The potential role of new nuclear power in deep decarbonization

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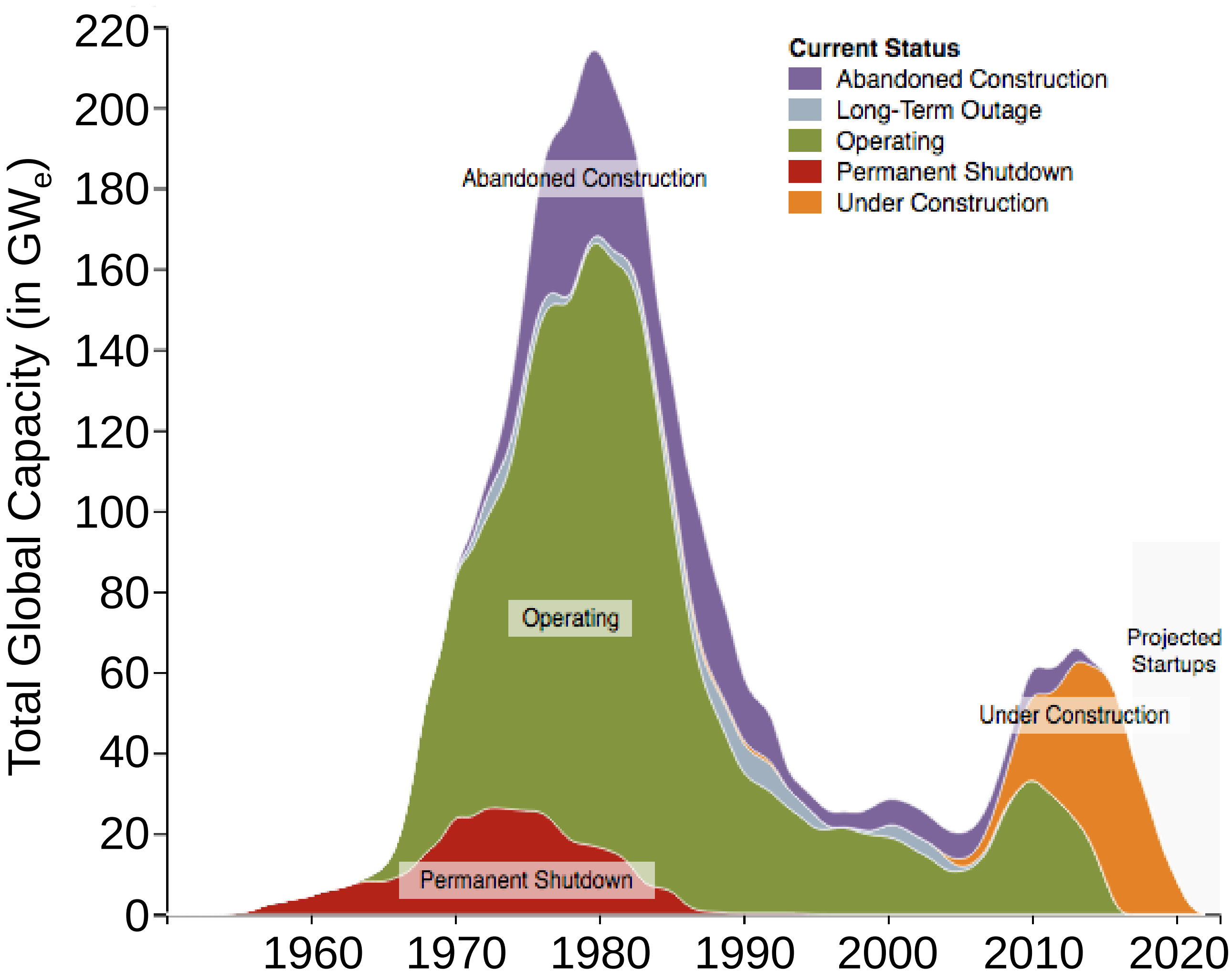
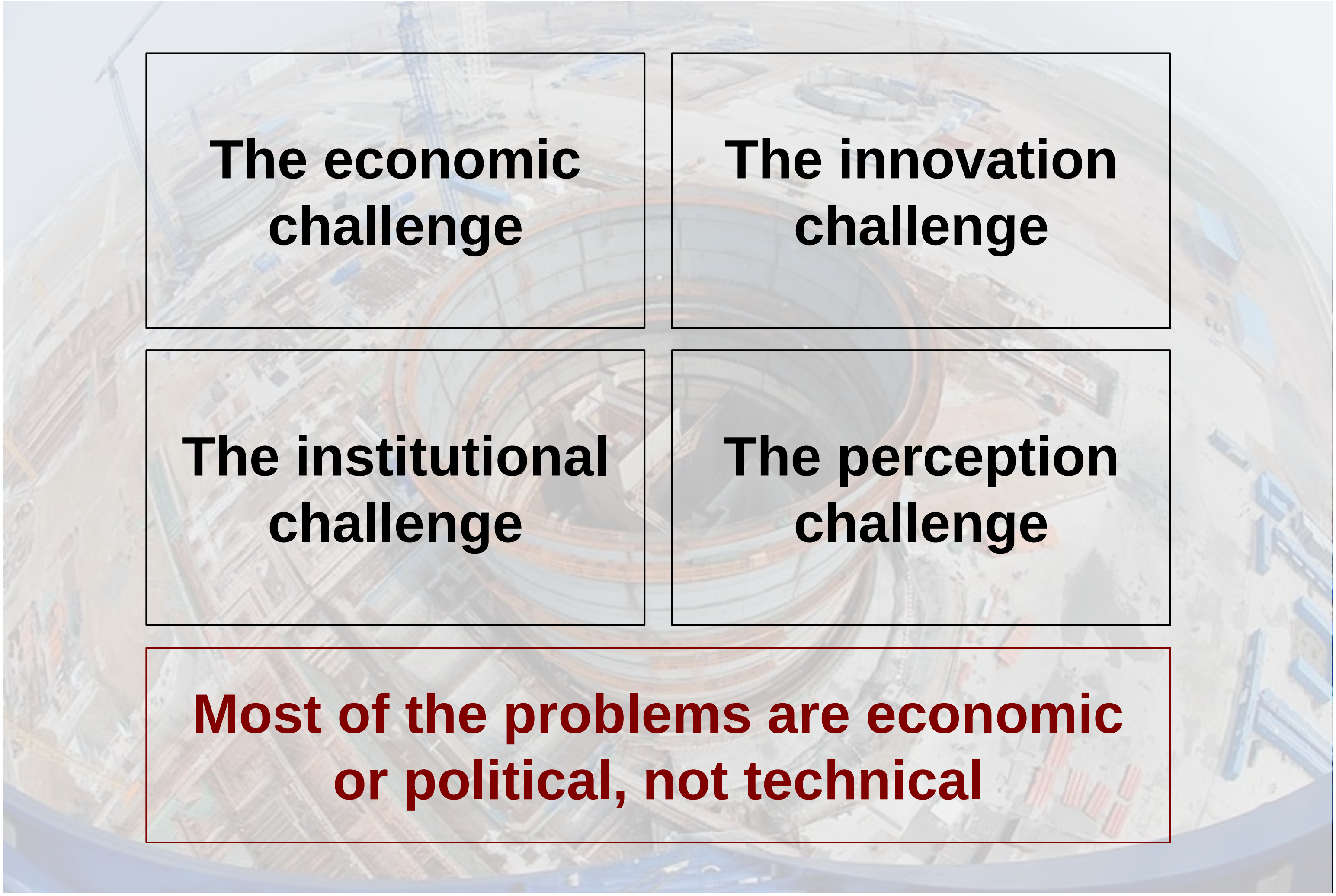
A snapshot of the nuclear enterprise



