NUCLEAR SAFETY AND NUCLEAR ECONOMICS, FUKUSHIMA REIGNITES THE NEVER-ENDING DEBATE:

NUCLEAR SAFETY AT AN AFFORDABLE COST, CAN WE HAVE BOTH? IS NUCLEAR POWER NOT WORTH THE RISK AT ANY PRICE?

Mark Cooper, Ph. D.

Senior Fellow for Economic Analysis
Institute for Energy and the Environment
Vermont Law School

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SUMMARY

The Central Challenge of Nuclear Power

In the wake of a severe nuclear accident like Fukushima, the attention of policymakers, regulators, and the public is riveted on the issue of nuclear safety. The scrutiny is so intense that it seems like the only thing that matters about nuclear reactors is their safety. This paper shows that in fact, and for good reason, the central tension throughout the 50-year history of commercial nuclear power in the United States has been the relationship between the safety and economics of nuclear reactors, tension that is far from resolved.

The paper presents an analysis of two aspects of the "infrastructure of safety regulation" (as the Vice Chairman of the Japanese Atomic Energy Commission called it. It examines the organizational structure of safety regulation and the continuing operational challenges that confront the safety of nuclear reactors. This analysis relies on a qualitative review of safety concerns and a quantitative review of performance in the 1970s (including the reaction to the accident at Three Mile Island), as well as the post-Fukushima reviews of nuclear safety.

The economic analysis is based on a comprehensive data set on virtually all U.S.nuclear reactors (251) planned or docketed at the Nuclear Regulatory Commission. Two dozen variables believed to influence three key junctures in the development of nuclear reactors are examined, the build/cancel decision, construction costs and repair/retire decisions. The variables include characteristics of the reactors (e.g. size, technology, builder), the nature of safety regulation (e.g. rules in place, fines imposed), the status of the industry (e.g. experience and activity), the conditions in the economy (e.g. inflation), and the status of the state utility industry (e.g. demand growth rate, numbers of reactors under construction, fuel types).

The Real world Roots of the Safety Debate

Sections II & III: In the late 1950s the vendors of nuclear reactors knew that their technology was untested and that nuclear safety issues had not been resolved, so they made it clear to policymakers in Washington that they would not build reactors if the Federal government did not shield them from the full liability of accidents. Having secured legislation in the late 1950s, electric utilities proposed a massive expansion of nuclear power over the course of a couple of decades that would have taken the industry from a handful of small reactors with a total generating capacity of about one Giga watt to over 250 reactors with a total capacity of almost 200 Giga watts (see Figure ES-1).

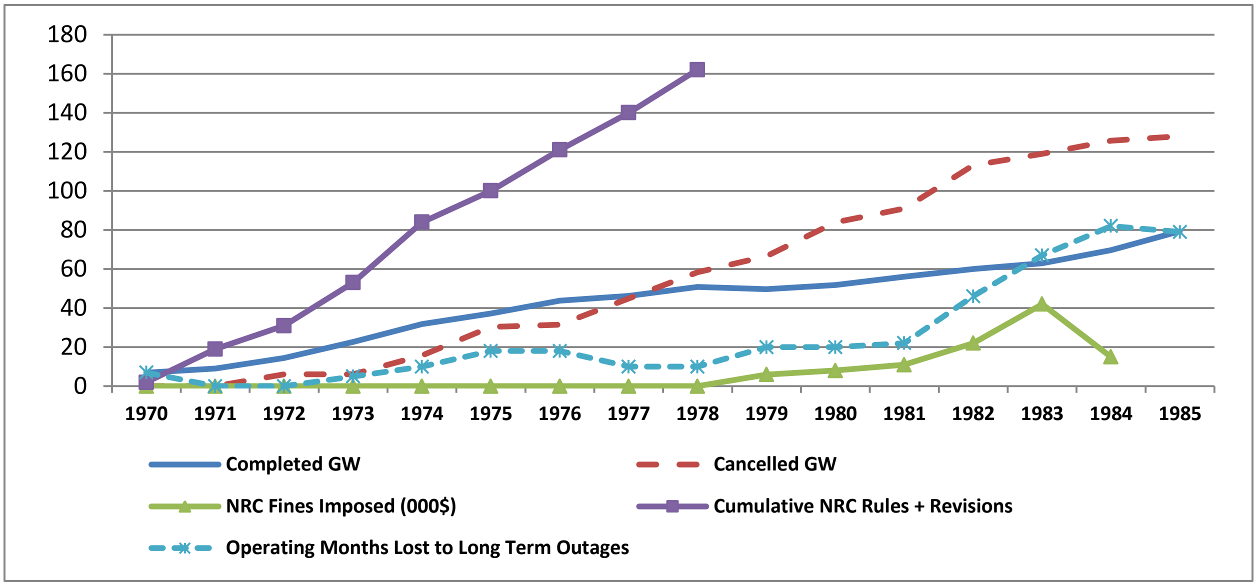
The expansion in size would have put large metropolitan areas with hundreds of millions of people in close proximity to nuclear reactors whose design and operation had never been fully tested. As more experience was gained with the operation of these huge reactors, the Nuclear Regulatory Commission (originally named the Atomic Energy Commission) became deeply concerned about the safety of nuclear power. Hundreds of safety regulations were written and revised over the course of the 1970s.

The U.S. and global experience with nuclear reactor development and operation provided a constant drum beat of incidents, near misses, and catastrophic accidents that demonstrated to regulators and the public that the concern about the safety of nuclear power was grounded in reality. The cost of the most severe accidents (e.g. Chernobyl and Fukushima) run into the hundreds of billions of dollars. The worst case scenarios (e.g. New York or Los Angeles) would exceed a trillion dollars.

The Current Safety Debate

Section IV: Confronted with catastrophic possibilities, safety regulators and others responsible for nuclear power seek to learn from major accidents. The pre-TMI debates about nuclear safety, the review of the TMI accident, and the post-Fukushima reviews exhibit strong similarities in finding flaws in nuclear safety regulation (see Table ES-2). These involve vitally important organizational characteristics of safety regulation as well as continuing operational challenges that confront the safety of nuclear reactors.

FIGURE ES-1: SAFETY REGULATION AND THE DISPOSITION OF NUCLEAR REACTORS



Sources: Fines: Tomain, *Nuclear Power Transformation* (Bloomington: Indiana University Press, 1987; Rules: Komanoff, Charles, *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics,* (New York: Van Nostrand, 1981); Total reactors Fred A. Heddleson, *Summary Data for U.S. Commercial Nuclear Power Plants in the United States*, Nuclear Safety Information Center, April 1978; U.S. Energy Information Administration, *Nuclear Generating Units, 1955-2009;* Cancelled reactors *Jonathan Koomey, Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes?*, June 24, 2011.

In the United States more than 80 percent of US reactors face one or more of the issues that have been highlighted by the Fukushima accident – seismic risk, fire hazard, and elevated spent fuel. (see Figure ES-2) of this kind. Moreover, half of those that do not exhibit one of these issues had a "near miss" in 2011. Clearly, safety remains a challenge in the United States, one that has been magnified by Fukushima.

If, as Tomain (1987: ix) argued, "TMI made the United States aware of unforeseen costs, just as Chernobyl made the world aware of unforeseen risks," then Fukushima has made the perception of those risks real and expanded their scope dramatically. Fukushima reminds us that nuclear accident happen, but are impossible to predict because of the complex and dynamic interplay of technological, human and natural factors. severe impacts can be imposed on such large, unprepared populations, but the magnitude of the impact is hard to grasp and communicate. The understanding of the sequence of events in accidents is highly imperfect, which means that the immediate reaction called for is very uncertain. The uncertainty and involuntary nature of the harm and the inability of responsible authorities to deal with it creates an augmented sense of risk. Thus the heightened sense of concern that is attached to nuclear power and the psychological distress suffered by the public is grounded in the nature of the risk of the technology, which is made quite evident by severe accidents, like Fukushima.

Traditionally, the focal point of analysis of the "harms" of nuclear power has been on the public health risks of exposure to radiation that may be released from a reactor, but Fukushima makes it clear that the social and economic impacts of a severe accident close to population centers are very serious and also deserve a great deal of attention. We are now having a debate about nuclear evacuation zones of 50 miles.. The disruption of daily life in a large area around a nuclear accident has become a focal point of concern. Large numbers of people may be temporarily or permanently uprooted. The fact that the Japanese government was considering evacuating Tokyo, 150 miles away and there are large dead exclusion zones a year later underscores this concern.

TABLE ES-2: THE INADEQUATE INFRASTRUCTURE OF NUCLEAR SAFETY REGULATION

ORGANIZATIONAL FLAWS

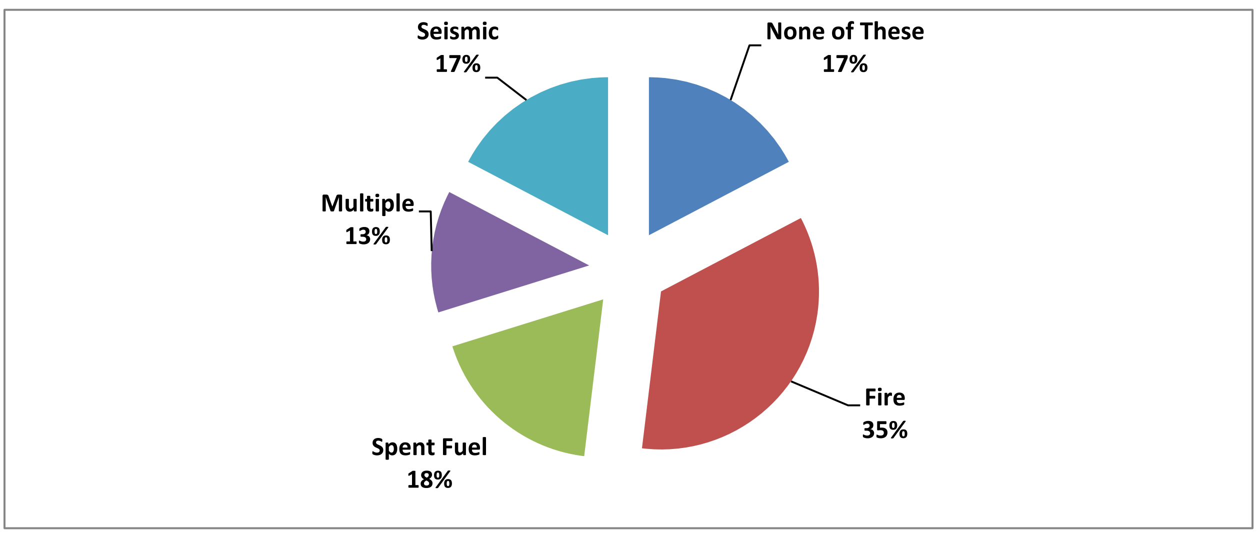
Lack of a Comprehensive, Consistent, Safety Regulation Framework
Denial of the Reality of Risk
Complexity, Confusion, and Chaos in the Response to a Severe Accident
Failure of Voluntary, Self-Regulation
Perverse Incentives in Commercial Attitudes toward Safety:
Deficient management process including planning, standard setting, inspection, communications
Failure to Resolve Important Safety Issues:
Failure to Retrofit Safety on Existing Reactors
The Challenge of Continuous Change and the Future of Safety

THE IMMEDIATE OPERATIONAL CHALLENGES

Design (event tolerance, cooling, venting, backup system resilience and redundancy),
Siting (reactor crowding, seismic and flooding vulnerabilities)
Waste storage,
Evacuation plans and
Cost increases

Source: Komanoff, C, 1981 *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics*, Van Nostrand, 1981. John G Kemeny *Report of The President's Commission on the Accident at Three Mile Island,* October 30, 1979; Nuclear Regulatory Commission, *TMI-2 Lessons Learned Task Force Final Report,* October 1979;Tatsujiro Suzuki, "Deconstructing the Zero-Risk Mindset: The Lessons and Future Responsibilities for a Post-Fukushima Nuclear Japan, " *Bulletin of the Atomic Scientists, September 20, 2011;* Nuclear Regulatory Commission, *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,* U.S. NRC, July 12, 2011; Yoshiro Nakagome, *JNES's Response to TEPCO Fukushima NPS Accident,* November 2011; Eurosafe Forum, Experience Feedback on the Fukushima Accident, November 8, 2011; D. Degueldre, T. Funshashi, O. Isnard, E. Scott de Martinville, M. Sognalia, "Harmonization in Emergency Preparedness and Response;" P. De Gelder, M. Vincke, M. Maque, E. Scott de Martinville, S. Rimkevicius, K. Yonebayashi, S. Sholmonitsky, *"The Evolution of the TSO Programme of Work after the Fukushima Daiichi NPS Acciden*t.

FIGURE ES-2: SIGNIFICANT ONGOING SAFETY ISSUES



Source: Union of Concerned Scientists, *Nuclear Power Information Tracker,* March 2012, http://www.ucsusa.org/nuclear_power/reactor-map/embedded-flash-map.html

Fukushima is a real economic disaster. The costs are estimated as high as a quarter of a trillion dollars. Tokyo Electric Power Company, the fourth largest utility in the world, was instantly pulled into virtual bankruptcy, when its stock plunge 90 percent, notwithstanding liability limits and governmental commitments to shoulder much of the cost. The Japanese grid is under severe stress. The economy has been damaged. Safety regulators have known about these potential impacts, but they were hypothetical. Fukushima makes them real.

Real World Economic Problems of Nuclear Reactors

Section V: Reactor cost overruns were endemic from the very beginning of the commercial industry because nuclear vendors and enthusiasts had underestimated the costs and overestimated the ability of economies of scale and "learning by doing" to lower the cost. The increasing demand for safety compounded the problem. The final reactors built cost ten times the initial estimates and by1978, the year before the worst nuclear accident in U.S. history, more reactor capacity had been cancelled than completed. After the TMI accident, the Nuclear Regulatory Commission stepped up its enforcement of safety rules, which extended the construction period and further increased the cost of reactors. No order for a new nuclear reactor was placed in the United States for over a quarter of a century.

Table ES-1: Statistically Significant Variables in the Econometric Analysis

Factors/variables	**Probability of building**	**Construction period**	**Overnight cost ($/kw)**
Stricter safety regulation	Less likely	Longer	More costly
Technology			PWR less costly
Larger capacity		Longer	Less Costly
Multiple Units at a site			Less Costly
Longer construction			More costly
More industry activity		Longer	More costly
More builder experience		Shorter	
Higher demand growth	More likely		
Higher interest rates			More costly
Post-TMI	Less likely		
Explained variance (R^2)	.91	.76	.82

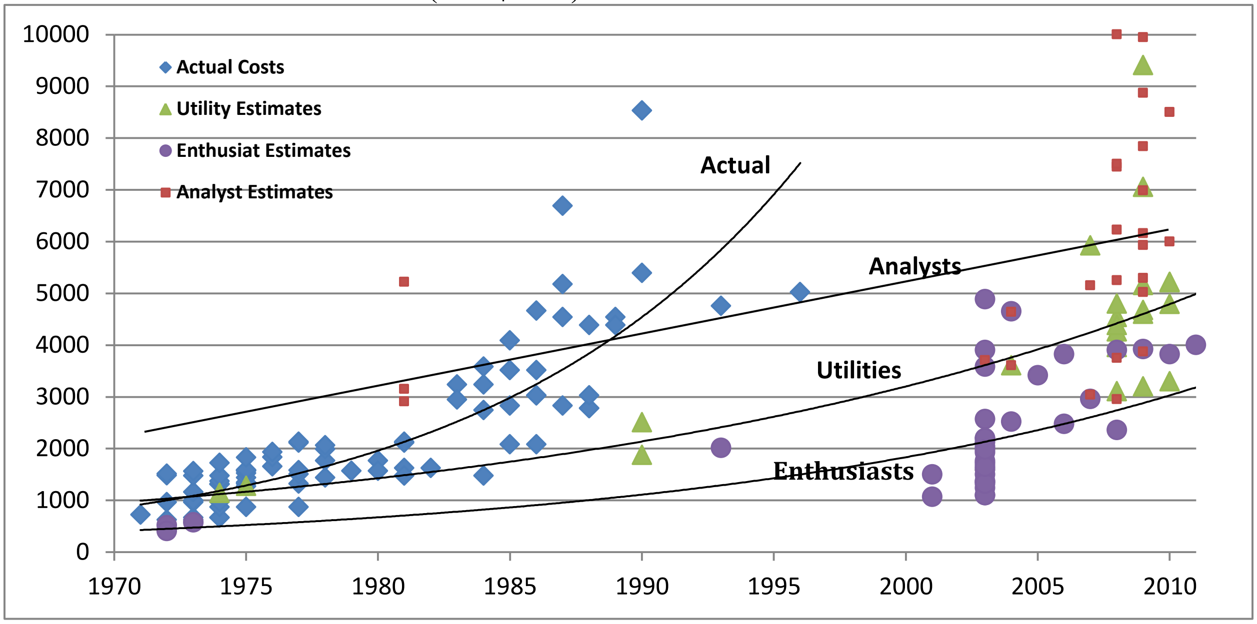
Table ES-1 summarizes the results of the statistical analysis. Safety is the most consistent explanatory variable, with stricter standards associated with less likelihood of building, longer construction period and higher cost. The findings on technology and industry characteristics reinforce the conclusion that the industry did not benefit from a "learning by doing" process. The belief that higher growth rates were associated with a higher probability of being completed and higher interest rates were associated with higher costs is confirmed in this statistical analysis. However, over the period of the 1970s-1980s, the amount of fossil fuel generation capacity added actually exceeded the amount of nuclear capacity cancelled. In other words, if the economics of nuclear reactors had not been so unfavorable, fewer would have been cancelled and more fossil fuel capacity would have been displaced.

Analysis of early retirements reinforces the above conclusions. A combination of factors causes retirement, but there tends to be a precipitating event like a major equipment failure, system deterioration, repeated accidents, increased safety requirements, etc. Economics is the most frequent proximate cause and safety is the most frequent factor that triggers the economic re-evaluation. Although popular opposition "caused" a couple of the retirements (a referendum in the case of Rancho Seco; state and local government in Shoreham), this was far from the primary factor and in some cases local opposition clearly failed (two referenda in eh cases of Trojan and Maine Yankee). External economic factors like declining demand or more cost competitive resources can render existing reactors uneconomic on a "stand alone" basis or (more often) in conjunction with one of the other factors.

The Current Economic Challenges

Section VI: In the 1970s and 1980s the nuclear industry could not overcome the problem of escalating costs and lower cost alternatives. It continues to be afflicted by the same problems. The "nuclear renaissance," which was loudly heralded with extremely optimistic cost projections proved to a re-run of the collapse of the "Great Bandwagon Market" of the 1970s and 1980s (see Figure ES-3). The industry could not live up to the hype and cost projections escalated rapidly. The estimates now used by utilities are three times the initial "renaissance" estimates, while independent analysts on Wall Street, put the cost estimates at five times the original estimates.

FIGURE ES-3: OVERNIGHT COSTS (2009$/KW) OF REACTOR CONSTRUCTION



Source: Actual Costs from Jonathan Koomey, and Nathan E. Hultman, 2007, "A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970-2005," *Energy Journal,* 2007; Projections updated from Mark Cooper, *The Economics of Nuclear Reactors: Renaissance or Relapse* (Institute for Energy and the Environment, Vermont Law School, June, June 2009).

The subsidy problem in nuclear reactor construction has actually become much more severe. The liability limitation is still in place and, given the magnitude of the impact of the Fukushima accident, the gap between private liability and public liability is likely to be much larger. In addition, the utilities proposing new nuclear reactors have demanded many more and larger direct subsidies. They have demanded much more direct ratepayer support in the form of advanced cost recovery. Since construction of nuclear reactors cannot be financed in normal capital markets, federal loan guarantees and partnership with public power that has independent bonding authority appear to be necessary ingredients to move projects forward.

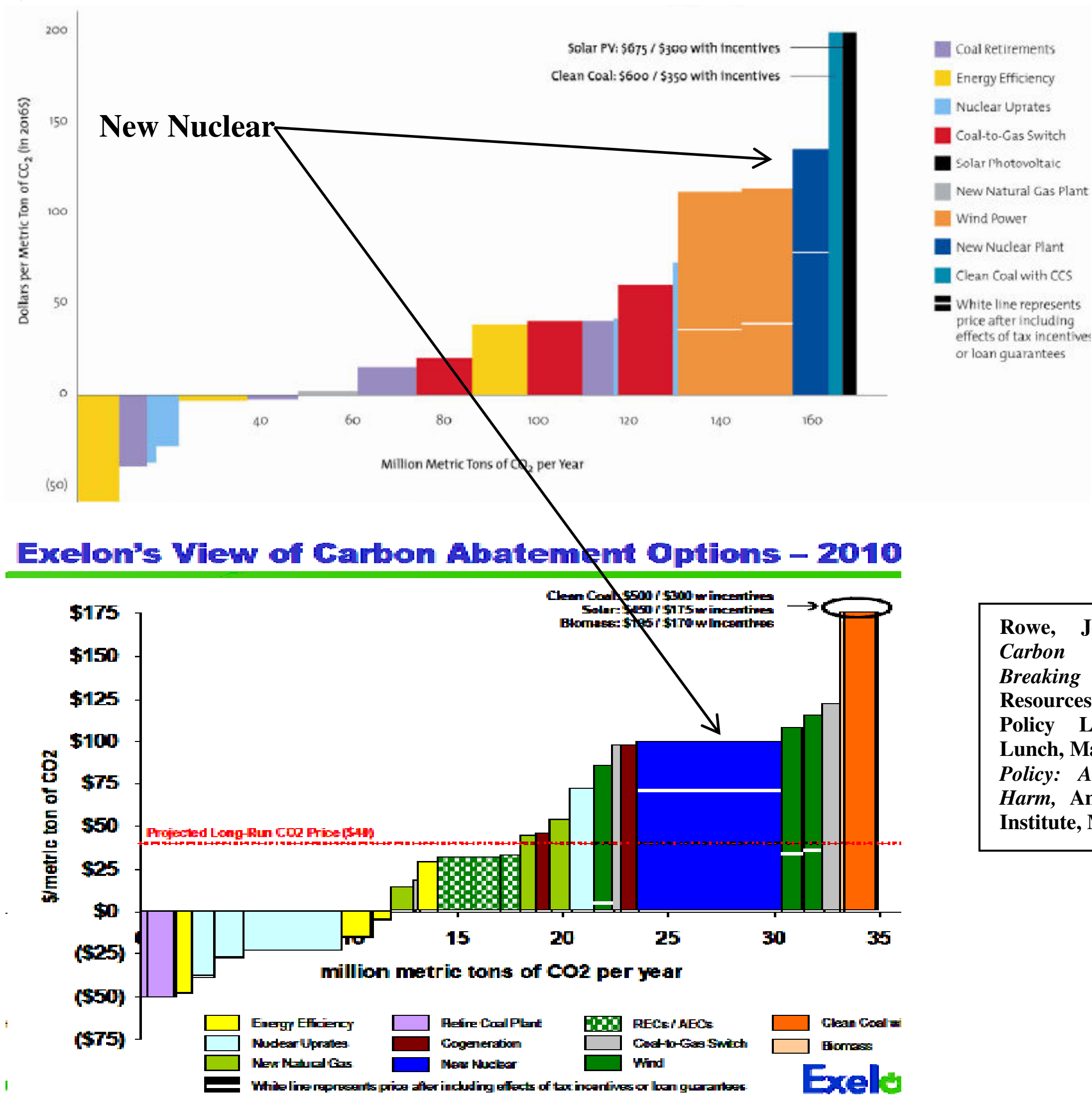
In addition to the challenge of cost escalation, nuclear power continues to be unable to meet the challenge of lower cost alternatives, even in a carbon-constrained future. Many analysts and utilities, including those that own operating nuclear reactors, have concluded that there are numerous lower cost alternatives available. As shown in Exhibit ES-4, even before Fukushima, nuclear was way up the supply curve of low carbon resources.

A NEW INFRASTRUCTURE OF DECISION MAKING

Section VII: As pressing as the need for a new "infrastructure of safety regulation" is in the nuclear sector, the need for a new "infrastructure of decision-making" for resource acquisition in the electricity sector is even greater. Fukushima reminds us that nuclear accidents fall into a realm of knowledge that involves unknown unknowns. The NRC identifies the challenge of dealing with "low likelihood, high consequence events," while the Office of Technology Assessment referred to "low probability, catastrophic accidents." The nuclear unknowns are part of an increasingly ambiguous decision-making space afflicted by price volatility, supply insecurity and growing concerns about environmental externalities that confronts those responsible for resource acquisition to ensure an affordable, reliable, secure, and sustainable supply of electricity.

FIGURE ES-4: TWO UTILITY VIEWS OF RESOURCE COST

PJM



Rowe, John, *Fixing the Carbon Problem without Breaking the Economy,* Resources for the Future Policy Leadership Forum Lunch, May 12, 2010; *Energy Policy: Above All, Do No Harm,* American Enterprise Institute, March 8, 2011

How does one make effective decisions in a space where the impacts of significant events or use of important resources are unclear (outcomes unknown) and the occurrence of those events or the availability and price of those resources are unpredictable (the probabilities are unknown)? A number of frameworks for navigating in regions where knowledge is extremely limited have been developed over the past half century in military strategy, space exploration, technology assessment, engineering science, and financial analysis.

As suggested by Figure ES-5, the efforts to map the terrain of knowledge start from the premise that there are two primary sources of ambiguity: lack of knowledge about the nature of outcomes and/or lack of knowledge about the probabilities of those outcomes. Four regions of knowledge result: risk, uncertainty, vagueness, and the unknown. The decision-making space is darkest where knowledge is lacking, but each region of knowledge presents a distinct challenge to the decision-maker. The crucial starting point for all these analyses is to admit that you don't know what you don't know and then develop tools for navigating with imperfect knowledge. Unfortunately, admitting what you do not know is not something that builders and operators of nuclear reactors are inclined to do. Their reaction is to insist their reactors are safe and commit to making them safer, but then complain bitterly about and resist additional safety measures that increase their costs.

In the current environment for resource acquisition must:

- identify the trade-offs between cost and risk to allow hedging to lower risk;
- maximize options to reduce exposure to uncertainty by buying time and keeping options open with small assets that can be added quickly;
- be flexible with respect to outcomes that are, at best, vague creating systems that monitor and can adapt to change in order to maintain system performance and minimize surprises by avoiding assets that have unknown or uncontrollable effects, and
- be insulated against ignorance of the unknown by buying insurance and building resilience with diversified asset portfolios that exhibit variety, balance and disparity resources.

Acquisition of nuclear facilities is particularly unattractive-- the antithesis of the type of asset a prudent investor wants to acquire, because of their long lead times and lives, large sunk costs, and high risk profile.

"Nuclear safety at an affordable cost, can we have both?" seems like a straightforward question to journalists and policy makers, but is actually a very complex question. Phrased as Tomain did shortly after Chernobyl the question is more pointed: "Is nuclear power not worth the risk at any cost?" If a simple answer is demanded, as it frequently is during post-accident review, then the answer must be no.

- If we use a market standard, nuclear power is neither affordable nor worth the risk.
- If the owners and operators of nuclear reactors had to face the full liability of a nuclear accident or meet alternatives in a competition unfettered by subsidies, no one would have built a nuclear reactor in the past, no one would build one today, and anyone who owns a reactor would exit the nuclear business as quickly as they could.
- The combination of a catastrophically dangerous resource, a complex technology, human frailties, and the uncertainties of natural events make it extremely difficult and unlikely that the negative answer can be changed to a positive.

The post-accident safety reviews have revealed that a "public myth of absolute safety" lulled the industry into a false sense of security and a "lack of preparedness." The post-Fukushima economic review must expose the myth of economic viability that has been created by half a century of subsidies. Thus, in formulating the answer, the lessons of half a century of nuclear power should be kept in mind.

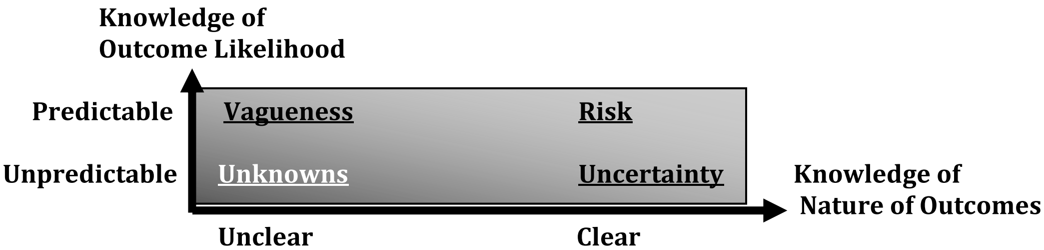
Nuclear power is a non-market phenomenon: It is certainly true that economics has decided, and will likely continue to decide, the fate of nuclear power. The fiction that investors and markets can make decisions about nuclear power in a vacuum is dangerous. Given the massive economic externalities of nuclear power (not to mention the national security and environmental externalities), policy-makers decide the fate of nuclear power by determining the rate of profit through subsidies.

Learn from history: Sound economic analysis requires that sunk costs be ignored, but the mandate for forward-looking analysis does not mean that the analyst should ignore history. Utilities claim that the cost of completing a new reactor or repairing an old one is lower than the cost of pursuing an alternative from scratch. The problem is that utilities are just as likely to underestimate and be unable to deliver on the promised "to-go" costs in the future as they have been in the past. Regulators must exercise independent judgment and take the risk of cost overruns into consideration.

Match risks and rewards: If the goal is to have cost-efficient decisions, risks must be shifted onto those who earn rewards. By reducing the rate of profit that utilities earn from subsidized project, policy-makers can offset the bias that subsidies (such as loan guarantees and advanced cost recovery) introduce into utility decision-making.

