. spectroscopy and laser methods.

(ii) Laboratory studies of space and geophysical plasmas

A significant amount of laboratory plasma research related to space and geophysical applications is being conducted in Canada, principally at the RCA Victor Laboratories, as well as at the Institute of Aerospace Studies and at the University of Western Ontario.

In an effort to get a better understanding of some of the phenomena involved and to account for the observations made both by space-craft and from the earth, resort has been made to laboratory experiments based on scaled models.

Some of the phenomena under investigation and the significant findings includes:

(a) Interaction of the solar wind with the magnetosphere where the magnetospheric boundary position and thickness have been studied in detail. Considerable information on plasma-magnetic field dynamic interaction, plasma trapping, east-west asymmetries, and hydromagnetic wave perturbations in the magnetospheric cavity has been obtained.

(b) Lunar-magnetosphere configuration showing a very extensive wake with magnetic field reversals and redistribution of magnetic field.

(c) Measurements of wave propagation in anisotropic plasmas for both circularly polarized and linearly polarized waves, which show excellent agreement with plasma theory.

(d) Sheaths surrounding space vehicles showing the nature and extent of sheaths surrounding ionospheric satellites, their control and influence on measurement instrumentation.

(e) The interaction of neutral and ion beams with the surface of space vehicles.

(f) The introduction of spurious signals into the circuits of Alouette I satellite by local plasma phenomena.

(iii) Optical and spectroscopic studies of plasmas

Although much of the subject matter of this section may be considered "diagnostics" in a wider sense, its importance in plasma studies merits special consideration. The University of Western Ontario and, more recently, the Centre for Research in Experimental

Space Science (York University) are engaged on a continuing basis in producing identification atlases, intensity measurements, and transition probabilities for a variety of elements, some under conditions of high ionization. The University of British Columbia is particularly active in the field of spectroscopic plasma diagnostics; line intensity measurements in short-lived plasmas were carried out and the decay of hydrogen plasma studied. In addition to the state of the plasma, its motion and velocity have been measured using Doppler shift techniques. At UTIAS, rotational temperatures of gases are being examined by means of electron beam-excited fluorescence. The RCA Victor Laboratories are engaged in emission spectroscopic exploration of gaseous afterglow.

A research group at NRC is actively engaged in the application of lasers to plasma physics. Lasers are being used as sources in the study of incoherent scattering and Faraday rotation in plasmas. Lasers are also being used to create plasmas directly by radiation breakdown, and theoretical and experiment work on radiation-supported shock waves is being pursued. Workers at the University of Western Ontario were engaged in the application of pulsed laser radiation to powdered solids with a view to obtaining spectroscopic data therefrom.

(iv) Ionization phenomena in gases

There is considerable overlap between this and the first section of this summary. Here, however, the emphasis is on experimental work. Workers at the universities of Montreal, Toronto, Saskatchewan, and British Columbia are active in the field of collision studies and the measurement of fundamental parameters such as Townsend coefficients, etc. Transport processes and the electrical conductivity of ionized gases are being measured at NRC, while diffusion coefficients are being investigated by researchers at the University of Saskatchewan. Much laboratory work on electromagnetic wave transmission through plasmas has been carried out at RCA Victor and at DRB. In addition to the optical and spectroscopic work on diagnostic techniques mentioned above, studies of microwave diagnostics have been carried out principally at RCA Victor but also at the University of British Columbia. Conductivity, Langmuir, and orbit analyzer probes are being investigated at NRC, UTIAS, and the Universities of Montreal and Saskatchewan.

(v) High temperature plasmas relating to thermonuclear research

Thermonuclear fusion research, in the sense of building reactors with a view to obtaining self-sustained fusion, is not carried out in this country. However, fusion-type machines are in operation that are capable of generating plasma in the range of temperatures and densities (though not of duration) that adequately represent thermonuclear conditions. Pinch machines are in operation at NRC, the University of British Columbia, and UTIAS, and are being used either as plasma sources for diagnostic studies or with a view to investigating instabilities. At NRC, light scattering and Faraday rotation measurements are being carried out, while at the University of British Columbia "flip" instabilities and those associated with the Rayleigh-Taylor and interchange mechanisms are under investigation. The relaxation length for ionization in a particular type of pinch machine is being studied at UTIAS.

(vi) Ionized gas dynamics

Plasma generated by hypersonic flight is of particular interest from the point of view of missile and satellite telemetry. Simulation of such conditions in hyper-velocity ranges and microwave measurements in such experiments is being carried out at CARDE.

The generation of ionized gases in shock tubes is being investigated at NRC, using conventional driving techniques, while UTIAS and the University of British Columbia are engaged in the study of electromagnetic shock tubes. Magnetohydrodynamic flows in boundary layers, heat transfer, and shock stand-off distance, are also under investigation at UTIAS. Some experiments on magnetohydrodynamic power generation are also being prepared at UTIAS.

Summary

It will be seen from the foregoing that the Canadian effort in plasma physics is spread over a wide spectrum and over a large number of individual research groups. The number of research subjects seems numerous but the effort in each is meagre, except for few noteworthy exceptions. There are noticeable gaps in the field in which the effort is either nonexistent or very small. Two examples are thermonuclear research and magnetohydrodynamic power generation.

D. Significant contributions

In spite of the fact that the effort is most areas is rather meagre, significant contributions have been made in a limited number of areas such as:

(i) Laser-plasma interaction
(ii) Photographic and spectroscopic studies of plasmas

(iii) Runaway electron streams
(iv) Plasma diagnostics
(v) Electromagnetic wave-plasma interaction
(vi) Theory of plasma transport phenomena
(vii) Simulation of geophysical plasma phenomena
(viii) Re-entry plasmas
(ix) Theory of cyclotron harmonic phenomena in the ionosphere.

In particular, the Canadian groups have established an international reputation in laser scattering from plasmas and in laboratory simulation of space and geophysical phenomena.

10.8 FINANCIAL SUPPORT (1966)

A. Universities

Total support[1]:

$597,000 of which 3.5% in universites–B
96.5% in universities–A

10.8% from US sources
89.2% from Canadian sources

50.5% in physics departments
49.5% in applied sciences departments

B. Government

Total support: $473,000

5.3% from US sources
94.7% from Canadian sources

C. Industry

Total support: $360,000

50% from US sources
50% from Canadian sources

The financial statistics also show that:

(i) The average cost per full-time, producing, professional researcher is approximately the same whether he is in a university, government, or industrial laboratory.

[1] does not include university provision of laboratory space, services, professors' salaries, or scholarships and bursaries of any kind.

(ii) The average support is about $30,000 per professional. This should be compared with the US where the Pake report quotes $100,000 per Ph.D. This emphasizes the fact that *no major facilities exist for any of the research groups in plasma physics in Canada and the groups on the average are undersupported.*

(iii) About 20% of the financial support comes from the US. This is heavily concentrated in industries that are equally dependent on US and Canadian sources.

(iv) The US financial support is usually let on the basis of 12-month contracts resulting from unsolicited proposals or from competitive bids.

(v) The universities depend primarily on yearly Canadian government (NRC, DRB, AECL) grants.

(vi) Industrial external support is almost entirely based on 1-year contracts (both US and Canadian).

A summary comparison of financial support for plasma physics between Canada and the US (as reported in the Pake Report)[1] is as follows:

	Canada (1966)		US (1963)	
Institute	Amount (thousands of dollars)	%	Amount (thousands of dollars)	%
Universities	597	42	12,900	14
Government	473	33	34,800	37
Industry	360	25	45,800[1]	49
Total	1,430	100	93,500	100

The Canadian effort in plasma physics amounts to 1.5% of that of the US (including the funds obtained from the US).

10.9 IMPORTANCE TO CANADIAN SCIENCE AND TECHNOLOGY

(i) The fourth state of matter

Plasmas comprise a fourth, and as yet relatively unknown, state of matter which there is no reason to believe will be less important than the gas, liquid, or solid state. The plasma state

[1] 78% is paid for directly by the US government.

encompasses a wide range of phenomena and is closely associated with other fields such as solid state, spectroscopy, atomic and molecular physics, space and astrophysics, etc. If science is to be pursued seriously in Canada a proportionate effort needs to be devoted to the physics of the plasma state.

(ii) Space phenomena

With the exception of planetary bodies and their immediate vicinity, most of the universe is composed of plasma. Thus, virtually any exploration of space becomes involved in plasma physics. Even where ground studies are made, the observations are often of phenomena associated with plasma interactions. Canada has a well-earned reputation in the areas of ionospheric and auroral studies and may be expected to remain a leader in these fields. In addition, the satellites Alouette I and II have given Canada an enviable lead in topside ionospheric work, which (it is to be hoped) will continue through and beyond the ISIS series of satellites.

The interactions between a spacecraft or other projectile and the space plasma is another area of plasma physics. In this area research can extend beyond the scientific measurements themselves and into the vehicle operations, thus influencing the engineering designs. Plasma physics also intrudes into the aerodynamic area in analysis of vehicle re-entry phenomena including such aspects as wake and communications problems.

Much of the plasma physics support function for space exploration can be done in the laboratory – studying interactions and electromagnetic propagation phenomena, evolving plasma diagnostic techniques for space, etc. In general, if Canada undertakes any type of space exploration or anti-missile defence, be it through space or ground observations, plasma physics will be required to play an important part.

(iii) Power generation

The possibilities of thermonuclear fusion gave modern plasma physics its first impetus (maintained by space exploration) and undoubtedly thermonuclear fusion will ultimately give economical power generation. A number of other nations are investing heavily in fusion research (e.g. in 1963 the effort in the United Kingdom is reported as $8.4 million, France $6.0 million, West Germany $4.6 million, United States $23.7 million). With a strong plasma physics activity, Canada would be in a position to exploit rapidly any future breakthrough in power generation.

There are, of course, related areas, such as magnetohydrodynamic power generation, where the investment for research has not been so great and much work remains to be done to obtain the necessary knowledge and technology. The same is true for plasma and ion propulsion technology. In particular magnetohydrodynamics potentially provides a conversion link to fission power stations.

(iv) Plasma devices

Into this area of plasma physics fall a wide variety of activities, ranging from microwave devices (active and passive), plasma torches, ion sources, surgical tools, lasers, and many solid state devices. Here, too, the initial investment need not be great, yet much remains to be done.

(v) Plasma technology

Included here are the wide areas of technology that incorporate or use plasma phenomena, e.g. surface physics studies and plasma chemistry. From such investigations one may expect broad advances in the technology of processing and manufacturing.

10.10 SUMMARY AND RECOMMENDATIONS

The total expenditure on plasma physics research in Canada was of the order of 1.4 million dollars in 1966. This is 1.5% of that spent in the United States in 1963. (Even of this, 20% of the funds came from the US). The Canadian effort is thus operating at a "sub-critical" level, has no major facilities to speak of, and in addition is too diverse in scope to be particularly effective. Plasma physics in Canada exists primarily by virtue of the efforts of a few isolated individuals, and currently stands in grave danger of losing its key people to other countries.

On the more positive side, nuclei for a number of effective plasma physics research groups do exist in Canada, and in some limited areas these have even earned an international reputation.

On the basis of the findings summarized in this report the following recommendations are made:

1. Support level in next five years

Considering the importance of plasma physics research to Canadian science and technology – the need for sophisticated plasma theory and laboratory experiments to aid space physics, astronomy, military plasma physics, power generation, plasma devices, etc., and the need to study the plasma state of matter for its own sake, coupled with the fact that each of the major technological nations is spending considerable sums in this area (for example, the United Kingdom $8.4 million, France $6 million, and West Germany $4.6 million on plasma fusion in 1963 alone) – a marked expansion of plasma physics research in Canada is deemed essential. In the next five years a three to fourfold increase of the Canadian effort resulting in an annual expenditure of $4 to 6 million is necessary to bring it up to an appropriate level.

