INL/CON-10-19031
PREPRINT

Managing the Nuclear Fuel Cycle, The Big Picture

INMM 2010

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July 2010

Managing the Nuclear Fuel Cycle, The Big Picture

America's Nuclear Industry — from 30,000 Feet

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Abstract:
The nuclear industry, at least in the United States, has failed to deliver on its promise of cheap, abundant energy. After pioneering the science and application and becoming a primary exporter of nuclear technologies, domestic use of nuclear power fell out-of-favor with the public and has been relatively stagnant for several decades. Recently, renewed interest has generated optimism and talk of a nuclear renaissance characterized by a new generation of safe, clean nuclear power plants in this country. But, as illustrated by recent policy shifts regarding closure of the fuel cycle and geologic disposal of high-level radioactive wastes, significant hurdles have yet to be overcome. Using the principles of system dynamics, this paper will take a holistic look at the nuclear industry and the interactions between the key players to explore both the intended and unintended consequences of efforts to address the issues that have impeded the growth of the industry and also to illustrate aspects which must be effectively addressed if the renaissance of our industry is to be achieved and sustained.

Introduction

After ushering in the nuclear age and developing the technologies for peaceful use of the atom, America has not constructed a new nuclear power facility for over 30 years. This stagnation of our domestic nuclear industry has been costly on several fronts,

> … there was a time when our country was the unquestioned leader but most of the world's new reactors are built overseas, by non-U.S. companies. Today it's possible for a country to order a Korean reactor, purchase uranium from Kazakhstan, have the uranium enriched and fabricated in Europe and never once be dependent upon support from the United States or subject to U.S. nonproliferation programs[1].

In July 2007, the NRC received the first new application to site a new nuclear plant in over three decades. Since that time, the NRC has received applications for an additional 28 units at 18 sites. Approval of these applications is contingent upon a 'waste confidence' ruling that essentially requires confidence that the fuel cycle has an acceptable closure path as a pre-condition for moving forward with construction of any new plants. A waste confidence ruling was issued in the affirmative in 1984 and re-affirmed in 1989 and 1999 based on the presumed availability of a geologic repository. However, after investing 25 years and nearly $14 billion in developing a technical basis and a license application for a high level radioactive waste (HLW) repository, the current administration has abandoned the project by eliminating its 2011 funding – and a wave of litigation has ensued. As a result, the NRC has since withheld approval of an update to the waste confidence ruling – thus adding significant uncertainty to the prospects of the license applications now before the Commission. And, although the present administration's stated policy is generally favorable towards moving forward with nuclear power, the future of the industry remains uncertain.[2]

The failure to achieve the envisioned growth and prosperity and the continued difficulties in moving the industry forward has been largely attributed to lack of public acceptance and the attendant lack of political will to 'stay the course'. What went wrong? Does responsibility for the failure rest with the process or with the participants? What has been learned? And how best are we to proceed in an era where both domestic and worldwide energy needs continue to grow – along with our awareness of the costs and environmental impacts of traditional energy sources?

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[1] Former Senator Pete Domenici, opening remarks before the Blue Ribbon Commission on America's Nuclear Future.
[2] "I think it is fair to say there's not only a possibility but perhaps even a likelihood that we will be restarting the nuclear industry in the U.S.", Secretary of Energy, Dr. Steven Chu, in his opening remarks before the BRC.

In March 2010, the Blue Ribbon Commission on America's Nuclear Future (BRC) was chartered to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle. Although their charge is to look forward, BRC Commissioners will undoubtedly ask these and other questions as they develop recommendations informed by experience gained from the costly course we've taken[3]. In his opening remarks at the BRC kick-off meeting in March, Dr. Richard Meserve stated,

> You can't look at any one piece in isolation. And all the pieces have to be looked at in light of a large number of factors. If we're going to consider anything that has to do with nuclear technology, you have to be satisfied as to safety, security, nonproliferation, economics, extension, availability of fuel and probably five other factors. And they all interplay with each other. They all need to be considered. And beyond that, what you do with the waste and think about with regard to the waste needs to be considered in regards to how the whole system works together. You need a production of fuel, reactors all need to work in synchrony with each other in a total system. This is actually a very complicated problem that we've embarked on and involves many factors in defining an optimal path is important and going to be challenging.