EXHIBIT ES-5: CONFRONTING AMBIGUITY IN THE INCREASINGLY COMPLEX TERRAIN OF KNOWLEDGE:

THE REGIONS OF KNOWLEDGE



TOPOGRAPHIC MAPS AND NAVIGATION TOOLS FOR THE REGIONS OF KNOWLEDGE

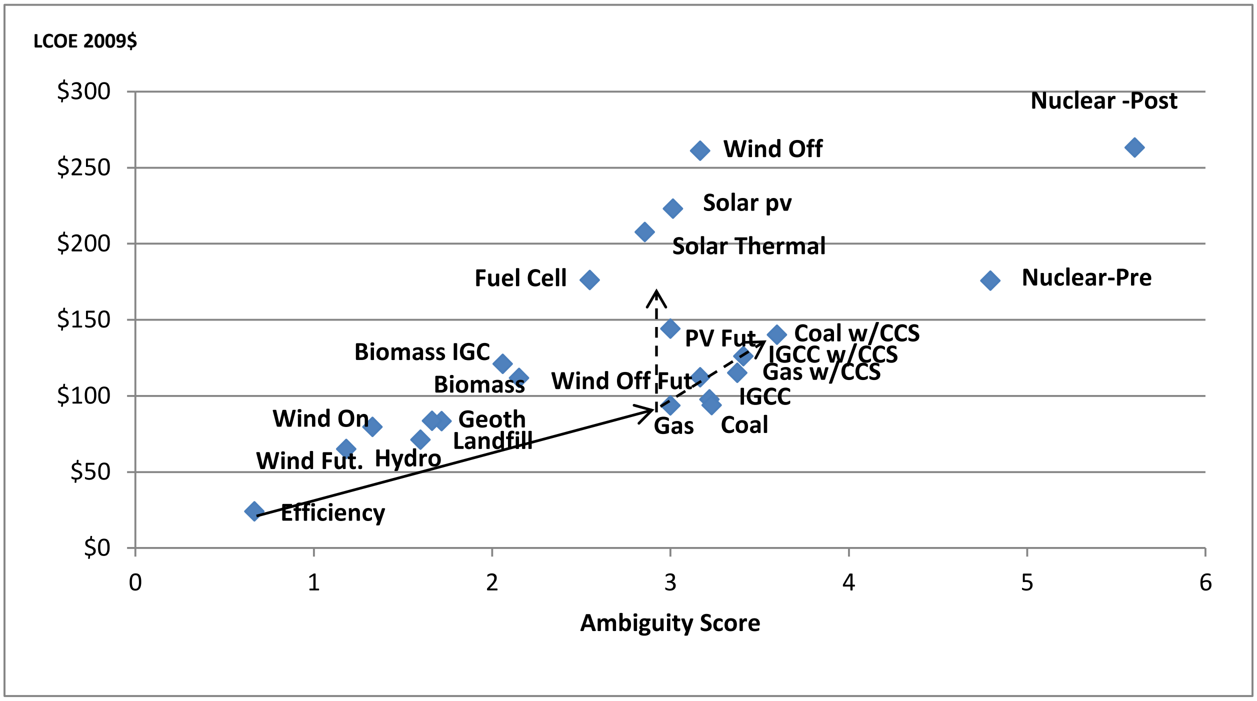
	UNKNOWNS	VAGUENESS	UNCERTAINTY	RISK
TOPOGRAPHIC MAPS				
Technology Risk Assessment				
Challenges	Unanticipated effects	Contested framing	Nonlinear systems	Familiar systems
Outcomes	Unclear	Unclear	Clear	Clear
Probabilities	Unpredictable	Predictable	Unpredictable	Predictable
Black Swan Theory				
Challenges	Black Swans Wild randomness	Sort of Safe	Safe	Extremely safe Mild randomness
Conditions	Extremely fragile	Quite robust	Quite robust	Extremely robust
Distributions	Fat tailed	Thin tailed	Fat tailed	Thin tailed
Payoffs	Complex	Complex	Simple	Simple
Reliability & Risk Mitigation Management				
Challenges	Chaos	Unforeseen uncertainty	Foreseen uncertainty	Variation
Conditions	Unknown/ unknowns	Unknown/ knowns	Known/ unknowns	Known/knowns
NAVIGATION TOOLS				
Analytic frameworks				
Approach	Multi-criteria analysis	Fuzzy logic	Decision heuristics	Statistics
Tools	Diversity assessment	Sensitivity analysis	Scenario analysis	Portfolio evaluation
Focus	Internal resources & structure	Internal resources & structure	External challenges	External challenges
Data	<u>Swan Search</u> Consistency Unintended consequences Externalities <u>Diversity</u> Structural Alternative Instrument Sufficiency	<u>Vagueness</u> Supply security Resource base Market scope Environmental impact Pollutants (air. Land water, waste) Greenhouse gasses	<u>Uncertainty</u> Capacity Construction period Sunk cost (Total capital = MW * $/MW)	<u>Cost -Risk</u> Levelized cost of energy Cost variability Fuel O&M Carbon Ccapital
Policy Tools				
Processes	Learning	Learning	Planning	Planning
Instruments	Insurance/diversity	Monitor & Adjust	Optionality	Hedging
Rules	<u>TECHNOLOGY RISK ASSESSMENT</u> Precaution Buy insurance for system survival Accept non-optimization Diversity Variety Balance Disparity <u>BLACK SWAN THEORY</u> Truncate Exposure Buy insurance for system survival Accept non-optimization Redundancy Numerical Functional Adaptive	<u>TECHNOLOGY RISK ASSESSMENT</u> Resilience Adaptability <u>BLACK SWAN THEORY</u> Multi- functionality What Works	<u>TECHNOLOGY RISK ASSESSMENT</u> Flexibility Across Time Across Space <u>BLACK SWAN THEORY</u> Optionality	<u>TECHNOLOGY RISK ASSESSMENT</u> Resilience Robustness Hedge <u>BLACK SWAN THEORY</u> Robust to Error Small, Confined, Early Mistakes Incentive & disincentives Avoid Moral Hazard Hedge

Sources: Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), Postscript; Andrew Stirling, *On Science and Precaution in the Management of Technological Risk* (European Science and Technology Observatory, May 1999), p. 17, *On the Economics and Analysis of Diversity* (Science Policy Research Unit, University of Sussex, 2000), Chapter 2; "Risk, Precaution and Science; Toward a More Constructive Policy Debate," *EMBO Reports,* 8:4, 2007; David A. Maluf, Yuri O. Gawdisk and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety,* N.D.; Gele B. Alleman, *Five Easy Pieces of Risk Management,* May 8, 2008; see also, Arnoud De Meyer, Christopher H. Lock and Michel t Pich, "Managing Project Uncertainty: From Variation to Chaos," *MIT Sloan Management Review,* Winter 2002.

Buy time: Given the severe problems that retrofitting poses and the current conditions of extreme uncertainty about changes in safety regulation, it is prudent to avoid large decisions that are difficult to reverse or modify. Flexibility is a valuable attribute of investments, and mistakes should be kept small.

Applying this approach to resource acquisition leads to clear pathways to the future built on resources that have attractive characteristics even in a carbon constrained world (see Exhibit ES-6).. The clearest finding is that nuclear does not belong on the near-term supply-curve and it does not appear to be an attractive resource for the long-term, in light of the potential availability of future renewables and carbon capture technologies. This is the same conclusion suggested by Exhibit ES-4, but it is much sharper when the other sources of ambiguity are incorporated into the analysis.

EXHIBIT ES-6: RESOURCE ACQUISITION PATHS BASED ON MULTI-CRITERIA EVALUATION



Sources: Mark Cooper, "Prudent Resource Acquisition in a Complex Decision Making Environment: Multidimensional Analysis Highlights the Superiority of Efficiency," *Current Approaches to Integrated Resource Planning, 2011 ACEEE National Conference on Energy Efficiency as a Resource*, Denver, September 26, 2011

To be sure, the burning question is whether the nations that have relied on nuclear power to a significant extent will be able to shift the resources base. There is no doubt that this is a significant technological and economic challenge that will not be easy. It is important to keep in mind that the outcome of the analysis can certainly vary from nation to nation because the natural resource endowments of nations vary. However, Fukushima reminds us that nuclear power is not easy either and embodies significant challenges that have been repeatedly underestimated or ignored.

I. INTRODUCTION

THE NEVER ENDING DEBATE OVER SAFETY AND ECONOMICS

Throughout the history of the commercial nuclear industry, the safety and cost of nuclear reactors have been a constant source of concern, analysis, and debate. Nuclear accidents are exclamation points in the continuous narrative of safety and economics.[1] Each of the three major accidents in the 50-year history of commercial nuclear power (Three Mile Island, Chernobyl, and Fukushima) has prompted a thorough re-examination of every aspect of nuclear power, which has led to more stringent safety requirement and higher costs.

In the wake of the severe accident at Fukushima the scrutiny is particularly intense and the implications for nuclear power in market economies, particularly the United States, more direct.

- Chernobyl could be dismissed as a product of Soviet technology and society, but the reactors at Fukushima are owned by a private company, Tokyo Electric Power Company (TEPCO), which is the largest utility in Asia and the fourth largest in the world.
- Japan is a nation with a reputation for discipline, scientific knowledge, and engineering prowess.
- A quarter of the existing U.S. reactors have the Fukushima technology(Nuclear Information Resource Service, 2011) and the majority of new reactors proposed in the US in the past decade are using other Japanese technologies, which the Japanese may be abandoning at home. (Inajama and Kada, 2011; Fackler, 2012).

The swift formation of a Nuclear Regulatory Commission (NRC) Fukushima Task Force attests to the urgent need to "determine whether the agency should make additional improvements to its regulatory system and to make recommendations to the Commission for its policy direction, in light of the accident at the Fukushima Daiichi Nuclear Power Plant." (NRC, 2011: vii) The report concluded that action was needed.

- **The regulatory approach to safety at the NRC is a "patchwork" in need of reform to provide a framework that is "logical, systematic, coherent, clear and consistent."** (NRC, 2011: 18… 20)

Thirty-two years earlier, an NRC Task Force was similarly formed "to identify and evaluate those safety concerns originating in the TMI-2 accident that require licensing actions… for presently operating reactors as well as for pending operating license (OL) and construction (CP) applications." (NRC, 1979: 1) The TMI Task Force reached a conclusion that is remarkably similar to the conclusion reached by the NRC Fukushima Task force.

- **The regulatory approach to safety was a "quiltwork" in need of substantial reform to provide "an articulate and widely noticed national nuclear safety policy with which to bind together the narrow and highly technical licensing requirements."** (NRC, 1979:1-2)

The impact of Fukushima is already apparent. A number of nations have moved swiftly to reconsider the role of nuclear reactors in their future electricity supply, with several concluding that it is no longer a technology on which they want to rely while others have scaled back their

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[1]Tomain (1987: ix), described nuclear accidents as follow: "TMI and Chernobyl serve as more than convenient mileposts in the history of nuclear power. TMI made the Unites States aware of unforeseen costs, just as Chernobyl made the world aware of unforeseen risks. These accidents are reminders of the complexities, risks, and costs of government-sponsored and regulated enterprises."

plans for new nuclear reactors.[2] Regulators across the globe have issued extensive recommendations on ways to improve nuclear safety ((Eurosafe forum, 2011; Nakagome, 2011; Nuclear Regulatory Commission, 2011. Financial analysts have downgraded nuclear utilities as an investment (Dow Jones, 2011; Tracy and Malik, 2011; Chatterjee, 2011; Jackson, 2011) and firms providing services have exited the sector. (Spiegel online, 2011; Business Green, 2011; Reuters, 2012; Charlotte Business Journal, 2011)) The Chairman of the NRC dissented from the approval of the first license to construct a new reactor issued by the NRC in over 30 years because he did not feel confident that safety regulation had yet fully digested the safety implications Fukushima. (Graves, 2012, Savannah Business Journal, 2012).

No debate about nuclear reactor safety in America goes on for long before the accident at Three Mile Island (TMI) becomes a topic of discussion. The post-Fukushima debate is not an exception. A blog-post from a Stanford consulting professor in the Department of Civil and Environmental Engineering, author of one of the most thorough studies of the cost of completed U.S. nuclear reactors, (Koomey, 2007) posed the question "Was the Three Mile Island Accident in 1979 the Main Cause of US Nuclear Power's Woes?" and answered with a firm "No." (Koomey, 2011)

This paper supports that conclusion with qualitative and quantitative analysis, but also adds a critically important nuance to that observation. The finding that TMI was not the main cause of nuclear power's difficulties in the U.S. must not mislead policy makers into thinking that nuclear safety and nuclear accidents do not matter or are unrelated. On the contrary, this paper shows that safety is the primary driver of nuclear economics and determinant of the fate of nuclear power. Nuclear accidents highlight and weave together the key themes of nuclear safety and nuclear economic in the never ending debate over nuclear power.

STUDYING THE PAST TO SHAPE THE FUTURE

To appreciate this critical nuance , one must be familiar with the pattern of the collapse of the nuclear building boom in the U.S. The reversal of fortune suffered by the nuclear industry in the United States was stunning. An April 1975 Public *Utility Fortnightly* article gushed about the benefits of nuclear reactors.

> The enormous benefits of nuclear power were reflected in an early 1975 *Public Utilities Fortnightly* survey of all American utilities that operated nuclear power plants as part of their electrical generating systems. The 24 companies concluded that "the peaceful atom" had saved their customers more than $750 million in their 1974 bills that they would have owed had their electricity come from fossil fuels. They also reported that in the same year "power from the atom" had saved "the equivalent of more than 247 million barrels of oil."[3]

A decade later, in February 1985, a dramatic cover story in *Forbes* magazine painted a completely different picture of nuclear power in America.

> The failure of the U.S. nuclear power program ranks as the largest managerial disaster in business history, a disaster on a monumental scale. The utility industry has already invested $125 billion in nuclear power, with an additional $140 billion to come before the decade is

[2] Lekander, et al., 2011, handicaps the reaction across the globe, on the basis of early reactions in the nations with nuclear reactors. Among the major nuclear states, the Japanese (Yamaguchi, 2011; Sekiguchi and Nishiyama, 2011; Watanabe and Sakamaki, 2011)), and Germans (Beinhardt, 201; Associated Press, 20111) have clearly pulled back. Nations with smaller nuclear power sectors (like Switzerland and Italy) have also decided for forego nuclear power.

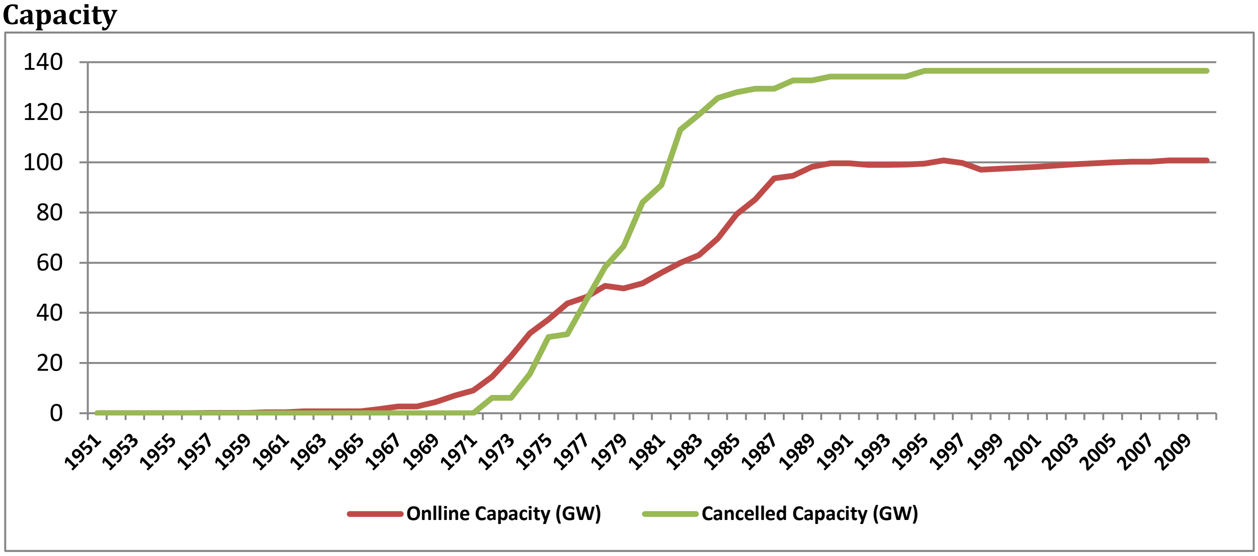
[3] April 24, 1975, cited in Bupp and Derian, 1981, pp. 7-8

out, and only the blind, or the biased, can now think that most of the money has been well spent. It is a defeat for the U.S. consumer and for the competitiveness of U.S. industry, for the utilities that undertook the program and for the private enterprise system that made it possible. (Cook, 1986)

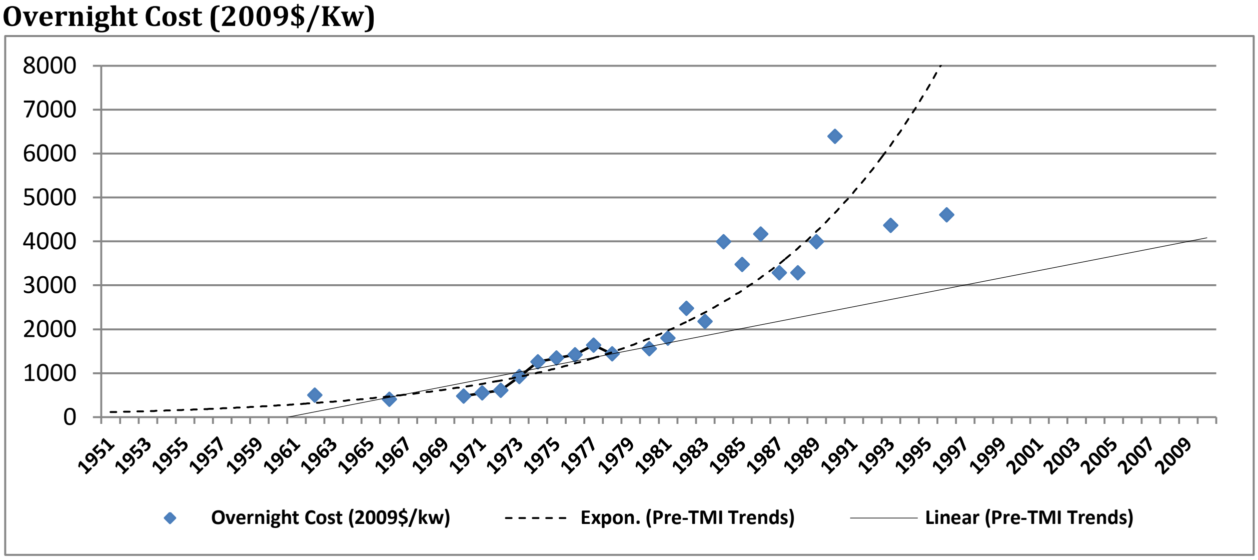
TMI occurred squarely in the middle of these two very different pictures of the performance of nuclear power. However, as shown in Exhibit I-1, by 1978, before TMI, the amount of capacity that had been cancelled exceeded the amount of capacity that had been completed. No new reactor orders were placed for 30 years after 1978 and the amount of completed capacity in the U.S. never exceeded the amount of cancelled capacity. Costs had already been rising and while they appeared to increase

EXHIBIT I-1: CUMULATIVE NUCLEAR CAPACITY AND OVERNIGHT COST

Capacity



Overnight Cost (2009$/Kw)

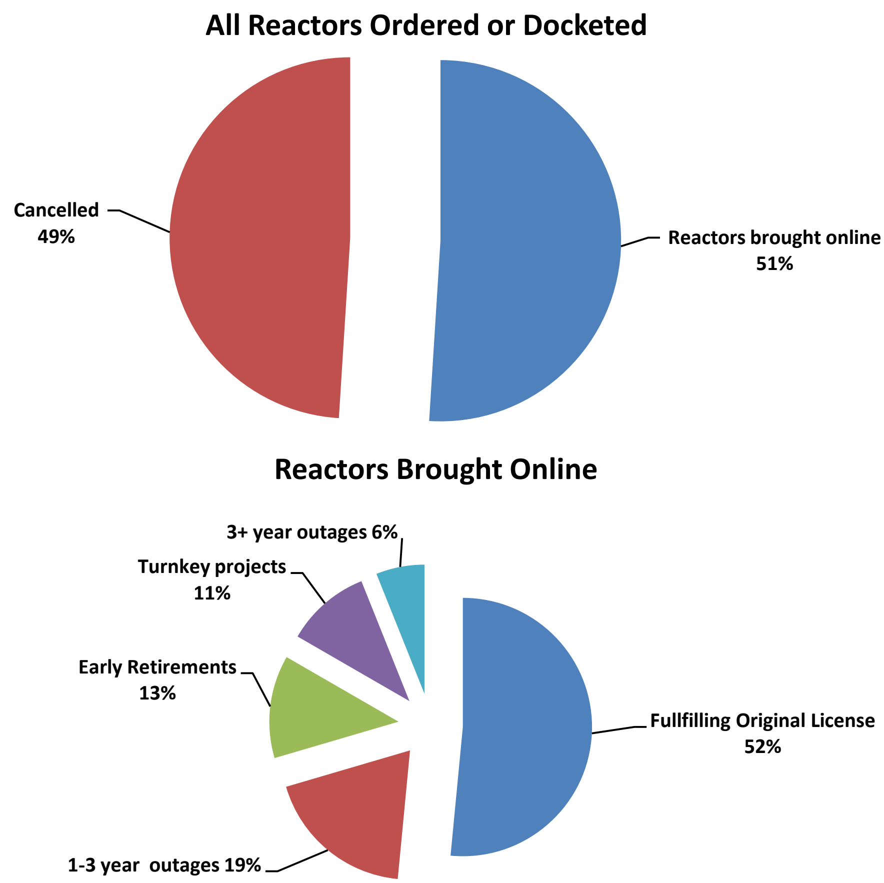


Sources: Jonathan Koomey, and Nathan E. Hultman, "A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970-2005," ***Energy Journal,*** **2007. Fred A. Heddleson,** ***Summary Data for U.S. Commercial Nuclear Power Plants in the United States*****, Nuclear Safety Information Center, April 1978; U.S. Energy Information Administration*****, Nuclear Generating Units, 1955-2009; Nuclear Power Plant Operations, 1957-2009.***

more rapidly after TMI, a case can be made that the post-TMI trend was merely an extension of the pre-TMI trend. TMI placed new burdens on the nuclear industry, but if TMI was the final nail in the coffin of the "Great Bandwagon Market," the causes of the death of nuclear reactor orders in the United States lay elsewhere.

Cancellations and cost escalation were not the whole story of collapse, as shown in Exhibit I-2. Not only were half the reactors ordered or docketed at the NRC cancelled, but many of those that were brought on line did not perform as advertised. The assumption that nuclear reactors hum along, once they are online, is not consistent with the U.S. experience. Of the reactors that were completed and brought online, 13 percent were retired early, 19 percent had extended outages of one to three years, and 6 percent had outages of more than three years. In other words, more than one-third of the reactors that were brought online did not just hum along. Another 11 percent were turnkey projects, which had large cost overruns and whose economics were unknown.

EXHIBIT I-2: U.S. NUCLEAR REACTORS: FINANCIAL AND ONLINE STATUS



Sources: Fred A. Heddleson, *Summary Data for U.S. Commercial Nuclear Power Plants in the United States*, Nuclear Safety Information Center, April 1978; U.S. Energy Information Administration*, Nuclear Generating Units, 1955-2009; Nuclear Power Plant Operations, 1957-2009.* David Lochbaum, *Walking a Nuclear Tightrope: Unlearned Lessons of Year-Plus Reactor Outages,* September 2006*; Jonathan Koomey, Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes?* June 24, 2011.

Looking beyond the high visibility inflection points in the history of the industry by reviewing the underlying processes that led to the dramatic reversal of fortune of the nuclear industry, this paper shows that the link between the pre- and post-TMI periods is the concern about safety. The failure to adequately address safety concerns by the industry created the chronic problem of cost escalation that ultimately undermined the technology. The four decade-long failure to 'articulate a logical, systematic, coherent clear and consistent' framework for nuclear safety regulation is the result of powerful and irreconcilable forces that are endemic to the nuclear industry.

- Nuclear safety is a continuously evolving, virtually unsolvable challenge, where failure has catastrophic consequences.
- The nuclear industry and its boosters are powerful actors whose economic interests blunt the political will to impose the requisite safety requirements on the industry.
- Insufficient attention to safety catches up with the industry.

Re-analyzing the historic relationship between nuclear reactor safety and nuclear economics in the United States in the wake of Fukushima is appropriate and revealing for several additional reasons.

First, in the 1970s and 1980s, the U.S. **built more** reactors than any other nation and also **cancelled more** orders for new reactors in that period than any other nation. In fact, the U.S. **cancelled more nuclear capacity than any other nation has ever built, including the U.S.** It is critically important, as regulators and decision makers consider how to adjust policies toward nuclear reactor construction and operation after Fukushima, to understand the factors that drove nuclear costs and affected both the "build/cancel" and the "repair/retire" decision in the past. The policies they adopt today will reflect and affect the relationship between safety and economics in decision making in the near future.

Second, because the U.S. provides a context in which a single economic system had a large nuclear sector with large numbers of completed and cancelled reactors, it provides an ideal opportunity to move beyond the qualitative and anecdotal evidence that typifies the debate and conduct statistical analysis of the factors that affect decisions and drive nuclear reactor costs.

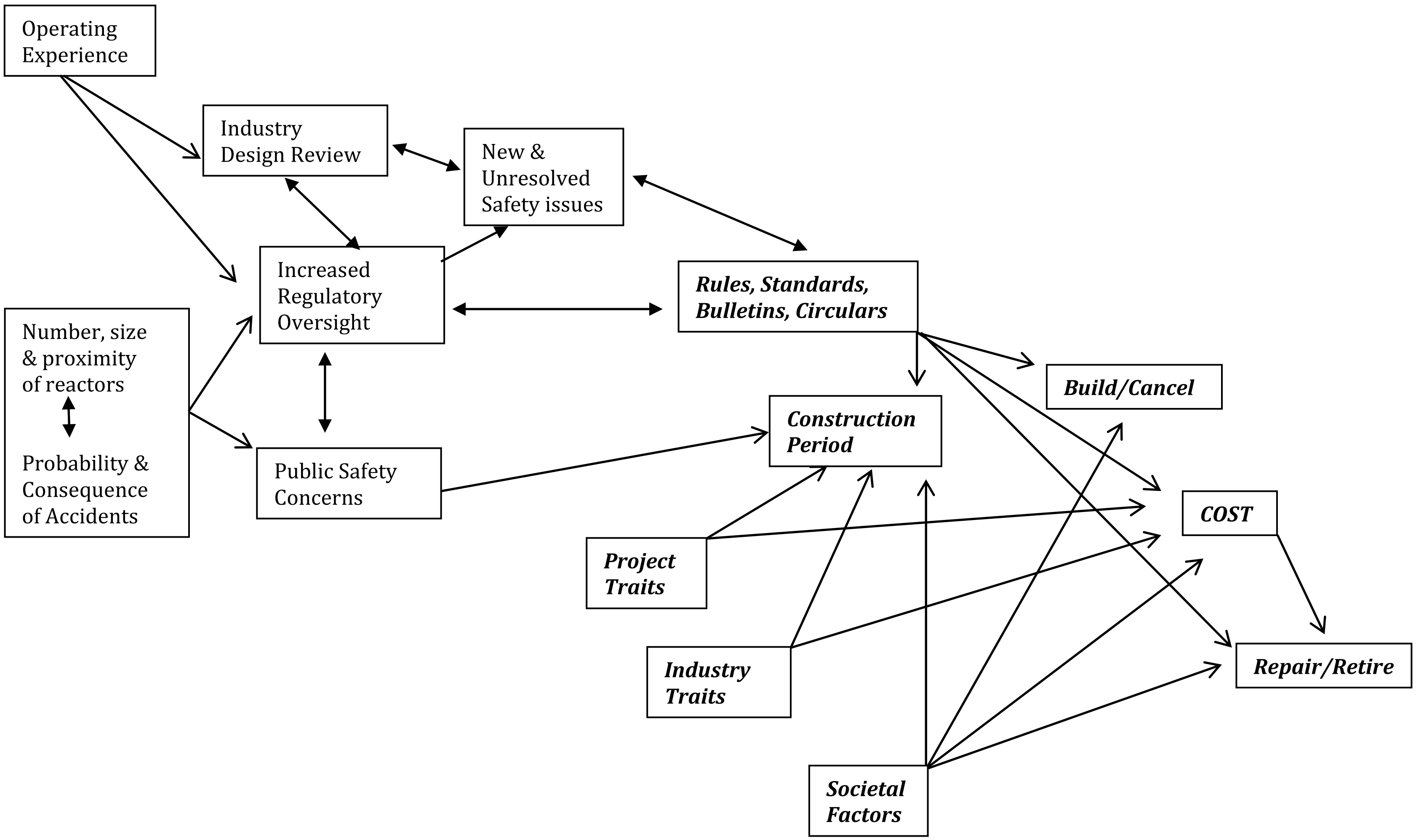
Third, after a major nuclear accident, a thorough review of energy options is inevitable. Because the U.S. government is so heavily involved in the nuclear industry, nuclear safety regulation has been subject to great scrutiny by both the safety regulator and independent analysts in the United States. Safety reviews after accidents highlight the link between safety and economics.

OUTLINE

The paper is divided into two parts, as described in Exhibit I-3. Part I deals with safety issues using qualitative, historical analysis. Part II deals with economics, using quantitative, statistical analysis. The discussion of safety deals with how safety regulation evolved through the interaction of the performance of the industry and the concerns about safety expressed by regulators, policymakers and the public. This is a political economy analysis that explains how safety regulation is inevitably tied and becomes a key determinant of the economics of nuclear

EXHIBIT I-3: A COMPLEX SOCIAL, POLITICAL & ECONOMIC MODEL OF NUCLEAR REACTOR SAFETY REGULATION, CONSTRUCTION AND COST

PART I: HISTORICAL & QUALITATIVE ANALYSIS OF NUCLEAR SAFETY **PART II: QUANTITATIVE & STATISTICAL ANALYSIS O F NUCLEAR ECONOMICS**



power.[4]

The analysis begins in Section II with a review of the U.S. experience of nuclear power in its formative period to develop a conceptual framework for understanding nuclear safety, nuclear economics, and the relationship between the two. The data for the review is qualitative. It is drawn from three earlier accounts of safety regulation and economics in the United States that were written at key moments in the history of nuclear power in the U.S.[5]

The qualitative analysis shows that regulators generally act (or are told to act) as if the possibility and impact of nuclear accidents and incidents should be reduced. Section III supports this observation by adding a quantitative dimension to this historical analysis. It presents an examination of the occurrence of problems, incidents, and accidents in the nuclear industry in the United States and globally. Looking at the history of the occurrence of such events and the magnitude of their impact provides evidence that supports the pivotal conclusion that concern about safety expressed by regulators, policymakers and the public is grounded in reality. The data is compiled from published listings of accidents and the operating characteristics of the industry, as well as official studies of the impact of accidents.

Section IV ties the past and the future together. It links them by showing the relationship between the safety and economics of nuclear reactors derived from the examination of the early years of the industry to the evaluation of the system of safety regulation after Fukushima. It relies on NRC self-evaluations conducted after the major accidents that commanded its attention. The direct link is made by comparing the NRC's own review of safety regulation after TMI to its initial review of safety regulation after Fukushima. The similarity between the two indicates that the lessons were not learned or acted upon. It adds another layer to the Fukushima qualitative analysis by examining the evaluations of other safety regulators and independent analysts.

Section V presents an assessment of the impact of safety and other factors, such as industry developments, project characteristics, and economic conditions, on key outcomes in the building of nuclear reactors: (1) the "build/cancel" decision, (2) the length of the construction period, (3) the overnight cost of construction, and (4) the "retire/repair" decision. It shows that safety was a key factor. This analysis is based on a data set that includes detail characteristics of 251 nuclear reactors in the United States.

Section VI offers observations about how the increased focus on safety after Fukushima will further exacerbate the economic challenges that building new nuclear reactors and old ones online

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[4] Tomain (1987) argued that the political element is central to the analysis of nuclear safety and regulation from the broad perspective of public safety and public subsidy and the narrow perspective of the limitation on liability that was conferred on the nuclear industry by the Government. From the economic side, the *Dictionary of Modern Economics* (Pearce, 1984) defines political economy as follows: " Until recent times the common nation for the study of the. economic process. The term has connotations of the interrelationship between the practical aspects of political action and the pure theory of economics. It is sometimes argued that classical political economy was concerned more with this aspect of the economy and that modern economists have tended to be more restricted in the range of their studies." From the political side, the *Oxford concise Dictionary of Politics* (McLean and McMillan, 2003: 415-416) define political economy as follows: **Political Economy:** The traditional meaning of the term political economy is that branch of the art of government concerned with the systematic inquiry into the nature and causes of the wealth of nations, although it is now often used loosely to describe political aspects of economic policy-making.... The economy is not seen by Smith as a self-propelling mechanism isolated from the wider society of which it is a part... The structure of society is thereby conceptualized on the basis of an understanding of its economic foundation.... The school of neoclassical economics is often reluctant to consider the political basis and the social implications of capitalist production and distribution. Political economics as a reflexive discipline analyzing the fundamental political issues which arise from the accumulation and distribution of the surplus product in capitalism offers a vigorous challenge to the disciplinary boundaries which characterize modern social science. As discussed below,

[5] Bupp and Darien, 1978, wrote just before TMI, therefore shedding light on the safety and economic issues the industry faced before a major accident changed the terrain of the industry. Komanoff, 1981, wrote just after TMI and took a different view of safety and economics prior to TMI, Tomain, 1987, wrote just after Chernobyl and dedicated his book to "those who suffered from Chernobyl."

face. First, it discusses how Fukushima affects the way safety is viewed by decision makers. It then presents the key finding for traditional regulatory and policy analysis. Finally, it offers observations on the economic future of nuclear power in the United States and market economies in general.

As a conclusion, Section VII argues that in light of the immense uncertainty surrounding nuclear power and resource acquisition in the electricity sector, a new "infrastructure of decision making" is needed. It shows that the conclusion in Section VI that nuclear power is not an attractive choice because it is uneconomic is dramatically strengthened when the other sources of ambiguity are factored into the analysis.

PART I:

THE ROOTS OF NUCLEAR SAFETY REGULATION

II. QUALITATIVE ASSESSMENT OF U.S. NUCLEAR SAFETY

Three sources provide the basis for the following discussion. Bupp and Derien (1978) provided a critique of nuclear economics in 1978, just before Three Mile Island. They viewed safety as an important political issue, but devoted little attention to it as an analytic issue.

