NUCLEAR AND RADIATION CHEMISTRY

Report of Committee 12

on

Survey of Chemical Research

and Development in Canada

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General Introduction:

The subjects of nuclear chemistry and radiation chemistry have long been regarded, particularly by those who do not themselves work in these fields, as siamese twins, linked together in time and space. It is certainly true that the war time atomic energy project in Canada gave rise to the study of radiation chemistry in this country, and also to the rebirth of nuclear chemistry; the latter subject having its origin in the pioneering work of Rutherford and Soddy at McGill in the early years of this century. It is also a truism that these disciplines are today found together in atomic energy establishments not only in Canada, but elsewhere in the world; it is not surprising therefore that a single committee to survey these fields should be thought of as natural and appropriate.

Nevertheless, these subjects are in fact distinct and separate disciplines, as will be apparent from the definitions and discussions presented in Parts I and II of this report. To anticipate these definitions very briefly, radiation chemistry (Part I) is the study of chemical reactions which are induced by absorption of ionizing radiation. It is most closely related to the well known discipline of photochemistry. Nuclear chemistry (Part II) may be regarded as the study of the properties and the reactions of the atomic nucleus, and is therefore a close relative of nuclear physics. The familiar and overworked term "radiochemistry" is avoided because it has become so ill-defined and ambiguous as to be almost meaningless.

Collection of Data:

Two basic questionnaires appropriate for each of the two disciplines were prepared and each of these in turn was produced in two forms, one for university respondents and the other for workers

in government or industrial laboratories. These questionnaires were then sent to all known practitioners of these subjects in Canada. The questionnaire was accompanied by a full list of recipients and each respondent was asked to add the names of other persons the committee may have overlooked. All the data in this report was obtained in this way.*

The response to our questionnaires was extremely good; 80% of those polled replied, generally in great detail, and supplied the committee with a large variety of opinions. We believe that the 20% who did not reply represented mainly those who are only marginally in one or other of these fields; in a few cases, questionnaires were sent to persons formerly active in these areas; not unexpectedly, not all of these persons replied. In short, we have facts and opinions from practically the entire Canadian scientific community engaged in research and development in these subjects.

The committee is aware of the use in other surveys of the concept of a full time equivalent (F.T.E.) according to which a faculty member who states that he spends 25% of his time on research activities would be counted as 0.25 F.T.E. Again, another faculty member who spends 25% of his time divided between two fields might be counted as 0.12 F.T.E. in each of these fields. Similar division of time and interest could be made for persons in government research laboratories.

No calculations of F.T.E. have been made in compiling this report. We have adopted the pragmatic view that a scientist who declares himself to be practicing in one or other of these areas, and moreover is known to be from other evidence (e.g. publications known to the committee), is counted in fact as a practitioner and tabulated accordingly. We recognize that this practice leads to an overestimate of the number of scientists involved, and that the same person might be counted and listed again by another committee as active in their field of study. We know, for example, of several persons having active programs in radiation chemistry who also work and publish in the fields of gas phase kinetics or in the field of high polymers. However, we do not regard these admitted inconsistencies as serious, inasmuch as no crucial arguments are developed or conclusions drawn from manpower data adduced in this part of the survey.

*Illustrative comparisons of Committee 12 and C.I.C. data are given in the Appendix, Page 38, Table IX.

PART I - RADIATION CHEMISTRY

Definition and Scope:

Radiation chemistry may be defined as the study of chemical reactions induced by the absorption of ionising radiation. The term radiation includes high energy charged particles as well as X- or γ-rays. The source of the radiation may be a radioactive nucleus or a high energy machine --cyclotron, betatron, or linear accelerator.

Chemical reactions resulting from nuclear transformations of the atoms of a reactant molecule are discussed under nuclear or hot atom chemistry and are not included in radiation chemistry as such. By tradition the radiation chemist has also limited himself to the use of particle or photon energies which are incapable of initiating nuclear transformations.

In passing through matter ionising radiation loses its energy in producing free electrons and a variety of ions and neutral excited molecules. The observed chemical change in the irradiated medium is the net result of the reactions and interactions of all of these species. It is at once apparent that any radiation-induced reaction is far more complex than a typical photochemical reaction. In these latter reactions, the wave-length of the irradiating photons is usually chosen to produce a single discrete neutral excited state of the absorbing molecule. While the inherent complexity of radiation chemistry represents a distinct disadvantage,there are a number of intrinsic characteristics which have spurred on its development. In the first place, the use of highly penetrating X- or γ-radiation at present provides one of the best and in many instances the only method for creating and studying the reactions of ions and free electrons in solids, liquids and gases at normal pressures. Secondly, carefully designed radiation-chemical experiments can provide information about the reactions of highly excited states of neutral molecules. These states are not accessible to study by the techniques of ultra-violet or even vacuum U.V. photochemistry.

Historical Development in Canada.

Chemical effects of ionising radiation were observed simultaneously with the discovery of radioactivity at the turn of the last century. However, apart from the pioneering studies of Mund, Lind, Lea and their collaborators little quantitative work in this field was done until high intensity radiation sources became readily available at the end of the second world war. The building of the Chalk River laboratories, beginning in early 1943, gave Canadian chemists a unique opportunity to contribute to the development of this new and challenging field. Furthermore, an enormous incentive was provided by the Canadian Government's decision to develop nuclear power reactors. Because of the earlier contributions of scientists like the late E.W.R. Steacie, Canada already had strong schools in the fields of photochemistry and kinetics. The experience carried over by graduates of these schools was undoubtedly a major factor contributing to the successful development of radiation chemistry in Canada.

Most of the early work was done in the Government laboratories at Montreal, Chalk River and Ottawa. However, Professor J.W.T. Spinks, who was then an established photochemist at the University of Saskatchewan, and during the war years was a part of the group in Montreal, (see Part II) realized the potential of this new science, and began the training of graduate students in the field of radiation chemistry in the early 1950's. In addition to chemical studies, much basic work on the ferrous sulphate dosimeter was conducted in collaboration with Dr. H.E. Johns, who was then also at the University of Saskatchewan in the Department of Physics. Many Saskatchewan alumnae have continued to make significant contributions to radiation chemistry both in Canada and elsewhere. Dr. Spinks' book with R.J. Woods, "An Introduction to Radiation Chemistry" is still the only general text on the subject.