1) Median age of 30 years
2) Bimodal distribution
3) Radical expansion difficult

Bulletin of the Atomic Scientists (2017) Global Nuclear Power Database. Accessed 17 Jan 2018

Why is radical expansion difficult?



China AP1000® Project Photos (May 2011)

The economic challenge

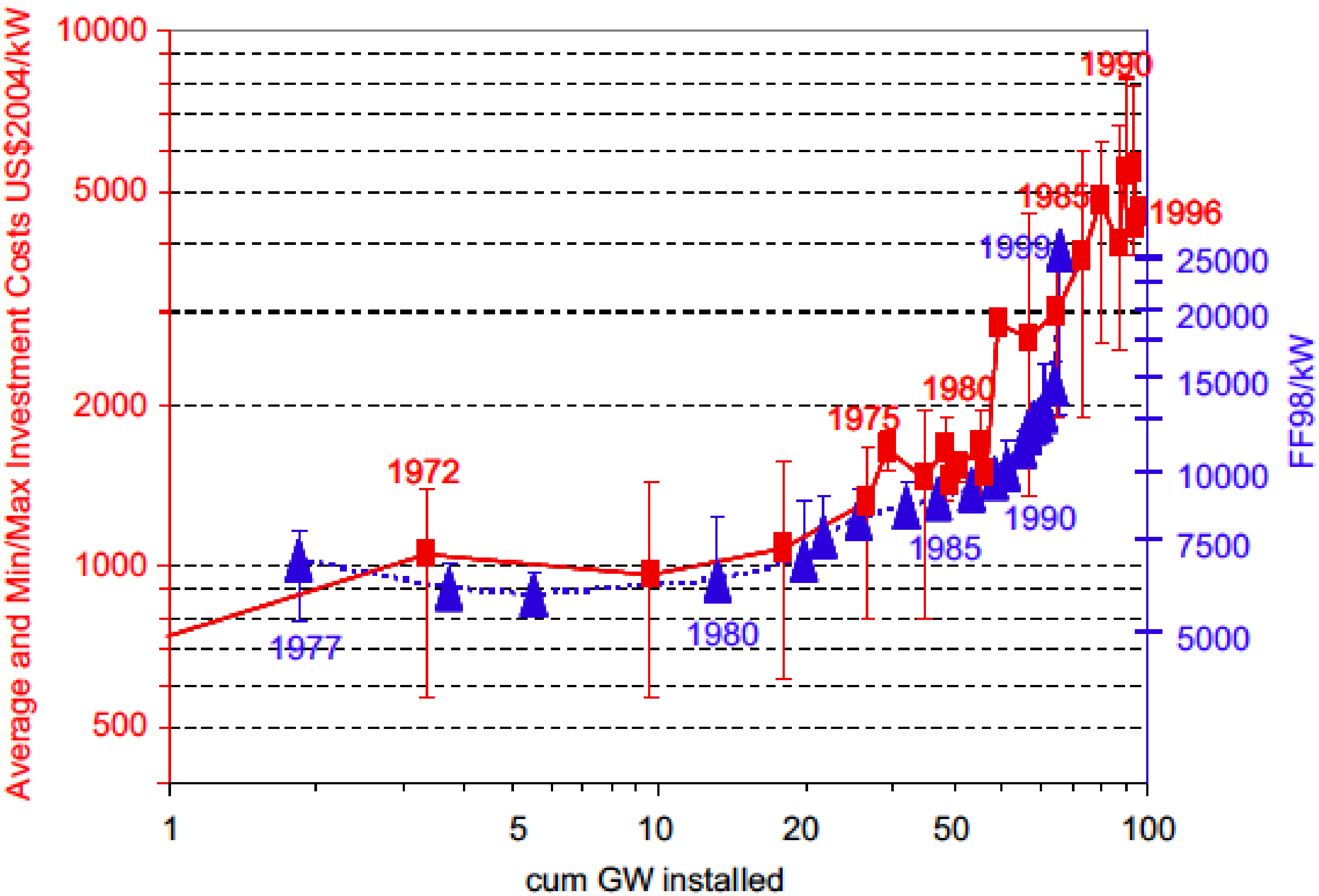
The innovation challenge