This increase must come principally from the Canadian government since even in a highly technological and heavily industrialized nation such as the US the government pays for 85% of all plasma physics research, including 78% of that done in industry. Availability of manpower is not a problem at present. The effort is clearly "dollar-limited."

2. Establishment of viable groups

The first step urgently needing implementation is to stabilize and make viable the existing groups in Canada that possess the key people (or nuclei) for plasma physics research. Viability can be achieved only if the groups are comprised of at least 5 or 6 professional staff. The course of action recommended is:

(i) Universities–A should be encouraged to grow to at least 5 or 6 full-time staff members. The fragmentation of the research program within these groups could be overcome by appointing heads for each group to coordinate the effort. By the same token group grants would encourage such coordination. The grants should be sufficient to provide for postdoctorate fellows and full-time technicians.

(ii) Universities–B at present "enjoy" virtually no financial support but must in future be given every opportunity to grow into viable groups if they can attract capable people and formulate appropriate research programs.

(iii) Government – (a) a need exists for a viable group associated with military plasma physics (b) the two NRC groups would both benefit by being amalgamated into a single unit.

(iv) Industry – Current plasma research suffers from the short-term (annual) nature of contract support. This "quantization" leads to instability of the research group and considerable wasted effort. The immediate remedy is to provide sufficient long-term supported programs of a two- or three-year duration to permit the plasma physics research in industry to function in a more effective manner.

3. Nature and support of plasma physics research in university, government, and industrial laboratories

(i) *Universities* – Since plasma physics is multidisciplined and can be performed with small-scale experiments at modest cost it forms an excellent vehicle for graduate training. For the same reason it can attract capable university staff desiring to do "free independent" research. Thus the research in universities should be concerned principally with student training and be determined primarily by the interests of the university staff. It would be undesirable to give the university research too specific an orientation. The grants for such research should nominally be for a three-year period – a period consistent with the average time interval for training a doctorate student.

(ii) *Government* – The government laboratories must perform research in areas of national concern (such as defence), and in addition must possess a capability that permits members of the group to carry out independent research and to participate in any formulation of national needs and a national program. This can be done only by a budget sufficient to meet not only "in-house" needs but to support some programs of national concern as well.

(iii) *Industry* – Comparative statistics show that 49% of the total effort on plasmas in the United States is conducted by industry whereas in Canada it is 25% of the total and 15.7% of the Canadian-supported plasma research. Hence plasma physics research needs to be encouraged in Canadian industry, particularly in the areas that aid the space and defence programs as well as those that are concerned with plasma devices and applications of plasmas. With the great need for improving the technological position of Canadian industry, it is at least as important to attract and retain key people in industrial research as in government and university laboratories. Hence industrial research must be of a nature and of a standard to challenge key people, since industry offers virtually the only means whereby the "fall-out" of research can be translated into economic benefits in a direct and least time-consuming manner.

It is recommended that increased full-funded government support of a long-term nature be available to industry. Secondly, cost-sharing schemes for joint government-industrial projects should be instigated on a sliding scale, the government/industry cost ratio being determined by the basic research/applied research or development content of the program. Thirdly, no vehicle currently exists for support of an idea from a scientist in industry unless it is in direct aid to a current Canadian defence project. Thus, grants must be made available for unsolicited ideas that merit support and that originate from industrial scientists.

The major criterion for support of plasma research in Canada, particularly in the next few critical years when research in this area must be built up to prevent its floundering indefinitely, must be to give full support to a good group or to a good man whatever the laboratory. Anything less will be disastrous to the future of plasma research in Canada.

4. Coordination of plasma research in Canada

A deliberate effort should be made to optimize the results of plasma physics research in Canada by:

(i) establishment of a national working committee on plasma physics charged with the responsibility of: (a) making recommendations on improved coordination of the plasma work in Canada so as to reduce the fragmentation in effort and increase the sophistication of the research; (b) Acting as a "watch dog" on the status of potentially important applications such as fusion power, magnetohydrodynamic generation, etc. to ensure that Canada maintains a position that will enable her to benefit from developments in these areas; (c) investigating the desirability of establishing a national institute to perform research in some of these important areas and of determining the need for major facilities.

Such a body would be comprised of the representatives of the major plasma research groups in the country, together with individuals responsible for allocation of the funds for plasma research.

(ii) encouragement of joint projects undertaken between groups in university, government, and industrial laboratories. Currently, university grants come principally from NRC and AECL; government laboratories operate mainly on their "in-house" budgets; and industry depends on US, company, and DRB support. Thus no vehicle whatsoever exists for collaborative efforts. This by the same token implies greater coordination between the Canadian granting agencies.

(iii) government allocation of sufficient funds *specifically for plasma research* to make it possible to increase the effort to the level necessary for good research, to make it possible to implement the recommendations of the national working committee, and to make collaborative programs between different groups in the country possible.

SECTION 11

THEORETICAL PHYSICS

W. Opechowski (Chairman), J. P. Bemier, L. E. H. Trainor and P. R. Wallace.

FOREWORD

To avoid a possible misunderstanding we want to remind the reader that theoretical physics is not just a "field of physics" like, for example, nuclear physics or solid state physics, but rather one of the two essential aspects of physicists' dealings with nature, whatever their field of research might be. We mention this point explicitly because in the Pake survey of physics in the US[1] only those theoretical physicists whose work is connected with elementary particle physics ("the central problem of contemporary theoretical physics") are subjects of discussion by the "Panel on theoretical physics," and such badly mutilated theoretical physics is then treated on the same footing as a "field of physics."

In our survey we have excluded only those theoretical physicists whose field of research belongs to macroscopic physics (for example, classical fluid dynamics, and, hence, oceanography, meteorology) as opposed to microscopic physics.

Our survey is based on answers to a questionnaire sent to universities, and on personal contact with a number of theoretical physicists. We have also received several briefs concerning some specific practical problems now facing theoretical physicists in Canada.

We wish to express our thanks to all those who have contributed to making this survey possible.

11.1 CHARACTERIZATION OF THEORETICAL PHYSICS

It is customary for practical purposes to divide physics into a certain number of "branches" or "fields" like, for example, nuclear

[1] Physics: Survey and Outlook, loc. cit. pp. 159-165.

physics, solid state physics, etc. This subdivision of physics into fields corresponds to a classification of research projects in physics according to the subject of research. This kind of classification, to be useful, must change with the progress of physics; in fact, there is nothing very fundamental about it, although it does reflect to some extent our general ideas about the nature of the physical world.

Another customary division of physics, into "experimental physics" and "theoretical physics", cuts across all the fields of physics, and is on the other hand very fundamental indeed: research in physics as in science generally, has necessarily these two equally essential aspects, an experimental one and a theoretical one, whatever the subject of research might be.

A physical experiment can neither be designed, nor described and interpreted, without using concepts previously evolved as a result of a theoretical activity; a meaningful experiment always implies the existence of a theory, however primitive the latter might be.

Conversely, a theoretical activity is not physics at all if it has no relation to actual or possible experiments, although this relation may be, and often is, very indirect. We shall make a few remarks about the nature of this relation because some serious misunderstandings about theoretical physics have occasionally arisen from a lack of clear ideas on this point.

While research in physics has necessarily an experimental and a theoretical aspect, the division of all physicists into experimental physicists and theoretical physicists is not a logical necessity but simply a consequence of the complexity of modern physics research. In fact, before the middle of the 19th century, such a division was entirely unknown. Experimental techniques and the conceptual structure of physics were simple enough for one competent person to have sufficient familiarity with both. This is no longer so, and most physicists nowadays belong to one or the other category. Hence, a misunderstanding concerning the nature of relations between theoretical and experimental aspects of physics may have an important influence on the role played by theoretical physicists in physics research.

Experimental and theoretical activities in science, and in physics in particular, are most specifically linked by what is usually described as "comparison between theory and experiment." In physics this usually means a comparison of two sets of numbers, one set obtained from experiment, another from theory. If, however, we look at the output of research in theoretical physics, as presented in the form of articles in physics journals, we see that only a small fraction of those articles reach conclusions concerning numbers to be compared with experimental data, or even contain any explicit reference to such conclusions or to experimental data. This is not surprising, for at least two reasons.

First, even in those fields of physics for which the fundamental concepts and mathematical formalism seem to be well established, a big step is usually necessary before one can apply these concepts and an appropriate mathematical formalism to discuss specific experimental results. Such a step almost always involves some simplifications and approximations, and much of theoretical research is spent on looking for appropriate simplifications, on discussing them, on devising approximate mathematical techniques, and on analyzing and improving the existing ones. Without such a critical discussion comparisons of numbers obtained from theory and experiment would be meaningless.

Second, in those fields for which the fundamental concepts are not well established, and specific mathematical formulations doubtful, for example in elementary particle physics or in physics of non-equilibrium properties of matter-in-bulk, research effort in theoretical physics mainly consists in attempts at guessing the "shape of things to come" and discussions of mathematical formalisms that might turn out to be useful in the future. To some experimental physicists this kind of work seems to be nothing more than speculation and the juggling of mathematical symbols. This is, however, a very short-sighted attitude because people capable of ingenious speculations and skillful juggling with mathematical symbols are, judging by the past history of physics, much more likely to contribute to impcrtant "breakthroughs" than those who, by applying well-known rules, can get numbers that are of immediate interest to experimental physicists.

Some may feel that the foregoing remarks are trivially true and hence superfluous. Unfortunately, we could not agree with them, because we have met competent physicists in Canada who believe that theoretical physicists should, as a rule, be attached to experimental research groups, that their value should be measured by their usefullness tothose groups, andthat the supportof their research work should be made dependent on their value so measured.

We believe that a wide acceptance of such a point of view would have a pernicious effect on physics.

This is particularly so since, whatever the field of research, the theoretical physicist works as part of the community of *all* physicists engaged in that field, not only those in a particular laboratory. Neither his interaction with experimentalists nor his judgment of what constitutes interesting or significant problems should be limited by local factors. By the nature of his work the experimentalist is always concerned with the particular, but the task of the theoretician is to strive for generalization.

Rather than being attached to experimental research groups the theoretical physicists themselves should normally form a more or less autonomous group within a university physics department or research laboratory. Local circumstances will determine how much autonomy they may need, and to what extent, if any, this autonomy should be expressed in the administrative structure of the department or laboratory. The important point is that the selection of theoreticians to fill available positions should be primarily in the hands of theoreticians who should have freedom to obtain and administer the research funds they need.

A theoretical physicist is not just somebody with a university degree in physics, not engaged in experimental research work, and spending his time carrying out some calculations of direct use to experimentalists. Rather, a theoretical physicist is one thoroughly familiar with the conceptual structure of modem physics and with the mathematical techniques used in handling these concepts. In fact, he should be even more than that; he should be a "natural philosopher" with all the connotations that the term implies. Almost every first class graduate student in physics can be trained to carry out useful calculations, but only some of these students are capable of becoming theoretical physicists in the above sense.

Traditionally, all a theoretical physicist needs for his research work is just "paper and pencils", and perhaps a few journals to tell him what other physicists are doing. Actually he needs much more of course. Like any other physicist he needs all those things that are implied by the fact that science, and physics in particular, is a collective activity. But perhaps even more than does the experimental physicist he needs collaborators in his research, and he needs personal contact through visits and travel with physicists working in the same field elsewhere. And he certainly needs computing facilities; for, despite what we have thought useful to emphasize concerning the various aspects of theoretical research activity, we would be the last to claim that physics could exist without frequent comparison of the two sets of numbers mentioned above.