Writing just after Three Mile Island, Komanoff (1981) looked at the pre-TMI safety issue in detail and developed a model of cost causation that highlighted safety issues. He concluded that the tension between safety and economics that had troubled the industry in its first decade would combine with the accident at TMI to extend and magnify the tension. By moving safety to a central place in the analysis he seemed to challenge the earlier Bupp and Derien analysis. This paper shows that the two arguments are not in conflict. Indeed, when combined they provide a compelling explanation for the central role of safety measures in nuclear reactor construction costs.

The third work cited is a book on the political/legal history of cancelled reactors written by Tomain (1987) shortly after Chernobyl. Safety had become an extremely prominent issue and Tomain emphasizes a key point that the two earlier analyses had not – the limitation on liability that the government provided to the nuclear industry played a key role in shaping the relationship between safety and economics in the America nuclear sector. Needless to say, in a market economy where risk is supposed to determine reward, the socialization of risk sends a strong signal about the nature of the investment and incentives for behavior that affect attention to safety. The safety risks of nuclear power were at the heart of the need to socialize risk. Socialization of risk is a supremely political act with extremely important economic consequences.

CONCERN ABOUT NUCLEAR SAFETY BEFORE THREE MILE ISLAND

During the late 1960s and 1970s, over 250 reactors were ordered in the U.S. in what came to be known as the "Great Bandwagon Market." (Bupp and Derien, 1978) The extremely rapid proposed growth raised concerns about safety and the Atomic Energy Commission (later reconstituted as the Nuclear Regulatory Commission) came to believe that nuclear safety was not sufficiently regulated. In fact, nuclear safety had been essentially unregulated in three respects – neither the market, nor the government, nor the industry was providing effective regulatory oversight.

First, Congress had stepped in with the Price-Anderson Act to limit the liability of the private sector companies that were building the new reactors. (Tomain, 1987) The Act (as later amended) required the utilities with nuclear reactors to obtain a small amount of private insurance and create a private, industry-wide insurance pool to cover liability up to a level that fell far below the level of liability that a severe accident would create.

Second, while private liability had been limited, public responsibility had not been asserted. The nuclear safety regulator had not instituted a comprehensive and vigorous program of public safety oversight. As the number of reactors on order and seeking licenses grew, so too did their proposed capacity. Their locations put them in much closer proximity to large population centers. The staff at the NRC became concerned that the prospect of rapid growth raised significant safety issues.

Third, the staff concerns were heightened by the troubling performance of the early reactors that came online. The operating experience exhibited repeated breakdowns; and design reviews revealed potentially significant failures for reactors that were already under construction.

Combining the growing size and poor performance of the fleet increased the possibility that a major accident would affect large numbers of people. This was alarming and heightened the concern about safety. Each of these aspects of the safety context played a role in deciding the fate of nuclear power in the United States.

The limit on liability was motivated by a simple, but important fact in the nuclear power sector: private companies simply would not build reactors if they were exposed to the full liability of a nuclear accident. Tomain quotes a Department of Energy document that states General Electric, one of the major reactor builders, threatened withdrawal from nuclear development activity, because GE would not proceed "with a cloud of bankruptcy hanging over its head." (Tomain, 1987: 9) A Westinghouse Executive also stated "We knew at the time that all questions (about safety risks) weren't answered. That's why we fully supported the Price-Anderson liability legislation. When I testified before Congress, I made it perfectly clear that we could not proceed as a private company without that kind of government backing." (Tomain, 1987: 9)

Comparing the liability limits to the then-current estimates of the cost of a severe incident, Tomain reached the obvious conclusion that the limits were far below the level of harm that could result from an accident and "additional costs incurred as a result of a nuclear incident will be absorbed by the victims." (Tomain, 1987: 9) Furthermore, the shifting of risk inevitably alters behavior, as Tomain noted:

> The government subsidy enables utilities to build plants without the normal checks against putting a defective product on the market... Government and industry have encouraged each other to participate in a long-term joint venture without assuming normal market risks. Instead, most risks are imposed on the public. [6]

Komanoff added the key link between poor industry practice and concerns about safety by explicating a series of NRC staff recommendations and testimony over the period from 1965 to 1975 that stressed the need for greater safety. As summarized in Exhibit II-1, the safety concerns existed from the earliest days of the industry, concerns that were reinforced by recurrent problems in the design and operation of reactors. Komanoff notes that at the beginning of the commercial industry regulators and industry thought they were setting standards at levels believed to be "conservative" because the technology was unproven in commercial operation, with the expectation that "favorable operating data would ultimately allow some standards to be relaxed." (Komanoff, 1981: 54) The opposite happened. The standards and the performance proved to be too low to ensure public safety.

As Exhibit II-1 shows, even with a very small number of comparatively small operating reactors "the ACRS concluded that a variety of reactor transients have occurred, a variety of protective features have malfunctioned or been unavailable on occasion, and a variety of defects have been found in operation." (Komanoff, 1981: 55) Exhibit II-1 gives a sample of the problems that the NRC staff had encountered. From this perspective, the key link between regulation and safety was the poor performance of the technologies deployed.

[6] Tomain, 1987: 9; This criticism of the Price Anderson Act is repeated at critical policy moments, such as when the act comes up for renewal (Brownstein: 1984).

EXHIBIT II-1: PRE-TMI SAFETY CONCERNS

GROWING SIZE, NUMBER, AND PROXIMITY TO POPULATION CENTERS

Advisory Committee on Reactor Safeguards(ACRS,1965): The orderly growth of the industry with concomitant increase in the number, size, power level and proximity of nuclear reactors to large population centers, will in the future, make desirable, even prudent, incorporating [stricter design standards] in many reactors (Komanoff, 1981: 26)

ACRS (1966): [A]s more and more reactors come into existence, particularly reactors of larger size and higher power density, the consequences of failure of emergency core cooling systems take on increased importance. (Komanoff, 1981: 47)

AEC Report (1967): The large number of plants now being constructed and planned for the future makes it prudent that even greater assurance be provided henceforth… Large increases in the number of reactors lead us to the desire to make still smaller the already small probability that an accident of any significance will occur.

AEC Staff (1967): The increase in this potential [from larger reactors] must be matched by corresponding improvements in the safety precautions and requirements if the safety status is to keep pace with advancing technology. The protective systems must have shorter response times, larger capacities and greater reliability to cope with the more rigorous demands presented by larger reactors. (Komanoff, 1981: 49)

AEC staff (1973): The present likelihood of a severe ATWS (Anticipated Transients Without Scram) event is … acceptably small in view of the limited number of plants now in operation… As more plants are built, however, the overall chance of ATWS will increase, and the staff believes that design improvements are appropriate to maintain and to improve the safety margins provided for protection of the public. (Komanoff, 1981: 26)

OPERATING EXPERIENCE (Komanoff, 1981, pp. 26-28, 54-55)

Design and Operation

Lack of quality control
Sticking and breaking of control rods, cracked main control rods
Rupture of a poison sparger ring
Failure of structural members within the pressure vessel
Faulty design of steam generator support
Cracks in large pipes and studs
Poor choice of materials for vital components
Melting of some fuel elements
Consecutive procedural errors
Faulty installation of control rods
Broken stud bolts at the vessel head closure
Fuel leakage
Malfunctioning vales, pumps and cables

Emergency

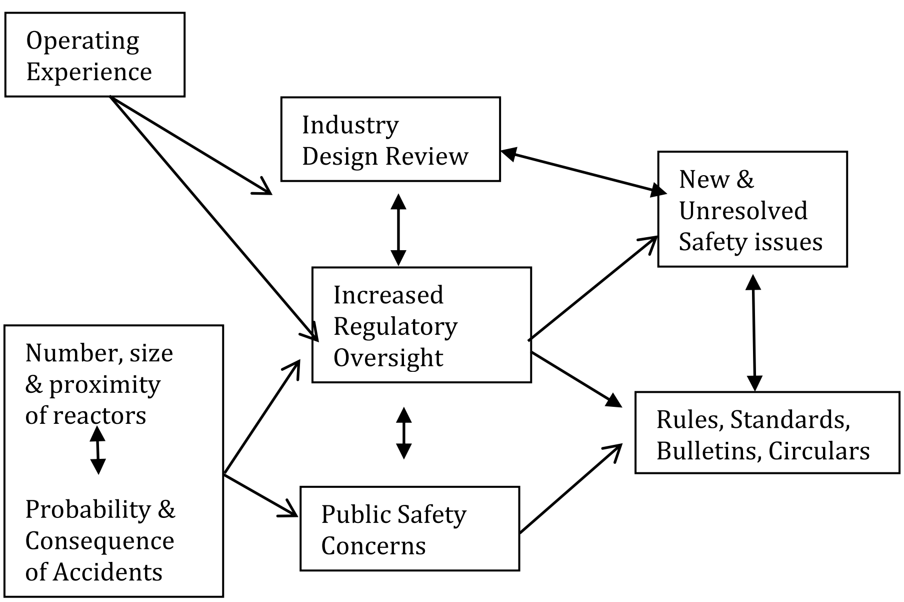
Loss of normal and emergency power in the same incident
Intermingling of systems for operation and safety
Simultaneous loss of all incoming power lines
Blowdown of a primary coolant system
Loss of protection provided by the capability for automatic scramming of control rods
Safety systems not wired up in accordance with design criteria even after extensive testing
Operator disabling of shutdown systems

Source: Komanoff, Charles, *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics,* (New York: Van Nostrand, 1981),

> New regulations also arise from detection of previously unrecognized reactor defects. Reviews of new plants by the reactor manufacturers and AEC/NRC have provided one such means of detection. For example, General Electric and Westinghouse discovered potentially large dynamic forces that could affect reactor containment structures and reactor vessel supports… Other safety issues leading to newer regulatory standards, including seismic and tornado protection, quality assurance problems, main streamline breaks, and intermingling of systems for reactor operation and shut down, have been identified in reviewing individual reactor applications and have been applied subsequently to other plants.
>
> Even more importantly, many unanticipated safety problems have been revealed by operating experience. Contrary to early expectation, increased reactor operation has generally warranted widening rather than reducing design margins. The "lack of perfection in design, construction and operation" of early reactors prompted the Advisory Committee on Reactor Safeguards to advocate use of more back-up safety systems. Fuel leaks, pipe cracks, and malfunctioning components later formed what NRC called a "considerable body of operating experience [indicating] the need for expanded technical review in areas previously thought to be not sufficiently important to warrant much attention."
>
> Adverse operating experience has also given rise to numerous regulatory guides and "unresolved safety issues." (Komanoff, 1981: 27.)

The Brown's Ferry fire in 1975, affecting reactors that ultimately had the longest outages in the industry, and the TMI accident in 1979, which led to the first premature retirement of an online reactor, came very early in the development of commercial nuclear reactors and confirmed the fears of the safety regulators that really bad accidents could occur. [7] A complex model of safety concerns emerges from the early history of the industry, as described in Exhibit II-2.

EXHIBIT II-2: SOCIAL AND INSTITUTION PROCESS UNDERLYING REACTOR SAFETY REGULATION



[7] Komanoff, 1981: 27, Major examples are the 1975 Browns Ferry fire, which led to costly new rules for fireproof construction and ventilation: reactor control breakdowns in 1978-1980 due to power failures to instruments that have prompted consideration of increased separation of "safety" from "non-safety" instruments; and the 1979 TMI accident which has sparked an across-the-board review of fundamental regulatory premises.

There were several recursive loops in the model as depicted in Exhibit II-2 that intensified the concern about safety. The increasing number and size of reactors and their proximity to large population centers triggered a concern about accidents and a felt need to reduce the probability and severity of potential accidents. Increased regulatory review caused increased design review, which accelerated the need for regulatory oversight. New and unresolved safety issues revealed by increased regulatory oversight reinforced the need for increased oversight. New and unresolved safety issues feed back into the perceived need to reduce the probability and severity of accidents. The consequent design reviews combined with operating experience to reveal new and highlight old unresolved safety concerns. This growing concern triggered an expansion of regulatory oversight. Increased oversight revealed more problems with the reactor designs and construction.

Public concern, stimulated by the growing number, size, and proximity of reactors, reinforced these underlying processes. Public concern then reinforced the need for greater oversight. Public concern also directly revealed safety issues and underscored the importance of unresolved safety issues. There is a recursive loop, here as well, with new and unresolved safety issues increasing public concern. As more issues are discovered, more rules are issued and oversight is stepped up as they remain unresolved.

Contrary to the complaints of the industry, the origin of the safety concern was not the result of regulators who were being overly cautious; it was based in substantial measure on deficiencies in the design and construction of the reactors.

NUCLEAR SAFETY AND NUCLEAR ECONOMICS

Motivated by these concerns in the period before TMI, the growth of standards and guides was dramatic, from 3 in 1970 to 143 by 1978, which had a dramatic impact on the cost of reactors. Komanoff cites a claim by an industry group that

> [r]equirements such as these approximately doubled the amount of materials, equipment, and labor and tripled the design engineering effort required per unit of nuclear capacity… Moreover, because many were mandated *during* construction – as new information relevant to safety emerged much construction lacked a fixed scope and had to be let under cost-plus contracts that undercut efforts to economize. Completed work was sometimes modified or removed, often with "ripple effect" on related systems. (Komanoff, 1981: 25)

Bupp and Derien argue it arose of the failure of economic discipline locating the origin of this problem resided in the nature of the technology and the industry.

> First, the design of the most advanced concepts often led to difficult engineering problems. Second… the potential manufacturers were evidently not interested in waiting for the results of lengthy experimental programs and prototype construction efforts so that they could choose the most efficient concepts…. They believed they could estimate the costs of these plants within a relatively narrow range…[T]hey believed they could count on "learning effects" to produce a savings which would inevitably compensate for any losses incurred on the early turnkey projects… [T]hese beliefs were serious errors in business judgment. (Bupp and Derien, 1978: 183-186)

The industry cost complaint was part of an ongoing battle that had developed between the industry and the NRC staff. As the staff's concerns about safety grew and were reflected in an increasing number of standards, the industry objected, but the regulators pointed to design, manufacturing and management errors, not regulation as the source of the problem. Bupp and Derien believed that that need to incorporate new safety measures during construction was, in significant part, a self-inflicted wound, caused by the rush to deploy and the failure of the industry to prototype development and testing before sinking costs in defective designs.

> By the early 1970s, two rather different explanations had developed in the United States about what had gone wrong with the economics of nuclear power. One was common among the purchasers of light water reactors; the other was held by government officials who were promoting and regulating the utilities. The electric utility generally placed the blame on the government's environmental protection policies, quality assurance requirements, and nuclear safety regulations. The government countered by pointing to the industry's poor labor productivity, manufacturing failures by the equipment suppliers, and management problems in plant construction.... These differences of opinion were the subject of numerous discussions within the nuclear power community during the early 1970s.
>
> The unfortunate thing about these discussions is that they minimized the real causes of the problem which they purportedly addressed….
>
> For 15 years many of those most closely identified with reactor commercialization have stubbornly refused to face up to the sheer technical complexity of the job that remained *after* the first prototype nuclear plants had been built in the mid- and late 1950s. Both industry and government refused to recognize that construction and successful operation of these prototypes – though it represented a very considerable technical achievement –was *the beginning and not near the completion* of a demanding undertaking. (Bupp and Derian, 1978: 154-155)

Bupp and Derian, locate the problem as early as the late 1960s, when it had already become apparent that the cost reductions the industry hoped would flow from increasing economies of scale and learning processes had not come to pass.

> Costs normally stabilize and often begin to decline fairly soon after a product's introduction… the reactor manufacturers repeatedly assured their customers that this kind of cost stabilization was bound to occur with nuclear power plants. But cost stabilization did not occur with light water reactors… The learning that usually lowers initial costs has not generally occurred in the nuclear power business. Contrary to the industry's own oft-repeated claim that reactor costs were "soon going to stabilize" and that "learning by doing" would produce cost decreases, just the opposite happened. Even more important, cost estimates did not become more accurate with time. (Bupp and Derian, 1978, pp. 72…79)

Thus, there was a parallel set of performance failures on safety and economics. The industry kept hoping and saying that things would get better, but they did not. The link between nuclear safety and nuclear economics was solidified by the accident at TMI. Komanoff supported his prediction of a continuing trend of increasing costs by noting that "post-TMI nuclear regulation will almost certainly reflect greater willingness than previously to pay more to obtain greater safety." (Komanoff, 1981: 34) He cited comments of Victor Gilinisky, a member of the NRC, who described the pre-TMI atmosphere as one that "placed the burden of proof… on the regulators to justify negative findings on safety matters and mandated only 'the most conservative requirements consistent with the commercial viability of nuclear power." (Komanoff, 1981: 34) TMI led to a change in the attitude "that led NRC Chairman Hendrie to put the nuclear industry on notice that "safety [not cost] must be the dominant element in our considerations." (Komanoff, 1981: 34)

In March of 1981, Komanoff concluded his chapter on "The Source of Nuclear Regulatory Requirements" by hypothesizing that new safety issues would continue to flow, even if there was a sharp decline of plans to build new reactors. Komanoff believed that even a reduction in the growth in the number of nuclear reactors would not eliminate the continuous flow of safety related concerns because operating experience would continue to reveal problems and issues.

> At some point, the per-reactor rate of detection of safety problems will almost certainly decline. But even then, the per-year rate would fall less rapidly – and might even continue to increase for some time – because of the growth in the number of operating plants. New safety issues will thus continually emerge, while old ones will be re-emphasized, inhibiting efforts to stabilize reactor design criteria and to standardize plants….
>
> Accordingly, the "environment of constant change," that so pervasively complicates nuclear design and construction should not be expected to improve significantly, short of a marked reduction in currently projected nuclear growth. Such a slowdown would ease, but by no means completely dispel, the pressures that lead to new regulatory requirements. Komanoff, 1981, p. 63)

NUCLEAR SAFETY AS A POLITICAL ISSUE

There is another dimension to the debate over safety regulation that is ever present. The link between safety and economics is undeniable, but the question of whether the demand for greater safety is "rational" is inevitably raised.

In 1978, Bupp and Derien straddled the line between "irrational" and "rational," by suggesting that the public concern was a public relations and political (rather than an economic) issue. "We have predicted since the mid-1970s that the cost of nuclear power was unlikely to stabilize as long as nuclear safety concerns – whether "rational" or "irrational" – were not appeased." (Bupp: ii).

Komanoff's explanation that links safety concerns and rising costs can be seen as a challenge to the earlier explanation for rising costs offered by Bupp and Derien. Bupp and Derien argued that the advocates of nuclear power had failed to understand the complexity and demanding nature of the technology and had made assumptions and promises about costs that were wildly optimistic. Safety was not the central issue, entering as a problem of "appeasing" safety concerns. In the Foreword to Komanoff's book, however, Bupp acknowledged the importance of Komanoff's argument, as follows:

> Komanoff has extended the argument here, with a major new twist: He proposes that the capital cost increases in the nuclear sector are primarily the result of efforts to contain total accident and environmental risks that would otherwise have expanded in proportion with the growth of the section. This is an important and challenging hypothesis, supported by both a quantitative analysis of costs and an historical review of nuclear regulation (Bupp: x).

The two explanations are not in conflict. Rather, they reinforce one another with the link provided by Tomain's observation on liability. The persistent economic crisis of nuclear reactor construction has its origins in a technology that was defective at its launch in an industry that did not face the full liability for its actions and was impatient to address issues before it deployed. It banked on the mistaken belief that learning by doing would alleviate economic and safety problems. In both the technology and safety areas that faith proved misplaced because the underlying problem was very real, fundamental and persistent. Experience revealed the defects that required more attention to safety.

Komanoff provided a great deal of evidence that the link between safety and economic was substantive (and therefore rational). Safety was not a question of public relations or appeasement; it was a core technical and economic challenge. In the foreword to Komanoff's book, the demonstration of "legitimate" bases for safety concerns that contributed to the severe economic problem of nuclear reactors led Bupp to acknowledge Komanoff's alternative hypothesis, although he continued “to prefer my own hypothesis: the basic cause of the cost increases that are documented here is a breakdown of the democratic political process.” (Komanoff, 1981. p. iii)

Komanoff’s concluded that “rising public apprehension has affected nuclear regulation,” (Komanoff, 1981, p. 59) but in his account the “apprehension” was anything but irrational. In his view, the troubling operating experience and expanding size of the nuclear sector justified the concern. He concluded that the public participation slowed the licensing process, rather than the construction process, and there was no relationship between the length of the licensing period and costs. He concluded that the growing public concern spawned independent analysis by experts and created an environment that encouraged whistle blowers that led to the discovery of real problems, while it strengthened the resolve of regulators and policy makers to demand more attention to scrutiny.

Tomain, who argued that the industry had put defective products in the market, took a view of the political process that was exactly opposite to that of Bupp and Dernier. It was not the breakdown of the democratic political process that played a key role in the demise of nuclear power, he argued, but it was the restoration of democratic processes. He approached “irrationality” from the industry side. The challenge of safety was always so severe, he pointed out, that the industry could never be viable without shifting the risk away from itself onto the public. From this point of view, the existence of nuclear power was always political. Writing in the mid-1980s, when huge cost overruns were being fought over at public utility commissions and in the courts and large numbers of reactors had been cancelled, the economic problem of the industry had hit home. Amidst the conflagration over cost and cost recovery, with Chernobyl a recent event, he argued that safety issues might be beyond economics, certainly not a mere public relations matter, but an inherently political issue and a fundamental moral question.

> Safety is integrally connected to financial matters. Health and safety issues must be acknowledged in assessing ways to ease the financial impact of abandonment costs… Therefore, to focus on the financial weakness of the industry is not, and should not be, a substitute for health and safety regulation….
>
> The seductive safety-financial exchange is consistent with the currently popular bureaucratic methodology of cost benefit analysis. An overreliance on cost-benefit data ignores fundamental, no quantifiable, assumptions such as: Is nuclear power worth the risk at any price? Risk assessment must be part of the overall decision-making process, and the costs of risk cannot be arbitrarily removed from normative issues.
>
> More important, safety and finances have a curious relationship. Politics are introduced at the intersection of safety and finances. No system is failsafe. Determining safety levels and allocating cost through a regulatory system are essentially political. Health, safety, and financial issues are best resolved through a politically responsive decision-making process.[8]

The Price Anderson Act that shifted risk from the commercial operators of nuclear reactors to the public is one of many subsidies that the nuclear industry received[9] and it may not be the largest (unless and until a major accident occurs). However, it highlights the fundamental contradiction at the core of nuclear safety policy. The commercial industry had been relieved of full private liability, but it resisted the efforts of the NRC to impose public responsibility. The risks were socialized, but the economics remained private and cost dominated safety at the outset. This tension created persistent (perhaps permanent) contradictions in the structure of safety regulation.

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[8] Tomain, 1987: 17. Needless to say, this observation crystalizes the need to study nuclear safety and nuclear economics from the point of view of political economy.

[9] While the value of the Price Anderson subsidy is notoriously difficult to estimate, the other subsidies are not without controversy (Kopolow, 2010).

The industry criticized the safety regulator for imposing costs that it deemed to be unnecessary, from within the cocoon of the limitation on private liability that had been created by Price Anderson.

With liability limited, the concern about safety was seen by the industry as an irrational, external constraint that impinged unnecessarily on industry economics. That constraint was made greater in part because the industry had failed to attend to safety and resisted efforts by the regulator to impose measures to improve safety. The failure to recognize the demands of the technology and the rush to push designs into the market helped to create the underlying problem of a defective product in the market and made finding a solution are challenging, especially since it is a very difficult product to recall.

Once the NRC became concerned about safety, testing, and experience showed that the technology needed work to improve safety, which raised costs, so the industry could not deliver on its economic promises. The industry used safety regulation as a scape goat to avoid responsibility for the problem it had created. Accidents shift the terms of the debate by strengthening the concern about safety, but it is difficult to overcome the underlying tensions and structure.

III. THE EMPIRICAL BASIS FOR CONCERN ABOUT THE SAFETY OF NUCLEAR REACTORS

There were several key aspects in the growing concern about nuclear reactor safety expressed by the NRC before TMI. One was the sheer size of the industry that was contemplated. A second was the operating experience. The third was the impact of larger reactors located closer to populations could have in the event of a severe accident. These are examined in this section to explore whether the concerns had grounding in reality.

THE SIZE OF THE SECTOR AND ITS PROXIMITY TO POPULATION CENTERS

In the late 1960s and early 1970s regulators were confronted with the prospect of a dramatic increase in the size of the industry, as shown in Exhibit III-1. The Exhibit shows the growth of the number and average size of reactors online with the year 1966 as the base. The planned capacity includes all reactors that had not been withdrawn, cancelled or postponed as of 1977.[10] In the early 1970s the reactors online were few and small. The size and number of reactors were slated to increase dramatically over the 1970s and 1980s. Not only was there nothing comparable in the commercial sector, but military nuclear reactors were equally few and small.[11] The industry had plans to grow the sector to almost 200 Giga watts with reactors as big as 1.3 Giga watts each at a time when the entire existing sector was less than one Giga watt with reactors averaging less than two-tenths of a Giga watt.

The second aspect of the proposed rapid expansion of nuclear reactor construction that caused concern among the safety regulators was the proximity to population centers. Exhibit III-2 shows the metropolitan areas within a 20-mile and a 20-to-50-mile radius the reactors that were operational or targeted for construction in a 1977 report to the NRC. It lists each reactor that had been docketed but was not cancelled, withdrawn, or delayed. Clearly, there was a cause for concern. By the end of the building cycle, 23 of the nation's largest metropolitan areas would be within 20 miles of a large nuclear reactor and over 50 would be within fifty miles.

The "Great Band Wagon Market" was beyond ambitious. It was unachievable and downright irresponsible, deserving of the harsh judgments offered by Bupp and Derian, *Forbes* and Tomain. The tendency of the industry to overreach may be inherent in the sector. The announcement of federal loan guarantees called forth a flood of applications equal to ten times the amount set aside for the program (DOE Loan Guarantee Program, 2010) with legislative proposals that would have tripled the amount of nuclear capacity in the United States in about the time it took to grow to its current size. (Weigel, 2011).

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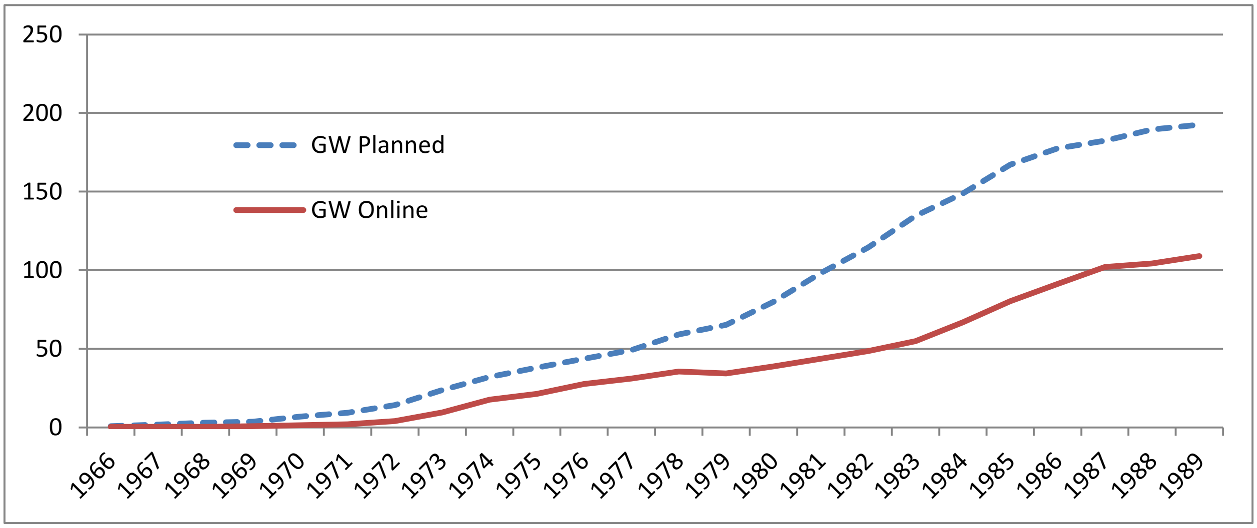
[10] Approximately 15 GW of capacity of units at sites that had existing capacity are included in the year for which the status of other reactors at that site is given. These additional units were likely actively "on the books" up until that point. Cancelled, withdrawn or postponed units at greenfield sites are not included in this count. The latter excludes about 10 GW of capacity from the count.

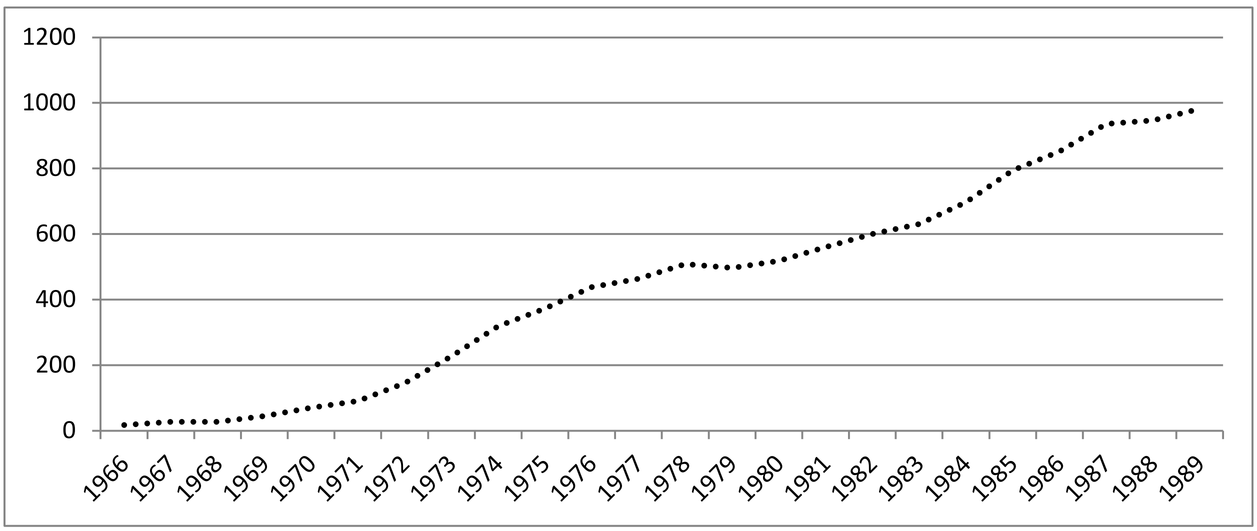
[11] In the early 1960s there are a cou0ple of dozen small reactors (about10 MW) on submarines, with one larger reactor on an aircraft carrier with a large reactor (200 MW) of a size equal to the commercial reactors of the day.

EXHIBIT III-1: THE DRAMATIC EXPANSION OF THE NUCLEAR SECTOR

CAPACITY



Average Reactor Capacity (MW)



Sources: Fred A. Heddleson, Summary Data for U.S. Commercial Nuclear Power Plants in the United States, Nuclear Safety Information Center, April 1978; U.S. Energy Information Administration, Nuclear Generating Units, 1955-2009; Nuclear Power Plant Operations, 1957-2009.