Since the initial development in the late 1940's, radiation chemistry has grown into one of the major research fields of Canadian physical chemists. There are at present twelve radiation chemists

working in the three laboratories of AECL. In addition, three radiation chemists are employed by the Defence Research Board, and four by the National Research Council Laboratories in Ottawa. Thirteen Canadian universities now have staff members who are actively engaged in research in this area. At least ten universities offer chemistry courses with some radiation chemistry content. Eight of those at which radiation chemistry research is conducted offer courses specifically in this field, most of these being at the graduate level. Our survey did not reveal any significant research or development involving radiation chemistry in Canadian industry.

Manpower

Tables I and II contain statistical information on the number of persons engaged in radiation chemistry research in Government laboratories and universities in Canada. (As indicated earlier, all the data in this report was obtained from the questionnaires prepared by Committee 12*).

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*Illustrative comparisons of Committee 12 and C.I.C. data are given in the Appendix, Page 38, Table IX.

TABLE I

Distribution of Manpower in Government Laboratories - Radiation Chemistry

Institution	Dept.	Prof. Staff	Technicians
DRB	Defence Chemical and Biological Research Labs	3	3
AECL	Whiteshell, WNRE	4	4
AECL	Chalk River Nuclear Laboratories	6	6
AECL	Commercial Products Division, Ottawa	2	5
NRC	Pure Chemistry Division Ottawa	2	-
NRC	Applied Physics Division Ottawa	2	-
	Totals	19	18

WNRE = Whiteshell Nuclear Research Establishment, Atomic Energy of Canada Ltd., Pinawa, Manitoba.

Manpower Statistics for Radiation Chemistry Research in Canadian Universities

University	Dept.	Prof. Staff	Present No. of students		Students Graduated Last 5 years		Next 5 yrs.	
			M.Sc.	Ph.D.	M.Sc.	Ph.D.	M.Sc.	Ph.D.
Alberta	Chem.	2	-	7	-	7	1	8
Brock	"	1	-	-	-	-	-	-
B.C.	"	1	3	-	1	-	5	5
Calgary	"	1	1	1	1	4	2	3
Laval	"	1	-	3	2	2	4	6
Manitoba	"	1	1	1	-	-	7	2
McGill	"	2	-	-	-	-	-	7
McMaster	Chem.Eng.	1	1	-	4	1	4	2
Queens	Chem.	1	1	-	-	-	3	2
Saskatchewan	Chem.	4	3	3	10	2	12	6
Toronto	Biophysics	1	-	2	-	-	n/a	n/a
Toronto	Chem.Eng.	2	-	3	n/a	n/a	n/a	n/a
Windsor	Chem.	1	2	-	-	-	1	5
Waterloo	Chem.Eng.	1	1	2	n/a	n/a	n/a	n/a
Totals		20	13	22	18	16	39	46

n/a = no information

The graduate programs established at the Universities of Alberta, Calgary, Laval and McMaster in the early 1960's have already produced a significant number of graduates. Radiation chemistry programs at Brock, B.C., Manitoba, McGill, Queen's and Windsor are just getting underway. Thus it is not surprising that the number of M.Sc. graduates for the next five years is expected to be double that for the previous five years and the number of Ph.D.'s to be increased threefold. However, much depends on the supply of graduate students, which has shown signs of waning in the past two years, and the estimates are probably overoptimistic by about 30%. At the present time, three chemical engineering departments are active in the field. This is encouraging since a need for greater emphasis on applied radiation chemistry seems to be apparent.

It is estimated that about seventy per cent of the students who graduated in the past five years have remained in Canada. Thirty per cent of these found jobs in universities, 45% in government labs and 25% in industry. Of those who left Canada, fewer (about 25%) went into universities and about equal proportions of the remainder into government and industry.

It should be emphasized that graduate work in radiation chemistry provides a very broad training. Students normally acquire a sound basic knowledge of the fields of mass spectrometry and photochemistry, along with a thorough grounding in kinetics and analytical chemistry. They are not therefore limited to this field after graduation and an appreciable number change. However, this is compensated by the fact that kineticists and photochemists not infrequently switch to radiation chemistry. Actually an increasing number of chemists are becoming engaged in photochemistry and radiation chemistry simultaneously.

Radiation chemistry has had a significant impact on science and nuclear technology in the last 10 years, and its growth is therefore likely to continue. It is estimated that 6 more university staff with interests in this field may be required by 1972. Industry and government laboratories may absorb another 15 Ph.D. graduates. Thus the supply of

Ph.D. graduates estimated in Table II appears to be sufficient, assuming that the necessary number of incoming students is available and that, as in the past, 70% remain in Canada after graduation. This situation represents a healthy comparison to the last 15 years, for of the 39 professionals currently working in universities or government laboratories, at least 30% came to Canada after having received the majority of their training elsewhere.

Financial Support

(i) Capital Funds

The government laboratories listed in Table I provide rather adequate financial support for research projects conducted within their precincts. This survey shows that in these laboratories, on the average, about $60,000 is expended in launching a new research project involving one professional chemist. It must be emphasized, however, that this sum includes large pieces of equipment such as Van de Graaffs and Febetrons, and these are usually shared by other workers in the same laboratory. Of course, new projects are not started by every staff member every year; over a period of years, the average injection of funds for capital equipment has been approximately $6,000 per staff member per year.

Table III shows the financial support provided for radiation chemistry research in Canadian universities. Not unexpectedly, the university radiation chemist usually has a harder time establishing himself with initial equipment he needs than does his colleague in the government laboratory. Half of the radiation chemists who reported in this survey stated that they had received no funds for major equipment from their universities over the past five years. The overall annual average was about $3,000. The overall average of capital equipment grants from NRC and other government agencies during the past five years was $4,400. Only one person indicated regular support from industry. Another reported a non-recurring $20,000 industrial contribution for equipment.

The present cost of an AECL Gamma Cell, a commonly used radiation source, is $17,000. While AECL has loaned several of these, the average university chemist has to meet the entire cost from his research grant. Those who establish research programs in departments without mass spectrometers and the other necessary analytical instrumentation are placed in an even more difficult situation. There is in fact a very real need for funds to purchase items of equipment in the $10,000 to $20,000 range. In this connection, government laboratories in general are able to mobilize their capital funds as required, so that new members of staff may begin significant research activity within a few weeks or at most, months, following their arrival in the laboratory. This capability is almost completely absent in university laboratories, and its absence contributes to much frustration and sheer waste of the talents of the young persons concerned. This problem, which is not unique to radiation chemistry, deserves more careful study than it appears to be receiving at present.