The institutional challenge

The perception challenge

Most of the problems are economic or political, not technical

New reactors are large and complex

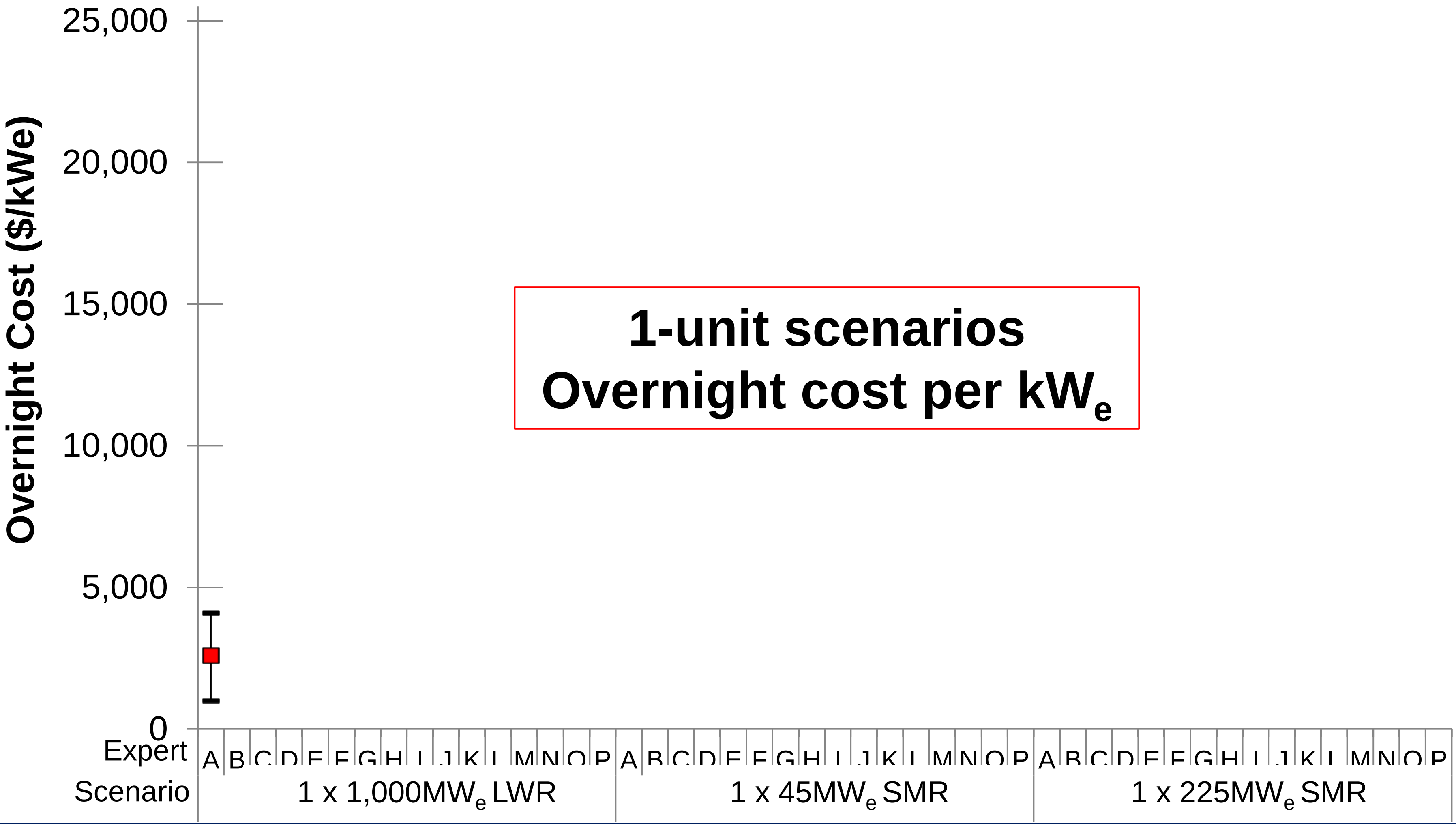


Grubler A (2010) The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* **38**:5174–5188

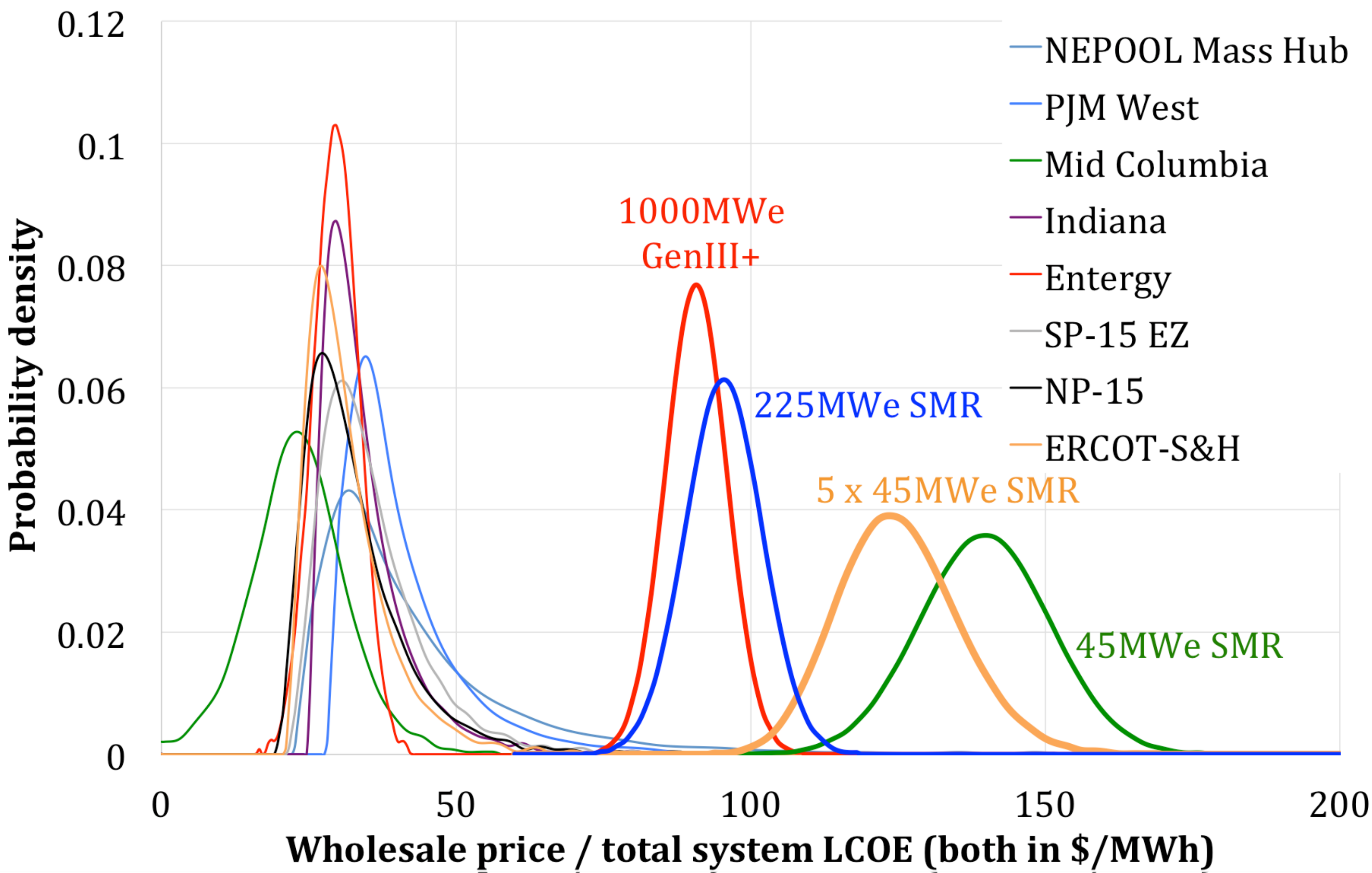
Is there room for innovation?