11.2 HISTORY OF THEORETICAL PHYSICS IN CANADA

Theoretical physics in Canada has no history in the customary sense of the word. This is best illustrated by the fact that there are apparently no more than six theoretical physicists in Canada over 50 years of age. More precisely, research in theoretical physics in Canada begins to be noticeable only some 25 years ago. Since that time, however, Canada has managed to catch up with other western countries, at least so far as the number of theoretical physicists at the universities is concerned.

11.3 ESTIMATE OF THE ACTIVITY IN TERMS OF MANPOWER AND DOLLARS

(i) Activity in terms of manpower

According to the Vogt Report[1], there were, at the beginning of 1965, 1,341 physicists active in Canada of whom 211 or 15% were theoretical physicists. It should be clear, however, from what we said in Section 11.1, that not everyone who carries out calculations pertaining to physical investigations is a theoretical physicist just as not everyone who works in a physics laboratory is a physicist. A person whose highest university degree is a B.Sc. is unlikely to have that familiarity with the conceptual structure and mathematical techniques of modern physics that would justify calling him a theoretical physicist. But, to quote again the Vogt Report, 79 out of the 211 persons (37%) had only a B.Sc. degree and only 83 had a Ph.D. degree; those having either an M.Sc. or a Ph.D. degree or both numbered 132. Thus, using the data of the Vogt Report, we would conclude that in the sense of Section 11.1 of the present report, there were approximately 130 theoretical physicists in Canada at the beginning of 1965.

We have tried to estimate without reference to the Vogt Report the number of theoretical physicists on the staff of physics departments of Canadian universities. This number will, of course, be smaller than the total number of theoretical physicists active in Canada, but not much smaller if we interpret the term theoretical physicist in the sense of Section 11.1. According to the Vogt Report, 76% of theoretical physicists in the sense of that survey were active in educational institutions. From personal knowledge and consultation with

[1] Statistical Report on Canadian Physicists, loc. cit.

others it is clear to us that the number of those whom we would call theoretical physicists is considerably higher among those 76% than among the remaining 24%. Admittedly, this way of arguing is somewhat vague, but more precise statements regarding numerical data would require an examination of all the individual cases, hardly feasible and not very useful in the present context. We did not feel that our task was to spot and count every single theoretical physicist in Canada. Some remarks on the theoretical physics activity in the government institutions and industry are made in Section 11.5.

Table I gives some data concerning the number of theoretical physicists at the "larger" universities, defined for this purpose as those whose physics departments have on their staff at least 3 theoretical physicists. In each case we have left it to the head of the physics department concerned to decide how many members of his department are to be regarded as theoretical physicists. We have reason to believe that in the majority of cases their decision would agree with ours. (Table I also contains data concerning the numbers of postdoctorate research fellows and graduate students in theoretical physics; these data are briefly discussed in Section 11.4)

There are 104 theoretical physicists on the staff of physics departments of the larger universities. We estimate the corresponding number in all universities to be about 125. We want to stress at this point that a certain number of theoretical physicists at the universities are on the staff of departments other than physics departments, such as chemistry, mathematics, astronomy, computing center, and even engineering departments. Their number is certainly not negligible, but rather difficult to estimate, partly for semantic reasons (some of them prefer to be called "theoretical chemists" or "astrophysicists" or "applied mathematicians"), and partly because they may be called "theoretical physicists" in view of their early academic training, despite their present activity.

The number of theoretical physicists both in the government institutions and in industry appears to be very small. For example, there are 3 in the Pure Physics Division of the National Research Council in Ottawa, and a few more than 10 at the Chalk River Laboratories.

The number of all theoretical physicists on the staff of Canadian universities, government laboratories, and industrial laboratories certainly does not exceed 200. To this "upper bound" one must add approximately 50 if one wants to include the postdoctorate research fellows, many of whom, however, are from abroad and probably will not stay in Canada (but will of course be replaced by other postdoctorate research fellows).

Table I.–DATA CONCERNING THEORETICAL PHYSICISTS IN THE UNIVERSITIES (Fall 1966)

	$t \geq 3$	$t \geq 6$	$t \geq 9$
N	18	10	2
T	104	72	19
P	439	290	103
T/P	0.24	0.25	0.18
D	42	36	14
D/T	0.40	0.50	0.74
G_d	99	80	29
G_d/G	0.11	0.11	0.11
G_m	73	56	19
G_m/G	0.08	0.08	0.07
$\frac{G_m+G_d}{T}$	1.65	1.89	2.52

Explanation of symbols:

N = number of university physics departments each of which has t theoretical physicists on the staff.

T = total number of theoretical physicists on the staff of these N universities.

P = total number of physicists on the staff of these N universities.

(The numbers t, T, P do not include the postdoctorate research fellows).

D = number of postdoctorate research fellows in theoretical physics.

G_d = number of Ph.D. students in theoretical physics.

G_m = number of M.Sc. students in theoretical physics.

G = number of all graduate students in physics.

(ii) Activity as measured by expenditure

The research grants awarded by the National Research Council constitute the main source of funds in support of research in theoretical physics at the Canadian universities.

At six of the 18 larger universities the theoretical physicists entirely depend on that source of funds, and in only one case is more than 50% of the funds obtained from other sources. On the average, per university, 74% of the funds for research in theoretical physics is obtained from the National Research Council.

It must be emphasized that these figures do not include the salaries that theoretical physicists receive as faculty members.

Other sources of funds are: other federal government institutions, provincial governments, and the universities themselves.

These data, as well as those below, refer to the academic year 1966-67.

There are 72 NRC grantees in theoretical physics in physics departments of the 18 larger universities, and the total of the grants awarded to them is $346,000, that is, $4,800 per grantee; 32 theoretical physicists at these universities do not have NRC research grants. There are 83 NRC grantees in theoretical physics in physics departments of all Canadian universities, and the total of the grants awarded to them is $373,000, that is, $4,500 per grantee.

Total financial support of theoretical physics at the physics departments of the 18 universities from all sources amounts to about $500,000. For all Canadian universities we estimate the total to be about $530,000.

The funds available to theoretical physicists are used predominantly to pay salaries of postdoctorate research fellows, and to support graduate students; only in much smaller degree are they used for travel and expenses connected with guest lecturers in theoretical physics.

(iii) Activity by subfield

A competent theoretical physicist often carries out research in more than one field. Therefore we have thought that the best way of measuring research activity in theoretical physics at the universities, among the various fields of physics, would be to find out what are the research topics of the Ph.D. students in theoretical physics. The results of our inquiry are summarized in Table II.

(iv) Activity in government & industry

As mentioned before, the number of theoretical physicists in government institutions is small. It is negligible in industry, simply because there is almost no fundamental research being done at industrial laboratories in Canada. In most other western countries, some of the "industrial" theoretical physicists have made important contributions to physics in general. We will not elaborate this point, but refer the reader to the discussion of this situation in Section 9 (Report on Solid State Physics).

Table II.—Distribution among Fields of Research (Fall 1966)

Nuclear physics	35%
High energy or elementary particle physics	22%
Solid state physics	13%
Atomic and molecular physics	13%
Plasma and statistical mechanics of gases	6%
Other	11%

Distribution of research activity in theoretical physics at the universities among various fields of physics as indicated by the number of PhD. students in theoretical physics. "Other" means predominantly investigations concerning the formalism of field theory and quantum mechanics. The error on the figures given in the table probably does not exceed 10% of each figure (it chiefly arises from the occasional difficulty of deciding to which field a given topic of research belongs).

11.4 NUMBER OF GRADUATE STUDENTS AND POSTDOCTORATE RESEARCH FELLOWS; IN PARTICULAR, THE NUMBER OF Ph.D. STUDENTS

An external measure of the research activity of a theoretical physics group at a university is the number of Ph.D. students and postdoctorate research fellows (also, to some extent, the number of M.Sc. students). Numerical data concerning these three groups of junior research workers in the 18 larger universities in November 1966 are given in Table I.

It is interesting to note that the ratio, G_m/G, of the number of Ph.D. students in theoretical physics to the number of all graduate students in physics does not depend, on the average, on the size of the university: it is equal to 11%. On the other hand the ratio, D/T, of the number of postdoctorate research fellows to the number of staff members in theoretical physics does increase, on the average, with the size of the university: it is 0.4 on the average for the 18 universities, but almost twice as large for the few largest universities.

The absolute number of Ph.D. students in theoretical physics in all Canadian universities probably does not exceed 105 (of which 99 study at 18 larger universities). One can expect that about 1/5 of this number will be granted the Ph.D. degree in 1967.

The distribution of the Ph.D. students in theoretical physics among the various fields of physics is given in Table II.

11.5 COMMENTS ON THE SITUATION OF THEORETICAL PHYSICS (AS DESCRIBED IN PREVIOUS SECTIONS)

In Section 11.2, 11.3 and 11.4 we have abstained from expressing any opinions with regard to the situation in theoretical physics as described by means of approximate statistical data presented in those sections. We want now to make some comments on that situation. The *first* obvious general question that arises is this: should the situation as summarized in Tables I and II be regarded as satisfactory? By sampling the opinions of theoretical physicists in Canada, we came to the following conclusions:

(i) The ratio T/P of the number of theoretical physicists to that of all physicists in an established university physics department should be about 1/3. This is the value of T/P characteristic of many leading physics departments abroad. As we have seen in Section 11.3 (Table I), the value of T/P in Canada is considerably lower, on the average about 1/4.

The same ratio T/P in a research institute (where staff members have no teaching duties) need not be so high as 1/3 but certainly not lower than 1/5. This follows from the assumption (accepted by theoreticians, but not by all experimentalists) that most senior and graduate courses are best taught by theoretical physicists. At the central Canadian government laboratory, the Pure Physics Division of NRC in Ottawa, the ratio T/P is about 1/20, a fact that many physicists in Canada (including the members of this committee) regard as very disturbing for more than one reason.

(ii) It is generally felt that, at a university physics department, there should be on the average about one postdoctorate research fellow for every staff member in theoretical physics actively engaged in research, hence the ratio D/T should be at least 3/4; actually it is, on the average, only 0.40.

(iii) The average graduate student/staff ratio $(G_m+G_d)/T$, in theoretical physics (which, incidentally, is somewhat lower than the same ratio in experimental physics) is not unreasonable, 1.65, although it becomes possibly a little too high, 2.5, for the largest universities.

A question to which we have no definite answer concerns the absolute number of Ph.D. students in theoretical physics: is this number too low or too high or just right? In our view this number (approximately 100) is about right, or perhaps a little too low since we are not sure that people receiving the Ph.D. degree in theoretical physics are really about to become theoretical physicists in the sense of our definition, not just "human computers" who cannot do much more than carry out some possibly useful calculations for which they were "programmed" by their research supervisors. Indications are that a considerable percentage of such people will never become theoretical physicists.

(iv) According to our data (Table II), more than half the theoretical physicists in Canada are engaged in research in the fields of nuclear, high energy, and elementary particle physics. That the percentage of those working in the field of nuclear physics in high (35%) is not surprising since Canadian contributions to the experimental research in this field of physics are probably more important, at least statistically speaking, than to any other field of physics.

In high energy physics the experimental effort in Canada is not large compared with the effort in other fields. One thus wonders a little at the high percentage (22%) of theoretical physicists in this field of physics. But the field is regarded by many as concerned with "the central problem of contemporary theoretical physics" (this is the phase quoted earlier from the Pake Report) and it is natural and proper that young, enthusiastic theoretical physicists should want to try guessing at least some features of the future theory governing this field.