(ii) Operating Funds

The average federal operating grant to university radiation chemists in 1966-7 was $8,800. (This figure is exclusive of graduate student support). Other sources of operating funds are indicated in Table III, together with annual expenditures for major equipment, averaged over the last five years. In estimating the university contributions shown in Table III, it has not been possible to estimate with precision the indirect contributions, e.g. library, space, heat, light, salaries etc. Only direct earmarked support has been included. Taking account of the number of faculty members involved, it appears that the total annual expenditure in all Canadian universities for radiation chemistry research was approximately $300,000. in the 1966-7 academic year.

TABLE III

Expenditures per Faculty Member in Canadian Universities on Radiation Chemistry Research

Source of Funds	Annual operating Fund, 1966-7	Average Annual Expenditure for Major Equipment, over last 5 yrs.
University	$1,500.	$3,300.
Federal Govt. (mainly NRC or DRB)	8,800.	4,400.
Prov. Govt.	400.	-
U.S. Govt.	600.	-
Industry	300.	500.
Total per staff member	$11,600.	$8,200.

Canadian Contributions and Prospects

Radiation chemical technology has been an essential component in the development of all types of nuclear reactors. In the early days at Chalk River, particular emphasis was placed on the radiation chemistry of water because of its use as a moderator and coolant. The continuing success of the NRX reactor at Chalk River, which began operating in early 1947, is an enduring monument to the success of the efforts of the radiation chemists of those days. More recent work at Chalk River and elsewhere in the world has shown that aromatic compounds are about two orders of magnitude more stable to radiation than are aliphatic hydrocarbons. This observation culminated in the design and construction of the Whiteshell WR-1 reactor, which uses terphenyls and related aromatic compounds as coolants. It is extremely unlikely that the successful development of WR-1 would have been possible without the earlier detailed

investigations of the extent of chemical degradation of these coolants under reactor conditions. Much of this important research was done at Chalk River. Extensive work on the determination of radiation field intensities in reactors was also required, and in this area radiation chemists at Chalk River again made a significant contribution.

It was pointed out in the Introduction that radiation can be used to produce electrons and ions as well as neutral excited molecules. An apt demonstration of this was obtained by observing the radiation-induced conductance of liquid hydrocarbons. Pioneer work on this novel and interesting aspect of the field was conducted by chemists at the University of Alberta. More recent experiments at Chalk River and Whiteshell have shown that hydrocarbon glasses at low temperatures become photo-conducting after exposure to ionising radiation. This is due to the photorelease of electrons trapped in the hydrocarbon matrix during the irradiation process. While these phenomena are primarily of fundamental interest, they also demonstrate the potential use of radiation as a catalyst for ionic reactions. As direct evidence for this, it has been shown in Germany that the capture of electrons in irradiated hydrogen cyanide leads to an anionic radiation-induced polymerisation. In Canada, fundamental work is being done both at McMaster and Laval on the radiation-induced polymerisation of styrene and isobutene. Both of these reactions are believed to proceed by cationic mechanisms, and there are interesting technological possibilities for the tailoring of polymer structure by the controlled application of radiation dose and electrical fields.

There are other chain reactions in which radiation may be employed as a catalyst. One of these, the hydrobromination of ethylene, is currently used on an industrial scale by the Dow Chemical Co. in the United States. Some of the earliest work on this reaction was done at the University of Saskatchewan. Another chain reaction of commercial potential is the chlorination of methane, and the polymerisation of inorganic materials by radiation is under study at AECL's Commercial Products Division.

Future technological advances may also be derived from studies of radiation-induced reactions at interfaces. Interesting studies of the radiolysis of vapours adsorbed on silica gel are in progress at Chalk River. Radiation-graft co-polymerisation may be used to modify the surface properties of natural and synthetic fibres. Work along these lines at AECL's Commercial Products Division, McMaster and Toronto has already shown considerable success. Related basic studies on modification of the properties of polymeric materials on exposure to ionizing radiation are in progress at McGill and Waterloo. These studies are of particular importance in the elucidation of problems in polymer science.

In spite of the favourable illustrations presented above, the potential of radiation chemistry for synthesis on a commercial scale must not be oversold. The high cost of radiation at present limits industrial applications to the production of very expensive materials or to the catalysis of long chain reactions such as polymerisation or the hydrobromination reaction already mentioned. Although the cost factor may become less serious in the future as a result of the accumulation of γ- sources in fuel disposal sites at nuclear power stations, much more fundamental and applied research will be required before a wide scale of industrial radiation chemical processes can be expected. The present rate of development of fundamental research in Canada appears to be adequate to support this. On the other hand, although excellent applied work has been done, much of it has been related to reactor technology and there is a need for greater effort in other areas. Probably the most effective approach would be the involvement of industry in joint programs with government or university laboratories. We note in this connection that Co-60 gamma rays are now used commercially in Canada (Ethicon Ltd., Peterborough) to sterilize sutures for medical use. Other commercial radiation chemical applications in Canada include radiation processing of heat shrinkable polyethylene films for wrapping food products (W.R. Grace and Co., Cooksville, Ontario). For the last seven years, the Commercial Products Division of AECL has been operating a Mobile Demonstration Irradiator,

which continues to assist groups to determine the effects of radiation on their products. It has been used to irradiate onions, potatoes, fish, mushrooms etc., and some commercially significant applications appear likely to emerge.

The early work of Lea and Gray in Britain showed that those parts of radiation chemistry concerned with aqueous systems and macromolecules should have special relevance to our understanding of the action of radiation on living cells. Thus there has always been a strong and beneficial liaison between radiation chemists and radiobiologists, and there is good reason to expect highly significant developments in this borderline area in the future. A considerable effort has already been devoted to studies of the free radicals formed by radiation damage in organic and biological materials. Scientists in the Department of Biophysics at the University of Toronto, and in the Chemistry Department at the University of Saskatchewan are working in this field, using the relatively new electron spin resonance techniques as a method of detection. Chemists at the Shirley Bay laboratory of DRB are using this technique to study free radicals formed from amino acids in aqueous systems. They are primarily concerned with the mechanism by which certain sulphur containing amino-compounds protect mammalian systems against radiation effects. The radiolysis of these protective agents is also being studied at the University of Calgary and at Shirley Bay by conventional techniques. The latter laboratory is also responsible for an extremely sensitive tissue-equivalent dosimeter.