EXHIBIT III-2: NUCLEAR EXPANSION NEAR LARGE CITIES

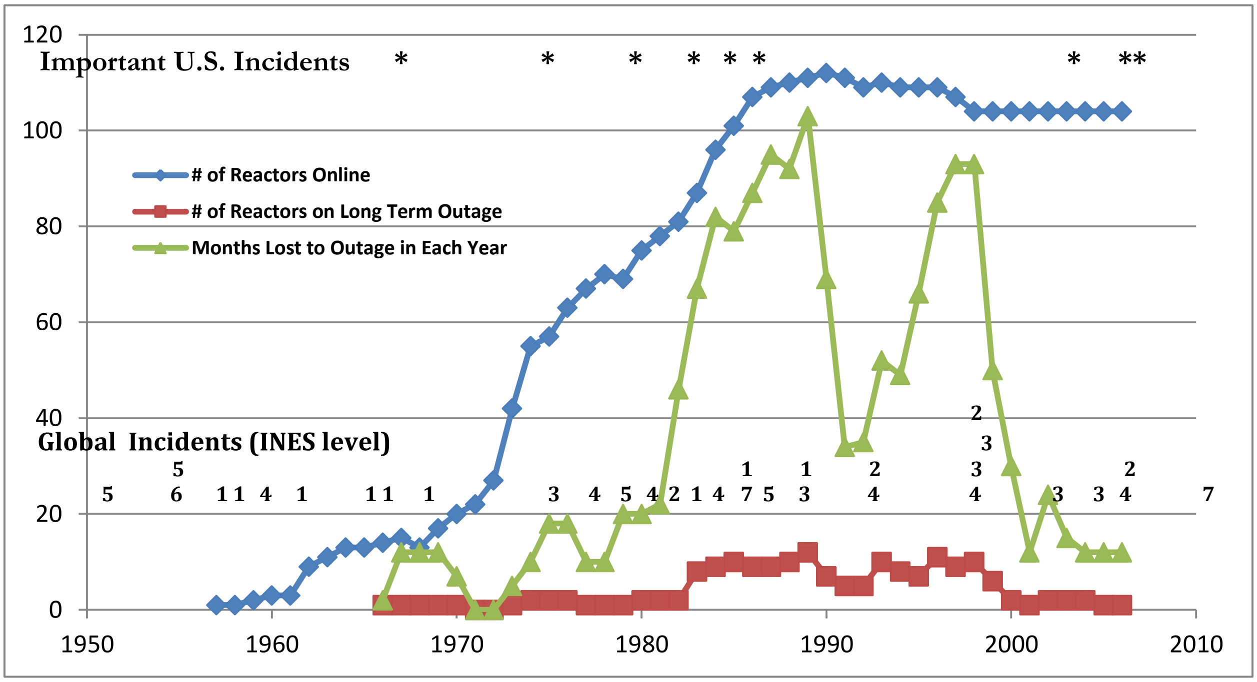
Operating		**Nearest Metropolis**
Year	20-miles or less	20-miles to 50-miles
1959		Chicago
1960		Pittsfield
1962	New York	
1966	Lancaster	
1967		San Diego
1969	Rochester	Atlantic City, Syracuse
1970		Chicago, Hartford, Minneapolis, Green Bay
1097	Davenport	Chicago, Kalamazoo
1972	Davenport, Holyoke Newport News	Miami, Brockton, Green Bay, Portland
1973	New York, Omaha, Lancaster Kinosha, Kinosha, Newport News	Miami, Huntsville, Minneapolis Greenville
1974	Syracuse, Lancaster, Harrisburg Cedar Rapids	Huntsville, Greenville, Greenville, Green bay, Minneapolis, Sacramento, D.C., D.C.
1975	Wilmington	Hartford, South Bend
1976	New York, Wilmington	Huntsville, Pittsburgh, West Palm
1977	Chattanooga	Denver, Richmond
1978	Harrisburg, Chattanooga	South Bend, Richmond, Cincinnati
1979	Wilmington, Charlotte	Chattanooga
1980	Charlotte, Wilkes-Barre	Detroit, San Diego, Chattanooga, Columbia, Huntsville
1981	Saginaw, Wilkes-Barre, Rockford Chicago, Baton Rouge, Decatur	San Diego, New Orleans, Huntsville, Cleveland
1982	Saginaw, Rockford, Chicago Columbia,	Richmond, Syracuse, Pittsburgh, Lawrence, Fort Worth Nashville, Nashville, Louisville
1983	Reading, Raleigh, Baton Rouge Charlotte, Tacoma, Tacoma	Atlantic City, West Palm, Richmond, Cleveland, Phoenix Nashville, Nashville, Phoenix
1984	Wilmington	Lawrence, Louisville
1985	Reading, Raleigh, Charlotte, Tacoma, Toledo	
1986	Wilmington	Hartford, Phoenix
1987	Toledo	
1988	Decatur, Charlotte	
1989	Raleigh	

Sources: Fred A. Heddleson, Summary Data for U.S. Commercial Nuclear Power Plants in the United States, Nuclear Safety Information Center, April 1978;

THE OCCURRENCE OF NUCLEAR INCIDENTS AND ACCIDENTS

The explosion of growth combined with the poor qualitative experience discussed in Section II to support the growing regulatory concern about safety. As we have seen in the qualitative analysis, the operating experience of the industry indicated that there were problems with the technology. The debate over whether these problems merit the attention that the NRC was giving it is interminable, but the fact that incidents and accidents occurred is quite clear. Exhibit III-3 sheds light on this issue.

EXHIBIT III-3: U.S. NUCLEAR INCIDENTS, ACCIDENTS AND LONG-TERM OUTAGES & GLOBAL ACCIDENTS



Sources: David Lochbaum, *Walking a Nuclear Tightrope: Unlearned Lessons of Year-Plus Reactor Outages,* September 2006*;* U.S. Energy Information Administration, Nuclear Generating Units, 1955-2009. *Nuclear Power Plant Accidents: Listed and Ranked since 1952,* Guardian.co.UK, , http://www.guardian.co.uk/news/datablog/2011/mar/14/nuclear-power-plant-accidents-list-rank, http://en.wikipedia.org/wiki/List_of_civilian_nuclear_accidents, *Nuclear Accidents in the United States,* Wikipedia, http://en.wikipedia.org/wiki/Nuclear_reactor_accidents_in_the_United_States;

The stars at the top of the graph indicate the year of a significant U.S. incident that involved explosions, fires, meltdowns, and/or release of radioactive materials.[12] The number of outages in the United States that lasted more than a year which were caused by safety concerns, damaged components, or the need to replace components is shown, listed by the year in which the outage commenced. The cost of an extended outage is substantial, averaging more than $1.5 billion, and ranging as high $11 billion. The number of reactors online is shown for reference. At the bottom, the graph also identifies major incidents in the global industry categorized according to the level of the International Nuclear Event Scale (INES) scale. The categorization of the severity of incidents is contentious. The INES, used in the Exhibit III-4, has seven levels, as follows:[13]

7 Major accident – Major release of radioactive material

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[12] Fermi (1966);Browns Ferry (1975); TI 1979); Ginna (1982); Browns Ferry (1985);Peach Bottom (1987);Braidwood (2005); Erwin (2006);

[13] I have categorized as level 1 any incident that has not been categorized officially.

6 Serious Accident—Significant release of radioactive material
5 Accident with wider consequences – Limited release of radioactive material
4 Accident with local consequences – Minor release of radioactive material
3 Serious incident – Exposure in excess of ten times the statutory annual limit
2 Incident – Exposure of a member of the public, significant failure in safety
1 Anomaly – Minor problems with safety

There was a stream of important incidents. As the number of reactors grew, long-outages grew as well, but they jumped markedly as the NRC ramped up its oversight of safety. The outages were common and costly. Almost one quart of all units suffered year-long outages. There was certainly more than enough qualitative and quantitative evidence in the U. S. experience to support the concerns raised by U.S. safety regulators, but the empirical evidence does not stop there. The global industry was having problems as well. Exhibit III-4 presents the elements that can be used to state expectations about future incidents, although with rare events like the more severe accidents, it is presumptuous to talk about probabilities.[14] Rather, this analysis should be taken to support the possibility of severe accidents, which we have seen in the qualitative analysis should be considered in designing the safety infrastructure of the industry. The possibility of such accidents is clearly demonstrated. The incidence of severe accidents did not begin to decline until the building cycle has long run its course.

It is easy to see how the picture painted by the experience of the industry could be a cause of concern to a regulator with the responsibility for safety. In the early 1970s the regulator would be aware of the fact that the industry was about to expand substantially, given the number of orders and requests for licenses. The regulator also observed a continuous flow of problems and incidents at home and abroad that are serious enough to indicate safety problems. Many events are low level, but involve possible releases, actual releases of radioactivity or serious operational problems. The real world evidence indicates an important safety problem in an industry that was expanding rapidly.

Moreover, some of the incidents are severe. Prior to TMI, the severe incidents occurred in both market economies (the U.S., Canada, UK, Switzerland, and Germany) as well as communist countries (Russia, Yugoslavia, Czechoslovakia). Moreover, the initial phase of operation witnessed the more severe incidents. As the industry started to ramp up, more severe incidents took place (first abroad, then at home). The data supported a conclusion that there was a problem with the technology that could become severe as the size of the industry grew.

After 60 years, it is clear that incidents and accidents are part of the nuclear landscape. They happened in the past and are likely to continue to happen. Thus regulators confronted with the prospect of a rapid increase in the number of reactors have cause for particular concern. The prospect of a "nuclear renaissance" would be exactly the kind of development to be concerned about. As we have seen, although the industry continuously predicted that stabilization of designs and costs was just around the corner, it never arrived. The difficulties of the French in Flamanville and Olkiluoto and the nineteen revisions to the AP1000 design at the NRC suggest the past is still prologue in the nuclear industry. (Cooper, 2010a)

[14] The inapplicability of applying probabilities to rare, but important events has become a major focus of recent financial analysis (Taleb, 2007) and technology Assessment (Stirling, 1999).

EXHIBIT III-4: ESTIMATING THE INCIDENCE OF NUCLEAR INCIDENTS AND ACCIDENTS

	ALL INCIDENTS					ACCIDENTS (LEVEL 4 & ABOVE)				ACCIDENTS (LEVEL 5 & ABOVE)		
Year	**# of Reactors online**	**Highest level incident in year**	**Operating years between incidents**	**Avg. # of reactors on line between incidents**	**Expected # of years between incidents based on Avg. # of reactors online**	**Operating years between incidents**	**Avg. # of reactors on line between**	**Expected # of years between incidents # of Reactors Avg.**	**Last**	**Operating years between incidents**	**Avg. # of reactors on line between**	**Expected # of years between incidents based on Avg. # of reactors online**
1952	1	5	2	1	2.0	2	1	2.0	2.0	2	1	2.0
1957	2	6	5	1.5	2.5	5	1.5	2.5	2.5	5	1.5	2.5
1958	3	1	3	2	1.5							
1959	4	1	4	4	1.0							
1961	6	4	11	5.5	1.8	18	4.5	4.0	3.0			
1964	9	1	24	8	3.0							
1966	11	1	21	10.5	2.1							
1967	12	1	12	11	1.1							
1969	14	1	27	13	2.1							
1975	141	3	49	92	0 .5							
1977	171	4	328	156	2.1	981	49	5.7	20.0			
1979	194	5	377	189	2.0	377	189	2.0	1.9	1356	61	22.2
1980	209	4	209	209	1.0	209	209	1.0	1.0			
1983	266	4	515	248	2.1	515	248	2.1	2.0			
1986	347	7	673	324	2.1	673	324	2.1	1.9	1927	275	5.6
1993	414	4	2809	401	7.0	2809	401	7.0	6.8			
1999	420	4	2532	422	5.9	2532	422	5.9	6.0			
2003	435	3	1725	431	4.0							
2005	444	3	884	442	2.0							
2006	444	4	442	444	1.0	3051	436	19.6	6.8			
2011	442	7	1762	441	4.0	1762	441	4.0	4.0	10154	473	24.0

Expected years between incidents = (operating years between incidents/ number of reactors online)/number of incidents in a year.

Data sources: Operating statistics: Du, Yangbo and John E. Parsons, "Capacity Factor Risk at Nuclear Power Plants," CEESPR, November 2010: Incidents and Accidents: http://en.wikipedia.org/wiki/List_of_civilian_nuclear_accidents, http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-world-wide.htm , http://www.guardian.co.uk/news/datablog/2011/mar/14/nuclear-power-plant-accidents-list-rank, http://en.wikipedia.org/wiki/Nuclear_reactor_accidents_in_the_United_States

THE MAGNITUDE OF POTENTIAL IMPACTS

The expected "value" of an accident is a function of its probability and the magnitude of its impact. The magnitude of the impact is the driving force behind the concern about the proximity of nuclear reactors to population centers discussed above. Severe, rare occurrences close to large population centers could impose unacceptable costs. Accidents at the level of widespread consequences (or higher) are much less frequent than the other lower level accidents, but still they happen. Even a quarter-century between such accidents may not seem very long when the magnitude of the impact is taken into account.

In late 1976, the government produced an incidence analysis, known as the Rasmussen Report (1976) that was intended to calm fears about nuclear accidents, which had been escalating rapidly as the number of proposed nuclear reactors increased dramatically. The analysis concluded that in an industry with 1,000 reactors, one could expect the worst case meltdown once every 10,000 years. At the time, there were almost 250 reactors on order in the U.S., although there have never been much more than 100 online in the U.S. in any given year. Since that 1976 projection was made, globally there has been an average of about 300 reactors online per year. In other words, the industry is less than one third the size assumed in the analysis. Given the much smaller size of the industry than that assumed in the analysis, the incidence projected by the Rasmussen report would have been closer to once every 30,000 years.

The projections proved to be far too optimistic. Four years after that analysis, TMI was a close call (1979). Eleven years later, Chernobyl achieved the highest level on the INES scale (1986). Twenty-six years later, Fukushima equaled the severity of Chernobyl (2011). The estimated probability of severe accidents was too low.

With the low probability placed on a severe accident in the Rasmussen report, even the projected impact of 3,300 fatalities and $14 billion in property losses had a very low expected value leading the authors of the Rasmussen Report to claim that

> The likelihood of reactor accidents is much smaller than that of many non-nuclear accidents having similar consequences. All non-nuclear accidents examined in this study, including fires, explosions, toxic chemical releases, dam failures, airplane crashes, earthquakes, hurricanes and tornadoes, are much more likely to occur and can have consequences comparable to, or larger than, those of nuclear accidents. (cited in Partridge, 1980: 2)

Scrutiny and criticism of the methodology of the Rasmussen report led the NRC to repudiate it in 1979 (Smith, 2006).

Six years after the 1975 Rasmussen Report, a new report on the impact of a severe accident offered damage assessments that were six times as large – on average about $92 billion and 86,000 casualties (of which about one- third were fatalities).[15] Adjusting that estimate for inflation, increases in population and the increased value of property, the average damage figure would be over $450 billion in today's dollars, with an accident at the reactors closest to the largest population centers running as high as $1.5 trillion.[16] The cost of Chernobyl is approaching $700 billion.[17] The

[15] The study is referred to as CRAC-II (**Calculation of Reactor Accident Consequences**) and provides the simulation results performed by Sandia National Laboratories for the Nuclear Regulatory Commission. The report is sometimes referred to as the CRAC-II report because it is the computer program used in the calculations, but the report is also known as the 1982 Sandia Siting Study or as NUREG/CR-2239. http://en.wikipedia.org/wiki/CRAC-II

[16] Indian Point 3 is the site of the most costly accident.

preliminary estimates of the cost of Fukushima are over $250 billion on the high end. (News on Japan, 2011) In other words, the second rationale for downplaying concern about nuclear safety was equally flawed.

The Rasmussen report offered natural disasters as a point of reference to make the expected costs seem small. Adjusting both the probability and the amount of damage estimates leads to a different conclusion. For example, studies commissioned by the World Health Organization estimate that there were an average of 350 natural disasters per year in the first decade of the 21st century with total damages for all disasters of about $100 billion per year. (Guha-Sapir, 2011, pp. 20-21.) By this measure, a single severe nuclear accident can impose costs that are larger than the costs of thousands of natural disasters that take place over many years. The third rationale for downplaying concern about nuclear safety was also flawed.

This quantitative evidence shows that the potential costs vastly exceed the liability limits that Congress has imposed. Ironically, the Rasmussen report provides a direct link to the liability issue. It appears to have been timed and touted as part of the effort to secure reauthorization of the Price Anderson Act. However, at the time of the Chernobyl accident, as Tomain pointed out, the estimate of the cost of a severe accident was almost thirty times as large as the cap on liability. Today with the cap raised to $12.5 billion the damages of a severe accident would still be about thirty times higher than the cap.

Moreover, the concern about liability expressed by the industry – that nuclear reactors simply would not be built and operated without socializing the risk by shifting it away from companies onto the public –appears to as true today as it was over 50 years ago. Recent analyses both before and after Fukushima support the conclusion that nuclear reactors continue to be virtually uninsurable in the private marketplace. (Vericherungsforen 2011, Froggatt, 2010)Thus, the incidence and impact of severe events returns us to the question of liability, with which we began the analysis in Section II.

THE REGULATORY REACTION TO THE THREAT TO PUBLIC SAFETY

These data show that the concerns about safety that have been expressed throughout the history of the nuclear industry were justified by the incidence and impact of nuclear accidents and suggest that there should be little wonder that these severe accidents capture so much attention. Accidents are frequent enough and severe accidents have such a huge impact that the struggle to improve the safety of nuclear reactors is likely to be never ending.

Confronted with a massive increase in the threat to public safety and the deficient performance of the nuclear reactors, safety regulators were compelled to respond. Exhibit III-5 shows the pattern of adoption of safety measures and one indicator of their impact. The change in attitude at the NRC is apparent in the adoption and revision of rules in the 1970s and the fines that started to be imposed after TMI. The number of reactors that were offline as part of an outage lasting more than one year for safety restoration rose after TMI and particularly after Chernobyl.

With one quarter of the reactors that were brought online having outages of more than one year and an average cost of over $1.5 billion per outage in 2005 dollars (with the highest cost being over $11 billion) they deserve some analysis. There are three causes of these outages.

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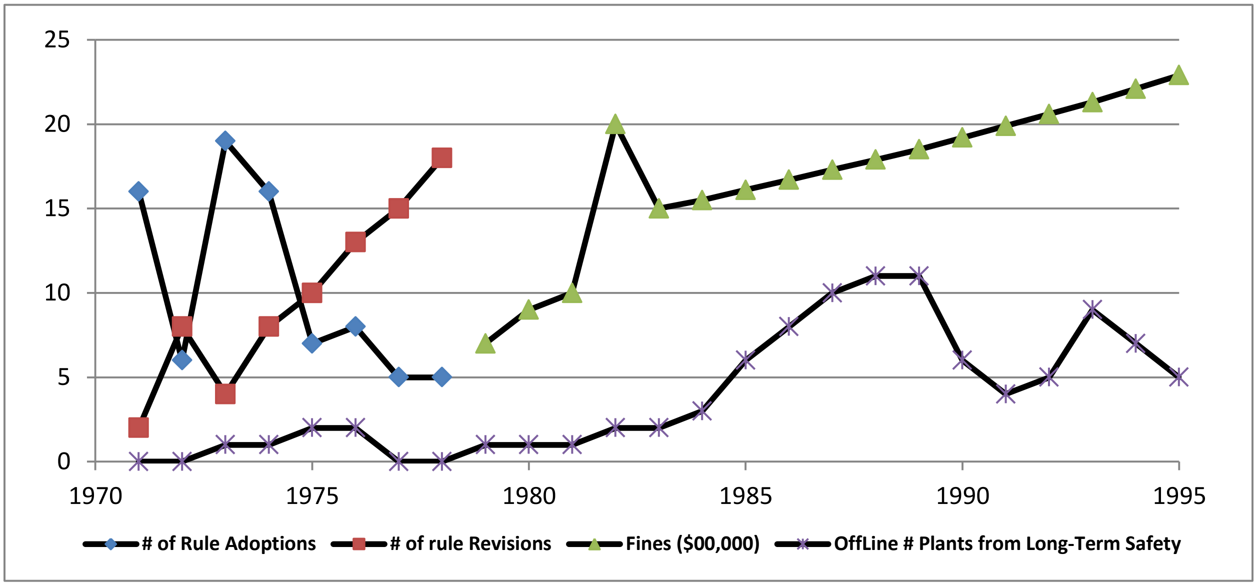
[17] Estimates vary and increase over time, with the cost in Belarus put at $235 (in 2003, The Chernobyl Forum, 2003-2005) with indications that the cost in other neighboring areas were at least ad large) and $287 billion in 2007 (Friends of the Earth Europe, 2007). Costs in the Ukraine were put at $336 billion in 2007. The total of over $600 billion would be higher in 2010 dollars.

- Replacement – to refresh parts that have worn out.
- Retrofit –to meet new standards that are developed as the result of new knowledge (e.g. beyond-design events) and operating experience
- Recovery – necessitated by breakage of major components

EXHIBIT III-5: SAFETY RULES AND FINES



Sources: Joseph P. Tomain, *Nuclear Power Transformation* (Bloomington: Indiana University Press, 1987; Charles Komanoff, *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics,* (New York: Van Nostrand, 1981); David Lochbaum, *Walking a Nuclear Tightrope: Unlearned Lessons of Year-Plus Reactor Outages,* September 2006*. NRC Annual Reports.*

The reactors that had extended outages were twice as likely to have been completed before TMI and therefore they were caught in the transition to greater safety regulation. Construction was started with half as many regulations in place, and the number more than tripled during the construction period.

The industry howled in response to these regulatory requirements, claiming that the safety regulator was imposing irrational regulations that undermined the economics of the industry. However, as we have seen, the Browns Ferry fire in 1975 and Three Mile Island in 1979 demonstrated to the NRC staff that really bad things could happen and vindicated their resolve. When the NRC itself looked at safety after TMI and again after Fukushima, when the Kemeny Commission looked at nuclear power after TMI and the Japanese Atomic Energy Agency looked at nuclear power after Fukushima, they all concluded, contrary to the complaints of the industry, that not enough had been done to ensure safety. These post-accident reviews are the subject of the next section.

IV. SAFETY AND REGULATION AS SEEN THROUGH POST ACCIDENT EVALUATIONS

THE GLOBALIZATION OF SCRUTINY OF SAFETY REGULATION AFTER ACCIDENTS

In the mid-1970s, the NRC was scrambling to get a handle on a defective product that was seen as posing an increasing threat to public safety. TMI confirmed and reinforced the concerns. This section reviews the responses of safety regulators to severe nuclear accidents in the context of an industry that is perpetually challenged by safety concerns. It relies primarily on the self-evaluations of the regulators in response to those accidents. The two U.S. task forces formed by the NRC to study major accidents provides the core data for this review, supplemented by observations of the Kemeny Commission formed in the United States to study TMI. Judging from the task force formed thirty years later to study Fukushima, in some important ways the NRC never did catch up.

In the 1970s, when regulators in the United States were grappling with safety regulation, with the huge numbers of reactors proposed and under construction, the United States towered over the nuclear sector in non-communist nations. By the time of the Fukushima accident, the distribution of nuclear reactors in non-communist nations was much more evenly spread. The opinion of regulators outside of the United States is influential as well. Of course, the opinion of the Japanese is of particular note.

The key elements of the Japanese evaluation of the accident at Fukushima, contained in "a 670-page report to the International Atomic Energy Agency" prepared by the Japanese Atomic Energy Commission" (JAEC), was summarized by the Vice chairman of the JAEC in an article in the Bulletin of Atomic Scientists (Suzuki, 2011). He argues that "Japan shouldn't be the only country reviewing and distilling the lessons from Fukushima. There are 436 nuclear plants operating in 31 countries. It is critical from the world's nuclear community and policy makers to learn from the information available so far." (Suzuki, 2011: 10) Exhibit IV-1 summarizes the preliminary results of the accident reviews from the nations that account for the vast majority of nuclear reactors in market economies. It summarizes the safety issues identified by nuclear technical safety organization (TSOs) around the globe in light of Fukushima. Exhibit IV-1a summarizes the analysis presented by representatives of four TSOs in France, Japan, Belgium, and Germany (Institut De Radioprotection et de Surete Nucleaire, 2011) to a major conference of TSOs conducted seven months after the accident at Fukushima. Exhibit IV-1b contains the Japanese self-evaluation presented to the International Atomic Energy Agency (IAEA). Exhibit IV-1c outlines the recommendations of the Nuclear Regulatory Commission's (NRC) Near Term Task Force.

The challenges perceived by those responsible for nuclear safety around the world in the wake of the Fukushima accident are quite substantial. As a representative from Spain to the Eurosafe conference put it "Nothing will be the same after Fukushima." (Bernaldo de Quiros, 2011) Ten days after that conference, the French TSO issued a report that would affect virtually every reactor in France, based on considerations such as the possibility that multiple units at a site could fail, cutting off all power for cooling, a lack of hardened ventilation systems to protect against seismic events, the need to incorporate evolving earthquake knowledge into risk assessment, etc. (Institute of Nuclear Safety, 2011)The French report also noted that full reviews of all reactors were ongoing. The historical experience in the U.S. and the fundamental changes in safety regulation that are emerging from the reviews of the Fukushima accident suggest that the escalation of cost will persist across the global industry, not just in Japan.

EXHIBIT IV-1: THE NEED FOR EXTENSIVE IMPROVEMENT IN SAFETY PRECAUTIONS: EUROSAFE

EXHIBIT IV-1A: EVOLUTION OF THE TECHNICAL SAFETY PROGRAM AFTER THE FUKUSHIMA EXPERIENCE ACCIDENT

Plant Vulnerabilities
- **Possible Event Causes**
  - Siting
  - Internal
  - Organizational
  - Combinations of causes
- **Probabilistic Safety Assessment**
  - Evolution of Knowledge
    - Seismology, geology, meteorology, etc.
  - Scope
    - Natural Phenomena
      - Seismic Tsunami, Tornado, Flooding
    - Attacks
    - Whole Site
  - Multiple Unit Vulnerabilities
  - Loss of Cooling
  - Loss of Heat Sink
  - Loss of Power (Station Black Out)

Behavior of Fuel
- Spent Fuel Pools
  - Loss of Water
  - Presence of Debris
- Hydrogen
  - Production
  - Transport
  - Explosion
  - Role of Cladding
- Use of Unusual Measures
  - Seawater for Cooling

Severe Accident Progression
- **Core Degradation**
- **Cliff - Edge problem**
- **Emergency Management**
  - Infrastructure and Competence
    - Organization
    - Training and Tutoring
    - Exercise and Preparation
  - Preparedness for Unforeseen
  - Standard of Preparedness
  - Standard of Competence

Human Reliability Assessment
- **Under Accident Stress**
  - Multiple Units
  - Extreme Radiation
  - Fatigue Due to Isolation

Need for External Support

Maintenance of Resources Over Time

Communications-Information
- For Responders
- Between Safety Regulators
- For the Public

Source: Eurosafe Forum, Experience Feedback on the Fukushima Accident, November 8, 2011; D. Degueldre, T. Funshashi, O. Isnard, E. Scott de Martinville, M. Sognalia, "Harmonization in Emergency Preparedness and Response;" P. De Gelder, M. Vincke, M. Maque, E. Scott de Martinville, S. Rimkevicius, K. Yonebayashi, S. Sholmonitsky, "The Evolution of the TSO Programme of Work after the Fukushima Daiichi NPS Accident

EXHIBIT IV-1: CONT'D.

EXHIBIT IV-1B: LESSONS LEARNED REPORTED TO THE IAEA MINISTERIAL CONFERENCE AND 2011 GENERAL CONFERENCE

Prevention of severe accident	Design Basis	1. Revision of design basis earthquake/tsunami
	Enhancement of safety functions	2. Power supplies 3. Reactor/Containment cooling 4. Spent Fuel Cooling
	Accident management measures	5. Enhancement of regulatory requirements
	Additional considerations	6. Multi-unit site issues 7. Plant layout (e.g. elevation of SFP) 8. Water tightness (essential systems)
Mitigation and preparedness for severe accidents	Enhancement of mitigation measures	9. Hydrogen explosion prevention measures 10. Enhanced containment vent
	Improvement of accident response activities	11. Response environment and equipment 12. Radiation control (equipment, training, etc.) 13. Severe accident response training
	Enhancement of instrumentation	14. Instrumentation for reactor, PCV, SFP, etc.
	Central control of external support	15. Rescue Teams, equipment, experts, etc.
Response to nuclear emergency	Combination of nuclear emergency and natural disaster	16. Preparedness for loss of general infrastructure
	Radiation monitoring and prediction	17. More organized environmental monitoring 18. Effective use of radiological prediction system
	Organization and communication	19. Improved coordination among response organizations 20. Improved public communications
	International cooperation	21. Improved communication and response to proposed assistance
	Evacuation and radiation protection	22. Clarification of criteria
Enhancement of safety infrastructure	Regulatory organization	23. Unification of regulatory bodies into independent "Nuclear Safety and Security Agency"
	Regulatory frameworks and approaches	24. Revision of regulations, standards and guides 25. Enhancement of system independence and diversity 26. Effective use of PSAs
	Human resources	27. Enhancement of human resources in the areas of Nuclear safety and emergency preparedness
Strengthening of safety culture	Strengthening of safety culture	28. Reconstruction of safety culture in all organizations involved in nuclear activities

Source: Yoshiro Nakagome, *JNES's Response to TEPCO Fukushima NPS Accident,* November 2011,

EXHIBIT IV-1: CONT'D.

EXHIBIT IV-1C: RECOMMENDATIONS FOR ENHANCING REACTOR SAFETY IN THE 21ST CENTURY: THE NEAR-TERM TASK FORCE REVIEW OF INSIGHTS FROM THE FUKUSHIMA DAI-ICHI ACCIDENT

Clarifying the Regulatory Framework

1. The Task Force recommends establishing a logical, systematic, and coherent regulatory framework for adequate protection that appropriately balances defense-in-depth and risk considerations. (Section 3)

Ensuring Protection

2. The Task Force recommends that the NRC require licensees to reevaluate and upgrade as necessary the design-basis seismic and flooding protection of structures, systems, and components for each operating reactor. (Section 4.1.1)
3. The Task Force recommends, as part of the longer term review, that the NRC evaluate potential enhancements to the capability to prevent or mitigate seismically induced fires and floods. (Section 4.1.2)

Enhancing Mitigation

4. The Task Force recommends that the NRC strengthen station blackout mitigation capability at all operating and new reactors for design-basis and beyond-design-basis external events. (Section 4.2.1)
5. The Task Force recommends requiring reliable hardened vent designs in boiling water reactor facilities with Mark I and Mark II containments. (Section 4.2.2)
6. The Task Force recommends, as part of the longer term review, that the NRC identify insights about hydrogen control and mitigation inside containment or in other buildings as additional information is revealed through further study of the Fukushima Dai-ichi accident. (Section 4.2.3)
7. The Task Force recommends enhancing spent fuel pool makeup capability and instrumentation for the spent fuel pool. (Section 4.2.4)
8. The Task Force recommends strengthening and integrating onsite emergency response capabilities such as emergency operating procedures, severe accident management guidelines, and extensive damage mitigation guidelines. (Section 4.2.5)

Strengthening Emergency Preparedness

9. The Task Force recommends that the NRC require that facility emergency plans address prolonged station blackout and multiunit events. (Section 4.3.1)
10. The Task Force recommends, as part of the longer term review, that the NRC pursue additional emergency preparedness topics related to multiunit events and prolonged station blackout. (Section 4.3.1)
11. The Task Force recommends, as part of the longer term review, that the NRC should pursue emergency preparedness topics related to decision making, radiation monitoring, and public education. (Section 4.3.2)

Improving the Efficiency of NRC Programs

12. The Task Force recommends that the NRC strengthen regulatory oversight of licensee safety performance (i.e., the Reactor Oversight Process) by focusing more attention on defense-in-depth requirements consistent with the recommended defense-in-depth framework. (Section 5.1)

Source: Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident, U.S. NRC, July 12, 2011.

Suzuki's call for all of the nuclear nations to learn the lessons of Fukushima has an ironic twist to it, when the Japanese recommendations for lessons learned from Fukushima are placed side-by-side with the recommendations of the President's Commission on the Accident at Three Mile Island (NRC, 1979; the Kemeny Commission, 1980). TMI should have been a teachable moment in which many of the same lessons should have been learned in Japan and the U.S. Many of the themes we have identified above in the pre-TMI struggle with safety regulation were documented in the NRC's post-TMI report evaluations and they persist in the post-Fukushima Task Force reports. (NRC, 2011) They are also highlighted in the Japanese post-Fukushima report. The struggle with nuclear safety is never-ending.

The U.S. short-term recommendations reflect each of the major areas of concern, but the near-term list is much shorter.[18] Moreover, even though the U.S. list of safety concerns raised by Fukushima is shorter, it has become a focal point of dispute among the five NRC commissioners and a target of criticism from the industry. (Zornick, 2011)

The accidents and the reports are quite complex and reflect a large number of issues, many of which were unique to each accident. However, there are numerous themes that are remarkably similar between the two, which reflect many of the concerns about safety that had developed prior to TMI. These indicate clearly that a much more aggressive effort to reform the regulation of safety is needed. The dynamic manner in which this complex technology interacts with its environment requires a more responsive approach to regulation. The NRC did not follow through on its big reform recommendations after TMI. Self-regulation remained paramount and, absent full liability, is unable to provide sufficient incentive to attend to safety.

LACK OF A COMPREHENSIVE, CONSISTENT SAFETY REGULATION FRAMEWORK

The NRC lacks a coherent, comprehensive overall approach. In the analysis of TMI, the Task Force criticized the "quiltwork"[19] approach and lack of an "articulate" overall policy.