- The industry's answer to the scale problem is to **go small**.
- Small modular reactors (SMRs): many sizes & technologies
- <u>Case for SMRs is being made on multiple fronts:</u>
  - **Economics:** factory fabrication; modular construction; bigger market due to smaller size and alternative end-use applications; increased flexibility in sizing and siting
  - **Safety:** Passive safety systems; smaller radionuclide inventory; fewer risk drivers (e.g. spent fuel pool)
  - **Waste:** produce less waste; powered by spent fuel
  - **Proliferation:** anti-tampering technologies; some eliminate on-site refueling

1) The **economic** challenge

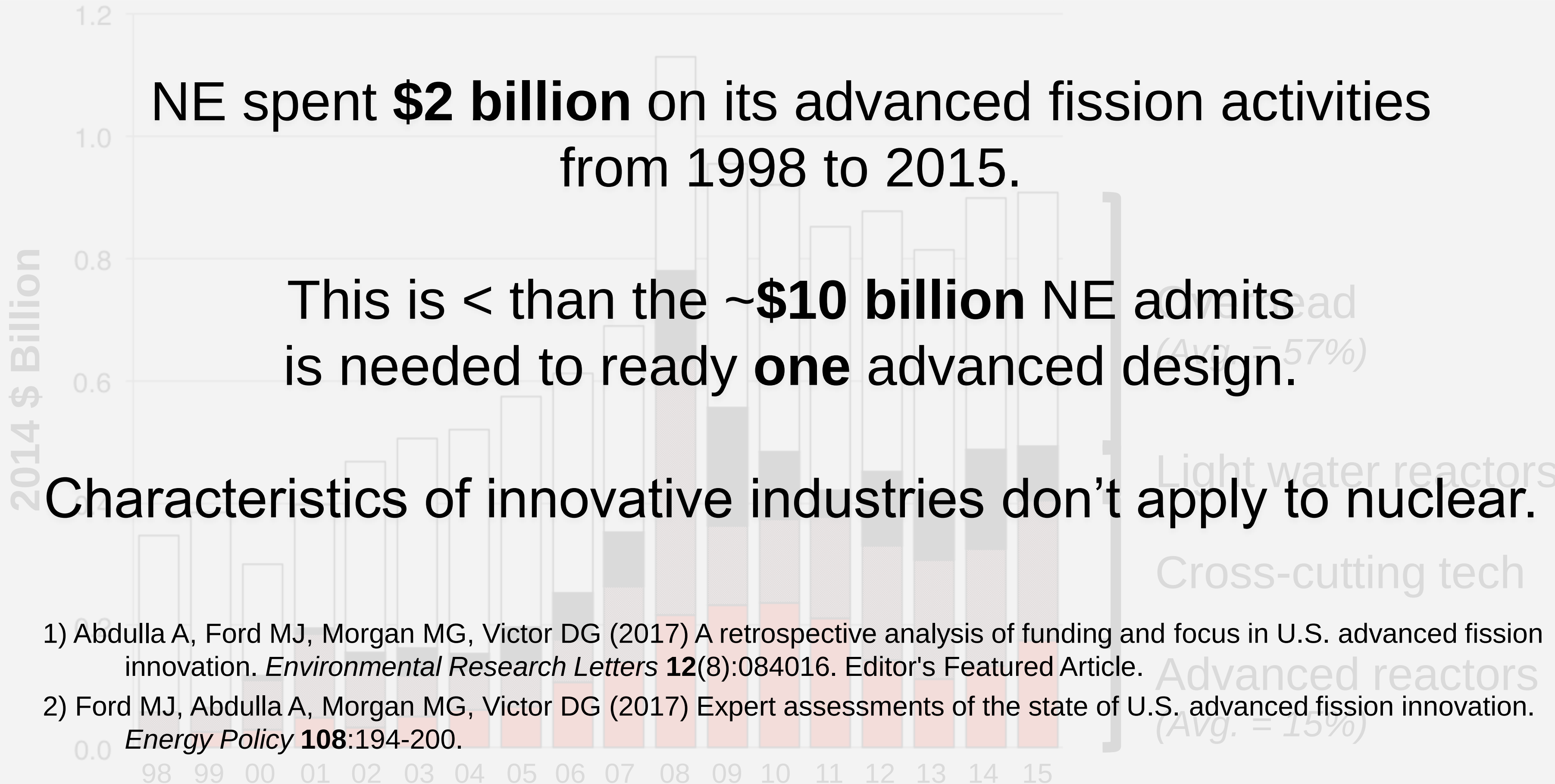


SMRs will likely incur a premium



1) Abdulla A, Azevedo IL, Morgan MG (2013) Expert Assessments of the cost of light water small modular reactors. *Proc Nat Acad Sci USA* **110**(24):9686-9691

2) The **innovation** challenge



NE spent **$2 billion** on its advanced fission activities from 1998 to 2015.

This is < than the ~**$10 billion** NE admits is needed to ready **one** advanced design.

Characteristics of innovative industries don't apply to nuclear.

1) Abdulla A, Ford MJ, Morgan MG, Victor DG (2017) A retrospective analysis of funding and focus in U.S. advanced fission innovation. *Environmental Research Letters* **12**(8):084016. Editor's Featured Article.

2) Ford MJ, Abdulla A, Morgan MG, Victor DG (2017) Expert assessments of the state of U.S. advanced fission innovation. *Energy Policy* **108**:194-200.