What is, however, really alarming is the low percentage (13%) of theoretical physicists in solid state physics. This probably reflects the fact that the experimental research in this field of physics is underdeveloped in Canada as compared with the United States and other western countries. The reasons for this highly unsatisfactory situation in solid state physics in Canada are analyzed in Section 9 (Report on Solid State Physics), and we refer the reader again to that section. Both from the point of view of fundamental research (quantum-mechanical many body problem, description of non-equilibrium phenomena at very low temperatures), and from the point of view of applications in other fields of physics and in technology, the study and prediction of the properties of matter-in-bulk under various conditions, especially in the solid state, is of such paramount importance that much more effort should be devoted to this field of physics.

The *second* general question that arises in connection with the data presented in Section 11.3 is this: is the level of financial support of research in theoretical physics sufficient? We discuss this question in Section 11.6, which deals with future financial requirements of research in theoretical physics.

11.6 FUTURE FINANCIAL REQUIREMENTS

As we have seen in Section 11.3, the average NRC research grant in theoretical physics is $4,500 per annum, and the average financial support from all sources for all theoretical physicists in some $4,200 per theoretical physicist. This level of support is certainly too low if the following desiderata, which we believe to be justified, are accepted:

On the average a theoretical physicist should be in a position:

(i) to have a postdoctorate research fellow (some senior theoretical physicists will have more than one, some junior theoretical physicists none at all);

(ii) to go at least once, and preferably twice a year to a meeting, or small conference, at which the latest advances in his field are presented and discussed (it is also important to provide travel assistance to postdoctorate fellows and to graduate students presenting papers at scientific meetings);

(iii) to consult other specialists in his field either by inviting them for discussions, and possibly seminar lectures, or by visiting other research centers himself;

(iv) to support good graduate students, some of whom are not eligible for scholarship support from other sources;

(v) to arrange in reasonable degree whatever part-time assistance (summer students, programmers, etc) seems essential to his work.

If we consider only these five points, keeping in mind that the present minimum stipend of a postdoctorate research fellow is $6,000 per annum (plus some $800 for travel to and from the university physics department in question), and also that the present level of support for a full-time graduate student is about $3,000 per annum, we obtain approximately $11,500 per annum per theoretical physicist as the minimum desirable average level of support. Actually even this is too low because we have disregarded the desirability of overseas travel, and we have not allowed for such an important item as publication charges.

Turning now to the question of future financial requirements (during the next five years), we should first of all point out that the above minimum desirable financial support per annum per theoretical physicist ($11,500) will have to be raised, primarily for two reasons: first, the minimum stipend of a postdoctorate research fellow probably will and certainly should increase by at least $2,000 in the next two or three years; second, the percentage of "senior" theoretical physicists will also increase as a consequence of the "catching-up" process mentioned in Section 11.2.

If we take these two circumstances into account, the desirable average level of support per annum per theoretical physicist over the next five years will be about $16,000. Assuming that the National Research Council will continue to provide about 3/4 of the support of research in theoretical physics, the size of the average NRC grant in theoretical physics will have to be about $12,000, which is 2.7 times the size of the present (1966-67) average NRC grant in theoretical physics.

It should be emphasized that these estimates of future requirements include no charges for the use of computing facilities because we have assumed that the National Research Council will continue its present policy of making these facilities available (through its direct support of the computing centers) without charge to the individual user's grant. The estimates would have to be revised if that policy should change. We recommend, however, that the present policy be continued.

To complete this sketch of future financial requirements it is necessary to make a guess concerning the increase in the total number of theoretical physicists in the near future. Assuming that the number of all physicists in Canada will increase by 50% over the next five years, and remembering that about 1/3 of all physicists at the universities should be theoreticians (see Section 11.5) while the actual fraction is at present 1/4, we conclude that the total number of theoretical physicists should increase, during that period, by a factor nearly 2, that is to about 350.

One final point should be mentioned in connection with future requirements. Many theoretical physicists in Canada feel that there should be in this country a central ("national"?) Institute of Theoretical Physics. We believe that this idea deserves serious consideration.

11.7 GRANT SUPPORT MECHANISM

In Section 11.5 we have argued that the support of research in theoretical physics, expressed in dollars, is insufficient. However, if we compare the funds made available for research in theoretical physics by the National Research Council with those in experimental physics during the past two years, we come to the conclusion that, in this relative sense, the level of support of research in theoretical physics is no longer unreasonably low. This means that whatever the imperfections of the present NRC grant-awarding mechanism may be, they do not manifest themselves in discrimination against theoretical physicists. Nevertheless, many theoretical physicists are of the opinion that the near-uniqueness of the National Research Council as a source of financial support of research in theoretical physics is unhealthy, especially if one considers the fact that NRC is in competition with the universities for funds. More sources of financial support (that is, more than the present 1/4 on the average—see Section 11.3) would be very desirable. We agree with this opinion in principle. We should like to point out, however, that actually the National Research Council is, at least at present, discriminating against itself in theoretical physics: we have seen that the research in theoretical physics at the NRC laboratories is almost nonexistent.

Section 12

BIOPHYSICS

H.E. Johns (Chairman), C.E. Challice, J.A. McCarter and E. Llewellyn Thomas

12.1 INTRODUCTION

This report is a survey and outlook on biophysics in Canada. It includes a definition of biophysics and a discussion of the areas that this committee feels are included within it. It lists, and classifies under subheadings, the projects in biophysics that are now under investigation in Canada and indicates the number of scientists involved, the number of students being trained, and the estimated total cost in dollars of each of these projects. An attempt is made to estimate the growth of biophysics in Canada in the next five years. In addition, the cost per scientist now, and in five years time, is estimated. The committee has found that biophysics research is being done in many different environments; including university departments of physics, chemistry, biology, biophysics, engineering, physiology, and medicine, as well as in hospitals, research institutes, government laboratories, and industry.

The report attempts to cover the field of biophysics as defined below; opinions expressed are the combined opinions of the four committee members, each of whom has some interest and experience in the field of biophysics. However, because of the indeterminate boundaries of the field of biophysics, the committee often had difficulty in deciding whether certain projects should or should not be included in the report. This difficulty is compounded by the diverse backgrounds of many of the people who are now doing biophysics. These include persons trained in physics, chemistry, biology, physiology, biochemistry, engineering, medicine, and agriculture. Because of the diversity of biophysical research some work that might properly be classified as biophysics may have been missed.

The report includes a discussion of the significance of biophysics to Canadian science and makes suggestions concerning the future development of biophysics in Canada; it ends with a brief discussion of some of the most important unanswered questions in biophysics.

12.2 DEFINITION OF BIOPHYSICS

The committee adopted the following definition of biophysics– "Biophysics is the study of biological or medical problems using the methods and concepts of physics." This definition implies that the biophysicist may be (a) a scientist engaged in making quantitative measurements on biological phenomena with a view to explaining them in physical and mathematical terms, or (b) a scientist engaged in instrument development where basic biophysical problems are being investigated and in which the development of the instrument is an essential step, or (c) an engineer concerned with the application of biophysical knowledge to practical medical problems.

A good deal of research in biology and medicine makes routine use of instruments that have been developed by engineers and biophysicists. This research, while valuable, does not fall within our definition of biophysics, unless the investigator is primarily concerned with explaining basic mechanisms of the biological system in terms of physical principles.

12.3 AREAS OR SUBFIELDS OF BIOPHYSICS

The committee felt that biophysics could be divided conveniently into four main areas: (1) physiological biophysics–the use of biophysical techniques to study basic physiological problems; (2) molecular biophysics–the use of methods and concepts of physics to investigate cells and large molecules; (3) engineering biophysics – the use of engineering concepts and methods in the study of living systems and the solution of medical problems; and (4) radiation biophysics – the use of electromagnetic radiation to perturb and study living systems. The members of the committee were chosen so that each of these areas of interest would be represented.

At the request of the Steering Committee the committee also surveyed the work being done in radiological and health physics across Canada, although there is some question as to whether these fields can be strictly classified as biophysics.

There are a number of areas related to biophysics that this committee did not investigate. For example, psychophysics was omitted, although this is the oldest area of biophysics (it was developed by the great classical physicists and was closely associated with the development of the discipline of physics itself). Today however it is chiefly studied by psychologists and psychophysiologists.

12.4 STATISTICAL STUDY

Tables I to V give the titles of the biophysical projects under way at the present time in Canada. These tables include the numbers of professional staff working in 1967 on the various projects. For Tables I, II, III, and IV the column "Scientists" (i.e. professional staff) includes in general only those with the Ph.D. degree or its equivalent. For Table V the professional staff includes scientists with the B.A., M.A., or Ph.D. degrees or their equivalents. The number of scientists expected in each project in 1972 was estimated by the committee on the basis of information supplied by the departments or institutions concerned. The committee used its own judgment to adjust these figures either up or down when they felt projections by the group involved were unrealistic. Although these adjustments may have been large in a few cases, their effect on the overall total is small (probably less than 10%).

The numbers entered in the columns labelled "Graduate students" give the average numbers of students present in a group at a given time. As a rough guide, the committee assumed that the number of students graduating per year will be half the figure given in the tables for M.Sc. students and one quarter the figure given for Ph.D. students. In projecting these figures to 1972, the committee used its discretion in adjusting the estimates supplied by the departments and institutions.

To arrive at the dollar input in 1967 the committee included the following items: total annual grants from external agencies; average capital grants from the parent organization; student support (if such was not included in any of the above items); and, finally, an estimate of the portion of the salary of the professional staff spent on the research project. As a rough guide we estimated that most university professors devote 75% of their time and effort to graduate teaching and research. In estimating the expected cost in 1972, an attempt was made to include the natural increase in cost of a project due to inflation.

Table I. – MOLECULAR BIOPHYSICS

Title of Project	Scientists		Graduate students M.Sc.		Graduate students Ph.D.		Support in thousands of dollars	
	1967	1972	1967	1972	1967	1972	1967	1972
A. Structure of macromolecules								
X-ray diffraction studies on enzymes	1	2	1	2	0	1	30	50
Structure of haemoglobin by ESR	1	2	1	2	0	1	15	60
Study of haemoproteins	1	1	1	2	0	1	21	37
Study of macromolecules	1	4	0	3	0	1	15	120
Electro-optical properties of proteins	1	1	0	0	0	0	35	47
Hydration effects on DNA	1	1	1	1	1	2	41	65
X-ray diffraction of macromolecules	1	2	1	2	0	2	20	65
Structure and conformation of protein aging, effects of radiation	5	12	10	12	12	20	340	600
B. Structure of viruses and virus cell relationships, differentiation, and immunology								
Virus cell relationships and protein synthesis	2	3	1	2	3	4	100	150
Virus host interactions	3	4	0	5	0	3	90	140
Differentiation and immunology	5	6	3	4	2	4	200	300
Structure of viruses	3	3	1	1	1	1	85	105

C. Macromolecular functions and molecular genetics								
Protein synthesis	1	3	0	5	0	3	30	140
Molecular biophysics histones, protein s.	5	7	0	0	0	0	175	245
Function of macromolecules	7	8	0	0	0	0	270	350
Molecular genetics	3	6	2	4	4	8	120	240
Macromolecular interactions	1	1	2	2	1	3	35	53
D. Membrane and membrane transport								
Membranes	2	3	0	0	3	5	55	80
Energy transformation and photosynthesis	2	4	2	2	0	6	45	135
E. Miscellaneous biophysics								
Molecular biophysics	0	4	0	4	0	4	0	130
Molecular biology	0	8	0	8	0	12	0	350
Totals	46	85	26	61	27	81	1,722	3,462