> What seems to be missing is the common denominator of an articulate and widely noticed national nuclear safety policy with which to bind together the narrow and highly technical licensing requirements. NRC, (1979: 1-2)

Thirty years later the NRC task force on Fukushima criticized the NRC's approach as a "patchwork" that resulted in gaps.[20] While the Task Force concluded that the threat was not imminent, it concluded that there was an urgent need for major improvement in safety regulation.

> Continued operation and continued licensing activities do not pose an imminent risk to the public… However, the Task Force also concludes that a more balanced application of the Commission's defense-in-depth philosophy using risk insights would provide an enhanced

[18] The detailed list of steps in the appendix puts more meat on the bones and moves the U.S. recommendation closer to the international recommendations.

[19] NRC, (1979: 1-2) The result of our short-term work and the various other efforts within the NRC and industry have undoubtedly initiated needed improvements in nuclear safety. But much more is needed beyond these reactionary steps. The Task Force acknowledges and appreciates the unique opportunity it has to stand back and look broadly at the past and the future of reactor safety regulation. This opportunity has led us to a critical scrutiny of NRC safety policy. What we found is that prescriptive and narrow licensing requirement only add to the quiltwork of regulatory practice and do little to directly address the nation's heightened concern for the safety of nuclear power plants…

[20]NRC (2011: pp. viii, 18-20), ix. This regulatory approach, established and supplemented piece-by-piece over the decades, has addressed many safety concerns and issues, using the best information and techniques available at the time. The result is a patchwork of regulatory requirements and other safety initiatives, all important, but not all given equivalent consideration and treatment by licensees or during NRC technical review and inspection…. The Task Force concludes that the NRC's safety approach is incomplete without a strong program for dealing with the unexpected, including severe accident

> regulatory framework that is logical, systematic, coherent, and better understood. Such a framework would support appropriate requirements for increased capability to address events of low likelihood and high consequence, thus significantly enhancing safety NRC. (2011: vii-viii)

The Task Force recognized that "a comprehensive reevaluation and restructuring of the regulatory framework would be no small feat," but concluded "that additional steps would be prudent to further enhance the NRC regulatory framework to encompass protections for accidents beyond the design basis. (NRC, 2011: 22).

The response demanded by the Japanese government to the Fukushima accident is similar to the recommended response from the United States. TMI and Fukushima Task Forces noted above.

> The Japanese government has expressed the lessons it has learned from this event and, so far, has reacted accordingly: It has demanded that stronger tools and systems be put in place to prevent – and respond to – a severe accident, that a national response to a nuclear emergency be established, and that a safety regulatory infrastructure be developed. (Suzuki, 2011: 10)

DENIAL OF THE REALITY OF RISK

The report of the President's Commission on the Accident at Three Mile Island (the Kemeny Commission), offers an observation on the need to change the safety mentality so that the inherent risk of nuclear reactor operation is recognized.

> [T]he belief that nuclear power plants are sufficiently safe grew into a conviction. One must recognize this to understand why many key steps that could have prevented the accident at Three Mile Island were not taken. The Commission is convinced that this attitude must be changed to one that says nuclear power is by its very nature potentially dangerous, and, therefore one must continually question whether the safeguards already in place are sufficient to prevent major accidents. A comprehensive system is required in which equipment and human beings are treated with equal importance. (Kemeny Commission, 1980: 25).

Suzuki offered an identical observation.

> In Japan, probabilistic safety assessment – or probabilistic risk assessment as it is sometimes referred to – has not always been effectively used in the overall review process at nuclear power plants. And Fukushima is a raw example of this: By not factoring in a rare event like a large-scale tsunami, Japan did not make sufficient efforts to improve the reliability of the assessments. In the weeks after the disaster, the Japanese government recommended swift utilization of probabilistic safety assessments and the improvement of safety measures (including effective accident management based on safety assessments). This is necessary to move Japanese safety regulation to something that is more risk-based and more effective – and this would mean a departure from being a "zero-risk" culture. (Suzuki, 2011: 11)

COMPLEXITY, CONFUSION AND CHAOS IN THE RESPONSE TO A SEVERE ACCIDENT

The Kemeny Commission found a breakdown at all levels in the TMI accident. "Wherever we looked, we found problems with the human beings who operate the plant, with the management that runs the key organizations, and with the agency that is charged with assuring the safety of nuclear power plants." (Kemeny, 1980: 25). The Kemeny Commission concluded that:

> the response to the emergency was dominated by an atmosphere of almost total confusion. There was a lack of communications at almost all levels. Many key recommendations were made by individuals who were not in possession of accurate information, and those who managed the accident were slow to realize the significance and implications of the events that had taken place. (Kemeny, 1980, 27).

Suzuki notes a similar breakdown in Fukushima.

> "Within hours of this disaster, came the painful realization that the nuclear infrastructure – from technical matters, like backup generators, to more administrative concerns, like which agency is responsible for injecting coolant into a reactor – was flawed and devastatingly complex." (Suzuki, 2011: 9)

> Immediately after the accident, the atmosphere at the Fukushima plant was anything but smooth and calm… Within days of the Fukushima accident, it was apparent that responsibilities had not been clearly defined between the national and local emergency response offices, between the national government and Tepco, or among the relevant agencies within the Japanese government… there was incredible confusion and misunderstanding. Even something as critical as injecting seawater to cool the reactors was misperceived. (Suzuki, 2011: 13)

Communications during the accident were poor not only between responsible authorities, but also with the public. "Information has been partial and late, and continues to be so. To us, the most helpful information has often come from other countries' safety authorities, such as those in the U.S. and France." (Ledeker, et al., 2011, 17).

FAILURE OF VOLUNTARY, SELF-REGULATION

The NRC has long relied on voluntary self-regulatory actions by the industry as the key component of the safety regime. [21] The TMI Task Force concluded that under the self-regulatory approach, the industry had failed to pay adequate attention to key safety issues. The post-TMI report recommended two measures. On the one hand, it proposed to provide stronger incentives to elicit more appropriate behaviors.[22] On the other, it concluded that the staff would have to become more directly involved in the regulation of safety.[23] The TMI task force noted the industry response to TMI in creating an Institute for Nuclear Power Operations (INPO) and pointed out that "There are two motives for industry participation in INPO, namely public safety and corporate finances." It asserted authority by adding that "The NRC must soon decide what reliance, if any, to place on the future effectiveness of INPO in achieving its objectives and pointed to lengthy recommendations it is making on operator licensing and qualifications," (NRC, 1979: 2-4). It indicated that the NRC needed to act independently of industry "voluntary" efforts in key operation and training areas.

[21] NRC, (1979: 1-2) Specifically, the primary deficiency in reactor safety technology identified by the accident was the inadequate attention that had been paid by all levels and segments of the technology to the human element and its fundamental role in both the prevention of accidents and the response to accidents. Thus, our policy recommendations and our specific ideas for stimulating and accomplishing change concentrated heavily on operations reliability and the associated design and licensing review measure that support or augment operations reliability. But an important qualifier must be added to this conclusion. That is, if the basic responsibility for public safety is to *remain in the private sector,* in the hands of the individual licensees for commercial nuclear power plants, then significant change in the attention to operations reliability must take place in the licensed industry…

[22] NRC (1979a, 5) The Lessons Learned Task Force is therefore recommending that, upon approval by the Director of NRR, rulemaking proceedings be initiated on an immediately effective basis. This method of rulemaking will permit the prompt imposition of these requirements and will… cause existing facilities to comply with the requirements sooner.

[23] NRC, (1979: 2-3) Notwithstanding the challenge to licensees provided in our earlier proposed increase in the incentive for good operations management, which we still support, the Task Force has also concluded that the NRC staff must give increased attention to the detailed methods of obtaining improvements in operational safety

The Fukushima Task Force did not spend nearly as much time explaining the joint responsibilities and cajoling the industry but it did conclude that "continued reliance on industry initiatives for a fundamental level of defense-in-depth similarly would leave gaps in the NRC regulatory approach." (NRC, 2011: 16-17) It identified key voluntary measures that had been on the table since TMI that the industry had not taken up with vigor, including Severe Accident Management Guidelines (SAMG), Probabilistic Risk Analysis (PRA), Individual Plant Examinations for External Events (IPEEE), and Extensive Damage Mitigation Guidelines (EDMG). [24] It recommended that these processes that had been voluntary should become mandatory to achieve a uniform, higher level of safety across the industry.[25]

In its report to the IAEA, the Japanese government reached the same conclusion about voluntary self-regulation. It recommended that accident management measures should "be changed from voluntary efforts to legal requirements and be developed by using a probabilistic safety assessment."(Suzuki, 2011: 14)

FAILURE TO RESOLVE IMPORTANT SAFETY ISSUES:

The TMI Task Force report points out that the TMI-2 accident highlighted the need to address "Unresolved Safety Issues." It noted that the problem of unresolved issues had been targeted by an Act of Congress. "Section 210 of the Energy Reorganization Act of 1974 requires the development of a plan for specification, analysis, and progress reports for unresolved safety issues." (NRC, 1979: 4-6) The failure to resolve these issues, long after the Congressional mandate and in the wake of the TMI accident led the NRC to recommend that "a permanent, dedicated group should be created to continue with the expeditious resolution of these issues. (NRC, 1979: 4-6)

> This function needs to be continued and formally institutionalized to arrive at a resolution of current unresolved safety issues as well as those unresolved safety issues that will likely be identified as a result of the TMI-2 accident including some of our final recommendations in

[24] NRC (2011) Ultimately, the Commission encouraged licensees to use the newly developed PRA methodology to search for vulnerabilities (in the Individual Plant Examination (IPE) program and Individual Plant Examination for External Events (IPEEE) program) and requested information on their findings. The Commission also encouraged the development of SAMGs based on PRA insights and severe accident research. However, the Commission did not take action to require the IPEs, IPEEEs, SAMGs.

The NRC encouraged but did not require licensees to develop and implement SAMGs. Since the SAMGs are voluntary and targeted to technical support staff, the formal training and licensing of plant operators does not address them… The inspectors collected information on the initial implementation, ongoing training, and maintenance of the SAMGs under TI 2515/184. The results of the inspection under the SAMG TI reinforced the value of making SAMGs a requirement. The inspectors observed inconsistent implementation of SAMGs and attributed it to the voluntary nature of this initiative. (47-48)

With the exception of a few special cases, licensees of operating reactors are not required to develop or maintain a PRA, although all licensees currently have a PRA. These PRAs are of varying scope and are generally not required to meet NRC-endorsed quality standards. (19)

[25] With regard to the IPEEE program, the staff performed a limited review of the IPEEE submittals to determine whether the licensees' IPEEE processes were capable of identifying and addressing severe accident vulnerabilities caused by external events…. However, the NRC reviews did not attempt to validate or verify the licensees' IPEEE results or the acceptability of proposed improvements. Further, the IPEEE analyses did not document the potential safety impacts of proposed improvements, and plants were not required to report completion of proposed improvements to the NRC. (29)

The effectiveness of onsite emergency actions is a very important part of the overall safety of nuclear power plants. The NRC could strengthen the current system substantially by requiring more formal, rigorous, and frequent training of reactor operators and other onsite emergency response staff on realistic accident scenarios with realistic conditions. (49)

Through these two inspection activities, the Task Force also had the opportunity to compare industry activities under a required program and a similar voluntary initiative (i.e., EDMGs and SAMGs). Both programs had been effectively implemented, including initial program formulation and licensee staff training. Those programs are now 10 to 20 years old, and some licensees have maintained both programs in a manner expected for an important safety activity, including in terms of maintenance, configuration control, training, and retraining. However, some licensees have treated the industry voluntary initiative (the SAMG program) in a significantly less rigorous and formal manner, so much so that the SAMG inspection would have resulted in multiple violations had it been associated with a required program. The results of the SAMG inspection do not indicate, nor does the Task Force conclude that, the SAMGs would not have been effective if needed. However, indications of programmatic weaknesses in the maintenance of the SAMGs are sufficient to recommend strengthening this important activity. (64)

the appendix to this report, and as the result of future operating experience. (NRC, 1979: 4-6)

This finding and statement reflects the contentious nature of the safety process that we have identified in the previous section. In identifying key safety issues, the TMI task force repeatedly noted that TMI highlighted issues that had already been flagged as safety issues that had gone unresolved.[26] Several of these were reflected in the list of issues identified in Exhibit II-1, such as the interaction between safety and non-safety grade equipment,[27] hydrogen control measures,[28] and the simultaneous failure of multiple systems.[29] These resonate in the analysis of the Fukushima accident. The Fukushima Task Force identified a number of important systems that had not been updated including Station Black Out (SBO), Systematic Evaluation Program (SEP), and EDMG.[30] The insufficiency of current policy with respect to Station Black Out is essentially a road map to the Fukushima accident.

> The implementing guidance for SBO focuses on high winds and heavy snowfalls in assessing potential external causes of loss of offsite power, but does not consider the likelihood of loss of offsite power from other causes such as earthquakes and flooding. Also, the SBO rule does not require the ability to maintain reactor coolant system integrity (i.e., PWR reactor coolant pump seal integrity) or to cool spent fuel. Further, the SBO rule focuses on preventing fuel damage and therefore does not consider the potential for the buildup of hydrogen gas inside containment during a prolonged SBO condition and the potential need to power hydrogen igniters in certain containment designs to mitigate the buildup of hydrogen. Nor does it consider containment overpressure considerations and the need to vent the containment in certain designs. Finally, the SBO rule does not require consideration of the impact on the station, and particularly on the onsite ac electrical power. NRC (2011: 35)

RETROFITTING SAFETY ON EXISTING REACTORS

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[26] NRC (1979: 7… 11…12) This and other operating experience raise a significant question about the performance qualifications of two types of valves in the primary coolant boundary; safety and relief valves… The NRC staff and the ACRS have for some years emphasized the need for special features and instruments to aid in accident diagnosis and control. Although some degree of capability of this type was available at TMI-2, and exists on other plants, the TMI-2 experience shows that more is needed…. In its study of the accident, the Task Force has found that, in the past, the full analytic capabilities of the licensees and reactor vendors have not been used in the development of emergency procedures for the training of reactor operators… The accident at TMI-2 emphasized a previously recognized need to significantly increase operations reliability…..

[27] NRC (1979: 3-2, 3-3) The second weakness in the current deterministic design requirements is the system used for classification and qualification of equipment….The interactions between non-safety-grade and safety grade equipment are numerous, varied, and complex and have not been systematically evaluated. Even though there is a general requirement that failure of non-safety grade equipment or structures should not initiate or aggravate an accident, there is no comprehensive and systematic demonstration that his has been accomplished.

[28] NRC (1979: 3-6) It appears from information that we have reviewed that hydrogen control measures, for degraded core events short of core melt, that might be feasible and effective in some containment designs would not be as effective in others.

[29] NRC (1979: 12) Among the many human or operational errors annually reported by the 70 plants no operation, there are only a few comparable in significance to the defeat of an entire safety function, that is, loss of auxiliary feed water. However, the fact that operation errors of this magnitude continue to occur at other plants emphasizes the need for improvement. The Task Force recommends prompt action to significantly change the trends of reactor operating experience in this area.

[30]NRC (2011:49) The Task Force also concludes that action is warranted to confirm, augment, consolidate, simplify, and strengthen current regulatory and industry programs in a manner that produces a single, comprehensive framework for accident mitigation, built around NRC-approved licensee technical specifications. These modified technical specifications would consolidate EOPs, SAMGs, EDMGs, and other important elements of emergency procedures, guidance, and tools in a manner that would clarify command and control and decision making during accidents.

NRC (2011: 37) Based on the preceding considerations, the Task Force concludes that, to have SBO equipment function effectively as a layer of defense-in-depth, it would need to be protected from flooding beyond the design basis. The Task Force has also concluded that the safety margin built into the design-basis flood would not be sufficient to provide the desired level of protection…. In addition, the EDMGs and associated equipment could be helpful and available promptly to the operators to mitigate accidents such as those that occurred at Fukushima. However, the two issues discussed above result in limited effectiveness of the EDMG strategies for naturally occurring events that typically affect more than one unit.

In the context of unresolved issues, the thorniest problem is that of retrofitting existing reactors. The TMI Task Force called for the adoption of a safety goal and then noted that

> a byproduct of the specification of a safety goal would be the clarification of backfitting decisions. Under this example, a proposed backfit would not need to provide substantial additional protection (as currently inferred under 10 CFR 50.109); anything required for safety would be sufficient. Similarly, a decision to backfit would naturally precipitate the need to backfit all nuclear plants, since it was required for safety, without agonizing over value impact studies or case-by-case determinations. (NRC, 1979: 4-3)

The Fukushima Task Force found that the Policy Statement on Safety Goals, adopted sixteen years after TMI (i.e. sixteen years before Fukushima) left a great deal to be desired, "In the Task Force deliberations, it became apparent that the existing guidance does not present a completely clear and consistent framework for decision making." (NRC, 2011: 4). Its recommendation make a series of distinctions that allow existing reactors to continue operating, while new safety rules are imposed, rules what will apply fully to new reactors

> As new information and new analytic techniques are developed, safety standards need to be reviewed, evaluated, and changed as necessary, to insure that they continue to address the NRC requirements to provide reasonable assurance of adequate protection of public health and safety. The Task Force believes, based on its review of the information currently available from Japan and current regulation that the time has come for such a change. (NRC 2011, 18).

The perennial problem of aging plants confronted with new knowledge about reactors and accidents is highlighted by Fukushima, since the reactors are among the oldest commercial reactors still in operation.

> The Japanese government must re-evaluate measures against age-related degradation of existing facilities to ensure structural reliability; it also must incorporate new knowledge and expertise (such as warnings presented by seismic and tsunami experts)…. It will clarify technical requirements based on new laws and regulations, probably including "retrofitting" (i.e. Applying new regulations to existing plants)." (Suzuki, 1011: 16).

The difficulty of dealing with the retrofitting issue in the industry is evident in the quote above, where, in spite of an extremely severe accident, a requirement to retrofit is only seen as probable. The critical issues are familiar by now: multiple failures, prolonged black out, hydrogen explosions, venting problems, cooling problems, and emergency response (Suzuki, 2011, 10-12).

THE CHALLENGE OF CONTINUOUS CHANGE AND THE FUTURE OF SAFETY:

The post-TMI Task force noted the occurrence of 'beyond-design events,' "The accident also involved a sequence of events more severe than those included in current design basis events, and thus it raises the question of whether other event should be included or whether additional accident mitigation features should be required." (NRC, 1979: 3-1) At one level it implicitly acknowledged the continual challenges that nuclear safety faces in a section entitled "Preparation for the Unusual."

> Everyone connected with nuclear power technology must accept as a fact that unusual situation can occur and accidents happen. Operations personnel in particular must not have a mindset that future accidents are impossible. The experience of Three Mile Island has not been sufficient to eradicate that mind set in all quarters and the effects of the experience will

> fade with time. This is probably the single most important human factor with which this industry and the NRC had to content. (NRC 1979: 2-7).

The Fukushima Task Force reached a similar conclusion that continuous change was inevitable in the safety space. It emphasized the importance of "beyond design challenges."

> The Task Force concluded that the Fukushima Dai-ichi accident similarly provides new insights regarding low-likelihood, high consequence events that warrant enhancements to defense-in-depth on the basis of redefining the level of protection that is regarded as adequate. (NRC, 2011: viii)
>
> In the Task Force deliberations, it became apparent that the existing guidance does not present a completely clear and consistent framework for decision making… (4) Adequate protection has been, and should continue to be, an evolving safety standard supported by new scientific information, technologies, methods, and operating experience. .. As new information and new analytical techniques are developed, safety standards need to be reviewed, evaluated, and changed, as necessary, to insure that they continue to address the NRC's requirements to provide reasonable assurance of adequate protection of public health and safety. (NRC, 2011,?)

A similar challenge lies in the difficulty of keeping up to date with new knowledge. The TMI report found that the industry had failed to adopt Probabilistic Risk Analysis. (NRC (1979: 3-2) The Fukushima Task Force found a number of analytic and data tools that had not been adopted.[31]

Suzuki notes the challenge of identifying the set of events that should be considered in designing for safety by pointing to a historical record that could easily have demanded inclusion of much more extreme events in the safety analysts of Fukushima.[32] Thus, deciding the temporal and geographic scope of the history to be included in design is challenging, particularly as the science advances. Since this had been pointed out in several recent reviews of nuclear safety in Japan, he flags the problem of how minority opinions should be reflected (Suzuki, 2011: 11)

PERVERSE INCENTIVES IN COMMERCIAL ATTITUDES TOWARD SAFETY:

Bupp and Derien argued that the vendors of nuclear reactors made a big mistake thinking they could easily transfer and scale up the technology they had been supplying to the military for civilian commercial needs. The NRC appears to have made a similar mistake with respect to regulation by deferring to industry.

The TMI Task Force gives a prominent place to a plea for the industry to adhere to the principle of personal responsibility that Admiral Rickover had demanded from the nuclear navy (NRC, 1979: 2-3). The nuclear navy may be a wonderful example of a system that can cope with nuclear power, but it is largely irrelevant to the commercial operation of nuclear reactors. The nuclear navy is based on small reactors in highly controlled environments with an extremely disciplined work force governed by the unique principles of military service. Utilities operating nuclear reactors are fundamentally different institutions. They operate much larger reactors in

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[31] NRC, 2011: 28 The SEP, mentioned earlier, was a one-time evaluation, and integrated plant safety assessments were published in the early 1980s for each of the plants included in the SEP. The SEP covered several technical topics, including protection from natural phenomena (i.e., floods, seismic events, tornadoes, high winds). Even that reassessment was conducted before satellite imaging, Doppler radar, and well-established theories of plate tectonics were available. It is clear that our current state of knowledge far exceeds that available to decision makers three decades ago.

[32] Fukushima has an earthquake and tsunami of similar magnitude in its history, over 1,000 years earlier. Moreover, there were several events in much more recent times in areas close to Fukushima that far exceeded the design basis of the Fukushima reactors (Noggerath, Geller and Gusiakov, 2011). Thus, deciding the temporal and geographic scope of the history to be included in design is challenging, particularly as the science advances.

uncontrolled environments with an essentially economic motivation and safety incentives watered down by limited liability and entirely different forms of discipline. The members of the Nuclear Regulatory Commission are not general officers and the Chairman is not Admiral Rickover; they are political appointees approved by the Senate.

Suzuki repeatedly states that the actions (or inactions) of the company and government officials that seemed insufficient were based on confusion under "stressful" conditions and concludes that they did the best they could. (Suzuki, 2011: 12, 15). However, others have argued that the incentives for nuclear operators create safety vulnerabilities in a variety of ways.

There is mounting evidence of a tendency to underreact to safety problems. The cause may be partially psychological; the plant operators just cannot accept that their detailed safety measures have failed. The cause may be partly economic; the plant operators want to solve the problem with the least interruption possible, but by trying to tailor the response, things are allowed to get out of control. "The decision to start cooling the reactors with sea water was not taken immediately, as this would destroy the reactors. Therefore, important time was lost in cooling the reactors before they overheated." (Lekeder, et al., 2011, 17).

The problem is not limited to accidents. The economic incentive to undervalue safety is also evident on an ongoing basis in the tendency of utilities and regulators to react to violation of existing standards by lowering the standard, rather than require the utility to take the sometimes expensive steps to meet it. (Donn, 2011; Sullivan, 20111; Wielawski, 2011) When accidents focus intense spotlights on safety regulation, it reveals this underlying pattern of perverse incentives.

An analysis by UBS raises several issues about the nature of risk and liability that do not receive a great deal of attention in the regulatory commission considerations. These issues are generally beyond the scope of expertise and the portfolios of safety regulations, but they are important nonetheless.

> Finally, Fukushima is a case of underestimated tail risk; the design of the power plant never anticipated the scale of tsunami that hit it, and the company seems to have had no contingency plan for such an event occurring. Also the financial consequences of this tail risk were not clearly considered and the ultimate division of liability between the operator and the government is now the subject of uncertainty…
>
> Other events could have similarly devastating effect that the regulator may not have previously considered. These could include asset concentration risk (too many units on the same site or in close proximity producing a disproportionate amount of the regions [sic] required generation).
>
> Secondly, the scale of the financial effect of a tail risk event such as the one at Fukushima Daiichi is probably not fully considered in costs of capital…
>
> Before Fukushima, TEPCO was viewed as a low risk regulated utility, mainly bought for its stable earnings and dividends. However, the events at Fukushima have led to an 80% decline in its share price and discussions about the future viability of the company…This additional risk linked to nuclear exposure has not, it seems to us, been properly priced in by the market. (Lekander, 2011: 3).

The UBS analysis points to asset concentration – the crowding of too many reactors on one site as a financial risk, but Fukushima raises the fundamental question of whether this practice poses a significant safety risk that is driven by economics. Crowding half a dozen reactors into one site saves money, but it makes them more vulnerable and puts more power at risk. Almost all of the proposed new reactors in the U.S. try to capture these economic benefits by planning to add the 3rd, 4th, 5th and 6th units to existing sites, but in doing so they may also incur additional safety risk.

PART II:

NUCLEAR ECONOMICS BEFORE AND AFTER FUKUSHIMA

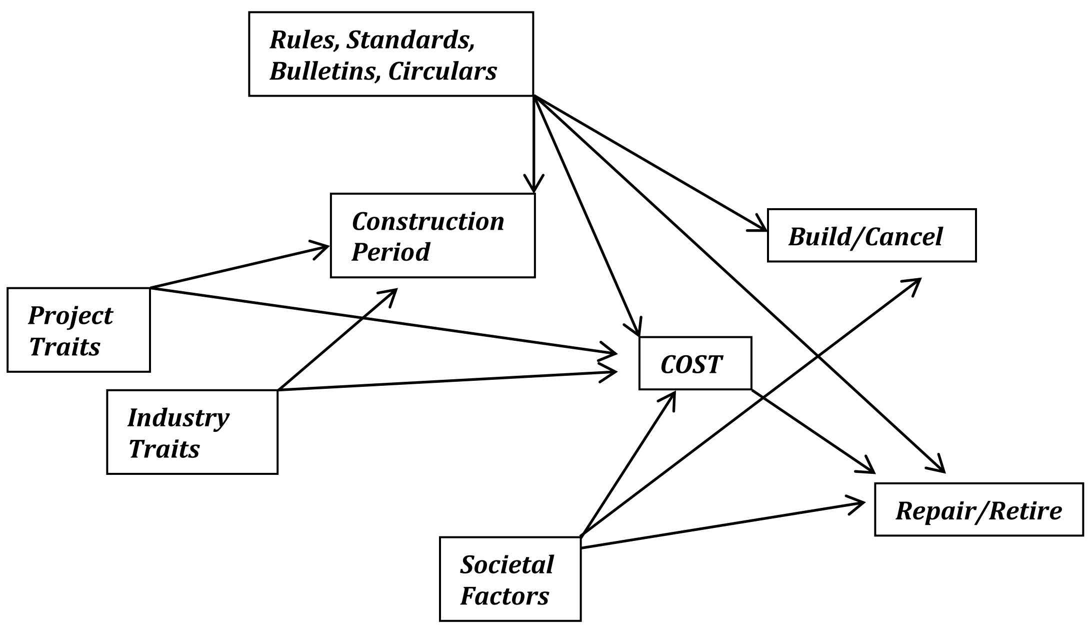
V. QUANTITATIVE ANALYSIS OF NUCLEAR PERFORMANCE

This section presents a statistical analysis of the performance of the nuclear sector in the United States in the period between 1966 and 1996, with comparisons to the French nuclear performance. Taken together France and the United States account for about one-third of the reactors in the world and one-half of those in market economies. Between them they also have a large number of pressurized water reactors, which are the most popular technology in the United States.

A COMPREHENSIVE MODEL OF CONSTRUCTION AND OPERATION DECISION POINTS

Komanoff used the safety issue as context, or background, for analyzing the cost escalation that had afflicted the nuclear industry in the 1970s. He then developed models to explain cost escalation in the 1970s which were used to project costs for 1988. The cost model included project costs, industry characteristics, builder characteristics as well as economy wide factors (demand growth, interest rates). He did not directly include safety. In this paper we incorporate the safety issue directly into the econometric analysis. As depicted in Exhibit V-1. We have added measures of safety to a comprehensive set of societal and project variables to assess the importance of safety regulation in the key decisions about nuclear reactor construction.

EXHIBIT V-1: DETERMINANTS OF KEY ECONOMIC CHARACTERISTICS AND DECISIONS



The analysis expands on what has been done in the past in several important ways. First, and foremost, it presents an econometric analysis of the build/cancel decision. In a sense since half of the reactors were not completed, this is the most important decision of all.

Second, the data base is expanded to include many more reactors. While the multivariate analysis relies on 222 of the total of 260 reactors identified, several of the simpler quantitative discussions include 250 reactors.

Third, many more variables are included in the database of nuclear reactors that was begun by Komanoff in 1981 and expanded by Koomey and Hultman (2007) and Koomey, (2011). The safety variables are based on historical research. Using Komanoff's Appendix to his Chapter 4, an index was created to show the growth of regulations and standards over the 1970s. Using Tomain's analysis of fines after TMI (augmented by NRC annual reports) an index was created to show the increasing attention to enforcement after Three Mile Island through the end of the U.S. building cycle. This approach captures the two phases of regulatory activity discussed above and avoids the problem of colinearity between the two measures. The safety variables used in the econometric analysis identify the number of rules (or average fines) in place at the date of start of construction or cancellation. For projects that were brought to completion, changes in the regulatory environment over the construction period are calculated, since this has been highlighted as a driver of construction period and costs.

Fourth, in addition to adding the safety variables, other variables have been added to capture the effects of factors that have been cited as important causes of escalating costs and/or cancellations. The project, industry and builder characteristics have been defined in an earlier study. Measures of market conditions that have frequently been cited as important to decision-making or costs are also included. These include the interest rate at the start of the project and growth rates of demand for electricity.

The primary approach to the analysis is a multiple regression. Since the build/cancel decision is a binary dependent variable, probit analysis is used. All other analyses use linear least squares, which is appropriate for continuous dependent variables. All standard errors are robust. Only statistically significant variables are included in the regression equations below.

BIVARIATE RELATIONSHIPS

The variables, with their mean levels broken down by key categories, pre v. post TMI and built v. cancelled are presented in Exhibit V-2 with short definitions. Exhibit V-2 provides an opportunity to reflect on bivariate relationships that are frequently mentioned in the debate over nuclear reactor construction in the U.S.

Compared to reactors complete before TMI, reactors that were completed after TMI exhibited the following characteristics:

- faced many more rules and revisions and fines were much higher;
- took almost twice as long to build;
- were much more costly;
- had higher interest rates at the start of construction and lower growth rates at the completion.

Compared to the conditions under which the decision was made to build reactors, reactors that were not completed

- faced many more rules and revisions and fines were much higher;
- were larger;
- faced higher costs and interest rates, lower growth rates; and
- existed in states that already had a much higher level of nuclear power in their generation mix.