3) The **institutional** challenge

A floating SMR build-own-operate-return (BOOR) model:

- Enhance proliferation resistance; limit tech spread.
- May provide advantages in terms of EPZ risk, water withdrawal, and decommissioning.
- **Once construction standards grow to approximate military or nuc specifications, cost may be prohibitive.**

DCNS (2014)

Modern Power Systems (2014)

1) Ford MJ, Abdulla A, Morgan MG (2017) Evaluating the cost, safety and proliferation risks of fSMRs. Risk Analysis.
2) Abdulla A, Morgan MG (2015) Nuclear Power for the Developing World. Issues in Science and Technology.

4) The **perception** challenge

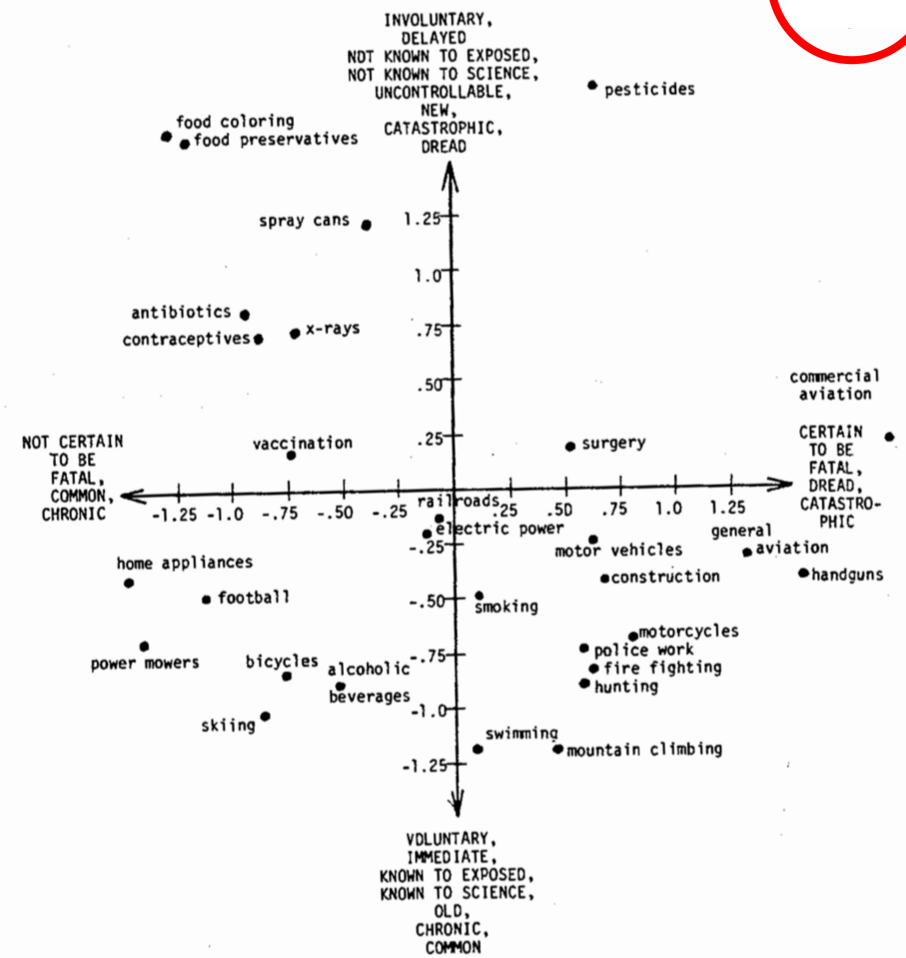


Fig. 7. Location of risk items within the two-factor space.

- Nuclear power elicits uniquely negative attitudes.
- Its risks are deemed involuntary, immediate, unknown, uncontrollable, catastrophic. Public "dreads" it.
- Industry's response has been a focus on actuarial risk: new generation of safer reactors.

We disentangle actuarial and dread risks

Stripping nuclear of its label—but not its **catastrophic** risk—results in a large and statistically significant increase in support.

Such an expansion in nuclear power would require more than 40 additional plants to be constructed in the U.S. on top of the current fleet of 99.

1) Abdulla A, Vaishnav P, Sergi B, Victor DG. Disentangling stigma from actuarial risk: the cautionary story of nuclear power. Under Review at *Environmental Research Letters*.

Conclusions and implications

- One SMR unit will cost less in absolute terms than large Gen III+ nuclear plants. They move the discussion from affordability to economic competitiveness.
- Without significant changes, the advanced reactor R&D effort in the U.S. will not yield results that matter in the timeframe necessary to decarbonize the energy sector.
- Developing accident-proof reactors not good enough for nuclear power to gain wide global acceptability.
- In world where nuclear, CCS, gas, and batteries are unacceptable, eliminating emissions becomes impossible.
- **Diagnosis grim, but feasible prescriptions exist. I'm optimistic (this for the Q&A session).**

Acknowledgments

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UC San Diego Frontiers of Innovation Scholars Program