The key problems in the radiation chemistry of liquids and solids arise mainly from our lack of direct knowledge of the behaviour of electrons in condensed media. At present, the details of their mechanism of energy loss and the spatial distribution of positive ions, electrons and excited molecules at the time when they become susceptible to chemical reaction are arrived at mainly by inference from the results

of gas phase experiments. The radiation-conductivity experiments and other associated work at the University of Alberta have provided a significant improvement in our understanding of this aspect of radiation chemistry. Information about radiation effects on solids has come from spectroscopic and electron spin resonance investigations at Chalk River of trapped electrons and free radicals in organic glasses. Studies of the decomposition of inorganic compounds by conventional and by electron spin resonance methods have been performed at the University of Saskatchewan.

Another problem of more general importance in the science is the lack of quantitative information regarding charge and energy transfer processes in condensed media. Valuable contributions in this area were made through the use of isotopically labeled hydrocarbons in experiments at Chalk River. Experiments concerned with energy and charge transfer to hydrocarbons sandwiched in inert gas matrices were also initiated there, and these have since been continued at Queen's University.

At the present time the first 10^{-9} second of the lifetime of an electron in a liquid medium remains a mystery. However, the newly developed technique of pulsed radiolysis permits observations of irradiated solutions at times of the order of 10^{-8} second after a sharp intense pulse of radiation, lasting about 10^{-9} second, has been delivered. When samples of very pure liquid water are subjected to pulse radiolysis a transient blue coloration is observed. Theoretical and chemical studies have shown that this is due to the presence of electrons trapped in sheaths of polarised water molecules. The discovery of these solvated electrons in American and British laboratories is undoubtedly the most significant development in the recent history of radiation chemistry. Extensive work on their reactions with a wide range of biological, organic and inorganic compounds has already been done elsewhere, and linear accelerators for such studies have recently been established at the Universities of Saskatchewan and Toronto, in collaboration with Departments of Physics.

Most radiation chemists agree that the technique of pulsed radiolysis affords one of the greatest opportunities for further developments in their field. Thus the establishment of at least one well equipped and technically supported linear accelerator facility in Canada, specifically for pulsed radiolysis studies would seem highly desirable. This might best be done on a co-operative basis amongst chemists, and should be so administered as to be accessible to workers in both government laboratories and in university departments. It is estimated that a facility of the most modern design, completely housed, would cost approximately $500,000.

Studies of the reactions of solvated electrons and other reactive species in irradiated aqueous systems are in progress at the Universities of Manitoba, Saskatchewan and Windsor. Striking experiments recently performed at the University of British Columbia have demonstrated that solvated electrons may be intermediates in many familiar chemical processes such as: the solution of alkali metals in water, redox reactions and cathodic reductions. This particular Canadian contribution is unique, and may lead to a new and better understanding of redox reactions and electrode processes in aqueous and other media.

There is much more direct information relating to the behaviour of electrons in gaseous systems. Because of electron impact spectroscopy and mass spectrometry, the energy loss processes of fast electrons and the identities of the primary positive ions and excited molecules in an irradiated gas can often be inferred with a reasonable degree of certainty. Reactions of positive ions with neutral molecules are also readily accessible to study by mass spectrometry, and research in this area has been extensive. Chemists at the University of Alberta have recently employed high energy electron, proton and alpha-particle beams in mass spectrometer ion sources. Their results are of particular importance to our understanding of the energy loss processes in irradiated systems. A further development from this laboratory is a technique for the mass

spectrometric identification of ions in irradiated systems at normal pressures. The temperature dependence of the clustering of several different types of neutral molecules around positive ions has already been examined, and heats of association have been calculated. It is evident that this work is of profound importance to current concepts of ion-solvation.

Unfortunately, although gas phase processes are generally better understood, comparatively little work on gas phase radiolysis has been done to date. However, the Canadian effort in this area is now expanding rapidly. Luminescence from irradiated gases has been investigated at Laval University, and the gas phase radiolysis of water vapour is under study at Whiteshell. At Chalk River the effect of radiation intensity on the radiolysis of several gases is being investigated, as well as the free radical intermediates formed in them. Studies of ion lifetimes are now underway at NRC, where significant work on the radiolysis of hydrocarbons has already been done. Research on the mechanism of electron capture in hydrogen halides is in progress at the University of Calgary, and evidence of interesting electron transfer reactions between different negative ions has been obtained at the University of Alberta. At the present time there is relatively little information about reactions of electrons and negative ions in gaseous systems. Thus any conclusions derived from radiation chemistry would be of interest.

In conclusion, radiation chemistry has already made significant contributions to general scientific knowledge, as well as to nuclear technology. As our understanding of radiolysis mechanisms becomes more detailed, the number of these contributions should increase. Also important developments in radiation biology may be anticipated. The great promise of fundamental radiation chemistry lies in its potential contribution to our understanding of ionic and electron reactions, as photochemistry has contributed to our knowledge of free radical processes.

PART II - NUCLEAR CHEMISTRY

Definition of the Field

Definitions are arbitrary, and it is difficult to define the boundaries of nuclear chemistry to everyone's satisfaction. For the purposes of the survey the definition adopted has been work done on the following main topics by people with experience and training in chemistry:

A. Properties and Reactions of the Atomic Nucleus.
   1. Nuclear structure
   2. Nuclear transformations, α - , β - , γ - decay, neutron and proton emission, spectroscopy.
   3. Nuclear reactions at low and high energy.
   4. Formation of synthetic elements, trans-uranium elements.

B. Radioactivity in Atomic and Molecular Studies.
   1. The chemistry of the elements at very low concentration, tracer chemistry, carrier-free techniques.
   2. Hot-atom chemistry,
   3. Slowing and stopping of ions in matter.
   4. Research and development on the methods of activation analysis.
   5. Mössbauer effect.

C. Radioactivity in Geology and Astronomy.
   1. Formation of the elements, nucleosynthesis, natural abundances.
   2. Research and development on "nuclear clocks".
   3. Isotopic variations in the oceans, the atmosphere and space.

   (Topic C is also covered in part by Committee 19, and the interested reader is referred to their report in this series).

Topics in which the nuclear aspect is of secondary importance have been excluded. For example, inorganic and physical chemistry research made with the aid of radioactive tracers will be reported in the Inorganic and Physical Chemistry sections of this survey. Neutron activation

analysis is considered to be another advanced technique in the armoury of the analytical chemist, to be used where it has advantages, and is a topic dealt with by the Analytical Chemistry Committee. On the other hand, the investigation of the possibility of using nuclear reactions induced by fast charged particles from accelerators to elucidate the composition and structure of thin oxide layers on metals is likely to be the pursuit of a nuclear chemist. These exclusions while severely limiting the scope of nuclear chemistry, avoid undue duplication in the overall survey.