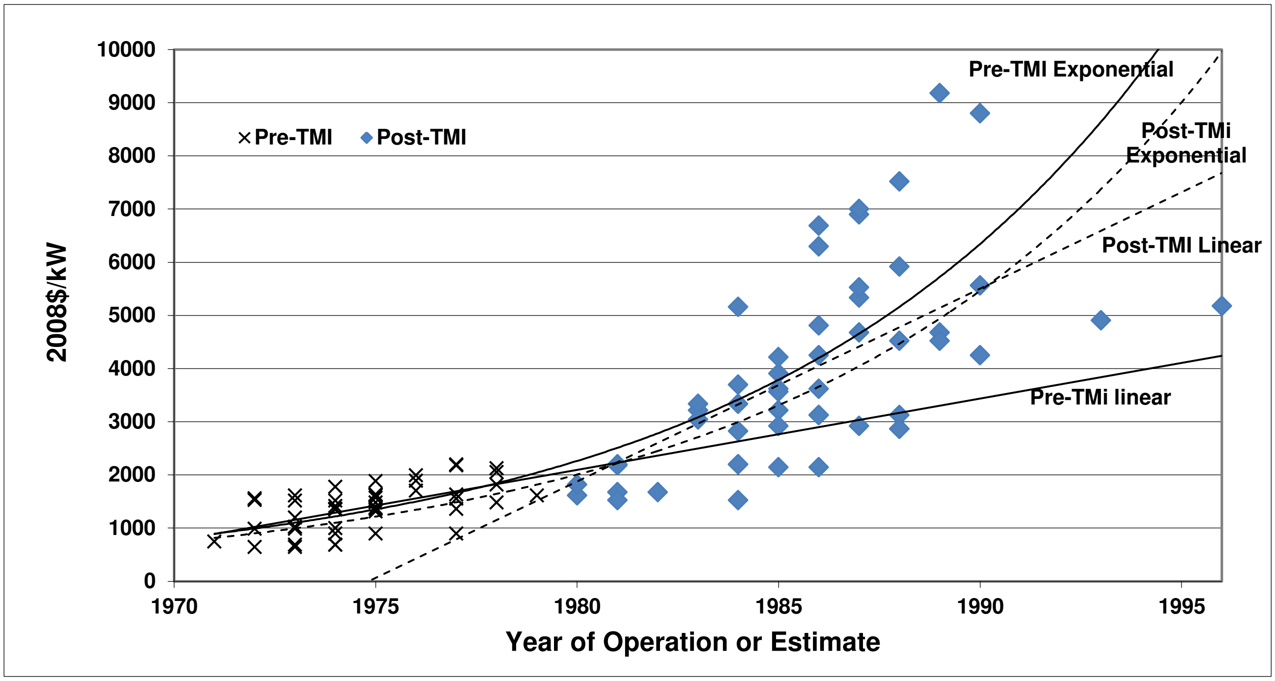
EXHIBIT V-2: VARIABLES IN THE ANALYSIS

	Reactor	Definition	Pre-TMI	Post-TMI	Built	Canceled
Outcomes	Cost Per kw	Overnight Cost/kw in 2009$	1065	3448		
	Outages	Long-term years lost (avg. for outage)	5.9	2.5		
	Early Retirement	Percent of reactors	20	6		
	Construction Period	# of yrs between permit & Operation	6.02	11.67		
Project	Technology	1=BWR & other; 2=PWR (% PWR)	94	70	66	75
	Capacity	MW	769	1080	907	1095
	2nd Unit	2nd or 3rd unit at a site with (%)	27	33		
	Permit Year		1968	1974		
	Operating Year		1973	1985		
Industry	Activity	Number of units under construction at construction start-up	32.4	74.2	50.8	712
	Experience	Number of reactors completed prior to completion of a new reactor	5.4	36.2	19.1	66.2
	Average cost at Start	Cost of all completed reactors, prior to start/cancel decision	574	861	701	1280
Builder	Activity	Number of units under construction when new unit started	2.6	2.3		
	Experience	Total number of units under construction prior to build start	4.1	7.5		
Safety	Rules and Standards	# adopted by NRC during 1970s At completion of reactor	77	149	107	139
		Construction start or cancellation	3.3	50.3	24.2	80.3
	Fines ($000)	Construction start or cancellation	0	19	8.5	912
		Construction End	91	1620		
	Change in Safety					
	Rules	Increase in rules start to finish	51	83		
	Revisions	Revisions of rules start to finish	91	151		
	Fines	Increase in fines start to finish	50	155		
Market	Interest Rates		6.2	8.1	7.1	10.7
	Electricity Growth Rates					
	at start of project	% per year, previous 10 years	6.8	6.9	6.7	3.7
	at end of project	% per year previous 10 years	7.9	2.3		
State	Growth of competing % per year,	Previous 10 years	9.0	8.5	8.9	4.2
	% nuclear in year of decision		2.5	9.8	5.9	14.8

Data sources: : Jonathan Koomey, and Nathan E. Hultman, 2007, "A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970-2005," *Energy Journal,* 2007; Joseph P. Tomain, *Nuclear Power Transformation* (Bloomington: Indiana University Press, 1987; Komanoff, Charles, *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics,* (New York: Van Nostrand, 1981); Energy Information Administration, State Electricity Data Base, *Jonathan Koomey,* Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes? June 24, 2011. Bureau of Labor Statistics, Consumer Price Index.

A closer look at the important bivariate relationships provides important insights into the nature of cost escalation in the nuclear industry, particularly when similarities between the U.S. and France are considered. Exhibit V-3 shows the trend of overnight costs for all nuclear reactors completed in the United States. It shows the pre and post TMI trends modeled both as linear and curvilinear relationships. The pattern of cost escalation existed before TMI and, with linear projections appears to have worsened after TMI. However, fitting an exponential curve to pre-TMI costs indicates little change in cost escalation. Thus, the impact of TMI is unclear based on the simple correlation between time and overnight cost.

EXHIBIT V-3: U.S. NUCLEAR REACTOR OVERNIGHT COSTS (2008$)



Sources: Jonathan Koomey, and Nathan E. Hultman, 2007, "A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970-2005," *Energy Journal,* 2007; Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives,* Institute for Energy and the Environment, Vermont Law School, September, 2010.

In fact, time is not a very good explanatory variable here for another reason. The theoretical relationship between time and cost is uncertain. If time represents experience, then we would expect a negative relationship. The industry hoped that time would lower cost, as more experience was gained and economies of scale were achieved. On the other hand, if time represents aging or the accumulation of bad operating experience, as discussed in the previous section, for existing reactors, we might expect a positive relationship, as wear and tear requires additional cost. Neither of these prior expectations obtains. We must look beyond time as a simple measure to examine the underlying processes that are assumed, in theory, to vary with time.

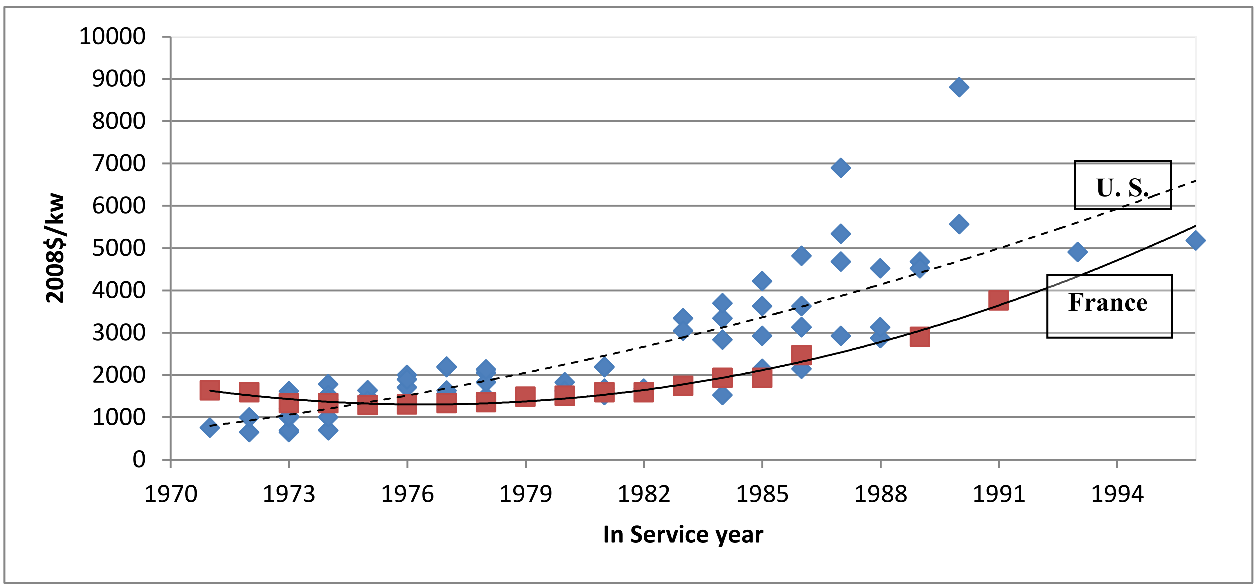
Exhibit V-4 shows the costs for pressurized water reactors in the U.S. and France. About two-thirds of the U.S. reactors used PWR technology, while all the French reactors used this technology (in fact the French PWR industry was launched with a licensed U.S. design, American Pressurized Water Reactor). The French tried to "Frenchify" this design over time and the worst of the cost escalation followed this endeavor. However, it remained basically a PWR design.[33] The PWR technology was the dominant technology in the U.S. as well. There are 69 pressurized water reactors in the U. S. database, compared to the 54 in the French database. Virtually all of the

[33] Grubler, 2009. Two papers have been published based on the data (Komanoff, 2010), is the second). One presents the original range of estimates per year. The other presents point estimates for each year. The French data looks smoother than the U.S. data because the cost estimates are year-by-year costs for all reactors put under construction in a given year. Even if specific reactor costs were used, the French cost curve is likely to be smoother, because there was a single monopoly company in France in contrast to over a dozen companies in the U.S.

currently proposed reactors in the U.S. for which there are site-specific projections are PWRs of one form or another and all of the generic costs estimates in recent years have been for PWR technologies. The remainder of the discussion of bivariate relationships focuses on PWR technology.

The U.S. cost increase was similar to, but somewhat higher than the French. In France in the first decade, from about $1,000/kW to $2,000/k, with the average cost for the decade of about $1,250/kW. In the second decade the French going from $2,000/kW to $3,000/kW. By the end of the 1980s, French reactors were consistently in the range of $2,000/kW to $3,000/kW. In the U.S., costs for PWRs increased from $1,000/ kW (including turnkey plants) to about $2,000/kW by the end of the 1970s. In the 1980s cost escalation was faster in the U.S in the second decade, while the U.S. costs increased to an average of $3,600/kW, with a number of units much higher. Most of the reactors in the U.S. were in the $4,000/kW to $6,000/kW range by the late1980s.

EXHIBIT V-4: OVERNIGHT COSTS OF PRESSURIZED WATER REACTORS (2008$)



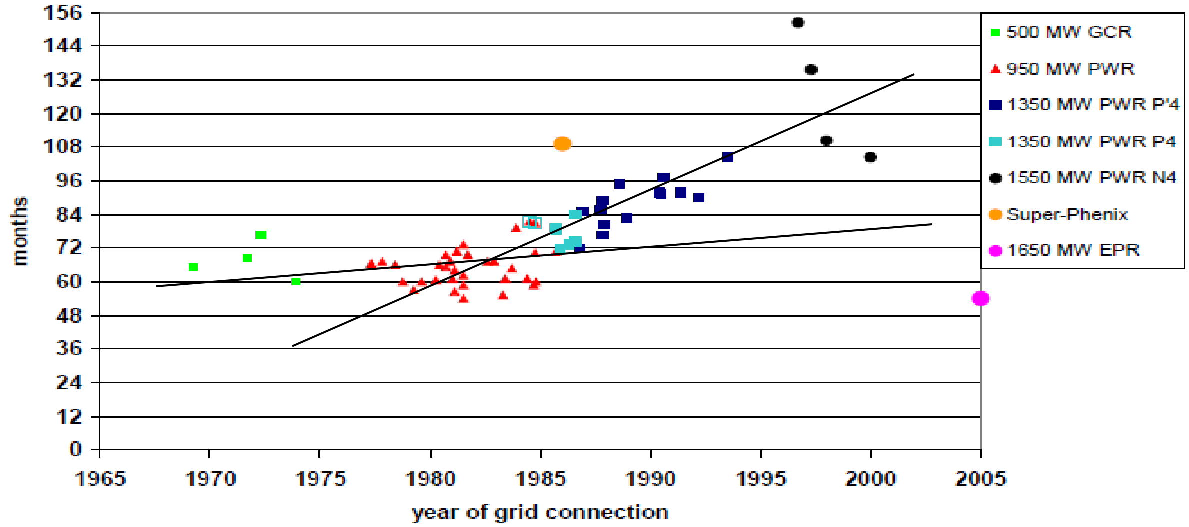
Source: Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives,* Institute for Energy and the Environment, Vermont Law School, September, 2010; Arnulf Grubler, *An Assessment of the Costs of the French Nuclear PWR Program: 1970-2000,* International Institute for Applied Systems analysis, October 6, 2009.

The primary driver of costs in both the U.S and France was the increasing length of construction period. (Bupp and Dernier, 1978, Mooz, 1979; and Komanoff, 1981) Capital costs mount and compound in the early construction period as they linger on the books before the reactor is used and useful and can be depreciated. The key to cost reduction would have been to reduce the length of time it took to construct new reactors. The experience in both countries was the opposite – i.e. construction periods in both countries increased substantially over time (see Exhibit V-5). The French construction periods were relatively stable at between five and six years in the period between 1970 and 1985 and then doubled in the second half of the 1980s due to a shift in design, the scaling up of the reactors, and the need to stretch out projects as excess capacity became apparent. In the U.S., construction periods consistently increased from the 1970s to the 1990s.

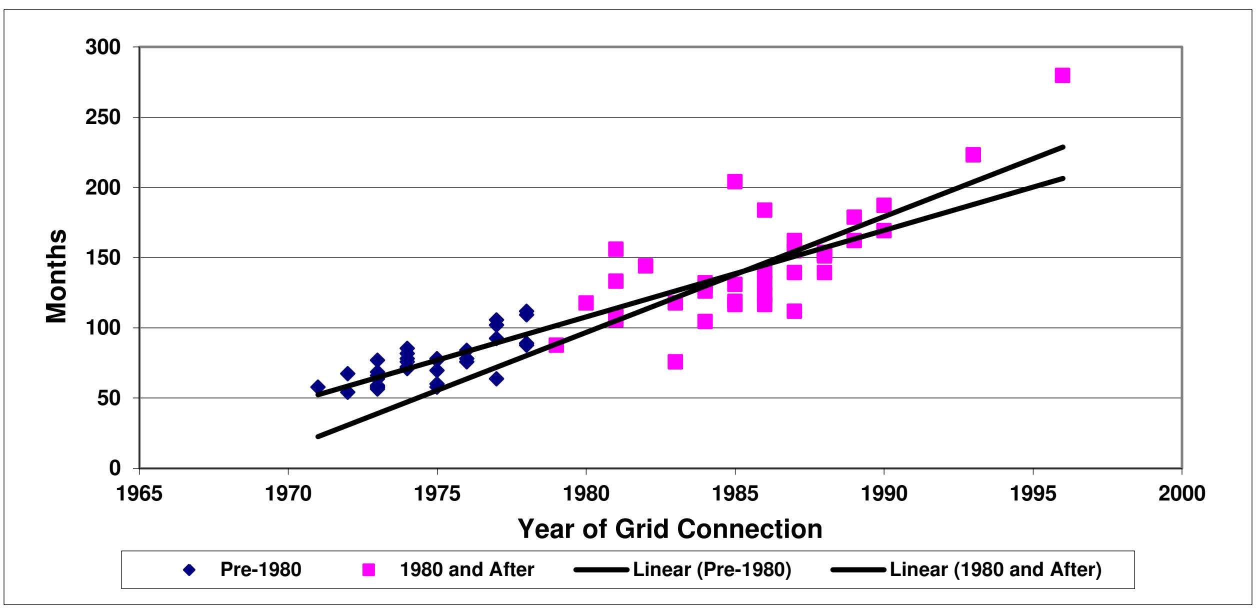
Exhibit V-5 identifies reactors completed before 1980 and those completed after. The first few reactors took about the same amount of time as the French and then there was a steady threefold increase. The later reactors had a higher rate of construction period increase in the U.S., but the problem clearly existed prior to the TMI accident.[34] The U.S. and French data strongly indicates that TMI was not the sole cause of the problem.

EXHIBIT V-5: CONSTRUCTION PERIODS, PRESSURIZED WATER REACTORS

FRANCE



UNITED STATES



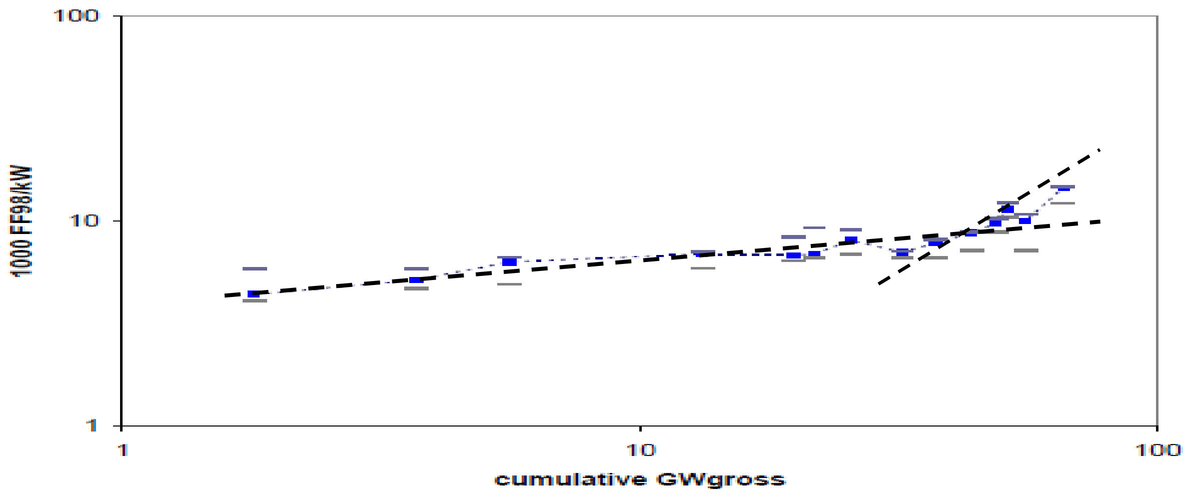
Source: Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives,* Institute for Energy and the Environment, Vermont Law School, September, database, updated; Arnulf Grubler, *An Assessment of the Costs of the French Nuclear PWR Program: 1970-2000,* International Institute for Applied Systems analysis, October 6, 2009.

[34] Bupp and Dernier, 1978, Mooz, 1978, 1979, Komanoff, 1981, all relied on cost data that antedate TMI. Faber, 1991, showed that the negative impact of nuclear reactor construction on utility financial situation also antedated TMI.

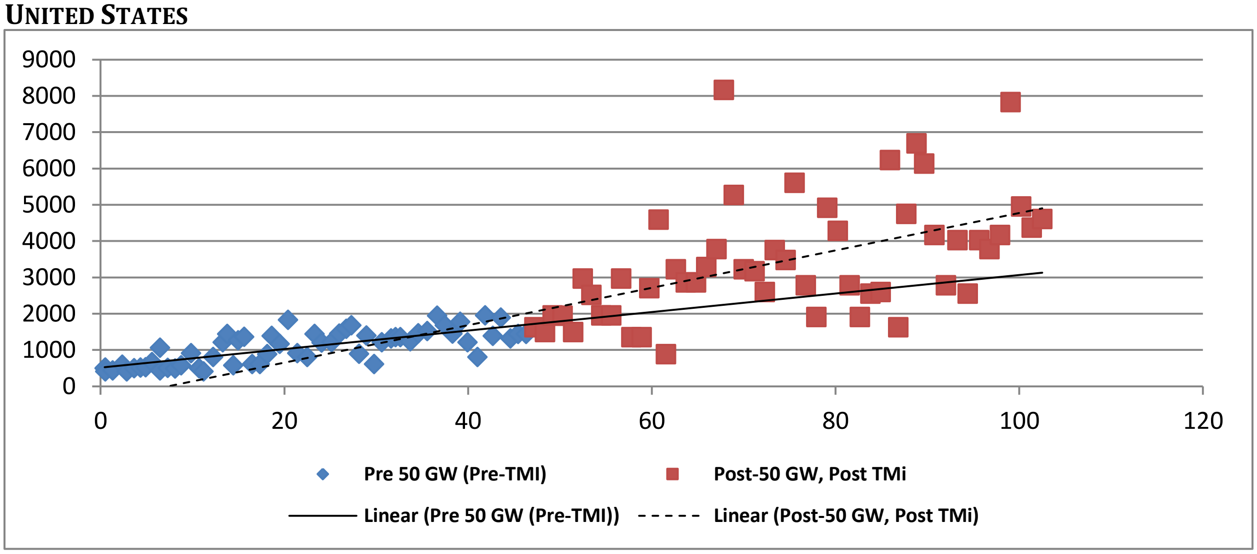
One of the factors that industry hoped would lower costs was increasing experience. The economies of scale that might drive prices down are not sufficient to offset other factors. As shown in Exhibit V-6 it did not do so. The inherent technology characteristics of nuclear power (large-scale, complex, and with lumpy investments) introduce a significant economic risk of cost overruns

EXHIBIT V-6: FRENCH AND U.S. LEARNING CURVES: PRESSURIZED WATER REACTORS

FRANCE



UNITED STATES



Source: Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives,* Institute for Energy and the Environment, Vermont Law School, September, database, updated; Arnulf Grubler, *An Assessment of the Costs of the French Nuclear PWR Program: 1970-2000,* International Institute for Applied Systems analysis, October 6, 2009.

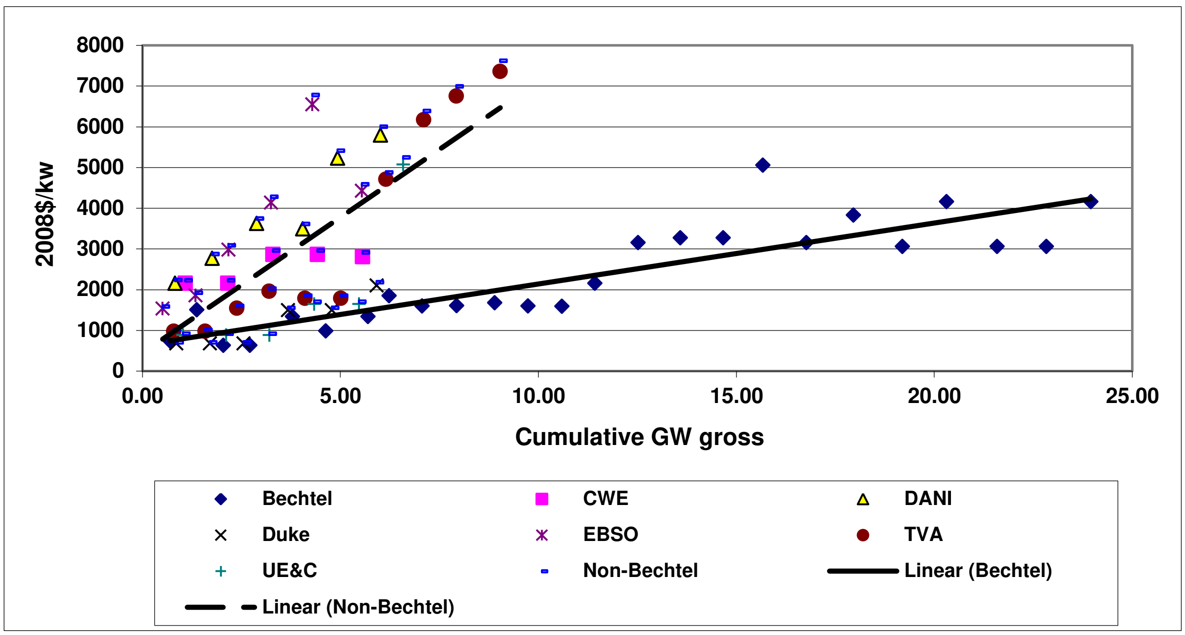
in the build-up process. Just as in the United States, the experience of rising construction costs drove the French to seek large reactors;[35] hoping unit economies of scale would offset the upward trend. "But as it turned out later, the expectations of significant economies of scale proved unfounded: any

[35] Grubler, p. 16, "The reason for this increase in reactor unit scale was primarily economic: significant economies of scale were sought and expected to encounter increasing tendencies for cost escalation. With the completion of the first reactors, the earlier optimistic assumptions about construction duration and investment costs faced a harsh reality check. The first reactor completed, at Fessenheim, took two years longer to build than originally projected, accruing additional interest during construction that further added to other cost escalation factors. As more experience was accumulated, the cost projections of the PEON Commission, as well as the internal ones of ÉDF, started to rise as well, adding urgency to the economic rationale for the move to the 1.3 GW PWR design."

cost reductions from larger components were more than offset by more complex construction sites, longer construction times, and the need to fix the inevitable technical problems arising from significant design changes." (Grubler, p. 11)

Anticipated economic gains from standardization and ever larger unit scales not only have failed to materialize, but the corresponding increasing complexity in design and in construction operations have reversed the anticipated learning effects to their contrary: cost escalation. (Grubler, p. iii) In France, all the reactors are built by one company, so the build-up of complete reactors is both the industry and the company experience curve. In the U.S., there are multiple companies so we should distinguish the industry experience curve from the company curve. Exhibit V-7 does so and finds that, for every utility and every range of experience, there was a cost escalation with experience, rather than a reduction. However, there is a distinction between the companies.

EXHIBIT V-7: U. S. COMPANY LEARNING CURVES



Source: Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives,* Institute for Energy and the Environment, Vermont Law School, September, database, updated

Bechtel built a large number and had lower costs, but even for Bechtel, there was a steady, moderate increase in costs. Two other constructors had low and moderately rising costs that paralleled Bechtel (Duke and UE&C) [36] although they built far fewer reactors. The other builders had much higher costs that rose faster.

[36] Grubler suggests that utilities building reactors may overcome some principal agent problems by unifying the interest of the utility and the builder and thereby achieve lower cost.

MULTIVARIATE ANALYSIS

The multivariate, econometric analysis shows that several of the important bivariate relationships mentioned above are statistically significant and quantitatively meaningful in the multivariate context (see Exhibit V-7). The Exhibit shows the results for all reactors (with technology included as an independent variable) and for PWR only. It uses the log of overnight costs as the dependent variable and shows the Beta coefficients. This yields results that can be easily explained. For example, each additional rule raised the cost by 1.79 percent; reactors at multiple unit sites were 29.72 percent less costly than standalone units.

EXHIBIT V-8: REGRESSION MODELS OF SAFETY AND ECONOMICS

	PWR ONLY				ALL REACTORS			
	Build/ Cancel		Construct period	Cost/KW (log n)	Build/ Cancel		Construct period	Cost/kw (log n)
Safety								
Number of rules	-.0448***	-0.0899***		.0174***	-.0407***	-.0674***		.0179***
Increase in rules			.0479***	.0123***			.0484***	.0096***
Revisions								
Fines imposed	-.0008***	-.0024***	.0299***		-.0009***	-.0038***	.0839***	
Change in fines			.0044***				.0042***	
Project								
Technology	na	na	na	Na				-.1965***
Capacity			.0026*	-.0006**			.0028*	-.0009***
Construction years			na	.0725***			na	.0827***
Multi-Unit				-.2262***				-.2972***
Market Conditions								
Industry								
Experience								
Activity			.06*21	.0147***			.0746*	.0161***
Builder								
Experience			-.1628*				-.09*	
Economy								
Interest Rates				.1276***				.0817*
Demand Growth	.1442***	.3408***			.1066*			
TMI		-.518***				-5.066***		
R^2	0.686	.917	0.81	.864	0.657	.908	0.76	.824
TMI as safety proxy			0.598	.801			0.622	.766

The safety variables are the most consistent predictors across all the analyses – build/cancel, construction period and cost – and across the subgroups of reactors. The number of rules and standards in force and revisions, the fines being charged and the changes in fines appear in several equations. Safety alone accounts for a high percentage of the variance in each of the dependent variables. Models without safety explain less variance, except in the case of cost. The higher the number of rules and fines, the more likely a reactor was to be cancelled. Increases in rules and fines are associated with longer construction periods. The number of rules and revisions are associated higher costs.

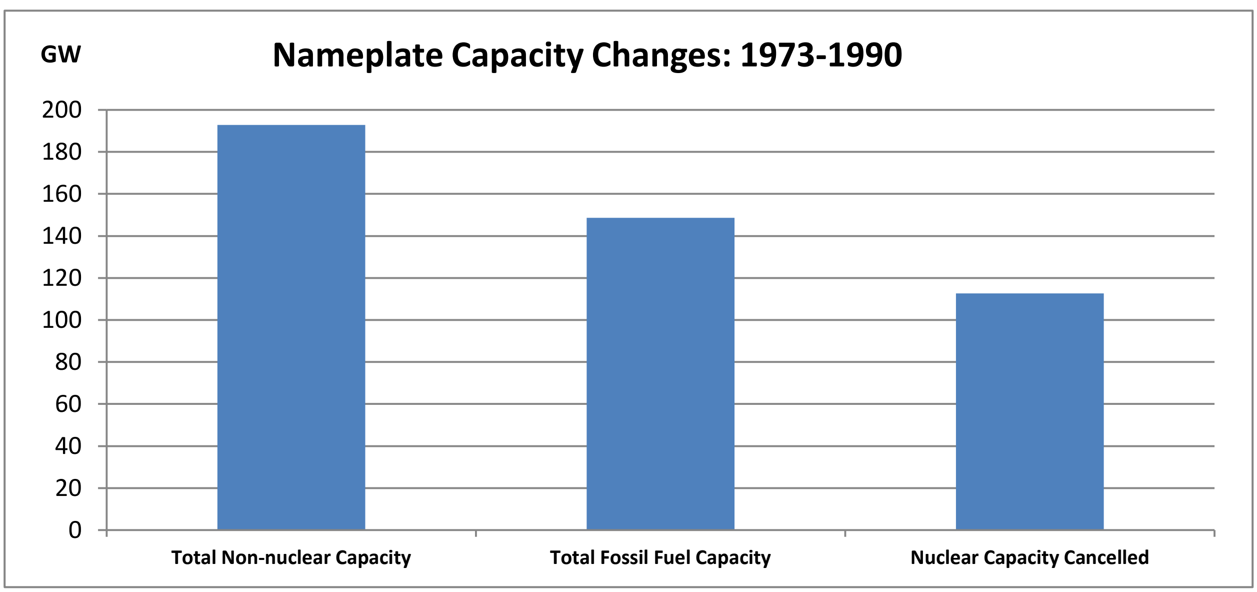
The independent effect of TMI is tested by including a dummy variable where all years after 1979 have a value of 1. TMI does not exhibit statistically significant relationships when entered into the models explaining the construction period or cost. Using TMI as a proxy for safety results in much lower explained variance. TMI had a substantial effect on the build/cancel decision, strongly negatively correlated with the build decision. It adds 25 percentage points to the amount of variance explained and reduces the significance of demand growth in the model for all reactors. The coefficients on the safety variables increase in the models with the TMI variable. Simple linear regressions yield identical results and shows that multi-colinearity is not a problem

Among the non-safety variables, interest rates play an important role in the cost model. Higher interest rates are associated with longer construction periods and higher costs. Consistent with long standing cost modeling, among the project characteristics, pressurized water reactors and second units are less costly, while longer construction periods are associated with higher costs.

One of the factors that is frequently cited as playing a key role in the demise of nuclear reactor construction that and turns up in the multivariate analysis of the build/cancel decision is the growth rate of demand. The impact of demand growth is tested in three ways – the growth rate at the build/cancel date, growth rate at the operating date, and the change in growth rate between those two dates. This finding should be placed in context as follows. The higher the growth rate at the point of decision, the less likely a reactor was to be cancelled.

While nuclear reactors were being cancelled at a very quick pace, coal (and a few gas) plants continued to be built. In other words, there was demand for generation but nuclear could not compete with coal. More fossil fuel capacity was being brought on line than nuclear capacity was cancelled. This perspective on demand growth is provided in Exhibit V-9. The role of growth of demand can be explained as follows: It is reasonable to argue that if demand had continued to grow at the extremely high rate of 8 percent per year as in the 1960s, it is likely that more reactors would have been built. The industry would have been pushed farther up the supply curve to meet demand. The important point, however, is that nuclear was not the economic choice. When demand growth slowed nuclear could not replace fossil fuel capacity at the margin.

EXHIBIT V-9: NAMEPLATE CAPACITY CHANGES: 1973-1990



Source: Energy Information Administration, Electricity Annual.

This issue reverberates today. As the decision about what to do with nuclear reactors (old and new) in the wake of Fukushima are made, a central concern is the availability and cost of alternatives. In the 1970s and 1980s, the choice was between coal and nuclear. The question was never whether or not to build nuclear reactors; it was always, which capacity should be built to meet the need for electricity. The options on the table are critically important. This is exactly the question that the nations that are most heavily dependent on nuclear power are grappling with after Fukushima, but today they have a much wider range of options to choose from including efficiency, renewables and natural gas.

THE REPAIR/RETIRE DECISION

Nuclear reactors do not age gracefully. Time not only causes wear and tear, it also exposes reactors to events that occur only rarely, and reveals design issues that were not recognized or never addressed when the reactor was constructed. Retrofitting old reactors is costly, so the trade-off between safety and economics is put under a microscope.

Exhibit V-10 identifies the US reactors of significant size that have been shuttered before their licenses expired, or kept off line for lengthy periods of time at sites with major safety events. Quantitative and qualitative analysis of the early retirements provide insight into the decision to retire reactors.