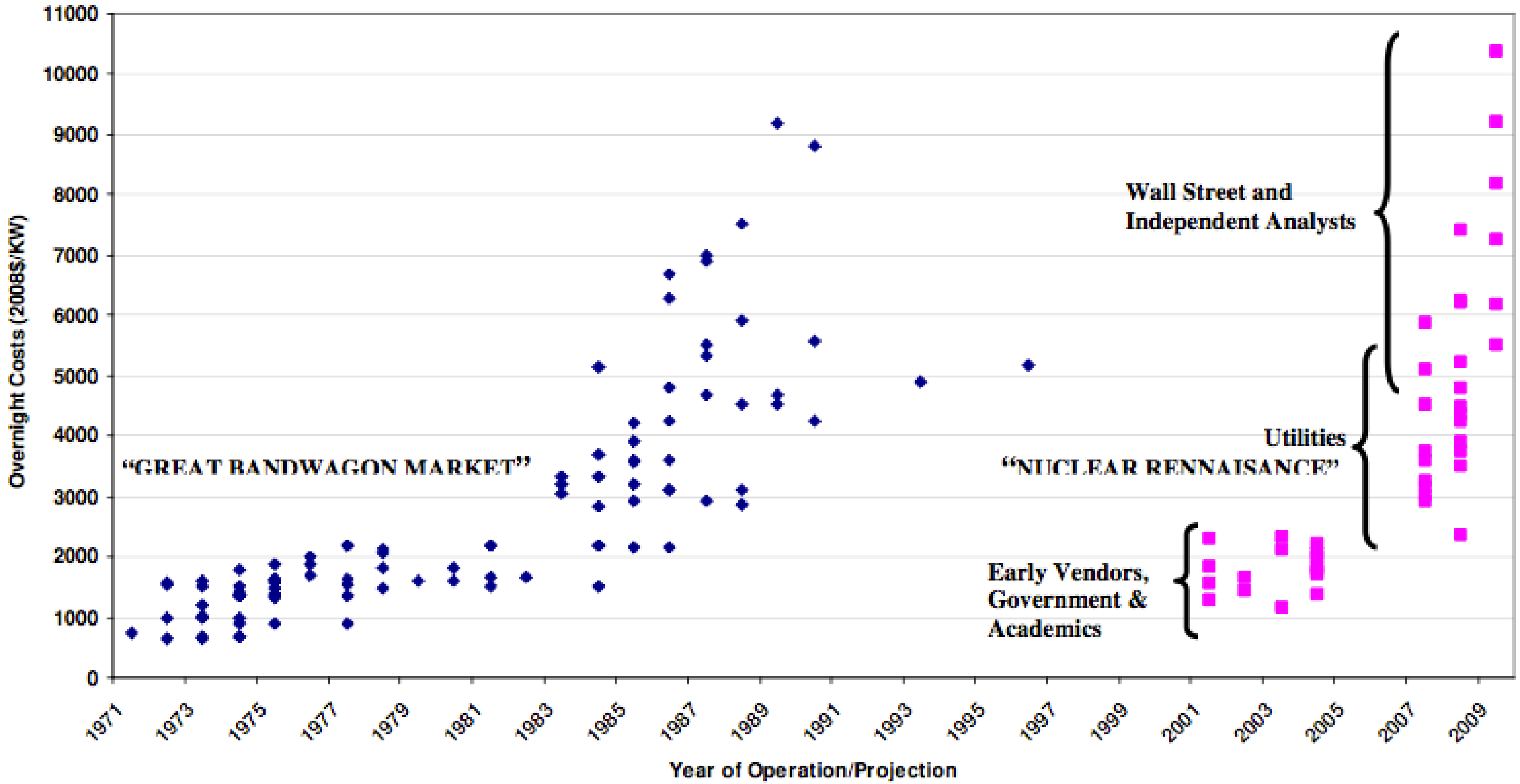
Supplementary Slides

“No…evidence of economies of scale”

“**As shown, no consistent evidence of economies of scale can be found among the PV systems** in our pricing sample that achieved commercial operation in 2014 …

“**More notable are the price penalties for projects larger than 100 MW_{AC}** … these mega-scale projects – some of which involve more than 8 million modules and project sites of nearly 10 square miles – **may face greater administrative, regulatory, and interconnection costs than do smaller projects.**”

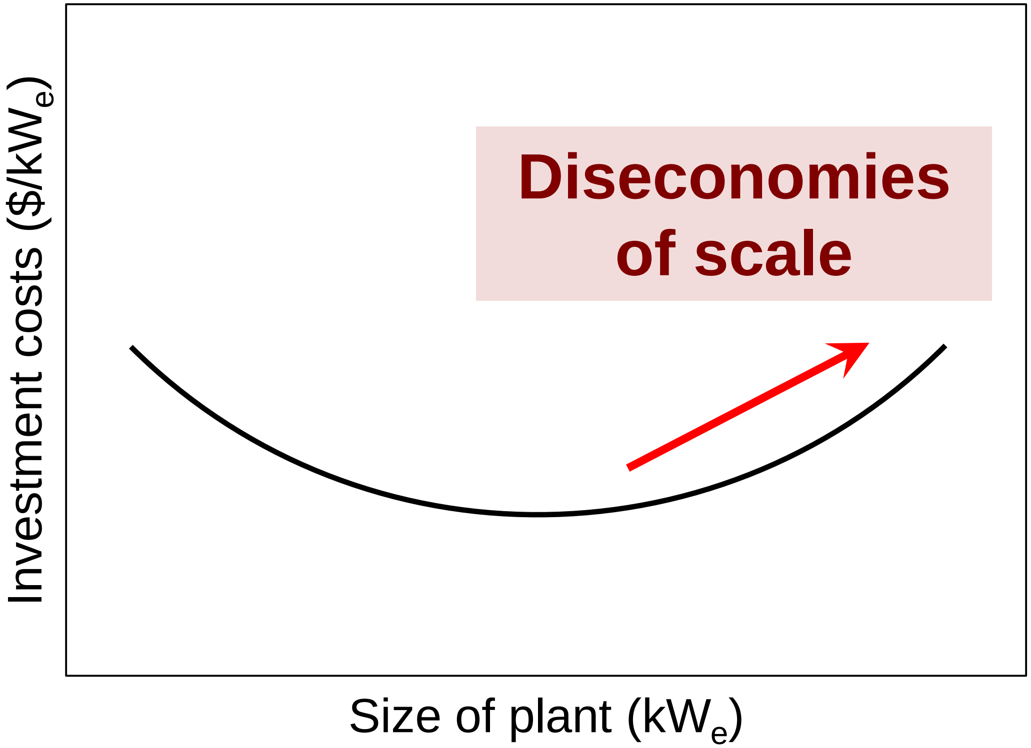
Nuclear cost control is non-existent



Cooper M (2009) *The Economics of Nuclear Reactors: Renaissance or Relapse?* (Institute for Energy and the Environment, Vermont Law School, South Royalton, VT, USA). Figure ES-1.

Economics of scale doomed industry

- Based on a misunderstanding of basic economic theory



You'd think this view is now accepted

Adam Smith Institute: https://www.adamsmith.org/blog/economics/economic-nonsense-32-economies-of-scale-mean-that-bigger-is-better

The South Korean experience

Opportunities:

- Two-dozen reactors with more than $23GW_e$ of capacity
- Provided ~30% of country's electricity in 2016.
- Competitive nuclear supplier, with its greatest success in the UAE (4 x APR1400s sold for the Barakah site).
- Interest in (and industrial policy suited for) becoming major nuclear exporter.

Now for the bad news

Challenges:

- The ascendant nuclear supplier ***until 8 months ago***
- Strong anti-nuclear movement: Fukushima + North Korea.
- New president who is backing away from nuclear power domestically, but still touting its export potential:
  - *"I expect the government of South Korea to continue to sell its world renowned expertise in nuclear technology to the world even if it is cut back at home" – M. Whitaker*
- Only managed to convince the world that APR1400 reactor was "proven" because it was building it at home. Hard to sustain a reactor export market if it rolls back domestically.
- Operational experience would be marginal; that is a recipe for poor execution and devastating consequences.