The Growth of Nuclear Chemistry in Canada

Nuclear chemistry in Canada began with the Twentieth century; the achievements of Rutherford and Soddy at McGill in the early years of this century are well known and need not be repeated here. It is perhaps less well known that Otto Hahn, the co-discoverer of fission, was also a Rutherford student at McGill in these years.

Before going on to trace Canadian developments following the discovery of fission by Hahn and Strassmann in 1938, interest in natural radioactivity, chiefly for medical purposes, should be mentioned. The most noteworthy Canadian chemical achievement on this topic was the development of the radium industry in the early 1930's. The process used to isolate radium at the Port Hope, Ontario, plant of Eldorado Gold Mines Ltd. was essentially that developed by the Curies, although the preliminary treatment of the pitchblende was worked out by the Mines Branch in Ottawa. In full operation, the average monthly output from the Port Hope refinery was about 8 grams, valued at about one quarter of a million dollars.

Following the realization of the significance of nuclear energy for peaceful and military applications, a joint United Kingdom-Canadian atomic energy research project was started in Montreal in 1942. It attracted a distinguished group of scientists from overseas as well as many outstanding young Canadians. The collaboration of Canadian universities was sought at this time and Thode with his co-workers at McMaster University participated in the nuclear research using mass spectrometric methods.

The Montreal Laboratory, housed in the University of Montreal, rapidly out-grew its quarters as new staff joined and the move to the Chalk River site occurred in 1946. The project became a purely Canadian venture under the National Research Council and eventually developed into Atomic Energy of Canada Ltd., a Crown Company with responsibility for research and development in the atomic energy field in Canada.

The wartime achievements of the chemists in the Montreal and Chalk River laboratories were first revealed to the scientific community at a Conference on Nuclear Chemistry in 1947 sponsored by the Chemical Institute of Canada at McMaster University. Working independently of parallel developments in the U.S. atomic program, these scientists had isolated micrograms of plutonium from irradiated uranium supplied by the U.S. Manhattan Project, studied its chemical properties and worked out methods for separating grams of plutonium from kilograms of uranium. The yields of the myriad fission products had been measured and the radioactive decay properties of the important ones established. When it is remembered the U.S. effort that lead to the development of the first plutonium bomb, used at Nagasaki, is considered by many to be one of the most remarkable feats of chemical science and technology in the period of the Second World War, the accomplishments of the chemists working in the Montreal and Chalk River laboratories are more properly appreciated.

Subsequent developments in nuclear chemistry are closely related to the availability of suitable nuclear research facilities in Canada and these are summarized in Table IV.

The high flux reactors at Chalk River were used to continue the work on transuranium element isotopes and in the course of years all the unstable elements from neptunium to fermium (atomic numbers 93-100) were studied in these laboratories. The heaviest of these elements were the subjects of joint investigations in which scientists from the Knolls Atomic Power Laboratory, Schenectady, N.Y., participated, using both the NRX reactor

and the Materials Testing Reactor in Idaho. Fission by slow neutrons also received continuing attention, while the need to know the appropriate constants for other reactions involving slow neutrons led to many measurements of such quantities. These measurements and work relating to the production of isotopes fostered a steady interest in the decay properties of the radioactive species formed in reactors and methods for determining their rates of disintegration.

The McGill cyclotron made possible studies of nuclear reactions at energies higher than any that had been available in Canada previously and greatly widened the scope of nuclear research. The McGill chemists have used it for an extensive series of investigations of fission and spallation reactions in the energy region where direct interactions with nucleons in the nucleus are gaining in importance relative to those reactions in which the compound nucleus model provides a satisfactory description of the processes. Such work requires accurate measurement of the yields of the radioactive products of the reactions and the McGill group has made outstanding contributions to methods used to assay radioactive substances.

The University of Saskatchewan betatron was used at times for the preparation of tracers and 'hot-atom' studies. Nuclear chemists from AECL also utilized the special features of this accelerator to make an extensive series of photofission experiments in collaboration with the nuclear physicists there. It is to be expected that the new high energy electron Linac at Saskatoon will, in its turn, be called into play for nuclear chemistry research in Canada.

As mentioned earlier, chemists at McMaster participated in the atomic energy program in the early days of the Montreal Laboratory. This interest has been maintained with particular attention being paid to the use of mass spectrometric techniques. These include their application to the determination of the yields and properties of the fission products as well as nuclear reaction cross sections. Nuclear research at McMaster University was greatly facilitated by the acquisition of a nuclear reactor in 1959. Early interests were continued and new programs in activation analysis, hot-atom chemistry and nuclear

spectroscopy were initiated. The scope of these researches will, no doubt, be extended when the Tandem Accelerator is in operation, so that it is to be expected that McMaster will continue to be a strong centre for nuclear chemistry research.

New facilities suitable for research in nuclear chemistry have recently been installed at a number of other Canadian universities or at AECL as shown in Table IV.

TABLE IV

Major Research Facilities of Use to Nuclear Chemists in Canada

Facility	Institution	Date of Operation
Nuclear Reactor NRX	Chalk River Nuclear Laboratories	1947
Cyclotron (100 MeV protons)	McGill University	1949
Betatron (22 MeV electrons)	University of Saskatchewan	1952-66
Nuclear Reactor NRU	Chalk River Nuclear Laboratories	1957
Nuclear Reactor	McMaster University	1959
Tandem Accelerator (12 MeV Protons)	Chalk River Nuclear Laboratories	1959-66
Cyclotron (40 MeV protons)	University of Manitoba	1965
Linac (150 MeV electrons)	University of Saskatchewan	1966
Electron Linac (35 MeV electrons)	University of Toronto	1967
Tandem Accelerator (20 MeV protons)	Chalk River Nuclear Laboratories	1967
Tandem Accelerator (12 MeV protons)	Université de Montréal	1967
Tandem Accelerator (15 MeV protons)	McMaster University	expected 1968

(Low energy Van de Graaffs omitted)

The electron linear accelerator recently brought into operation at the University of Toronto has already been used for nuclear chemistry investigations of photofission of thorium and uranium. Many of the other facilities listed in Table IV are potential sources for further expansion of the field in Canada.

Very little has been said in this historical outline about the more applied areas of nuclear chemistry. As was pointed out in the definition of the field, we feel that these aspects of nuclear research belong more properly in areas considered by other Committees. Since the applications have in many cases grown from research interests or resulted from a scaling-up of laboratory processes the dividing lines are not easily distinguished. Some mention may, therefore, not be out of place here, especially as the accomplishments are no less noteworthy than some already reported.