A quantitative analysis of the characteristics of early retired reactors reveals that they were older, smaller reactors built before the ramp up in safety and are not worth repairing or keeping on line with new safety requirements when they are imposed, or when the reactors are in need of significant repair. Rather than fix them, they are retired.

On average, compared to reactors that were not retired early, early retirements had the following characteristics:

- Less likely to be pressurized water reactors (53% v. 63%)
- Brought online earlier (on average 1972 v. 1979)
- Much more likely to have been brought online before TMI (82% v. 50%)
- Smaller (558 MW v. 964 MW)
- Less likely to have suffered safety related outage (12% v 33%)
- More likely to have suffered damage or component related outages (24% v. 11%)
- None of the early retirements suffered multiple long term outages (0% v. 9%).

Qualitatively, the decision to retire a reactor early takes place under the following conditions. Since shuttering a nuclear reactor that has not reached the end of its license is a major decision, we should not be surprised to find that there is generally a combination of factors that underlie it (such as major equipment failure, system deterioration, repeated accidents, and increased safety requirements). Economics is the most frequent proximate cause, and safety is the most frequent factor that triggers the economic reevaluation. Although popular opposition "caused" a couple of the retirements (a referendum in the case of Rancho Seco; state and local government in the case of Shoreham), this was far from the primary factor, and in some cases local opposition clearly failed (two referenda failed in the case of Trojan and Maine Yankee). External economic factors, such as declining demand or more-cost-competitive resources, can render existing reactors uneconomic on a "stand-alone" basis or (more often) in conjunction with one of the other factors.

EXHIBIT V-10: SIGNIFICANTLY EARLY RETIREMENTS AND REACTORS WITH OUTAGES EXCEEDING 5 YEARS

Reactor	Shutdown (outage)	Operate Years	Cause of Shutdown
Connecticut Yankee (a)	1996	29	[A]n economic study that that due to changing market conditions, electric customers would save money if the plant were closed… Other considerations included use of current plant employees… prevention of long-term maintenance costs, and the availability of low-level waste disposal.
Browns Ferry (c)	(21 yr outage)	18	Unit One was shut down for a year after a fire in 1975 damaged the unit. The unit
Browns Ferry 2	(6.7 yr. outage)	29	was subsequently repaired and operated from 1976 through 1985, when all three
Brown Ferry 3	(10.7 yr outage)	25	[U]nits shut down for operational and management issues… TVA undertook an effort to restore Unit One to operational status, spending $1.8 billion
Dresden I (b)	1978	18	[H]history of minor steam leaks and erosion in steam piping ... fuel failures… admiralty brass (Cu-Ni) heat exchange surfaces, including Main Condenser…. carbon steel in the Secondary Feedwater System may have also contributed to the elevated corrosion radionuclide levels…to backfit…. additional regulations were issued as a result of Three Mile Island. estimated cost to bring Dresden Unit 1 into compliance… more than $300 million.
Fermi I (b)	1972	2	In October 1966, a zirconium plate at the bottom of the reactor vessel became loose and blocked sodium coolant flow to some fuel subassemblies. Two subassemblies started to melt… Three years and nine months later, cleanup completed, fuel replaced, and Fermi 1 was restarted in 1972. In November 1972… the decision to decommission Fermi 1.
Fort St. Vrain (d)	1989	13	Control rod drive assemblies, steam generator ring headers, low plant availability, prohibitive fuel costs
Humboldt Bay (c)	1980	17	[M]ain cause of the temperature increase was a blockage in one of the spigots that caused an insufficient amount of coolant to enter; not noticed by the operators until the core temperature alarms sounded.
Indian Point I (c)	1974	12	The Unit 1 reactor was shut down on October 31, 1974 because the emergency core cooling system did not meet regulatory requirements
La Crosse (WI) (c)	1987	17	In April 1987, shut down because the small size of the plant made it no longer economically viable.
Maine Yankee (c)	1997	25	NRC staff identified so many problems that "it would be too costly to correct these deficiencies to the extent required… decided to shut the plant down."
Millstone I (c)	199	28	On February 20, 1996 a leaking valve forced the shutdown of this unit, and unit 2; multiple equipment failures were found.
Peach Bottom I (PA)	1974	7	Small, experimental Helium cooled graphite core
Rancho Seco (d)	1989	15	Concern about safety coupled with poor performance; referendum
San Onofre I (d)	1992	14	Economic analysis of costs and benefits, steam generator degradation, seismic retrofit
Shoreham (d)	1987	0	Evacuation plan, local opposition
Three Mile Island II (c)	1979	0.33	The incident was rated a five on the INES Scale: Accident With
Three Mile Island I	(6.6 yr. outage)	29	Wider Consequences total cleanup cost of about $1 billion. International Nuclear Event.
Trojan I (d)	1992	16	Steam generator replacement, tube leaks, regulatory uncertainty
Yankee Rowe (d)	1991	18	Reactor vessel embrittlement, Steam gen. tube damage
Zion I (c)	1997	22	[C]ontrol-room operator accidentally shut down Reactor 1 and then tried to restart without following procedures…. ComEd concluded that the plant could not produce competitively priced power because it would have cost $435 million to order steam generators which would not pay for themselves license expired in 2013.

Sources: (a) Company Web Site; (b) NRC Web Site; (c) Wikipedia; (d) Office of Technology Assessment, *Aging Nuclear Power Plants: Managing Plant Life and Decommissioning,* September 1993.

This issue resonates today as older reactors are re-examined in light of new safety concerns and consideration of alternatives. This is the central issue involved in the major national policy reviews being undertaken abroad and the individual reactor evaluations being made by utilities in the United States.

VI. THE POST-FUKUSHIMA CHALLENGES TO NUCLEAR POWER

Having demonstrated the link between safety and economic and the important role of accidents in redefining the never-ending debate over nuclear safety, we have laid the basis for considering how Fukushima will affect the future of nuclear reactor construction and operation in the United States and around the world. This section draws three sets of lessons from the study of the relationship between nuclear safety and nuclear economics. First, we examine how the scope of safety concern is likely to expand, placing more pressure on nuclear economics. Second, in the spirit of "lessons learned," which pervades the post-accident reviews, we offer observations on how policy maker reviews are likely to put more pressure on nuclear economics. Third, we consider how costs will be affected compared to alternatives.

THE SAFETY CHALLENGES

The safety challenges to nuclear power are likely to escalate after Fukushima, which will, once again, compound the economic challenge. Tomain (1987: ix) argued that "TMI made the United States aware of unforeseen costs, just as Chernobyl made the world aware of unforeseen risks." Fukushima has made the perception of those risks real and expanded their scope dramatically.

Emphasizing the enduring institutional challenges of nuclear safety, as was done in Part I, should not obscure the severe near-term specific challenges faced by nuclear reactors. Exhibit VI-1 summarizes the institutional issues discussed above and lists five broad categories of immediate operational challenges.

EXHIBIT VI-1: THE INADEQUATE INFRASTRUCTURE OF NUCLEAR SAFETY REGULATION

ORGANIZATIONAL FLAWS

Lack of a Comprehensive, Consistent, Safety Regulation Framework
Denial of the Reality of Risk
Complexity, Confusion, and Chaos in the Response to a Severe Accident
Failure of Voluntary, Self-Regulation
Perverse Incentives in Commercial Attitudes toward Safety:
Deficient management process including planning, standard setting, inspection, communications
Failure to Resolve Important Safety Issues:
Failure to Retrofit Safety on Existing Reactors
The Challenge of Continuous Change and the Future of Safety

THE IMMEDIATE OPERATIONAL CHALLENGES

Design (event tolerance, cooling, venting, backup system resilience and redundancy),
Siting (reactor crowding, seismic and flooding vulnerabilities)
Waste storage,
Evacuation plans and
Cost increases

Source: Nuclear Regulatory Commission, *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,* U.S. NRC, July 12, 2011; Yoshiro Nakagome, *JNES's Response to TEPCO Fukushima NPS Accident,* November 2011; Eurosafe Forum, Experience Feedback on the Fukushima Accident, November 8, 2011; D. Degueldre, T. Funshashi, O. Isnard, E. Scott de Martinville, M. Sognalia, "Harmonization in Emergency Preparedness and Response;" P. De Gelder, M. Vincke, M. Maque, E. Scott de Martinville, S. Rimkevicius, K. Yonebayashi, S. Sholmonitsky, *"The Evolution of the TSO Programme of Work after the Fukushima Daiichi NPS Acciden*t; Komanoff, C, 1981 *Power Plant Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics*, Van Nostrand, 1981. John G Kemeny *Report of The President's Commission on the Accident at Three Mile Island,* October 30, 1979; Nuclear Regulatory Commission, *TMI-2 Lessons Learned Task Force Final Report,* October 1979;Tatsujiro Suzuki, "Deconstructing the Zero-Risk Mindset: The Lessons and Future Responsibilities for a Post-Fukushima Nuclear Japan, " *Bulletin of the Atomic Scientists, September 20, 2011*

Scrutiny of nuclear reactor safety is heightened because some people look more carefully at the track record, but even more importantly, more people pay attention to the ongoing struggle with safety. Safety requirements have and will continue to become more stringent in over a dozen safety areas of concern that resonate in the US , including design issues like event tolerance,[37] cooling, (Morse, 2011; Watts and Goldenberg, 201; Tabuchi and Wald, 2011) venting, (Tabuchi, Bradsher and Wald, 2011; Harrell, 2011; Wald, 2011, Paine and Yamaguchi, 2011) backup system resilience and redundancy,[38] siting issues like reactor crowding, (Snow, 2011), waste storage, (Power, 2011; Wald, 2011b), evacuation plans (NBC, 2011; Felker, 2011), and management processes including planning, standard setting, inspection, communications (Landers, 2011, Hagens, 2011, Flatow, 201; Nuclear Intelligence Weekly, 2011]).

"Cost increases are inevitable"[39] and the cost problem is compounded by the fact that reviewing nuclear reactor safety *after* an accident reveals an endemic tendency to undervalue safety *before* an accident—namely, past violations of standards that did not result in enforcement actions (Onishi and Fackler, 2011) but instead in lowered standards to avoid increased expenses related to safety. (Sullivan, 2011; Kageyama and Pritchard, 2011b; AP Impact, 2011) When eyebrows are raised, costs go up as the demand to tackle old problems intensifies.

By the first anniversary of Fukushima, 96 percent of the reactors in Japan were offline (Fackler, 2012). Every reactor in France was undergoing mandatory upgrades for backup power and venting, at a cost of more than $1 billion per site.[40] Germany began closing aging reactors and has decided to abandon nuclear power all of which suggests that license extensions will be harder to come by, and additional plants will be retired (Lekander, et al., 2011).

In the United States the concerns expressed about safety affect a large part of the fleet. The Union of Concerned Scientists (2012) tracks ongoing safety issues at operating nuclear reactors in the United States and finds that leakage of radioactive materials is a pervasive problem at almost 90 percent of all reactors. Exhibit VI-2 shows three issues that have been highlighted by Fukushima: seismic risk, fire hazard, and elevated spent fuel storage. More than 80 percent of US reactors face one or more of these issues. All of the boiling water reactors (therefore all of the reactors that have the Fukushima design) have at least one of these issues. Three-quarters of the pressurized water reactors have an issue. Half of those that do not exhibit one of these issues had a "near miss" in 2011. Clearly, safety remains a challenge in the United States, one that has been magnified by Fukushima.

Whether this will lead to early retirements or decision not to seek or grant license extensions remains to be seen. It may change the ownership pattern of nuclear reactors in the United States, where half of the operators have only one project, which can make compliance with new regulations more costly (as there are fewer units over which to spread any fixed costs). Moreover, judging from the fact that the Nuclear Regulatory Commission is on the defensive to prove it is doing its job of ensuring safety (NRC, 2011) and that there is international pressure on nations to cooperate and ensure safety (IAEA, 2011; Behr, 2011), the effort to further streamline

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[37] Murawski, 2011, "The extent of the fixes required in this country won't be clear until the Nuclear Regulatory Commission issues it first round of safety guidelines in July. But executives at the Shearon Harris plant, less than 25 miles from Raleigh, said they expect the NRC to review a nuclear plant's ability to withstand earthquakes, flooding and high winds. "Post-Fukushima, the NRC continued to pursue "questions regarding the AP 1000'shield building, as well as the peak accident pressures expected within containment" (NRC News, 2011).

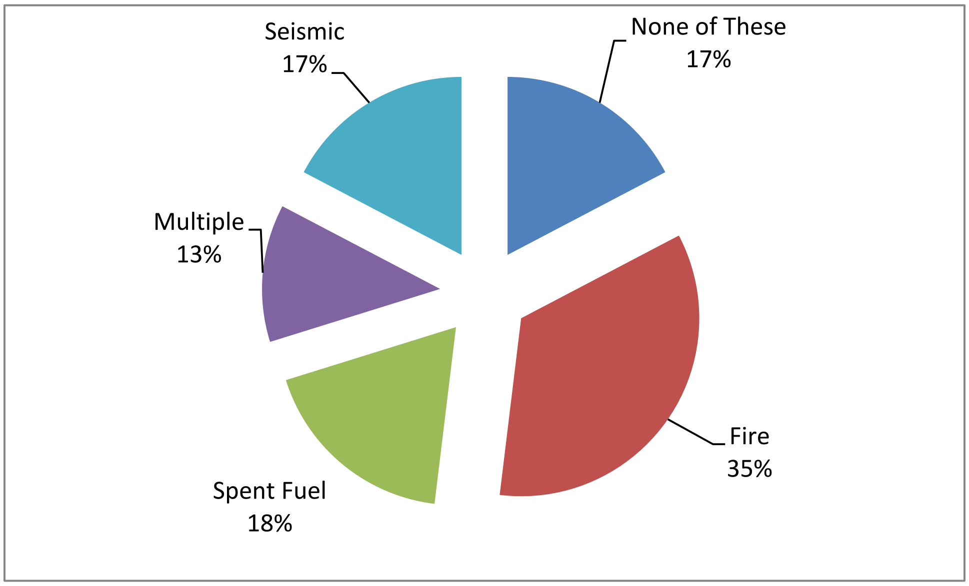
[38] International Atomic Energy Agency, 2011, (hereafter IAEA Preliminary)calls for "defence in depth, physical separation, diversity and redundance," Dow Jones, 2011; Goldring, 2011,

[39] This is a quote from John Rowe, Exelon CEO (Malik, 2009) Paulson, 2011, notes likely increase inland costs;

[40] World Nuclear News, 2012, reports that new safety related costs would more than double a 15 –year, $65 billion maintenance program at 58 operating reactors.

regulation in the United States—which nuclear advocates argue is necessary to make nuclear power more affordable—will likely encounter stiffer resistance after Fukushima.

EXHIBIT VI-2: SIGNIFICANT ONGOING SAFETY ISSUES



Source: Union of Concerned Scientists, *Nuclear Power Information Tracker,* March 2012
http://www.ucsusa.org/nuclear_power/reactor-map/embedded-flash-map.html

The combination of persistent institutional weaknesses and immediate technical challenges does not tell the whole story of the transformation of the safety issue. Traditionally, the focal point of analysis of the "harms" of nuclear power has been on the public health risks of exposure to radiation that may be released from a reactor. Death from radiation induced cancers certainly deserves a great deal of attention, but Fukushima makes it clear that the social and economic impacts of a severe accident close to population centers are very serious and also deserve a great deal of attention.

We are now having a debate about nuclear evacuation zones of 50 miles. Back in 1977 before TMI, when the Nuclear Regulatory Commission was first becoming extremely concerned about safety, they counted the population within only two miles. The disruption of daily life in a large area around a nuclear accident has become a focal point of concern. Large numbers of people may be temporarily or permanently uprooted. The fact that the Japanese government was considering evacuating Tokyo, 150 miles away (Fackler, 2012) and reports of large dead zones a year later underscore this concern. (Harlan, 2011; Aulakh, 2012; Fujita, 2012))

Fukushima is a real economic disaster. The costs are estimated as high as a quarter of a trillion dollars. The Japanese grid is under severe stress. The economy has been damaged. Safety regulators have known about these potential impacts, but they were hypothetical. Fukushima makes them real.

The post-accident reviews of the "safety regulatory infrastructure" underscore the severe problem that nuclear power suffers when it comes to low probability, very-high impact events. They are highly uncertain and not well understood. The severe impacts can be imposed on large areas and populations that are not prepared. These problems affect nuclear power at all times, as described by an analysis of aging reactors prepared in 1993 by the U. S. Office of Technology Assessment.

> As is true for many modern enterprises, the risks and benefits of nuclear power plant operation are imperfectly understood by the public and, to a lesser degree, by the scientific community. 'Public preferences and perspectives for different dimensions of risk appear related to several factors include whether the risk is voluntary or imposed, involves low probability, catastrophic accidents, or frequent accidents of limited extent; is well understood scientifically **and by the public; is natural (e.g. radiation exposure from radon or sunlight) or technological** (radiation from nuclear power plant accidents); accompanies highly beneficial activities (e.g. are the alternatives to nuclear power preferable?) or is familiar or unfamiliar. From the perspective of public perception and acceptance, nuclear power has scored poorly on these counts. (OTA, 1993: 5)

A similar, but broader, framework for assessing the perception of risk of technologies can be found in the literature of technology risk, as summarized in Exhibit VI-3. Nuclear reactor accidents magnify the underlying factors that increase the perception of risk of nuclear power. The failures of the "safety regulatory infrastructure" and the magnitude of the impact justify the heightened sense of oncern that is attached to nuclear power. The psychological distress suffered by the public is grounded in the nature of the risk of the technology, which is made quite evident by severe addicts. There is a good reason to believe that "nothing will be the same after Fukushima."

EXHIBIT VI-3: EVALUATION OF TECHNOLOGY IMPACTS: ROUTINE IMPLEMENTATION OR RARE EVENTS

Occurrence	Nature	Distribution	Response
Office of Technology Assessment			
Probability	Rare catastrophic v. frequent limited impact Natural v. technological	Voluntary v. Imposed High benefits v alternatives available	Familiar v. unfamiliar
European Science and Technology Observatory			
Probability Certainty of assessment	Severity, magnitude Immediacy Gravity Persistence	Benefits and Costs Spatial distribution Intergroup Intergenerational Vulnerable groups Fairness Human v. nonhuman Voluntary Immediacy	Controllability Reversibility Trust in institutions Familiarity Mobilization potential

Sources: Office of Technology Assessment, Aging Nuclear Power Plants: Managing Plant Life and Decommissioning, September 1993, p. 5. Andrew Sterling, 1999, *On Science and Precaution in the Management of Technological Risk,* European Science and Technology Observatory, pp. 11, 13.

RE-EXAMINATION OF NUCLEAR POWER BY TRADITIONAL DECISION MAKING INSTITUTIONS

With a technology as complex and dangerous as nuclear reactors, safety concerns continuously evolve and the technology never stabilizes. Operating experience, aging reactors and beyond design events continually challenge the safety regime in place. New information and events push policymakers to continuously adjust their perception of the cost and benefits of all options and the value of buying time to gather more information before major decisions must be made. Financial analysts must adjust their perception of the risks that nuclear power faces across a number of areas – policy, regulatory, execution, marketplace, and financial, which are described in Exhibit VI-4.

The Safety Regulator: The Nuclear Regulatory Commission has been an inconsistent (to say the least) regulator of safety, so much so that its own task forces investigating the operation of reactors and the implications of accidents have repeatedly called for major reform and strengthening of safety regulation. Regulators must re-consider whether safety regulation is adequate which may increase marketplace, execution and financial risk as they

- require more resources to be expended on safety,
- lengthen the construction period, and
- demand retrofits of existing plants, which could spur early retirement or decisions not to extend licenses.

Policy makers: In the wake of a major accident, there is a natural inclination to re-examine all aspects of all options to meet the need for electricity, which makes good sense, especially where a policy decision (limited liability) has created the industry and regulation must replace market forces to ensure safety. Policy makers raise regulatory policy and financial risk as they

- re-assess standards of care and safety,
- re-examine regulatory processes that sets safety standards,
- re-valuate of the weighting of societal costs and benefits of all available options, and
- consideration of the value of gathering more information before committing substantial resources that are locked in.

The Public: Several aspects of the long standing public input into the decision making process are energized by a severe accident which results in a diminished level of support because to the

- magnitude of the impact,
- inability to explain ongoing events and long-term consequences,
- poor communications, and
- post-accident reviews that show genuine lack of planning and preparedness.

Financial analysts: Financial analysts evaluate the impact of these changes on the economic viability of nuclear power. For financial analysts and those studying the economics of the nuclear industry, this issue was top of mind. Barely three weeks after Fukushima, UBS offered the opinion that costs would rise. The cost nuclear reactors will be increase because they are

- more difficult to complete (execution risk),
- less attractive compared to alternative options (marketplace risk),
- less popular with policymakers (policy risk) and
- impose more financial risk on utilities (financial risk).

EXHIBIT VI-4: The Types of Risks Affecting New Nuclear Reactor Projects

Category	Source	Specific Risks
Technology risk stems from the fact that the new generation of nuclear reactors is new and uncertain. Cost estimates have increased dramatically over the past five years, doubling or tripling. At the same time, costs of efficiency and renewable technologies declining and availability is rising.	New technology risk	First-of-a-kind costs Long lead-time
	Alternative technologies	Efficiency potential identified Renewable cost declines
Policy risk stems from the fact that federal policy is in flux. While nuclear advocates have looked to climate policy, which may put a price tag on carbon emissions, as a primary driver of the opportunity to expand the role of nuclear power, they have failed to take account of the equally strong possibility that climate policy will create a very substantial mandate for conservation and renewables, which will dramatically shrink the need for new, nonrenewable generating, large baseload capacity.	Shifting focus	Emphasis on efficiency reduces need Emphasis on renewables reduces need
	Flexible GHG reductions	Lowers carbon cost
Regulatory risk stems from the chance that regulators will move slowly in approving reactors or authorizing their cost recovery. The new designs have proven challenging, with the reference designs going through numerous revisions. Site-specific issues, which cannot be standardized, have proven contentious. While a few states have approved construction work in progress and other measures to ensure cost recovery, the vast majority has not.	NRC regulatory reviews	Lack of experience Change of requirements Design flaws and revisions Site-specific contentions
	Loan guarantee conditions	Taxpayer protections inhibit guarantees
	Rate review	Recovery of costs challenged
Execution risk stems from the fact that reactors have not been built in the U.S. in decades and the industry does not have a great deal of capacity. Of the 19 projects that have applied for licenses at the Nuclear Regulatory Commission, 17 have suffered from one or more of the following problems: delay, cancellation, cost escalation or financial downgrade.	Construction risk	Lack of experience Counterparty risk
	Engineering, procurement and construction contract uncertainties	Cost escalation and volatility Cost overruns
	Size, cost and complexity	Delays Rework costs
Marketplace risk on the demand-side flows from the current recession, the worst since the Great Depression, which has not only resulted in the largest drop in electricity demand since the 1970s, but also appears to have caused a fundamental shift in consumption patterns that will dramatically lower the long-term growth rate of electricity demand. On the supply-side of the market, there are a host of alternatives that have lower cost to meet the need for electricity in a carbon-constrained environment and there is growing confidence in the cost and availability of these alternatives.	Uncertain demand growth	Slowing due to recession Shifting due to debt and loss of wealth
	Uncertain fuel costs	Natural gas price decline
	Reactor costs	Long lead time Cost overruns Rate shock reduces demand
Financial risk stems from all of the above risks and are magnified by tight conditions in money markets and the fact that utility balance sheets are weak and too small to support the large size of nuclear reactor projects. The nature of the projects imposes additional financial risks, so much so that, for most utilities, the projects are so large that Moody's has called them "bet the farm" decisions.	General conditions	Tight money New liquidity requirements High-risk premiums
	Utility finance	Increased nuclear operating exposure Existing debt and need to refinance Financial ratio deterioration Rising cost of debt Limited & declining cash & equivalents Weak balance sheets Underfunded pension plans
	Project finance	High hurdle rate for risky projects Impact of large project Debt load and service burden impact Capital structure distortion

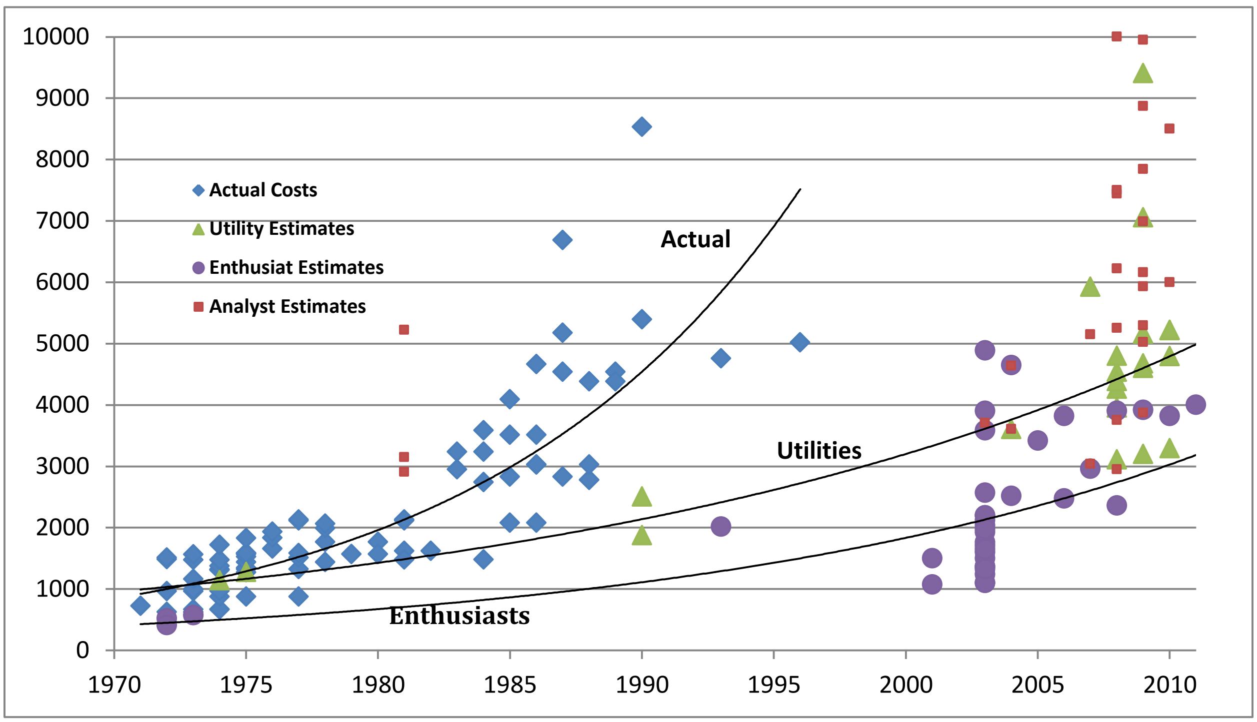
Sources: Mark Cooper, *All Risk, No Reward, for Taxpayers and Ratepayers, t*he Economics of Subsidizing the 'Nuclear Renaissance' with Loan Guarantees and Construction Work in Progress, Institute for Energy and the Environment, Vermont Law School, November 2009

THE FUTURE OF NUCLEAR REACTOR ECONOMICS IN THE U.S.

The economics of nuclear reactor construction had faltered long before Fukushima, just as it faltered before TMI, stumbling over the very same problems that have afflicted it throughout its history. The industry simply cannot estimate the cost of construction and is totally dependent on subsidies in a a space where there are numerous less costly alternatives available.

Exhibit VI-5 shows the rising cost of reactors completed during the "Great Bandwagon Market" along with the cost projections made since the declaration of a "nuclear renaissance." The hyping of a renaissance was launched by nuclear enthusiasts in powerful places with cost estimates that were ridiculously low. The cost estimates now used by utilities are three times as high as the initial renaissance estimates. Independent analysts on Wall Street, put the cost estimates at five times the original estimates.

EXHIBIT VI-5: OVERNIGHT COSTS (2009$/KW) OF REACTOR CONSTRUCTION



Source: Mark Cooper, 2009, *The Economics of Nuclear Reactors: Renaissance or Relapse* (Institute for Energy and the Environment, Vermont Law School, June, updated; Actual Costs from Jonathan Koomey, and Nathan E. Hultman, 2007, "A Reactor Level Analysis of Busbar Costs for US Nuclear Plants, 1970-2005," *Energy Journal,* 2007; Projections updated from Mark Cooper, 2009, *The Economics of Nuclear Reactors: Renaissance or Relapse* (Institute for Energy and the Environment, Vermont Law School, June 2009).

This escalation of cost projections has occurred before construction has begun and the construction phase has historically seen significant cost escalation. The French experience in Flamanville and Olkiluoto supports the suspicion that costs will escalate once construction begins (Schneider, Froggatt and Thomas, 2012). The one project that is approaching construction in the United States is shrouded by claims of confidentiality, but there appears to be some delay and cost escalation. (Pavey, 2012; Atlanta Business Journal, 2011; Shain, 2010; Downey, 2012) The subsidy problem in nuclear reactor construction has actually become much more severe (Cooper, 2009c, 2011a,e). The liability limitation is still in place and, given the magnitude of the impact of the

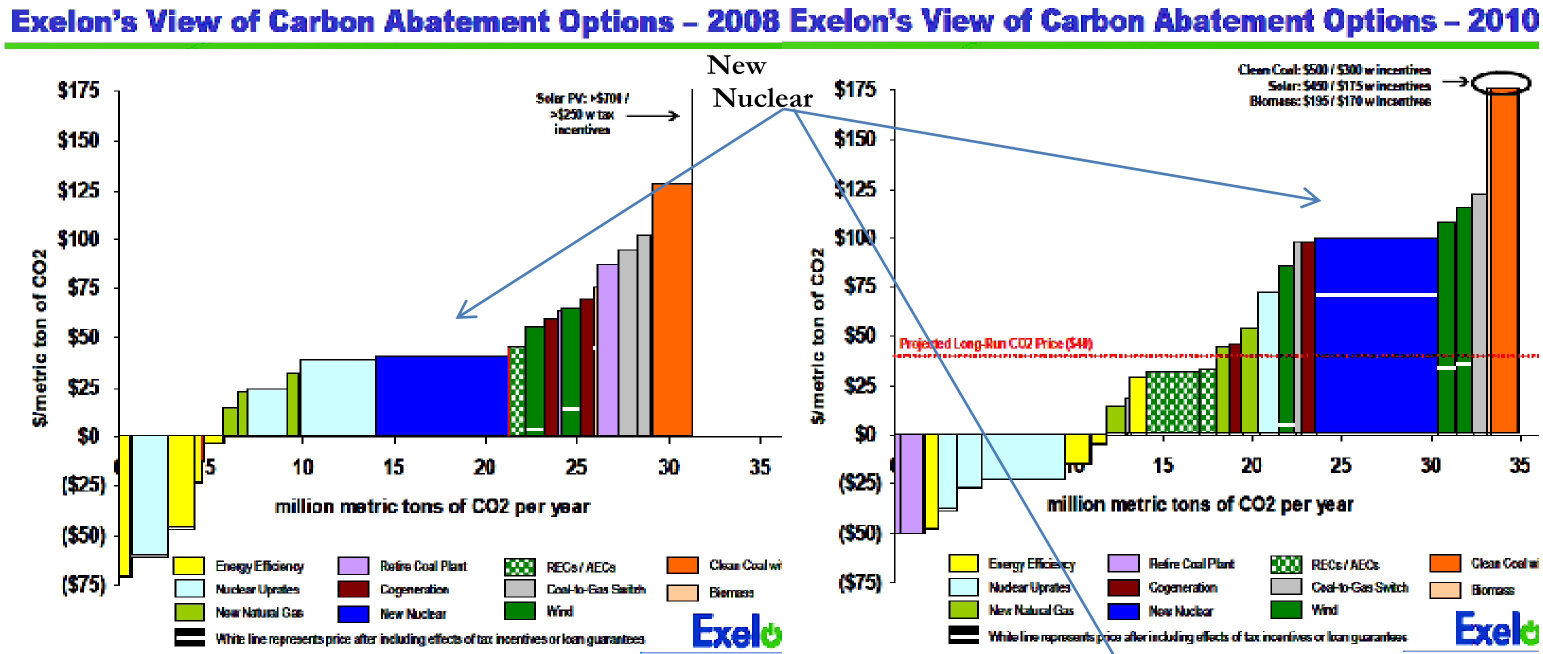
Fukushima accident the gap between private liability and public liability is likely to be much larger. In addition, the utilities proposing to construct new nuclear reactors have demanded many more and larger direct subsidies. They have asked for and been granted much more direct ratepayer support. Early recovery for costs that are virtually guaranteed has been the price of nuclear construction in the South Eastern United States (North Carolina, South Carolina, Georgia and Florida). Since construction of nuclear reactors cannot be financed in normal capital markets, federal loan guarantees and partnership with public power that has independent bonding authority appear to be necessary ingredients to move projects forward. The EPC contracts that have been signed have not been subject to public scrutiny, but they may well contain provisions that make them more like the turnkey contracts signed at the start of the "Great Bandwagon Market" than the commercial contracts under which over 90 percent of reactors were built in the Unites States.