Table II. – PHYSIOLOGICAL BIOPHYSICS

Title of Project	Scientists		Graduate students				Support in thousands of dollars	
			M.Sc.		Ph.D.			
	1967	1972	1967	1972	1967	1972	1967	1972
A. Muscle and membrane physiology								
Membrane potential fluctuations	1	2	1	2	0	1	20	40
Structure and physiology of muscle and membrane	2	4	0	5	0	2	50	120
Structure and function of heart muscle	1	2	2	4	2	3	30	50
Membrane transport	2	5	0	2	0	2	60	130
Electrolytes in cytoplasma and muscle. Intracellular flying spot microscopy	4	6	0	0	1	4	140	250
Force deformation relationships in the myocardium	1	1	2	1	0	2	35	40
Active transport through membranes	1	1	2	0	2	0	24	32
Physics of muscle and cell wall	6	6	2	3	4	6	180	250
B. Electrophysiology								
Electrophysiology	3	5	0	2	1	4	75	135
Neurophysiology and neuropharmacology	2	3	1	1	0	3	80	120

Basic electrophysiology	1	3	1	2	1	4	37	75
Neurophysiology	2	3	1	2	1	3	94	130
Electrobiology	2	7	4	10	1	15	110	400
Computer analysis of electrocardio-grams	3	5	0	2	0	1	110	160
Effect of physical parameters on microscopic growth	1	2	2	5	1	2	37	75
Oxygen evolution in photosynthesis and physiology under high pressure	1.5	5	0	4	0	6	50	175
Microclimate of clothes	3	3	0	0	0	0	75	100
Effect of noise and vibration on man	3	3	0	0	0	0	90	100
Effects of pressure on cell division	1	1	1	2	3	3	65	95
Electrophysiology of central nervous system	5	9	5	8	1	4	180	400
C. Respiratory biophysics								
Study of blood oxygen saturation	1	2	0	2	0	2	35	70
Ventilation studies	2	3	0	0	0	1	44	80
Respiration of birds in flight	1.5	1.5	0	0	0	0	30	40
Oximetry	2.5	2.5	0	0	1	1	45	60
Respiratory biophysics	2	2	0	0	1	1	45	60
Hemorheology	1	1	0	0	0	0	30	30
Gas mixtures in diving	2	2	0	0	0	0	45	60
Basic physiological studies using tracers	1	2	1	1	1	2	65	100

Table II (Continued)

Title of Project	Scientists		Graduate students M.Sc.		Graduate students Ph.D.		Support in thousands of dollars	
	1967	1972	1967	1973	1967	1972	1967	1972
D. Miscellaneous								
Model systems for animal behavior	4	4	5	4	4	5	125	220
Bioenergetics on animal systems	2	3	2	3	2	4	86	135
Detection of tissue differences using impedance	1	3	1	2	0	1	55	125
Analogues of endocrine systems	3	5	0	2	1	2	70	125
Vestibular biophysics	2	4	0	0	2	4	70	120
Physiological control systems	2	5	4	15	1	4	45	200
Totals	72.5	116	37	84	31	92	2,332	4,302

Table III. – ENGINEERING BIOPHYSICS

Title of Project	Scientists		Graduate students				Support in thousands of dollars	
			M.Sc.		Ph.D.			
	1967	1972	1967	1972	1967	1972	1967	1972
A. Development of biomedical instrumentation								
Biomedical electronics	5	11	12	12	6	16	200	500
Cardiac pacemakers and modelling	2	4	2	3	0	2	65	100
Myoelectric control for prostheses	4	4	0	0	1	2	115	130
B. Application of biomedical instrumentation								
Haemodyalysis	1	1	0	0	0	0	30	40
Blood coagulation	1	1	0	0	0	0	15	15
Detection of epileptic seizures	1	1	0	0	0	0	40	50
Totals	19	30	15	19	9	31	612	1,120

Table IV. – RADIATION BIOPHYSICS

Title of Project	Scientists		Graduate students				Support in thousands of dollars	
			M.Sc.		Ph.D.			
	1967	1972	1967	1972	1967	1972	1967	1972
A. Radiation studies at the molecular and chemical level								
Flash radiolysis	2	3	2	2	2	3	80	120
Ultraviolet damage to nucleic acids	3	3	3	3	3	3	90	120
Ultraviolet induced changes in pyrimidines	2	3	0	0	0	0	60	100
B. Radiation studies at the cellular level								
Effects of radiation on water in biological system	1	1	0	0	1	2	30	45
Radiobiology of cells	6	16	5	10	0	8	235	570
Cellular radiobiology and chemotherapy	5	6	4	5	3	4	235	300
Effects of microwaves on muscle	1	1	1	1	0	0	5	5
C. Radiation studies at the level of the whole organism								
Radiobiology at level of organism	1	2	4	6	3	4	57	110
Metabolism of isotopes	4	6	0	1	0	1	120	200
Metabolic studies in humans, whole body counting	1	3	1	2	0	1	40	125

D. Radiation dosimetry and instrumentation

Clinical and medical physics	2	2	2	3	0	1	65	90
Radiation physics applied to medicine	1	1	1	1	1	2	40	55
Use of X-rays, ultrasound and isotopes in medical diagnoses	2	4	0	3	0	1	62	140
Dosimetry instrumentation and developments	5	7	0	0	0	0	175	245
Totals	36	58	23	37	13	32	1,294	2,225

Table V. – RADIOLOGICAL AND HEALTH PHYSICS

Institution	Scientists		Graduate students*				Support in thousands of dollars	
			M.Sc.		Ph.D.			
	1967	1972	1967	1972	1967	1972	1967	1972
A. Hospital physics								
1**	2.5	4	0.5	1	0	0	55	75
2	3	6	0	1	0	0	70	110
3	4	7	0	4	0	0	80	150
4	3	4	0	0	0	0	110	130
5	2	2	0	0	0	0	30	40
6	1	2	0	0	0	0	20	30
7	4	5	0	0	0	0	60	90
8	2.5	3	0	0	0	0	40	60
9	1	1	0	0	0	0	28	37
10	1	1	0	0	0	0	4	5
11	1	1	0.5	1	0	0	25	25
12	2	4	0	1	0	0	40	80
13	1	1	0	0	0	0	19	25
14	12	17	0	0	0	0	500	700
15	2	4	0	0	0	0	50	120
16	1	2	0	0	0	0	15	40
17	2	2	0	0	0	0	25	40
18	0	1	0	0	0	0	0	15
19	1	1	0	0	0	0	15	20
20	4	5	0	0	0	0	70	90

B. Health physics

1	7	8	0	0	0	0	170	300
2	10	10	0	0	0	0	350	400
3	5	10	0	0	0	0	175	350
4	19	24	0	0	0	0	700	900
5	6	9	2	3	0	0	120	200
6	10	10	0	0	0	0	350	400
Totals	107	144	3	11	0	0	3,121	4,432

*For this table Colombo trainees, who are not necessarily working for higher degrees, have been classed as graduate students.

**Numbers refer to different research groups.

The results in Tables I, II, III, and IV are summarized in Table VI. At present more scientists are involved in radiological and health physics than in any of the other subdivisions. It should be remembered, however, that many of the scientists in this category are not trained to the Ph.D. level, so that the number is not strictly comparable with the number of scientists employed in molecular biophysics, physiological biophysics, engineering biophysics, and radiation biophysics which, in the tables, include *only* those with the Ph.D. degree or its equivalent. The large group of radiological physicists are involved in the very important practical task of collaborating with the medical profession in the diagnosis and treatment of disease using electromagnetic radiation. The group in health physics are largely involved in the equally important task of measuring and controlling radiation hazards resulting from the extensive use of ionizing radiations in hospitals, research laboratories, and nuclear power developments.

The second largest group of biophysicists at the moment are involved in physiological biophysics. The committee found this group the most difficult to classify since most physiological research projects include a good deal of biophysics. It is quite possible that the true number of biophysicists in this branch is much larger than the value given in the table.

The next largest group are in molecular biophysics. Scientists in this area of biophysics tend to be concentrated into rather large research teams involving a good deal of collaborative research.

Scientific work in radiation biophysics is hard to distinguish from that done by workers in radiological or health physics. If the scientist involved was primarily interested in the basic mechanisms of radiation damage or related subjects, he was included in the radiation biophysics group; if he was primarily interested in the applications of radiation to biological or medical problems, he was placed in the radiological and health physics group.

Table VII summarizes the cost per scientist in each of the categories covered in Tables I to V. The higher cost of research in molecular biophysics results from the large cost of supplies – media and animals. The lower cost of engineering biophysics estimated in this survey may not be realistic, since certain back-up facilities, such as computers, are not included in the survey. The findings of the survey are in agreement with the general findings of the NRC, that a scientist and his research program cost about $35,000 per year.

Table VI. – SUMMARY OF TABLES I, II, III, IV, AND V

Environment	Scientists		Graduate students M.Sc.		Graduate students Ph.D.		Support in thousands of dollars	
	1967	1972	1967	1972	1967	1972	1967	1972
I. Molecular biophysics	46	85	26	61	27	81	1,722	3,462
II. Physiological biophysics	72.5	116	37	84	31	92	2,332	4,302
III. Engineering	19	30	15	19	9	31	612	1,120
IV. Radiation biophysics	36	58	23	37	13	32	1,294	2,225
Totals	173.5	289	101	201	80	236	5,960	11,109
V. Radiological and health physics	107	144	3	11	0	0	3,121	4,432
Totals	280.5	433	104	212	80	236	9,081	15,541

Table VII. – PRESENT AND EXPECTED COST PER SCIENTIST

	Present (1967)	Expected (1972)
1. Molecular biophysics	37,400	40,700
II. Physiological biophysics	32,200	37,100
III. Engineering biophysics	32,200	37,300
IV. Radiation biophysics	36,000	38,400
Average	34,500	38,400
V. Radiological and health physics	29,200	30,800

12.5 ENVIRONMENT IN WHICH BIOPHYSICS IS CARRIED OUT

The statistical data of Tables I to IV are reclassified in Table VIII to illustrate the environment in which biophysics is being carried out in Canada. At the moment less than 25% of the biophysics in Canada is located is biophysics departments; the rest of the biophysicists are sponsored by a wide variety of departments. The largest groups of this latter variety are those related to physiological and medical departments; the next largest groups are in biophysics departments of government laboratories. Table VIII includes several groups associated with physics departments that plan shortly to form separate biophysics departments. If the plans of these groups come to fruition, one can expect that in 1972 more biophysicists will be concentrated in specifically designated departments of biophysics than in any other single kind of organizational structure.

12.6 BIOPHYSICS AND CANADIAN SCIENCE

Biophysics now exists as an independent discipline and can be expected to make important scientific contributions in the following ways:

(i) Solution of basic biological problems

Many of the problems of biology are so complex that in the past they have been dealt with in a descriptive way. For this reason the training of many biologists has been, and still is, along descriptive

Table VIII. – ENVIRONMENT IN WHICH BIOPHYSICS RESEARCH IS BEING CONDUCTED CONSOLIDATED FROM TABLES I, II, III, IV.