The development of the nuclear-electric power program has involved nuclear and radio-chemical studies on an engineering scale. The location of failed fuel elements in the reactor, the release of fission products from failed fuel and the fate of these species in reactor systems has received a great deal of attention since the first Canadian high power reactor, NRX, went into operation in 1947. The chemist has participated as a member of a large group of reactor scientists and engineers so that his role is hard to delineate exactly. However, the achievement of the group is a matter of record. The NRX reactor reached full design power in January, 1949 and produced the highest neutron flux for research purposes in the world. It was joined in 1957 by the even more powerful NRU reactor. One important use to which these reactors have been put is fuel testing in engineering, loop-type experiments. On the basis of these tests, the first Canadian reactor used to generate electricity, the Nuclear Power Demonstration Reactor, or NPD, was designed and put into operation at Rolphton, Ontario. It has been supplying electricity, about 20 megawatts, to the Ontario Hydro-Electric Commission for several years. A full-scale commercial-size nuclear power station, at Douglas Point, Ontario went into operation in November 1966. Other nuclear

electric stations are being built at sites in Quebec and Ontario. In addition, a Canadian-type nuclear research reactor was installed at Trombay in India and currently two nuclear electric plants are being installed in India and Pakistan.

Canadian accomplishments in connection with the extraction of plutonium from irradiated natural uranium in the Montreal and Chalk River Laboratories have been mentioned already. This process involved solvent extraction of the plutonium. Subsequently, an anion exchange process was developed and operated on a plant scale. A method for extracting the fissile uranium isotope, ^{233}U, from irradiated natural thorium was also developed and thoroughly tested. Techniques for the concentration of fission products have also been devised. All these topics relating to the nuclear power program in Canada have had chemical support that can be traced to foundations in nuclear chemistry.

The use of radioactive isotopes for medical, agricultural, industrial and scientific research purposes has grown with the availability of nuclear reactors and radium now occupies a less prominent position in this field. The centre of isotope production has consequently shifted from Port Hope to Ottawa and Commercial Products, a part of Atomic Energy of Canada Limited, Many of the isotopes supplied by Commercial Products require chemical separation and purification; the common radioactive tracers ^{14}C, ^{32}P, ^{35}S and ^{131}I are good examples. The methods used to produce these isotopes are firmly rooted in nuclear chemistry and processes being developed for obtaining other isotopes in commercial quantities are considered an applied aspect of the subject.

Radioactivation methods of analysis using thermal neutrons have now developed to the point that we feel this area is rightly included in the Analytical Chemistry Section of this survey. However, it was not always so. There was a stage, when the techniques were being developed and before the practicability had been established, during which the nuclear aspects predominated. Canadian contributions during this period

were notable, particularly in the areas of forensic science and trace impurity analysis in metals. Development of new applications of what are essentially nuclear techniques for analytical purposes are in progress in the universities and government institutions.

Present Level of Nuclear Chemistry Activity in Canada

(i) Topics

Table V shows the topics in nuclear chemistry being investigated and the locations at which these investigations are being made. The needs of the moment and the availability of people or apparatus tend to shift at a particular institution, but the long term aims remain rather constant. For example, a study of the decay properties of a particular isotope of an element may have to await the outcome of a study on the chemistry of that element in order that a suitable source can be prepared. For this reason the topics and locations given in Table V cover the five year period 1962-7 rather than just the current situation.

TABLE V

Nuclear Chemistry Topics and their Location in Canadian Institutions

1.	Nuclear Fission	a) Low Energy:	McMaster University University of Toronto University of Waterloo CRNL
		b) High Energy:	McGill University University of Toronto
2.	Assay of Radio-nuclides		McGill University McMaster University Simon Fraser University University Laval CRNL NRC App. Physics Division
3.	Nuclear Decay Properties		McGill University McMaster University Simon Fraser University University of Waterloo CRNL
4.	Nuclear Reaction Mechanisms and Rates		McGill University McMaster University Simon Fraser University CRNL
5.	Activation Analysis		McMaster University Simon Fraser University University of Toronto CRNL
6.	Nuclear Chemical Methods		Carleton University University of Waterloo
7.	Hot-atom Chemistry		Carleton University McMaster University
8.	Isotopic Variations in the Environment		McMaster University CRNL
9.	Slowing and Stopping of Charged Particles in Matter		CRNL
10.	Mossbauer Effect		University of Waterloo
11.	Isotope Production		Commercial Products, AECL

(ii) Manpower

The numbers of nuclear chemistry staff, graduate students and post doctoral fellows, as well as their technical support are shown in Table VI. A further more detailed analysis of the university scene is given in Table VII.

TABLE VI

Manpower in Nuclear Chemistry 1966/67

	Professionals	Graduate Students	Post Doctoral Fellows	Technicians
University	12	30	11	1
AECL*	8	-	-	11
NRC (App. Phys. Div.	2	-	-	2

*Including Chalk River Nuclear Laboratories and Commercial Products Division

About half the fully trained nuclear chemists are in the universities. Of those in government laboratories, about half are engaged in applied research or development so that it is seen that most pure research in nuclear chemistry is done in the universities. In our opinion, this is as it should be. Nuclear chemistry is an eminently suitable field for training graduate students. This is because it is near the frontiers of knowledge and can excite the enthusiasm of the young. It avoids narrow specialization at too early a stage in a student's scientific career since it cuts across a number of the traditional academic disciplines, as well as sub-sections of chemistry itself. Furthermore, the student becomes acquainted with many aspects of modern technology, e.g. electronic and electrical equipment and high vacuum apparatus.

TABLE VII

Manpower Statistics for Nuclear Chemistry Research in Canadian Universities

University	Professional Staff	Present Number of Advanced Degree Students		Students Graduated		
		M.Sc.	Ph.D.	In last 5 yrs. M.Sc.	In last 5 yrs. Ph.D.	Expected in next 5 years
Carleton	1	1	2	3		10
Laval	1					6
McGill	1		5		15	20
McMaster	4	1	7	1	3	9
Saskatchewan	1					
Simon Fraser	2	2	3			6
Toronto	1	2	4	7	3	12
Waterloo	1	3				10
	12	9	21	11	21	73

There are good reasons for the continuation of the support of high quality research in pure nuclear chemistry in government laboratories. Perhaps the most important is that such research contributes to knowledge generally and adds to the reputation of Canadian science in particular. It attracts able staff members and ensures that new ideas and new techniques are quickly introduced for exploitation in related fields. For example, with the elucidation of the phenomenon of "channelling" of charged particles in crystal lattices at CRNL and elsewhere, the way was clear for the application of the channelling technique to studies of radiation damage in solids. Thus basic studies were quickly exploited in a more applied field, in this case not related to nuclear chemistry.