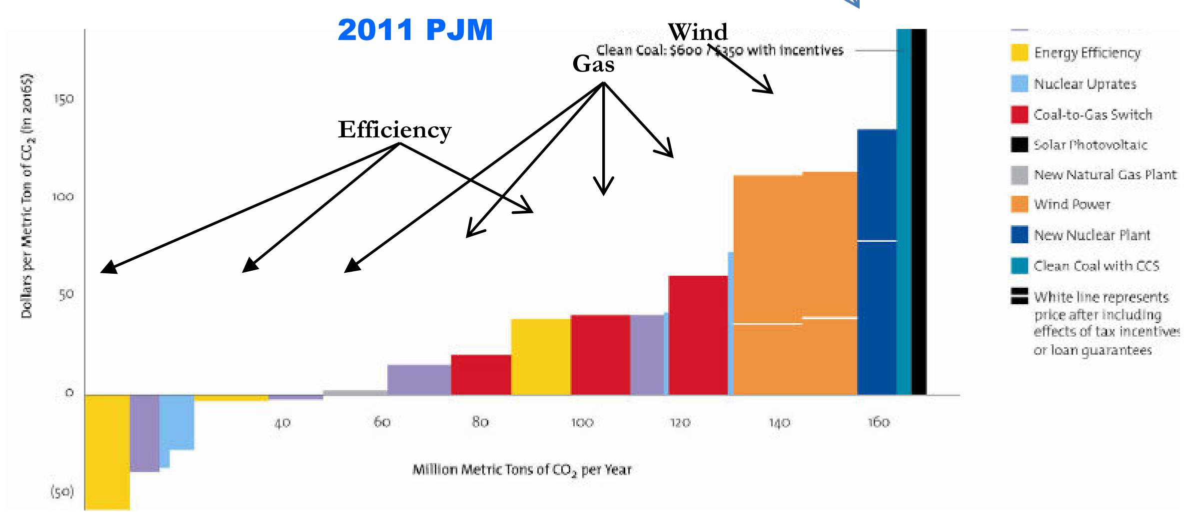
We have argued that if nuclear power had been economically preferable in the 1970 and 1980s, far fewer reactors would have been cancelled. Nuclear power could not compete against coal and a little natural gas. It has the same problem today. Exhibits VI-6 and VI-7 show three sets of estimates on the economics of various alternatives at present and in the near future from the CEO of the largest nuclear utility in the United States, the PJM power pool and the California Energy Commission. It is clear that today construction of new nuclear reactors cannot compete against a large number of alternatives – including efficiency, renewables, non-depleting resources. It is vastly more costly than coal and natural gas, unless one assumes aggressive climate change policy, in which case it becomes somewhat more competitive. Moreover, even before Fukushima, the cost trends were moving strongly in favor of the alternatives that are most abundant in the United States. Construction of new nuclear reactors is likely to become even less attractive than it is today.[41]

By bringing intense scrutiny to aging reactors, Fukushima prompts policy makers and the public to turn the tough questions that have been posed to proposals to build new reactors to the proposition that aging reactors should be retired, or not have their licenses extended. The increase in safety requirements may call license extensions and uprating of existing reactors into question.

[41] Lekander et al.,(2011: 1) Review of existing nuclear; higher cost for new nuclear: Most countries have announced in-depth nuclear reactor safety reviews and near-term moratoriums on new plants. We expect safety standards to be tightened, life extensions to be limited, and some plants to be 'sacrificed' to restore public confidence. Near-term policies are likely to favour gas and energy efficiency, and, to a lesser extent coal.

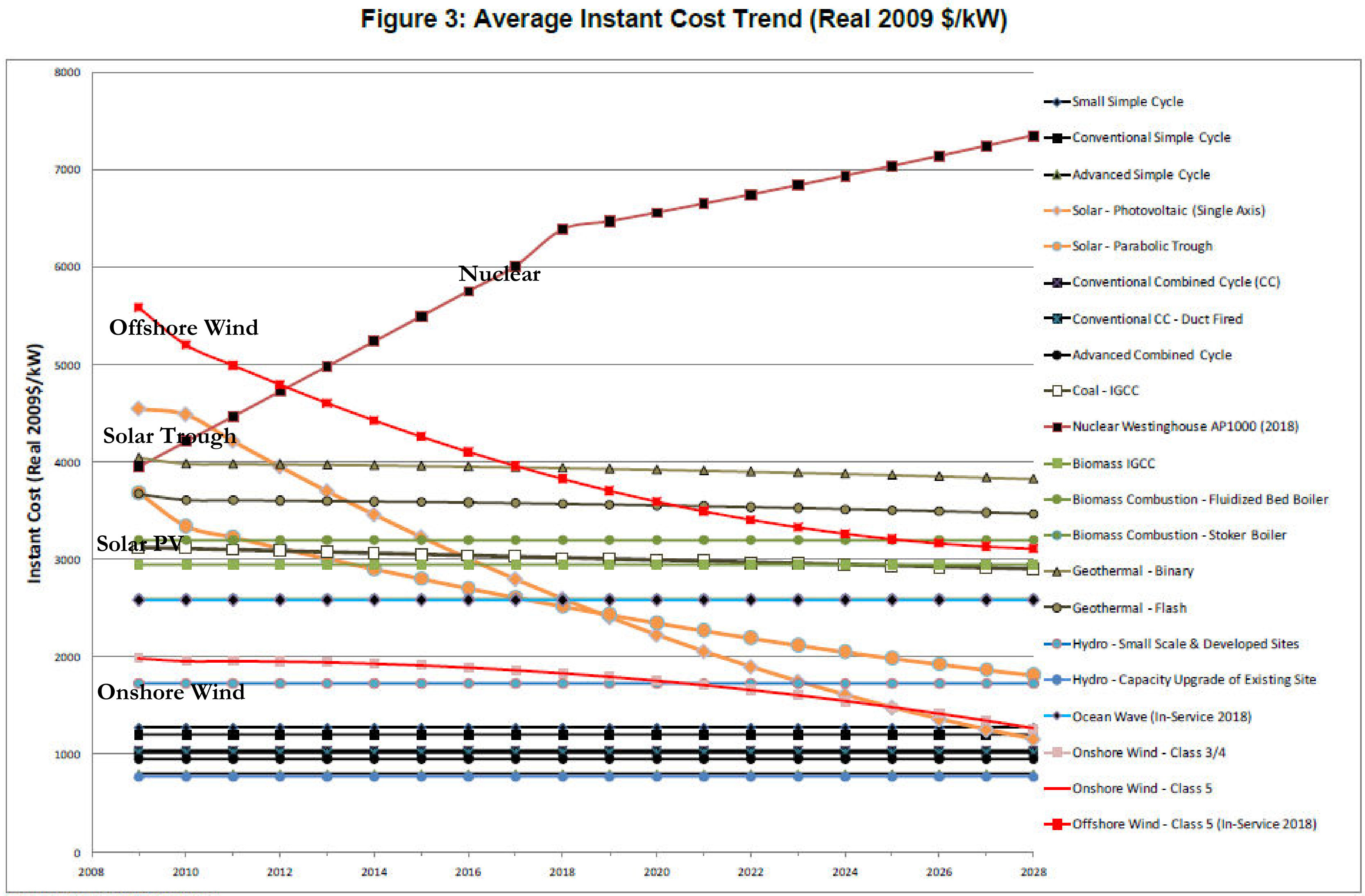
Exhibit VI-6: The Increasingly Dim View of Nuclear Economics and Improving View of Alternatives





Rowe, John, *Fixing the Carbon Problem without Breaking the Economy*, Resources for the Future Policy Leadership Forum Lunch, May 12, 2010; *Energy Policy: Above All, Do No Harm*, American Enterprise Institute, March 8, 2011

EXHIBIT VI-7: CALIFORNIA ENERGY COMMISSION OVERNIGHT COST TRENDS (JANUARY 2010)



Source: Energy Commission

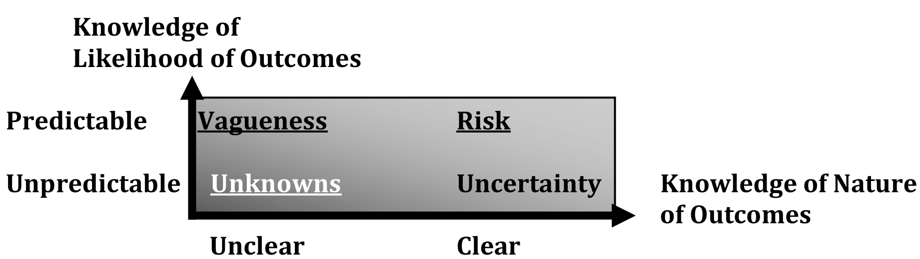
VII. BUILDING A NEW INFRASTRUCTURE OF DECISION MAKING

THE INCREASINGLY COMPLEX TERRAIN OF ELECTRICITY RESOURCE ACQUISITION

As we have seen, the post-accident reviews dig deeply into the technology of safety. However, the primary lessons learned have not been about individual technologies or specific threats; they have been about changes in what the Vice Chairman of the Japanese Atomic Energy Commission calls the "safety regulation infrastructure." When it comes to nuclear power, what we also need is a dramatic change in the "infrastructure of decision making."

The NRC identifies the challenge of dealing with "low likelihood, high consequence events," while the Office of Technology Assessment referred to "low probability, catastrophic accidents." Fukushima reminds us that nuclear accidents fall into a realm of knowledge that involves unknown unknowns (see Exhibit VII-1). Major accidents happen, as three cases in less than a quarter of a century attest, but they are impossible to predict because of the complex and dynamic interplay of technological, human and natural factors. The magnitude of the impact is hard to estimate or grasp. The understanding of the sequence of events in accidents is highly imperfect, which means that the immediate reaction called for is very uncertain. The uncertainty and involuntary nature of the harm and the inability of responsible authorities to deal with it create an augmented sense of risk that is very real to the public.

EXHIBIT VII-1: THE REGIONS OF KNOWLEDGE



To make matters worse, some of the alternatives to nuclear power have become more challenging. In in the past quarter of a century a fierce debate about the existence and response to climate change, a roller coaster ride in fossil fuel prices and a growing controversy over the environmental impact of expanding the supply of the fuel of choice (natural gas), have cast doubt on the three primary fuels on which the U.S. relies for almost 90 percent of its electricity. In spite of this uncertainty, electricity remains an essential building block of modern life, which means that decision makers are under constant real-time pressures to ensure electricity supply at affordable prices (Cooper 2011c,ef).

How does one make effective decisions in a space where the impacts of significant events or use of important resources are unclear(outcomes unknown) and the occurrence of those events or the availability and price of those resources are unpredictable (the probabilities are unknown)? Analysts across a number of disciplines including military strategy, space exploration, technology assessment, engineering science and financial analysis, have all developed frameworks for facilitating decision making under conditions of severe ambiguity, frameworks that share key characteristics. The issue has been popularized in the U.S. under the term "Black Swan Theory (Taleb, 2009) and the term applied to Fukushima (Hagens, 2011). However, as shown in Exhibit VII-2, there are many earlier efforts that address the same issue, and the broader concepts of failure to be prepared to deal with the unknown has also been applied to Fukushima. (Hixson, 2012)

EXHIBIT VII-2: CONFRONTING AMBIGUITY IN THE INCREASINGLY COMPLEX TERRAIN OF KNOWLEDGE: TOPOGRAPHIC MAPS AND NAVIGATION TOOLS FOR THE REGIONS OF KNOWLEDGE

	REGIONS			
TOOLS	**UNKNOWNS**	**VAGUENESS**	**UNCERTAINTY**	**RISK**
<u>Topographic Maps</u>				
<u>Technology Risk Assessment</u>				
Challenges	Unanticipated effects	Contested framing	Nonlinear systems	Familiar systems
Outcomes	Unclear	Unclear	Clear	Clear
Probabilities	Unpredictable	Predictable	Unpredictable	Predictable
<u>Black Swan Theory</u>				
Challenges	Black Swans Wild randomness	Sort of Safe	Safe	Extremely safe Mild randomness
Conditions	Extremely fragile	Quite robust	Quite robust	Extremely robust
Distributions	Fat tailed	Thin tailed	Fat tailed	Thin tailed
Payoffs	Complex	Complex	Simple	Simple
<u>Reliability & Risk Mitigation Management</u>				
Challenges	Chaos	Unforeseen uncertainty	Foreseen uncertainty	Variation
Conditions	Unknown/ unknowns	Unknown/ knowns	Known/ unknowns	Known/knowns
<u>NAVIGATION TOOLS</u>				
<u>Analytic frameworks</u>				
Approach	Multi-criteria analysis	Fuzzy logic	Decision heuristics	Statistics
Tools	Diversity assessment	Sensitivity analysis	Scenario analysis	Portfolio evaluation
Focus	Internal resources & structure	Internal resources & structure	External challenges	External challenges
Data	<u>Swan Search</u> Consistency Unintended consequences Externalities <u>Diversity</u> Structural Alternative Instrument Sufficiency	<u>Vagueness</u> Supply security Resource base Market scope Environmental impact Pollutants (air. Land water, waste) Greenhouse gasses	<u>Uncertainty</u> Capacity Construction period Sunk cost (Total capital = MW * $/MW)	<u>Cost -Risk</u> Levelized cost of energy Cost variability Fuel O&M Carbon ½ nuclear capital
<u>Policy Tools</u>				
Processes	Learning	Learning	Planning	Planning
Instruments	Insurance/diversity	Monitor & Adjust	Optionality	Hedging
Rules	<u>TECHNOLOGY RISK ASSESSMENT</u> Precaution Buy insurance for system survival Accept non-optimization Diversity Variety Balance Disparity <u>BLACK SWAN THEORY</u> Truncate Exposure Buy insurance for system survival Accept non-optimization Redundancy Numerical Functional Adaptive	<u>TECHNOLOGY RISK ASSESSMENT</u> Resilience Adaptability <u>BLACK SWAN THEORY</u> Multi- functionality What Works	<u>TECHNOLOGY RISK ASSESSMENT</u> Flexibility Across Time Across Space <u>BLACK SWAN THEORY</u> Optionality	<u>TECHNOLOGY RISK ASSESSMENT</u> Resilience Robustness Hedge <u>BLACK SWAN THEORY</u> Robust to Error Small, Confined, Early Mistakes Incentive & disincentives Avoid Moral Hazard Hedge
<u>Characterizations</u>				
Religious	Hell	Limbo	Purgatory	Land of the living
Greek Mythology	Pandora, Pythia	Damocles, Cassandra	Cyclops	Medusa

Sources: Nassim Nicholas Taleb, *The Black Swan* (New York: Random House, 2010), Postscript; Andrew Stirling, *On Science and Precaution in the Management of Technological Risk* (European Science and Technology Observatory, May 1999), p. 17, *On the Economics and Analysis of Diversity* (Science Policy Research Unit, University of Sussex, 2000), Chapter 2; "Risk, Precaution and Science; Toward a More Constructive Policy Debate," *EMBO Reports,* 8:4, 2007; David A. Maluf, Yuri O. Gawdisk and David G. Bell, *On Space Exploration and Human Error: A Paper on Reliability and Safety,* N.D.; Gele B. Alleman, *Five Easy Pieces of Risk Management,* May 8, 2008; see also, Arnoud De Meyer, Christopher H. Lock and Michel t Pich, "Managing Project Uncertainty: From Variation to Chaos," *MIT Sloan Management Review,* Winter 2002.

The efforts to map the terrain of knowledge start from the premise that there are two primary sources of ambiguity. Decision makers may lack knowledge about the nature of outcomes and/or they may lack knowledge about the probabilities of those outcomes. Four regions of knowledge result from this basic analytic scheme, risk, uncertainty, vagueness and the unknown. The decision making space is darkest where knowledge is lacking, but each region of knowledge presents a distinct challenge to the decision maker.

The crucial starting point for all these frameworks is to admit that you don't know what you don't know and then develop tools for navigating with imperfect knowledge. Unfortunately, admitting what you do not know is not something that builders and operators of nuclear reactors are inclined to do. Their reaction is to insist their reactors are safe enough and commit to making them safer, but then complain bitterly about and resist additional safety measures that increase their costs. This is the central contradiction of the political economy of nuclear safety and nuclear economics introduced in the introduction.

These two dimensions of knowledge have long been recognized in analytic models of decision making under uncertainty. They have been given different names, but the underlying concepts are the same. As shown in Exhibit VII-2, there are similar structures and recommendations in the literatures on the analysis of decision making. The topographic features of the terrain of knowledge show the primary challenge created by the conditions in the region. The bottom of the table gives two different ways of characterizing the regions that are deeply embedded in western culture, which suggest that the problem of drawing a knowledge map has a long history.

Under the navigational tools we include the analytic approaches and tools, as well as the data that are used in the analysis. The policy tools and rules are grouped according to the regions for which they are best suited, but they should be viewed as a mutually reinforcing global set of principles. The integrated approach allows the decision maker to array the options under consideration in a multi-attribute space.

Risk: In some circumstances the decision maker can clearly describe the outcomes and attach probabilities to them. Risk analysis allows the decision maker to hedge by creating a portfolio that balances more and less risky assets. This risk analysis has it origin in the financial sector and was first articulated over half a century ago.

Uncertainty: In some circumstances the decision maker can clearly describe the outcomes but cannot attach probabilities to them. Here the decision maker would like to keep options open – to delay decisions if possible – until more information reduces the uncertainty. If the decision maker cannot wait, then the path chosen should be flexible, so that it affords the opportunity to deal with whatever outcomes occur. Real option analysis also emerged from the financial sector – a little over a quarter of a century ago.

Vagueness: In yet another circumstance, decision makers may not be able to clearly identify the outcomes, but they know that the system will fluctuate. Here the decision maker wants to take an approach that can monitor the condition of the system and adapt as it changes. An approach to this situation of vagueness called "fuzzy logic" emerged from the computer science and engineering fields at about the same time as real option analysis.

Unknowns: In the most challenging situation, knowledge of the nature of the outcomes and probabilities is limited. Even in this state of ignorance, decision makers have strategies to cope and policies that can insulate the system. Here the analyst looks more inward, to the characteristics of the system, seeking to build systems that ensure the critical functions are performed adequately to maintain system viability under the most trying of circumstances. Multi-criteria evaluations of outcomes point to strategies that buy insurance and diversify assets, summarized in the expression, "put lots of eggs in lots of baskets." This framework has been developing for about two decades in technology risk assessment and the energy sector.

Thus, in the current environment resource acquisition must

- be hedged against risk
  - Identify the trade-offs between cost and risk and lower risk through hedging.
- maximize options to reduce uncertainty,
  - Reduce exposure to uncertainty by buying time.
  - Keep options open by acquiring small assets that can be added quickly.
- be flexible with respect to outcomes that are, at best, vague
  - Minimize surprises by avoiding assets that have unknown or uncontrollable effects.
  - Create systems that monitor conditions and can adapt to change in order to maintain system performance.
- be insulated against the unknown,
  - Buy insurance where possible.
  - Build resilience with diversified assets by increasing the variety, balance and disparity of the asset mix.

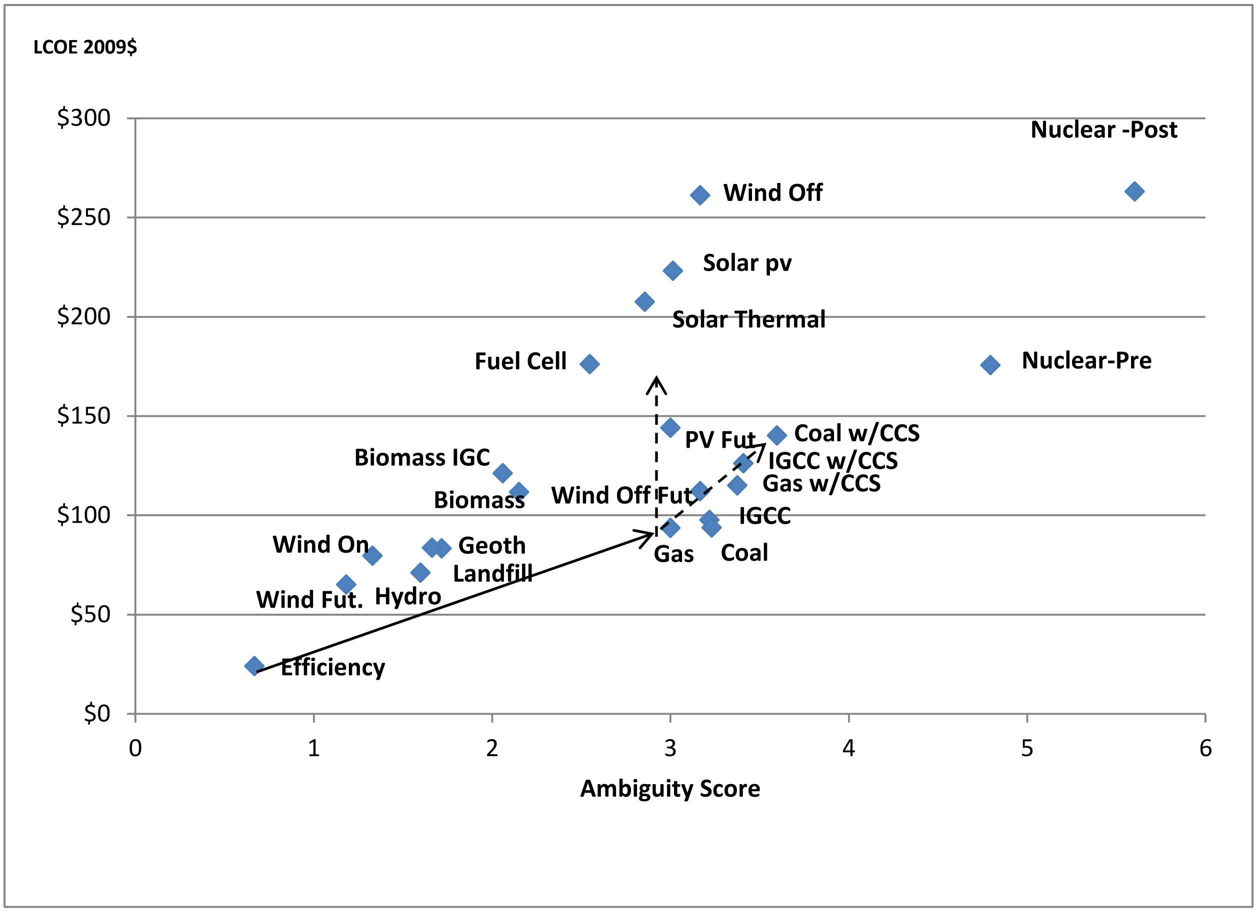
This analysis calls into question many of the long standing tendencies in utility resource acquisition and capital allocation. Acquisition of central station facilities, particularly nuclear, makes long-term commitments in exactly the wrong way for the current decision making environment. It commits to assets that have high risk (e.g. price volatility accident risk) or create large exposure to uncertainty (large size, long lead time, high capital costs, or long lives) with technologies that have vague long-term prospects (unstable resource availability and poorly understood environmental impacts).

Exhibit VII-3 presents the results of the application of this multi-criteria framework to U.S. resource acquisition (Cooper 2011c). The map of the terrain of resource acquisition in Exhibit VII-3 is consistent with the resource evaluations presented in Exhibit VI-5 and VI-6, above but sharpens the conclusion. Developing a multi-criteria framework that incorporates the risk, uncertainty and vagueness of the decision making environment provides a clearer picture of the best route forward.

The important take away is that the near term options that have attractive characteristic are abundant, even in a carbon constrained world. The resources with short lead times, lower cost and lower carbon can be implemented while the longer term alternatives are developed. It suggests that a diversified portfolio that relies in the near term on the alternatives to central station facilities and fossil fuels is achievable and preferable. The clearest finding is that nuclear does not belong on the near-term supply-curve and it does not appear to be an attractive resource for the long-term, in light of the potential availability of future renewables and carbon capture technologies.

Exhibit VII-3 answers the question, which resources should we acquire first? The next question is, will that sequence deliver sufficient resources to meet the need for electricity? In

EXHIBIT VII-3: RESOURCE ACQUISITION PATHS BASED ON MULTI-CRITERIA EVALUATION



Sources: Mark Cooper, "Prudent Resource Acquisition in a Complex Decision Making Environment: Multidimensional Analysis Highlights the Superiority of Efficiency," ***Current Approaches to Integrated Resource Planning, 2011 ACEEE National Conference on Energy Efficiency as a Resource*****, Denver, September 26, 2011**

earlier analysis we provided an affirmative answer to that question, as shown in Exhibit VII-4. To be sure, the burning question is whether the nations that have relied on nuclear power to a significant extent will be able to shift the resources base. There is no doubt that this is a significant technological and economic challenge that will not be easy (Fulton, et al., 2011; Torello, 2012). It is important to keep in mind that the outcome of the analysis can certainly vary from nation to nation because the natural resource endowments of nations vary (Cooper 2010a). However, Fukushima reminds us that nuclear power is not easy either and embodies significant challenges that have been repeatedly underestimated or ignored.

CONCLUSION, IF SIMPLE ANSWERS TO COMPLEX QUESTIONS ARE NECESSARY

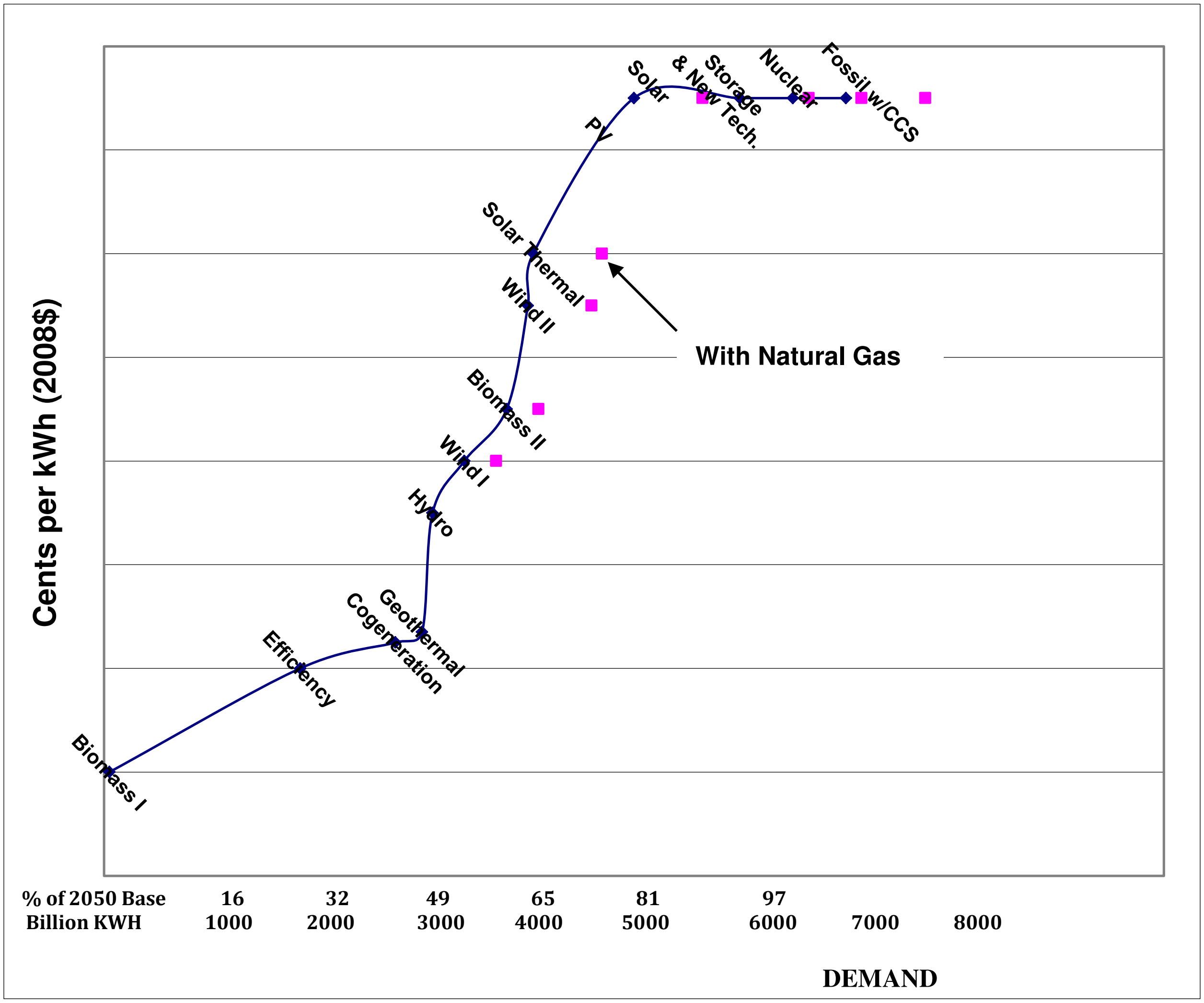
Journalists and policy makers insist on simple answers to a complex question:

- Nuclear safety and affordable reactors: can we have both?

Writing just after Chernobyl a quarter of a century ago, Tomain posed the question somewhat differently:

- Is Nuclear Power not worth the risk at any price?

EXHIBIT VII-4: MEETING ELECTRICITY NEEDS IN A CARBON CONSTRAINED ENVIRONMENT (COST OF ALTERNATIVES SUBSTITUTION CURVE)



Source: Mark Cooper, 2009, *The Economics of Nuclear Reactors: Renaissance or Relapse* (Institute for Energy and the Environment, Vermont Law School, June,

- These are extremely complex questions, but if a simple answer must be provided, there is one. If we use a market standard, the answer to both questions is an emphatic NO!
- If the owners and operators of nuclear reactors had to face the full liability of a nuclear accident and meet the alternatives in competition that is unfettered by subsidies, no one would have built a nuclear reactor in the past, no one would build a reactor today, and anyone who owned one would exit the nuclear business as quickly as they could.
- The combination of a catastrophically dangerous resource, a complex technology, human frailties, and the uncertainties of natural events make it extremely difficult and unlikely that the negative answer can be changed to a positive any time soon.

The post-accident safety reviews have revealed that a "public myth of absolute safety" lulled the industry into a false sense of security and a "lack of preparedness" (Funabishi and Kitazawa, 2012). The post-Fukushima economic review must expose the myth of economic viability that has been created by half a century of subsidies. Thus, in formulating the answer, the lessons of half a century of nuclear power should be kept in mind.

Nuclear power is a non-market phenomenon: It is certainly true that economics has decided, and will likely continue to decide, the fate of nuclear power, but the fiction that investors and markets can make decisions about nuclear power in a vacuum is dangerous. Given the massive economic externalities of nuclear power (not to mention the national security and environmental externalities), policy-makers decide the fate of nuclear power by determining the rate of profit through subsidies.

Match risks and rewards: If the goal is to have cost-efficient decisions, risks must be shifted onto those who earn rewards. By reducing the rate of profit that utilities earn from subsidized project, policy-makers can offset the bias that subsidies (such as loan guarantees and advanced cost recovery) introduce into utility decision-making.

Buy time: Given the severe problems that retrofitting poses and the current conditions of extreme uncertainty about changes in safety regulation, it is prudent to avoid large decisions that are difficult to reverse or modify. Flexibility is a valuable attribute of investments and mistakes should be kept small.

Learn from history: Sound economic analysis requires that sunk costs be ignored, but the mandate for forward-looking analysis does not mean that the analyst should ignore history. Utilities claim that the cost of completing a new reactor or repairing an old one is lower than the cost of pursuing an alternative from scratch. The problem is that utilities are just as likely to underestimate and be unable to deliver on the promised "to-go" costs as they have been to build nuclear reactors. Regulators must exercise independent judgment and take the risk of cost overruns

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