Environment	Scientists		Graduate students				Support in thousands of dollars	
			M.Sc.		Ph.D.			
	1967	1972	1967	1972	1967	1972	1967	1972
(University department or institution)								
Physics	8	16	9	16	2	15	201	522
Planned biophysics (from physics)	3	24	1	19	0	23	110	900
Biophysics	40	58	25	50	23	57	1,520	2,575
Biomedical engineering	10	20	16	29	7	23	325	840
Chemistry	6	13	12	14	13	23	375	653
Biology	10	15	13	19	13	18	358	652
Physiology and medical	47	76.5	19	40	18	62	1,488	2,625
Hospital and research institutes	8	14	5	10	2	8	282	505
Government laboratories	37.5	48.5	1	4	1	5	1,201	1,712
Industry	4	4	0	0	1	2	100	125
Totals	173.5	289	101	201	80	236	5,960	11,109

lines. In some fields of biology, however, the systems under investigation can be simplified and controlled to the point where the incisive quantitative methods of mathematics, physics, and chemistry can be applied. In fields of this kind, such as molecular biology, the biophysicist can make a very large contribution indeed. That this is so may be illustrated by the number of Nobel prizes that have been awarded recently for studies in medicine and biology in which biophysics was an essential element. These prize winners include Von Békésy, Huxley, Hodgkin, Eccles, Kendrew, Perutz, Crick, Watson, and Wilkins.

(ii) Development of instrumentation and techniques for medical and biological research

Physicists, chemists, and engineers have continually supplied biology and medicine with much of their sophisticated instrumentation. This is well illustrated in recent years by the development of such devices as the electron microscope, the ultracentrifuge, the electron-spin resonance spectrometer, the nuclear magnetic resonance spectrometer, scintillation counters, a variety of ultraviolet, visible and infrared spectrometers, isotope scanning devices, etc. These instruments are now the basic tools for a great deal of research in biology and medicine. With each new breakthrough in technique, basic discoveries in medicine and biology result. The biophysicist with his knowledge of both physics and biology will continue to play an essential part in the development of these new techniques.

(iii) Development of medical engineering

The application of engineering principles to medicine has become a very active field in recent years. The engineering biophysicist is involved in the following activities:

(1) Instrumentation – the development of a basic discovery that enables a reliable clinical instrument to be developed.

(2) Development of engineering techniques to solve biological problems. This is well illustrated in the use of radiotelemetry and remote monitoring of physiological variables, the use of analogue and digital computers to analyze data such as electrocardiograms, etc.

(3) Development of artificial organs – hearts, kidneys, limbs, blood vessels, heart valves, etc. As an illustration of this activity it may be noted that at the moment there are over 10,000 heart pacemakers and 20,000 artificial valves in successful operation in patients on this continent.

(4) Development of life support systems to supply controlled environment for hospital patients during critical periods. Examples of this include iron lungs, heart-lung pump systems, infant respirators, etc.

(5) Development of new synthetic plastics and alloys for medical implantation. This type of work requires the study of biological surfaces using electron microscopy and many of the testing techniques developed by the engineer in studying the materials used in engineering practice.

(6) Application of engineering concepts to medicine, involving the theory of systems, feedback mechanisms, etc. Operational research on the control of the flow of patients in large hospitals is a good example of the use of mathematics by the biophysical engineer.

(iv) Application of physics to medical treatment and preventive medicine.

The biophysicist has had a large part in the development of high-energy machines, cobalt-60 units, Van de Graaff generators, betatrons, and linear accelerators, for the treatment of cancer. He is now heavily involved in developing techniques for controlling and altering the radiation pattern in the patient to produce optimum results. The biophysicist is also responsible for controlling radiation hazards and in this sense is a public health engineer.

12.7 FUTURE DEVELOPMENT OF BIOPHYSICS IN CANADA – THE TRAINING OF BIOPHYSICISTS

The future development of biophysics in Canada requires the production of more and better-trained students to meet the many needs outlined in the last section. In order to increase the flow of students into biophysics the committee recommends:

(i) The establishment of biophysics units or departments in universities in Canada

Biophysics departments should be mainly at the postgraduate level and be involved in biophysical research. However, the possibility also exists of creating undergraduate programs in biophysics. Should such complete courses be established, it is essential that they should consist mainly of courses in mathematics, physics, and chemistry at the honors level, with some biological orientation in the final years. This could be accomplished by about three biological options in the final two years, e.g. third- or fourth-year courses in microbiology, physiology, anatomy, genetics, biochemistry, organic chemistry, etc. It has been argued in some circles that students with physics, chemistry, or engineering background would not have the proper prerequisites for some of the courses listed above. Experience in several universities, however, has shown that these courses do not present too difficult a challenge to well-motivated honors physics, chemistry, and engineering students.

By making this recommendation the committee does not wish to imply that biophysics should be taught only in biophysics departments. However, experience in a number of institutions has shown that the development of the discipline of biophysics under the aegis of a committee consisting of representatives from a number of the basic disciplines (such as biology, physics, chemistry, and medicine) has inherent disadvantages that lead ultimately to the establishment of a more or less independent biophysics department or group. It becomes apparent that rule by committee in this way does not lead to a coherent group. Often each of the basic disciplines represented on the committee tries to impose a requirement of "basic" knowledge from his discipline on *all* the graduate students. This leads to an unwieldy coursework requirement for the student, who has to spend too long a period in preparation before he is able to devote most of his time to his research project.

(ii) Entry into biophysics from a physical science background

The committee recommends the creation of third- and fourth-year options in biology for students in honors physics, chemistry, and engineering.

The fields of physics, chemistry, and engineering are so vast that no undergraduate course can hope to cover all branches of these sciences in an honors B.Sc. program. We think, therefore, that little would be lost to such honors courses if one option per year in biology were made available to students in their third and fourth years. Such options would be of interest to the students *per se,* and would enable a student who elected them to get some feeling for the field of biophysics. This would certainly increase the flow of honors students in the physical sciences into careers in biophysics.

(iii) Entry into biophysics from a biological sciences background

The committee recommends an increase in the content of mathematics, physics, and chemistry in honors programs in biology.

The committee is of the opinion that significant new advances in biology are unlikely to be made without the use of the concepts of mathematics, physics, and chemistry. Therefore the content of these basic sciences in the honors courses in biology should be increased, even at the expense of some biological subjects. It might be argued that such training could be given after an honors degree in biology. But experience has shown that, at this stage in their career, most biologists have neither the time nor the inclination to study mathematics, physics, and chemistry in enough depth to apply them effectively to their research in biology.

Much of the future advance in biological science rests on collaborative research projects involving scientists from different disciplines. Implementation of recommendations (i) to (iii) would, in a few years, create a body of scientists able to communicate with one another on a scientific level, and thus in a position to carry out significant interdisciplinary research.

12.8 DEVELOPMENT OF BIOPHYSICS RESEARCH PROGRAMS

In the last few years a number of scientists have been trained as biophysicists in Canada. Many of these have gone elsewhere to take advanced postdoctorate studies. Such postdoctorate studies are especially essential in biophysics since the field is very broad and, to be effective, the student must get experience in a number of fields of biophysics or biology. It is not unusual, for example, for a student from an honors background in physics or engineering to take four years to obtain a Ph.D. in molecular biophysics and then to spend two to three postdoctorate years in biochemistry. This crossing of disciplines is to be recommended. The problem now before us is to create environments that will attract scientists trained in this way back to Canada. Possible ways of doing this are:

(i) Increasing support for young scientists

The young scientist on returning to Canada may have great difficulty in getting a good research program established. If he does not succeed in doing this in the first two years he probably never will. To aid this scientist over this critical two-year period, universities should make the initial teaching load very small. In addition, the universities and granting agencies should find ways to support the young scientist with research equipment. As a very minimum he will usually require some $30,000 per year for two years to get a big enough program established to allow him to attract grants in his own right. In general, Canadian policy has not yet made this possible. In the US some of the agencies granting postdoctorate fellowships have recognized this need and have made available sums up to $10,000 per year to the fellow for the two years following the termination of his award. Fellowship-granting agencies in Canada should seriously consider this method of initial support for the young scientist.

(ii) Fostering group research

Biophysics is such a broad field that no one scientist can have a detailed knowledge of all the fields required in a biophysical research program. It is almost essential then that the biophysicist be associated with a large enough group to include the relevant specialists. The granting agencies must recognize this fact and encourage group research by group or block grants. Such block grants can also serve to protect the young scientist for the time necessary to estabish a going research program; under these conditions he can be expected to produce, otherwise his support should be removed.

(iii) Creation of a biophysics grant panel

Biophysics has come to exist as an independent discipline. In a number of universities, degrees are given in biophysics and increasing numbers of scholars are being attracted into interdisciplinary research. To ensure proper support for this research, granting agencies will need biophysicists to examine such research proposals. In the past, some biophysics applications have been rejected by physics panels as being biology, and by biology panels as being physics. This situation could be avoided in future by the creation of a separate biophysics grant panel.

The committee is strongly in favor of such a development.

12.9 IMPORTANT UNANSWERED QUESTIONS IN BIOPHYSICS

The important unanswered questions in biophysics can be classified under the following three broad categories, in each of which we can expect a major expansion in the next five years:

(i) Studies on single cells, and the relation between the cellular components and the macromolecules, DNA, RNA, and protein. This field of study is enormous, and important contributions are being made to it by both biochemists and biophysicists.

(ii) Studies on multicellular systems. This includes studies of muscle, nerve, brain, and control mechanisms. This type of biophysics is being carried out in biophysical, biochemical, and physiological laboratories. Progress in this field is made possible by the increase in our knowledge of the basic properties of single cells discussed above.

(iii) Engineering biophysics as applied to organ repair and replacement in humans. This type of biophysics is carried on in medical centers and in engineering centers related to medical groups.

APPENDIX

CLASSICAL PHYSICS SUBDIVISIONS

Acoustics

8001 Applied acoustics, instruments, and apparatus
8002 Architectural acoustics
8003 Ear and hearing
8004 Electroacoustics
8005 Infrasonics
8006 Mechanical vibrations and shock
8007 Musical instruments and music
8008 Noise
8010 Speech communications
8011 Theory of waves and vibrations
8012 Ultrasonics
8013 Underwater sound
8009 Other (specify)

Electromagnetism

8201 Antenna theory
8278 Electrical measurements and instruments
8202 Electromagnetic waves
8203 Electromagnetic wave propagation
8205 Electron microscopy, ion optics
8207 Magnetism
8210 Microwaves
8211 Physical electronics
8213 X-ray interactions
8214 X-ray phenomena
8215 X-ray technology
8209 Other (specify)

Mechanics

8401 Analytical mechanics
8402 Ballistics and flight dynamics
8403 Elasticity
8404 Friction
8405 High pressure physics
8406 Impact phenomena
8478 Instruments and measurements
8409 Other (specify)

Thermal Physics

8B01 Calorimetry
8B02 Heat transmission
8B03 High temperature physics

8B04 Low temperature physics
8B05 Temperature and its measurement
8B06 Thermal properties
8B95 Thermodynamics
8B07 Thermodynamic relations, equations of state
8B08 Thermodynamic tables
8B09 Other (specify)

Optics

8601 Atmospheric and space optics
8602 Color, colorimetry
8603 Fiber optics
8604 Geometrical optics
8605 Information theory, communications, image evaluation
8606 Infrared phenomena
8607 Interferometry
8608 Lasers
8610 Lenses
8611 Optical instruments, techniques, and devices
8612 Optical materials
8613 Photography illumination
8614 Physical optics
8615 Physiological optics
8616 Properties of thin films
8617 Radiometry, photometry
8618 Spectroscopy
8619 Other (specify)

Physics of Fluids

8701 Aerodynamics
8702 Aerosols
8703 Boundary layer effects
8704 Cavities and jets
8705 Compressible fluid dynamics
8706 Explosion phenomena
8708 Incompressible fluid dynamics
8710 Magneto fluid dynamics
8712 Rarefied gas flow
8713 Rheology (inc. plastic flow)
8714 Shock wave phenomena
8715 Structure and properties of fluids
8716 Superfluidity
8717 Transport phenomena, diffusion
8718 Turbulence
8719 Viscosity
8709 Other (specify)