The applied research and development programs of nuclear chemistry in government laboratories are related to the responsibilities these institutions have for meeting national aims. The effort amounts to about one quarter of the total Canadian manpower working on nuclear chemistry. In view of the place the nuclear-power industry occupies in the economy and Canada's internacional role in isotope standardization, the numbers are certainly not excessive.

(iii) Financial Support

Estimated operating and capital expenditures on nuclear chemistry in both university and government laboratories are given in Table VIII. The university estimates include contributions from both the university itself and government grants. The grants and university contributions to capital are accurately known but the university part of operating expenses is difficult to estimate with any degree of accuracy. Furthermore, what can be loosely termed 'overhead' has not been included in these estimates for either the universities or government laboratories. This may increase the operating figures given in Table VIII by 30%.

It should be pointed out that nuclear chemists depend on accelerator and reactor facilities but the capital and operating costs of these installations are not usually charged to the chemistry programs. This is another reason why the estimates in Table VIII err on the low side. The cost to the chemist of using such facilities is not negligible, however, for he must pay for the ancillary equipment he needs to make use of such facilities for his experiments.

TABLE VIII

Average Expenditure for Nuclear Chemistry Research per Professional Staff Member

Institution	Annual Operating Funds 1966-7	Annual Expenditures on Major Equipment (Averaged over last 5 years)
Universities	$20,000	$21,000
AECL	32,000	8,400
NRC (Applied Phys. Division	n/a	7,000

It is difficult to estimate the total expenditures for nuclear chemistry research in Canada for the reasons already given, and also because a significant number of respondents did not provide data about their financial support. From what information we have available, it is estimated that the total annual operating funds for all nuclear chemistry research in Canada do not exceed $500,000, while expenditures for major equipment in this field are probably less than $300,000 per annum.

Most university correspondents stated that their research was hampered by lack of major items of equipment, laboratory space, and funds for graduate students, post-doctoral fellows and technical staff. It was pointed out that since the results of nuclear chemistry research fall within areas in which the Atomic Energy Control Board has responsibilities, the AECB should therefore properly be able to provide operating and capital grants in support of such work. This would give recognition to the fact that on the average, equipment need in this field is more expensive than in other fields of chemistry. Thus the proposed AECB contributions would supplement NRC support. It is of course recognized that the AECB does already make substantial grants in aid of research in Canadian universities; the proposal is for additional small grants for smaller programs.

Although our correspondents reported that their research programs were inadequately funded, the majority conceded that, relative to the financial support provided for other areas of chemical research, the share allotted to nuclear chemistry is not unreasonable.

The Importance of Nuclear Chemistry in Canada at Present

Research in nuclear chemistry is important to Canada today because:

a) it is a highly suitable subject for graduate student training in universities, for reasons already mentioned. Activity in this sector is lively and in the last five years graduate students have co-authored some 50 papers that have appeared in the scientific literature.

b) applications of advances in nuclear chemistry will be of importance to Canadian industry, agriculture, science and medicine.

c) the training students receive in nuclear chemistry research will be of great value in their subsequent careers, not only if they continue with pure research in nuclear chemistry, but in other fields as well.

In the historical introduction above, some of the past applications of nuclear chemistry in Canada were outlined. These contributions continue. (i) An area in which there is considerable current interest in both university and government laboratories is the exploitation of the new, high-resolution, Ge(Li) gamma-ray detectors for activation analysis. These detectors promise to give increased discrimination between interfering elements and simplify procedures considerably. (ii) The "channelling" technique of exploring the lattice structure of crystals is being used to study methods of doping semi-conductor materials, especially by implanting foreign ions in crystals with an electrostatic accelerator. It also yields useful information about radiation damage during ion implantation. These studies may lead to

further advances in semi-conductor technology. The nuclear methods devised to study the ranges of energetic charged particles in solids are also being exploited to give information about impurities on surfaces. Because of their relevance to corrosion phenomena surface oxide layers are receiving most of the attention at the moment.
(iii) A third example of current applications of nuclear chemistry is the development of methods for using "tailor-made" isotopes for particular purposes. Two that can be mentioned are ^{125}I for special medical applications and ^{124}Sb for neutron sources.

Future Development of Nuclear Chemistry in Canada

Those who replied to our questionnaire were agreed that there would be an increase in demand for nuclear chemists in Canada in the next 5 - 10 years. Opinions differed on how large the increase would be and main reason for this is the uncertainty in the rate of installation of major nuclear facilities in the future. Replies from university staff forecast modest increases, whereas correspondents in government laboratories were more certain of increased demands for nuclear chemists, particularly for applied work.

There is general agreement that the graduate student population in Canadian universities is likely to continue to grow during the next 5 years, and this trend (indicated in Table VII) coupled to the recent emergence of several new university groups in nuclear chemistry, suggested very strongly that the absolute number of graduates in this subject is likely to increase significantly over present levels. However, there may be an important restriction on growth and that is the availability of suitable facilities for nuclear research.

The major nuclear research installations currently available are listed in Table IV. Accelerators that have come into operation since about 1965 have not yet been put to extensive use for graduate student training so that there is considerable potential available at present. However, some of it is at universities where there is not a nuclear

chemist on the teaching staff so that it may take time to develop. There is an additional limitation. Nuclear installations in Canadian universities are all primarily for nuclear physics research and according to "Physics in Canada - Survey and Outlook", the existing facilities will be saturated in the early 1970's. They may not, therefore, be available for training chemistry students. To prevent the saturation of facilities, Canadian physicists are proposing that a number of rather minor installations be placed in the universities and have also proposed two major pieces of nuclear apparatus: TRIUMF and ING. These proposals have received support from nuclear chemists associated with the sponsoring institutions, especially for the major facilities. Enthusiasm for the minor ones, usually low energy accelerators, is less because of their limited usefulness to the chemist, although they are very good for studies in special areas.

TRIUMF (Tri University Meson Facility) is an imaginative proposal put forward by a group of universities, the Universities of British Columbia, Victoria, Alberta and Simon Fraser University, for a meson-producing cyclotron. It would be used by several disciplines at these universities, including nuclear physics, chemistry and solid state. It has been suggested that it would serve about 30 university staff members and 70 graduate students in chemistry and similar numbers in physics, starting in late 1972.