Russia has always sought exports

Opportunities:

- 35 reactors with ~26GW_e of capacity.
- Traditionally provide one-sixth of country's electricity.
- Large, well developed, integrated nuclear supply chain.
- First nation to offer a serious Build-Own-Operate-Return (BOOR) option to customer nations:
  - *Nation would build the reactor in the customer/host nation, have a stake in its ownership, contract to operate it for its lifetime, and then take back the fuel.*
  - *Very attractive to emerging nuclear nations, though not always, and certainly not proven.*

Achievements fall short of hopes

Challenges:

- BOOR deployment strategy not proven:
  - *Fuel take-backs politically unpalatable in most polities.*
  - *Depends entirely on geopolitical relationships.*
  - *You are acquiring a strong geopolitical ally, but are entering a long-term (likely looooong-term) political alliance, which can be risky.*
- Quality concerns regarding components.
- Security concerns regarding I&C systems.
- Spotty project management and execution.

China: the last great hope

Opportunities:

- 38 reactors, 19 more under construction.
- Providing 3-4% of country's electricity.
- Largest nuclear build program, one of largest in history
  - *Able to negotiate advantageous terms with overseas nuclear suppliers, laying foundation for future Chinese development and deployment.*
- Enormous, though not unlimited, financial resources.
  - *Willing and able to support nuclear builds overseas.*
- Burgeoning supply chain and human resource base.
- Politically and financially strong advanced fission innovation program, benefiting from knowledge transfer from U.S. labs and knowledge exchange among the two.

Event in China would be nightmare

Challenges:

- An accident at a Chinese nuclear power plant is the enterprise’s ultimate nightmare.
- There are well-founded fears regarding quality control and assurance, and compliance with safety standards.
  - *Are the National Nuclear Safety Administration and the Ministry of Environmental Protection overwhelmed?*

Chinese City Backs Down on Proposed Nuclear Fuel Plant After Protests

点击查看本文中文版 | Read in Chinese

By CHRIS BUCKLEY AUG. 10, 2016

Do we trust the risk communicators?

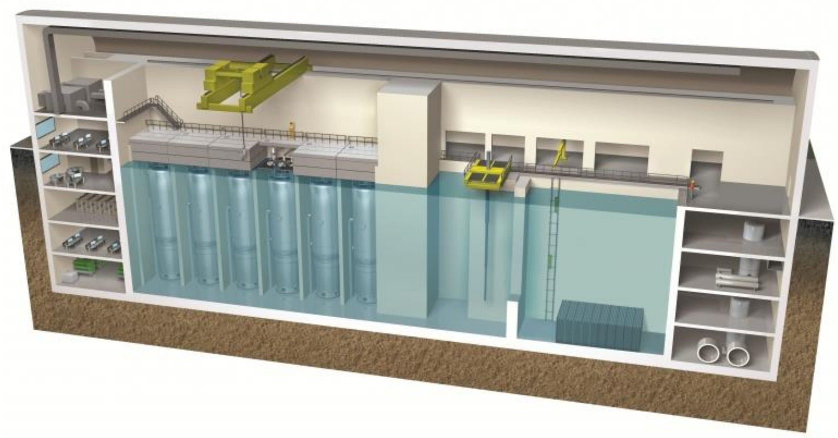
Response has been to:

1) Deploy a new generation of advanced reactor designs that are safer than current reactors
2) Develop accident and sabotage-proof designs (?)
3) Emphasize automation in future technologies
4) Appeal to stay the course, educating citizens about nuclear power's small risks and increasing their general scientific literacy and numeracy.

Would people's perception change if the core damage frequency is reduced to 10^{-8} from 10^{-7}?

Smallness → secondary innovations

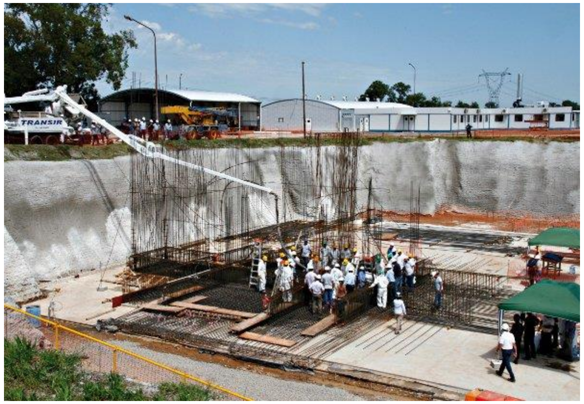
- Factory fabrication and shorter construction schedules
- Underground or aboveground deployment
- Land-based or sea-based deployment
- Increased flexibility with respect to geography and planning



DOE (2014); DCNS (2014); Modern Power Systems (2014)

Are SMRs available today?

Russia
Floating NPP
2 x 35MWe KLT-40S PWRs
Supposed: 2006
Anticipated: 2019



Argentina
CAREM
1 x 25MWe iPWR
30 years in planning

China
HTR-PM
2 x 105 MWe HTR
Ran a pilot plant at INET

KLT-40S: http://bellona.org/
CAREM: NEI/carem
HTR-PM: http://www.world-nuclear-news.org/

Are naval reactors SMRs?

http://hiketricities.com/wp-content/uploads/2012/09/DSC_0038.jpg

http://l7.alamy.com/zooms/d5e2cc9e1c61438ba536af82e65650ef/sverdlovsk-region-russia-10th-mar-2016-the-central-hall-of-the-4th-fkytfa.jpg

Problem 1: Advantages are speculative

“The academic-reactor designer is a dilettante. He has not had to assume any real responsibility in connection with his projects. He is free to luxuriate in elegant ideas, the practical shortcomings of which can be relegated to the category of "mere technical details." The practical-reactor designer must live with these same technical details. Although recalcitrant and awkward, they must be solved and cannot be put off until tomorrow. Their solution requires manpower, time and money.”

Ahem:

"An academic reactor or reactor plant almost always has the following basic characteristics: **(1)** It is simple. **(2)** It is small. **(3)** It is cheap. **(4)** It is light. **(5)** It can be built very quickly. **(6)** It is very flexible in purpose. **(7)** Very little development will be required. It will use off-the-shelf components. **(8)** The reactor is in the study phase. It is not being built now.