Other Physics Specialties

8X53 Constants, standards, units metrology, conversion factors
8X02 Energy conversion problems
8X03 Field theory
8X04 High vacuum techniques
8X05 Many body theory
8X06 Mathematical Physics
8X11 Statistical mechanics and kinetic theory

APPENDICES

APPENDIX A

ABBREVIATIONS USED IN THIS REPORT

AECB	Atomatic Energy Control Board
AECL	Atomic Energy of Canada Limited
ANL	Argonne National Laboratory (Chicago, Ill.)
APS	American Physical Society
BNL	Brookhaven National Laboratory (Upton, N.Y.)
CAP	Canadian Association of Physicists
CARDE	Canadian Armament Research and Development Establishment
cc	Cubic centimeters
cm/sec	Centimeters per second
cps	Cycles per second
CRESS	Center for Research in Experimental Space Science (York Univ.)
CRNL	Chalk River Nuclear Laboratories
DIR	Defence Industrial Research
DOT	Department of Transport
DRB	Defence Research Board
DRTE	Defence Research Telecommunications Establishment
Elect.	Electrical
Eng.	Engineering
ETH	Eidgenössische Technische Hochschule (Zurich)
FTE	Full time equivalent
GeV	Giga (billion) electron volts
GIRD	General Incentive for Research and Development
GNP	Gross national product
IGY	International Geophysical Year
ING	Intense neutron generator
ISAS	Institute for Space and Atmosphere Studies (Univ. of Saskatchewan)
ISIS	International Satellites for Ionospheric Studies
ISRU	International Scientific Radio Union
IUPAP	International Union of Pure and Applied Physics
KEGS	Canadian Exploration Geophysical Society
km	Kilometer (s)
LAMPF	Los Alamos Meson Physics Facility

M$	Million dollars
Mech.	Mechanical
MeV	Million electron volts
NASA	National Aeronautics and Space Administration (US)
NRC	National Research Council
NRE	Naval Research Establishment
PARL	Prince Albert Radar Laboratory (DRB)
PdF	Postdoctorate Fellow
PNL	Pacific Naval Laboratory
R & D	Research and development
RCA	Radio Corporation of America
SRI	Space Research Institute (McGill Univ.)
TRIUMF	Tri-Universities Meson Facility
UCLA	University of California at Los Angeles
UK	United Kingdom
US	United States of America
UTIAS	University of Toronto Institute of Aerospace Studies
WMO	World Meteorological Organization

Appendix B

DIVISION COMMITTEES

1. *Astronomy*
   - J. L. Locke (Chairman), Division of Radio and Electrical Engineering, National Research Council of Canada.
   - D. A. MacRae, Astronomy Department, University of Toronto.
   - W. H. Wehlau, Astronomy Department, University of Western Ontario.

2. *Upper Atmosphere and Space Physics*
   - P. A. Forsyth (Chairman), Physics Department, University of Western Ontario.

3. *Classical Physics*
   - G. J. Thiessen (Chairman), Division of Applied Physics, National Research Council of Canada.
   - A. I. Carswell, Research Laboratories R.C.A. Victor Co. Ltd.
   - J. Consitt, Ernst Leitz Canada Ltd.
   - R. H. Hay, Aluminum Laboratories Ltd.
   - H. S. Ribner, University of Toronto Institute of Space Studies.

4. *Earth Physics*
   - R. D. Russell (Chairman), Geophysics Department, University of British Columbia.
   - J. H. Hodgson. Seismology Division, Dominion Observatory.
   - A. D. Misener, Physics Department and Great Lakes Institute, University of Toronto.
   - K. Whitham, Geomagnetism Division, Dominion Observatory.

5. *Meteorology*
   - A. W. Brewer (Chairman), Physics Department, University of Toronto.
   - W. L. Godson, Dominion Meteorological Service of Canada.
   - B. W. Boville, Meteorology Department, McGill University.

6. *Atomic and Molecular Physics*

- J. L. Kerwin (Chairman), Département de Physique, Université Laval.
- G. G. Cloutier, Département de Physique, Université de Montréal.
- A. E. Douglas, Division of Pure Physics, National Reaserch Council of Canada.

7. *Nuclear Physics*

- A. E. Litherland (Chairman), Physics Department, University of Toronto.
- G. M. Griffiths, Physics Department, University of British Columbia.
- R. Lévesque, Département de Physique, Université de Montréal.

8. *Elementary Particle Physics*

- W. T. Sharp (Chairman), Mathematics Department, University of Toronto.
- C. K. Hargrove, Division of Pure Physics, National Research Council of Canada.
- D. G. Stairs, Physics Department, McGill University.

9. *Solid State Physics*

- R. R. Haering (Chairman), Physics Department, Simon Fraser University.
- M. J. Jericho, Physics Department, Dalhousie University.
- R. J. McIntyre, Research Laboratories, R.C.A. Victor Company Ltd. Radio Corporation of America.

10. *Plasma Physics*

- M. P. Bachynski (Chairman), Research Laboratories Division, R.C.A. Victor Company Ltd.
- S. A. Ramsden, Division of Applied Physics, National Research Council of Canada.
- H. M. Skarsgard, Physics Department, University of Saskatchewan.

11. *Theoretical Physics*

- W. Opechowski (Chairman), Physics Department, University of British Columbia.
- J.-P. Bernier, Département de Physique, Université de Montréal.
- L. E. H. Trainor, Physics Department, University of Toronto.
- P. R. Wallace, Physics Department, McGill University.

12. *Biophysics*

- H. E. Johns (Chairman), Department of Medical Biophysics, University of Toronto.
- C. E. Challice, Physics Department, University of Calgary.
- J. A. McCarter, Biophysics Department, University of Western Ontario.
- E. Llewellyn-Thomas, Department of Biomedical Electronics, University of Toronto.

Appendix C

INITIATION AND AGREEMENT

(i) Initiation

PRIVY COUNCIL OFFICE — BUREAU DU CONSEIL PRIVE

SCIENCE SECRETARIAT — SECRETARIAT DES SCIENCES

Room 103, East Block,
Ottawa 4, Ontario.

May 25, 1966.

Dr. R.E. Bell, President,
Canadian Association of Physicists,
c/o Foster Radiation Laboratory,
McGill University,
Montreal 2, P.Q.

Dear Dr. Bell,

The Science Secretariat sees the need for a comprehensive review of physics research in Canada, setting forth present strengths and weaknesses, and recommending future patterns of growth which are (a) realistically possible, (b) foresee future needs, and which (c) may serve to correct inadequacies or imbalances that exist at present.

Studies have been made in the past by the C.A.P. High Energy Committee for Elementary Particle Physics, and a study is being made for Nuclear Physics by an NRC Special Committee under the chairmanship of Professor Duckworth, but what is seriously lacking is an overview which puts these fields into perspective with other fields of physics, such as astrophysics, atomic and molecular physics, plasma physics, solid state physics, etc.

Such a study might well begin from the "Pake Report" recently prepared for the Committee on Science and Public Policy of the U.S.A., accepting the definitions and technical reviews of fields of physics developed therein, but drawing out the differences in establishment, national objectives, and methods of support that may exist in Canada, or ought to exist, in the view of physicists.

In our view, such a study is likely to be done best by the physicists themselves. This letter is written to invite the opinion of the Executive of the C.A.P., as to whether the Association would be interested in undertaking to carry out a study of the nature outlined.

Because the Science Council will very soon now come into operation, there is a certain urgency to the preparation of the report. We envisage an intensive study over the next few months, with some individuals spending a measurable fraction of their time on the work, say up to five days a month, culminating in a report which might be submitted to the Science Council for consideration. The Secretariat would be prepared, on the receipt of a satisfactory proposal, to enter into an agreement with the C.A.P. to cover the costs involved in conducting such a study and preparing the report.

If the Association would indeed be interested and willing, the Secretariat would welcome their proposal, which should include an outline of the method of approach, the people involved, the time scale, and an estimate of the total financial assistance required to cover the costs of travel, consulting fees, secretarial help, printing costs, and so on. We would prefer that the C.A.P. designate a single individual as responsible for managing the project. Included in the proposal could be the effort required for regular follow-up of the statistical survey begun last year by the C.A.P. with the Department of Labour.

The Secretariat would, of course, be prepared to assist the C.A.P. in obtaining access to information and statistics where needed.

Very truly yours,

F. A. Forward,
Director.

(ii) Agreement

MEMORANDUM OF AGREEMENT DATED

THE FIFTEENTH DAY OF JULY A.D. 1966

BETWEEN:

HER MAJESTY THE QUEEN IN RIGHT OF CANADA
(hereinafter referred to as "Her Majesty"),

OF THE FIRST PART,

AND

The Canadian Association of Physicists
(Dr. J.M. Robson, President),

OF THE SECOND PART.

WHEREAS the Privy Council Office (Science Secretariat) requires assistance in carrying out a survey, objectives, and outlook on physics in Canada and WHEREAS the Canadian Association of Physicists (Dr. J.M. Robson) has agreed to carry out this work. NOW THEREFORE THIS AGREEMENT WITNESSETH that the parties hereto, in consideration of the covenants hereinafter contained, covenant and agree with each other as follows:

The Canadian Association of Physicists (Dr. J.M. Robson) will carry out a comprehensive review of physics research in Canada, in Universities, Government and Industry. Will assess the significance of research in the various subdivisions of physics and the balance between them, taking into account the problems of financial support, personnel and organization. Will study the future of physics research in Canada and make a considered projection for the next few years with particular reference to the objectives of the programmes. Will provide a comprehensive draft report in typewritten form. Subdivisions of physics to be covered include the following, not necessarily with the same breakdown:

- Atomic & Molecular Physics
- Elementary Particle Physics
- Nuclear Physics
- Plasma Physics
- Solid State Physics
- Astronomy (including astro-physics & radio-astronomy)
- Upper atmosphere and space
- Meteorology
- Earth Physics
- Theoretical Physics
- Classical Physics
- Biophysics Physics

The contracting parties agree to a fee for the above mentioned work of $32,000 payable to the Canadian Association of Physicists as follows:

$10,000 on signing the contract
$10,000 on November 15, 1966
$12,000 on completion of the project

IN WITNESS WHEREOF Mr. H.B. Stewart, Director of Administration, has hereunto set his hand on behalf of Her Majesty the Queen in Right of Canada and Dr. J.M. Robson has hereunto set his hand on behalf of the Canadian Association of Physicists the day and year first above written.

Witness

H.B. Stewart

Witness

J.M. Robson,
President,
Canadian Association of Physicists

APPENDIX D

QUESTIONS FOR THE GUIDANCE OF SUBCOMMITTEE CHAIRMEN

SURVEY AND OUTLOOK OF PHYSICS RESEARCH IN CANADA

Each Divisional Committee has been asked to consider the following questions as applied to physics in Canada:

1. Define and describe the field covered and its boundaries.
2. Outline its history which has led to the Canadian national.
3. Estimate as well as the committee can the present level of activity in terms of physical manpower and of dollars.
4. Report on the number of students receiving doctorates in each divisional area.
5. Does your committee feel that in your division there is a proper distribution of the activity among industrial laboratories, government laboratories and the universities?
6. What are the significant unanswered questions in your field and what new opportunities do recent advances in general knowledge and technology present for advances in the field?
7. What substantive questions are Canadian physicists now trying to answer in this branch of physics? Has the attack on each question just begun, is it nearing an answer, or what?
8. What is the significance and importance of your field for other branches of physics, for science in general, and for Canadian technology?
9. Indicate any special considerations relative to your branch of physics which the answer to the foregoing questions do not adequately express.
10. What does your committee consider to be appropriate input of dollars and newly trained physicists into this field each year for the next 5 years beginning with 1967? What can your committee say about the 5 years following that period?
11. Discuss your committee's opinion on grant support mechanism in Canada.