The second major installation currently under consideration is ING (Intense Neutron Generator). The proposal for this advanced and rather radical project was put forward by the Chalk River Nuclear Laboratories to serve a number of groups of scientists including physicists, chemists, metallurgists and engineers. It would be available for university staff and graduate students. It has yet to receive government approval and, if approved, is not likely to be in operation before 1974.

The ING project would be a training ground for students of nuclear chemistry, and would also make available for isotope production higher neutron fluxes than any available today. Furthermore, isotopes of practical value that cannot be produced in fission nuclear reactors could be extracted from the target itself. This aspect of the project would require considerable research and development on means of obtaining new or improved isotope products for use in commerce, science and medicine.

Another emerging development in the nuclear field in Canada in the next decade is a major nuclear fuel reprocessing installation. At present, fuel from the Canadian power reactor program is sold in the world market for the values in transuranium elements it contains. When the amounts are large enough, it will be economic to extract these in Canada. Some of the products will be useful as extracted; others can be converted by irradiation with an intense source of neutrons to isotopes such as ^{238}Pu and ^{244}Cm. These are used as power sources in heart pacers, space satellites and other remote locations. As the technology advances it seems likely that the demand will grow and with it, the requirements for trained nuclear chemists will also increase.

In summary, there will be a growing need for nuclear chemists in Canada in the next decade, both within and outside the universities. A critical factor in the future is the provision of adequate research facilities for training nuclear chemistry students. Increasing exploitation of existing facilities should be encouraged. New major facilities for nuclear research will be required for the training of nuclear physicists and chemists in the next decade and steps should be taken now to ensure that these installations are ready when needed.

Summary and Recommendations:

1. This survey shows that five per cent of all candidates working towards M.Sc. or Ph.D. degrees in chemistry departments in Canadian universities have thesis topics in either radiation or nuclear chemistry. These disciplines may therefore be regarded as significant components of the total chemical research activity in Canada. This view is strengthened by examination of the number and quality of the research contributions being made in these fields by Canadian chemists.

2. Radiation chemistry research is well established in Canadian government laboratories (AECL, DRB and NRC), while nuclear chemistry is found mainly at AECL, with some lesser activity in other federal departments. The balance between government and university activity is judged to be reasonable in both these areas of research. No perceptible research or development work in industrial laboratories was disclosed by this survey.

3. The supply of M.Sc. and Ph.D. graduates trained in nuclear or radiation chemistry in Canada is likely to be sufficient to meet the country's needs for such persons, at least for the next five years.

4. Most university respondents felt that, relative to other areas of chemical research in Canada, financial support for nuclear and radiation chemistry appears not inadequate, although a number stated that the absolute amount was not sufficient for their program. Moreover,

there were reported many instances of insufficient support for young scientists starting work in university departments, a situation which we recognize is not unique to these disciplines. This problem is less frequently met in government laboratories, presumably because in the latter, capital funds to launch research programs of new, young members of staff can be mobilized when required. The problem seems to be not that the total funds provided to an individual over his working life are inadequate, but rather, the timing of this assistance is faulty. The philosophy of the present NRC grants system appears inadequate in this respect. The Committee therefore recommends most strongly that suitable administrative and financial arrangements be devised to accord better opportunity to the young university scientist.

5. In the context of financial support, we point out that the scientific content and technical implications of most of the work in Canadian universities involving nuclear and radiation chemistry lies within the area of special concern of the Atomic Energy Control Board (AECB). That being so, it would appear reasonable that the grants program of AECB, now restricted mainly to nuclear physics and other accelerator-based physics programs, be extended to nuclear and radiation chemistry to supplement the present NRC grants.

6. There is general agreement amongst radiation chemists that pulsed radiolysis studies offer exciting opportunities for tackling many of the unsolved problems in radiation chemistry. Despite this, there is not in Canada a single suitable facility which has been built and is being used <u>specifically</u> for this kind of study. We recommend that those principally concerned be encouraged to examine this situation in more detail, taking account of the expressed desire of many respondents that such a facility, if built, be available to radiation chemists from at least several co-operating government or university laboratories. It is estimated that a suitable facility, completely housed, would cost approximately $0.5 million.

7. Prospects for growth of university based research in nuclear chemistry are closely related to the number and availability of suitable nuclear research installations in Canada. Almost without exception such installations are primarily for nuclear physics research; several of these do not have as yet an associated significant nuclear chemical research activity. In this respect, for the short term, the growth prospects are good. However, according to "Physics in Canada - Survey and Outlook", the existing facilities will be fully utilized within three years by the needs of physics-related programs, and they may therefore not be available for training chemistry students. In the longer term, the proposed facilities TRIUMF and ING, if proceeded with, will provide ample new capacity for training of nuclear chemists both within and outside the universities.

8. Activities more properly described as development or applied science are, except for AECL's continuing contributions, virtually absent in nuclear chemistry. Applied work in radiation chemistry is to be found particularly at AECL and in several university departments of chemical engineering. While we do not endorse the view that radiation chemistry has unlimited prospects in tomorrow's chemical technology, we nevertheless recommend that well conceived applied radiation chemistry programs be sought out and supported more fully than at present. Areas of possible application are indicated in the body of this report.

APPENDIX

TABLE IX

Comparison of Data from

Committee 12 and C.I.C. Data

(1) Industry - Both surveys agree in finding no R. and D. classified as Radiation Chemistry or Nuclear Chemistry in industry.

(2) Government - Both surveys agree in finding no provincial government expenditure.

Manpower	Comm. 12 pp. 6 and 27		C.I.C. Table 16	
Radiation Chemistry	18 Prof.	18 Techn.	17.5 Prof.	28 Techn.
Nuclear Chemistry	10 "	13 "	12.4 "	17 "
Area 121	28 "	31 "	29.9 "	45 "

The higher technician count by the C.I.C. Survey may be due to the inclusion of more development work.

(3) Universities

Operating Expenditures

	Comm. 12	C.I.C. Table 37
Radiation Chemistry	$11,600 x 20 = 232,000	
Nuclear "	< 500,000	
Area 121	< 732,000	$546,000

University expenditures are notoriously difficult to assess.

Manpower	Comm. 12 pp. 6 and 28		C.I.C. Table 38	
	Acad. + P.D.F.	Grad. Stud.	Acad. + P.D.F.	Grad. Stud.
Radiation Chemistry	20	35		
Nuclear Chemistry	12	30	—	—
Area 121	32	65	36	49

The committee evidently located more graduate students than the C.I.C.

General Conclusion - The differences are not greater than might be expected between a very specific and a very wide survey.