"On the other hand a practical reactor can be distinguished by the following characteristics: **(1)** It is being built now. **(2)** It is behind schedule. **(3)** It requires an immense amount of development on apparently trivial items. **(4)** It is very expensive. **(5)** It takes a long time to build because of its engineering development problems. **(6)** It is large. **(7)** It is heavy. **(8)** It is complicated."

Problem 2: Nuclear innovation is hard

Take the characteristics of innovation in any industry, and try to apply them to nuclear power – it is very difficult. Examples:

- **Fail fast:** Developing a new nuclear energy system is anything but fast. Also, do you really want failure when extensive amounts of public money are being spent?
- **The size of the check:** R&D paradigms – like 70/20/10 – don't work here. This would be an enormous public works project, regardless of reactor scale. On the order of $10 billion. Little private capital.
- **Recruiting talent and collaborating internationally:** collaborating with non-Americans, Americans risk jail. Everything is sensitive and overclassified. Couple this with a convoluted and unreliable export control system.

Technology readiness levels (TRLs)

- A method to assess the level of a technology's maturity.
- Developed by NASA during the 1970s:
  - "A TRA is a systematic, metric-based process and accompanying report that assesses the maturity of certain technologies used in systems." (DoD, 2003)
- Adopted since by the Departments of Energy and Defense, as well as large companies; adapted for their needs

The goal of using TRLs is to reflect on critical gaps in tech demonstration and improve resource allocation

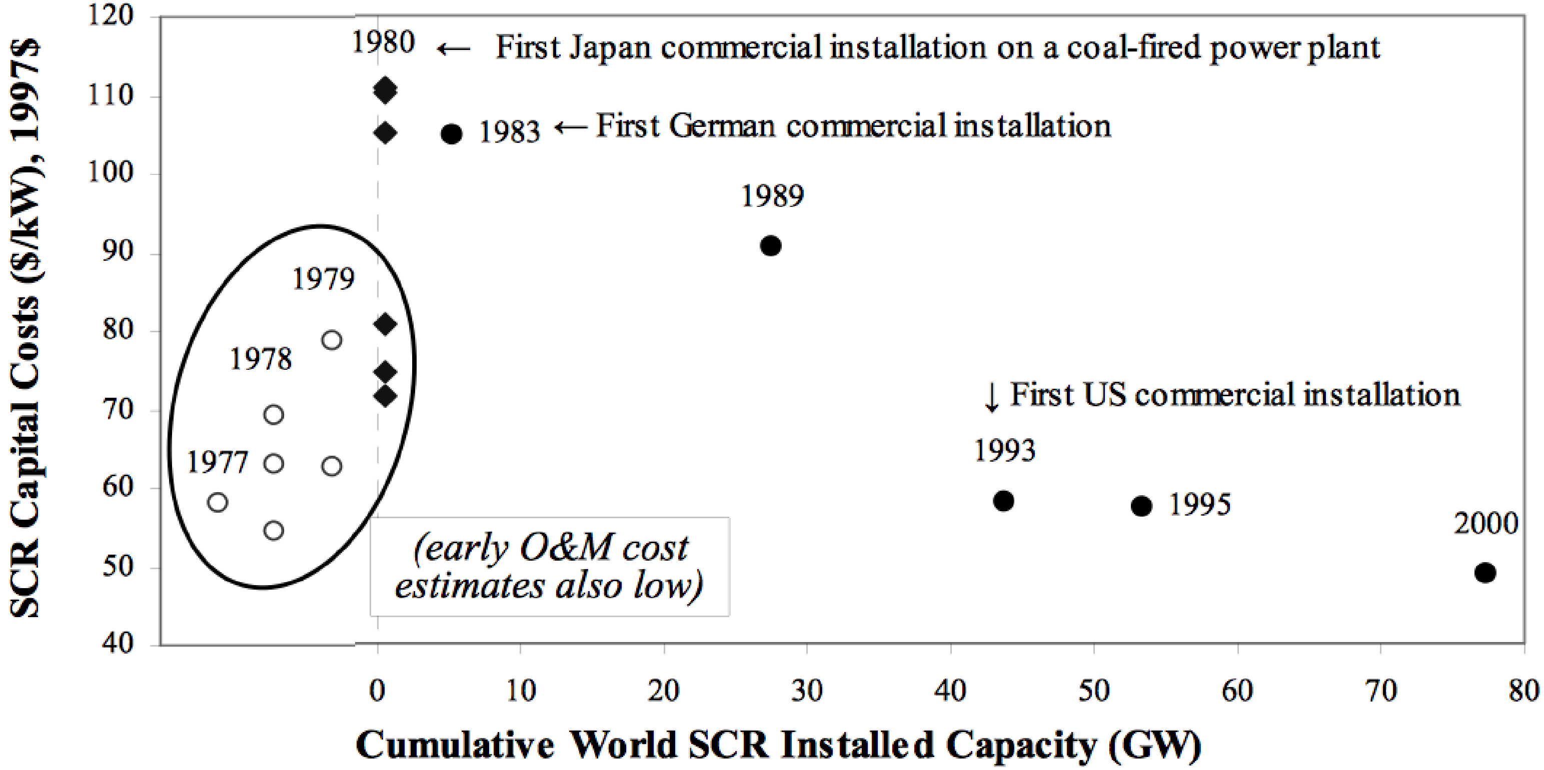
The Department of Energy's use of TRLs

U.S. Department of Energy (2010) Technology Readiness Assessment Report

TRL	Description
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or proof of concept.
4	Component and/or system validation in laboratory environment.
5	Laboratory scale, similar system validation in relevant environment.
6	Eng/pilot-scale, prototypical system validation in relevant environment.
7	Full-scale, prototypical system demonstrated in relevant environment.
8	Actual system completed and qualified through test and demonstration.
9	Actual system operated over the full range of expected conditions.

Learning curves are non-monotonic

- Increases in the costs of early projects as kinks worked out



Rubin ES (2010) Uncertainty in Experience Curves for Climate Policy Analysis: Some insights from case studies. Presentation to the NAS Workshop on Modeling the Economics of Greenhouse Gas Mitigation. (Washington, DC).

Problem 3: The market is changing

- There is a risk that, while addressing the problems of the past and the problems of their industry, nuclear engineers and corporate executives are forgetting to take fully into account utility, energy system, and grid operator requirements in the 21st century.