APPENDIX E
MEMORANDUM ON JOINT INSTITUTES FOR UNIVERSITY RESEARCH*

BRIEF SUBMITTED BY H. L. WELSH, UNIVERSITY OF TORONTO

The Second World War and the so-called "cold" war have caused a very rapid development of some phases of science and technology. In certain areas of basic science, notably nuclear physics and its extension, high energy physics, this situation has created a dilemma for the universities by making it difficult for them to compete with government organizations which have the government treasury more readily at their disposal. It is, however, axiomatic that if the universities are to carry out their traditional function of extending the frontiers of knowledge, facilities for nuclear research, even if they are very expensive, must be made available to university scientists.

The dilemma has been solved to a large extent in the United States and the United Kingdom either by giving massive financial support to selected individual universities or by setting up government-sponsored research establishments which are used by, and at least partially controlled by, a number of co-operating universities. The dilemma has not yet been solved in Canada and, unless steps are taken immediately, Canadian universities cannot be expected to occupy more than a mediocre position in physics on the roster of the universities of the world.

The present memorandum will attempt to show that joint institutes under the sponsorship of the Federal Government are the most feasible solution of the nuclear physics problem, and perhaps other research problems, in Canada. To this end a short description of the functioning of some of the well-known co-operative nuclear enterprises in other countries will be given.

(a) *Brookhaven National Laboratory* (Long Island, New York).

This laboratory was set up at the end of the war to provide joint facilities for expensive nuclear and high energy physics research for universities in the north-eastern part of the U.S.A. It is operated by

*Reproduced with permission from Report of the Commission to Study the Development of Graduate Programmes in Ontario Universities, by G.O. Arlt, F.K. Hare and J.W.T. Spinks, Department of University Affairs, Toronto (1966).

Associated Universities Inc. (A.U.I.), a group of nine universities, and is financed by the federal government through the Atomic Energy Commission. The Board of Governors, consisting of two members from each participating university, appoints the Director of the Laboratory and controls the budgeting and general policy. The laboratory can be used by any scientist, whether or not he is a member of one of the participating universities, provided the proposed project is approved by the Director and his advisers.

Although nearby universities were initially the chief users of Brookhaven National Laboratory, about forty universities (300 to 400 university scientists) now use the high energy particle accelerators for about 70% of their running time, and the geographic spread of users is still increasing. Parts of projects carried out at individual universities are financed by Atomic Energy Commission grants to the universities concerned.

(b) *Centre Européen de Recherche Nucléaire (CERN),*
Geneva, Switzerland.

In many ways CERN is like an international B.N.L. Each of the fourteen member nations appoints two delegates, who in turn appoint a Director. It is financed by the member nations with the intent that high energy facilities would be available to physicists of countries which could not by themselves afford the largest machines. It would appear that CERN has a higher proportion of "in-groups" than B.N.L., so that research groups coming for short periods to the laboratory do not perhaps receive as much consideration as obtains at other similar laboratories.

(c) *National Institute for Research in Nuclear Science* (NIRNS),
near Harwell, England.

This laboratory is set up on a plan similar to B.N.L., but without such a formal arrangement as the A.U.I. The policies are set by committees consisting mainly of university staff members so that the universities have a large say in the direction of the Institute. The financing of all NIRNS projects, on or off that site, is done by NIRNS which receives money from the Government.

The proximity of NIRNS to the Atomic Energy Research Establishment at Harwell greatly facilitated the setting up to the Institute. Its nearness to Oxford University has aided in setting the direction of the Institute firmly towards its avowed goal of assisting universities.

(d) *Argonne National Laboratory* (Chicago, Illinois).

The direction of this laboratory, which contains one of the largest accelerators in the United States, has recently been divided between the University of Chicago, which operates the laboratory, the Atomic Energy Commission, and the Mid-Western Universities Research Association. The facilities of this laboratory are now being used by a small high-energy physics group at the University of Toronto.

As already stated, large funds are given also by the U.S. Government to selected universities for large nuclear physics installations. The largest of these is the $120,000,000 electron accelerator now being built at Stanford University. However, there seems to be a prevalent opinion in the U.S.A. that "large" machines (i.e., with a total cost of more than, say, $15,000,000) in the future would not be put in the hands of individual universities but only in national laboratories or joint institutes.

The feasibility of joint institutes for university research in high energy physics appears to be proven from the foregoing examples, especially B.N.L. and NIRNS. It is certain that the principle of joint institutes is the only solution for high energy physics, or *even for expensive low energy nuclear physics installations,* in Canadian universities.

The present situation in nuclear physics in Canada should be outlined briefly. The most extensive nuclear physics facilities are located in the laboratories of Atomic Energy of Canada at Chalk River, Ontario, and are entirely under governmental control. Atomic Energy of Canada Limited has done signal service for the country in developing nuclear power, and a large research group in basic nuclear physics has been a necessary accompaniment of this development. The Chalk River Laboratory is the only one in Canada which can keep up to date in low energy nuclear physics; the latest machine for this type of research (M.P. Van de Graaf accelerator), which costs $5,000,000, will be installed at Chalk River in 1966. There is at present no high energy accelerator in Canada, a $20,000,000 joint universities proposal by the Canadian Association of Physics having been turned down in 1959.

A.E.C.L. has recently prepared a proposal for an Intense Neutron Generator (ING) which would probably cost in the neighbourhood of $100,000,000. Although ING is basically a nuclear power project it would furnish many opportunities for basic research. Canadian universities have been invited to participate in the extensive preliminary planning of the project and, eventually, in the use of its research facilities.

Although the Chalk River laboratories have established a world-wide reputation for Canada, especially in nuclear power matters, no parallel development has taken place in Canadian universities. Ten universities have installed or have on order low energy nuclear machines, none of which exceeds $1,000,000 in cost. The National Research Council has assisted the universities by paying a part of the capital expenditure for these installations. Although useful research can be done with these smaller machines, it is certain that no laboratory in Canada except that at Chalk River will be in the forefront of advances in nuclear physics. This means that even in low energy nuclear physics Canadian universities are at a great disadvantage.

If the present trend continues it is apparent that, even if substantial funds are made available for nuclear physics, these will be spread so thinly over many universities that no high level of research will be achieved. Since even smaller universities have quite legitimate aspirations in this important field of physics research, the assignation of two or three universities as the only centres of large-scale nuclear research in Canada does not appear to be a satisfactory solution.

It is therefore proposed that a system of joint institutes should be set up somewhat along the following lines:

(a) Atomic Energy of Canada should be asked to establish and maintain accelerator laboratories at two or three strategic locations, near large centres of population, across Canada.

(b) University scientists would constitute a large part of the scientific personnel of these "regional" laboratories and would participate fully in the scientific direction.

(c) The first installations might be the latest types of low energy nuclear physics machines, to be followed by a high energy installation as soon as possible in at least one of the laboratories. Alternately, if the ING project of A.E.C.L. materializes, the regional laboratories might engage in ancillary programmes of interest to the main project.

This scheme has many advantages of which the following might be mentioned:

(1) Government scientists will no longer be accused of taking the lion's share of the government's appropriation for basic research. The following is a quotation from the Glassco Report (vol. 4, p. 226): "In spite of an outstanding contradiction represented by the 'pure' laboratories of the National Research Council, it is generally

conceded that pure basic research is best done in the universities. Not only is the scholarly atmosphere and academic freedom conducive to scientific investigation, but the conduct of research within educational institutions has an important effect on the training of future scientists. These circumstances lead your Commissioners to the view that in the field of pure basic research government activity should not be increased, and the enlargement of existing, or the creation of new, laboratories of this type should be avoided."

(2) The need of university scientists for the best research facilities will be met, and the desire of many government scientists to have university connections will be satisfied. In fact, the university and government scientists become to a large extent a single body.

(3) Once a co-operative scheme of this type is begun the possibilities for future development become almost limitless. By eliminating the competition of government and university scientists for funds for nuclear research, the level of attainment can become very high indeed.
By drawing university engineering departments into the scheme and inviting the co-operation of industrial concerns, the institutes might undertake the planning of future devices and thus become a potent influence in Canada's economic development. It has been said that the Brookhaven accelerators were built by Canadian brains and American money. It would be greatly to our advantage to export Canadian accelerators rather than Canadian brain-power.

The possibilities of university participation in government-sponsored institutes are by no means confined to nuclear physics. Installations for optical or radio astronomy are very costly, and there are several cases of government-university co-operation in this field, particularly in the United States. Examples are:

(a) *The Kitt Peak National Observatory,* near Tucson, Arizona.

This observatory, equipped with several large optical telescopes, is operated by Associated Universities for Research in Astronomy under contract with the National Science Foundation. The observatory's facilities are available to astronomers in any university and, by charter, 60% of the telescope time is allotted to visiting scientists.

(b) *The National Radio Astronomy Observatory,* Green Bank, West Virginia.

This large establishment is sponsored by the National Science Foundation with actual operation being carried on by Associated Universities, Inc.; the same body which operates the Brookhaven National Laboratory. The observatory has a permanent scientific and technical staff, but university scientists are responsible for a large portion of the research carried on.

It should be noted that these examples have not been entirely ignored by the government astronomers responsible for the planning of the Queen Elizabeth II Observatory, to be set up by the Observatories Branch of the Department of Mines and Technical Surveys. General policy in the operation of the observatory will be based on the advice of an Associate Committee composed of astronomers and scientists from universities and government laboratories. The situation of astronomy in Canadian universities is rather anomalous in that the University of Toronto is the only university at the moment which has staff and facilities for conducting research and graduate work in astronomy.

Finally, one might mention another general area in which co-operation between universities and government would be most desirable. Some fields of research, such as meteorology, oceanography, etc., require extensive data-gathering facilities, the data then being worked over by research scientists. It seems obvious that university scientists should not get very much involved in actual data-gathering, but they would of course like to have the data at their disposal. For example, a large Great Lakes Institute, say, at Toronto operated by either the Provincial or the Federal government would enable the University of Toronto and other Ontario universities to engage in worthwhile limnological and oceanographic research. Facilities at the Bedford Oceanographic Institute at Halifax might also be placed at their disposal. Since government establishments of this type usually have difficulty in obtaining adequate scientific staff, it would clearly be to the government's advantage to sponsor research and graduate studies in these fields in universities. Indeed, it might be said to be characteristic of the Canadian scene that, while reasonable funds are available for government research, the universities which are the source of the scientific man-power have had very mediocre financial support.

It is clear that, while there are not limitless government funds available for university science, the funds which are, or will be made, available can be used to much better advantage. In the more expensive forms of research a close co-operation of government laboratories with the universities seems most desirable.

APPENDIX F

SUBMISSIONS AND ACKNOWLEDGEMENTS

The Steering Committee is indebted to many Canadian scientists and others who contributed to the substance of this report. In particular, it acknowledges useful submissions from the following people: Dr. W. B. Lewis and J. Mullin of AECL (see Section 7, Part II for frequent references to this submission); Dr. S. Breckon, Memorial University; Dr. F. L. Curzon, University of British Columbia; and Dr. J. D. Keys of the Department of Energy, Mines and Resources. It also acknowledges valuable assistance with statistical data from Drs. F. W. Simpson and W. Petrie of DRB, Mr. G. W. Donaldson of NRC, and Mr. R. K. Brown of the Department of Industry and Defence Production.