Developing a successful path forward for closing the nuclear fuel cycle is indeed a very challenging task. It is a complex, multi-variable problem with diverse constituencies having strongly held positions. Its economic consequences reach far into our future. And its security implications will affect nuclear policies and decisions around the globe. Past attempts have not been successful. What will be done differently this time around?

This paper suggests that tools exist to help ensure a more comprehensive discussion of the issues and to integrate diverse interests and form a more complete understanding of the issues underlying the present stalemate. These tools, originating from within the discipline of system dynamics, have been underutilized with respect to considering the influence of socio-economic factors when formulating policy and, if properly applied, promise to broaden our understanding of the issues and enable development of a path that takes some of the mystery out of the unseen, and seemingly intractable, powers that seem to govern 'the system'.

A brief history of system dynamics is provided below along with an introduction to its fundamental principles. Examples of its application within the nuclear industry are provided along with a brief discussion of the insights and opportunities. Within the scope of this paper, it is not possible to develop the principles in any depth. Rather, a broad summary is given with the intent of creating an interest and encouraging the reader to further exploration.

System Dynamics Origins

J.W. Forrester, a pioneer in development of computer hardware and software[4], is the key figure at the origin of the discipline of system dynamics. The discipline is founded in feedback control theory and computer modeling. Forrester was clearly a man of great vision. In the 1950s he recognized that feedback control theory could be applied to gain understanding of the response of virtually any system. Like mechanical systems governed by physical laws that can be mathematically modeled, he noted that social, political, and economic systems (referred to herein as

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[3] "We do need to spend a little bit of time learning from the lessons learned from the failed nuclear waste process in the United States so far.", Dr. Allison MacFarlane in her opening remarks before the BRC.

[4] Jay W Forrester led the project that developed the first digital computer (Whirlwind), invented magnetic-core random access memory, directed the SAGE project integrating radar and digital computing which was used as the basis for air defense systems for nearly three decades, and was inducted into the National Inventors Hall of Fame in 1979.

‘soft systems’) are also defined not only by their parts but also by their structural connections, transfer functions, bandwidth, time delays, etc.

Forrester noted that even experienced design engineers are rarely able to predict the responses of second and third order systems, yet the ‘soft systems’ that require governance are orders of magnitude more complex, often exhibiting 100^{th} (or higher) order interdependencies. As an accomplished computer designer, he was confident that ‘soft systems’ could be modeled in sufficient complexity to gain insights that would significantly improve our understanding and consequent ability to govern them effectively.

As a result, he worked to develop methodologies to enable the application of mathematical modeling and other ‘hard sciences’ to gain insights into the behavior of ‘soft systems’. His books, *Industrial Dynamics, Principles of Systems, World Dynamics, and Urban Dynamics*, made landmark contributions in our appreciation for the inter-related complexities that must be dealt with to successfully understand the behavior of large systems and to design policies for effective governance.

Forrester’s commitment to the value of developing explicit models is based largely on recognition that all mental images are models that are used as the basis for action. The process of making these mental models explicit imposes not only a rigor and discipline that forces a more thorough understanding, it also makes them available for external review and scrutiny – a process that allows them to benefit from differing mental models of other system participants.

Forrester envisioned that the principles of system dynamics could bridge the gap between the ‘hard sciences’ and the ‘soft sciences’ and thus lay the foundation for a new age of understanding. History will tell whether his prediction is true or not. But the present indication is that those representing the ‘hard sciences’ have been less enthusiastic about this union than envisioned. The phenomena being modeled can be tremendously complex. And, unlike modeling of physical systems, identifying and understanding relationships sufficiently to reduce the interactions to a credible model requires not a trip to the reference bookshelf but often days of meetings and discussions with diverse system participants – who most often do not think and process information like engineers are trained to do. Dealing with the loosely defined connections and correlations that define social, political, and economic systems is often a source of frustration for a mind trained to demand the precision required in the hard sciences. Engineers and scientists typically conclude that it’s just much easier to go back to the office and concentrate on things that behave in predictable ways – problems that yield to analytical tools.

On the other hand, these principles were enthusiastically received by those who must deal daily with the ‘soft sciences’. For those trained in arts, humanities, social sciences, etc., a process for identifying previously unseen and unappreciated influences that affect processes they care about – even loosely defined imprecise connections – is an exciting development. And it is taking hold in much of society. If you do not believe it, pay attention to the themes in your children’s literature. And consider how prevalent the concepts of sustainability, external costs, and other ‘systems’ type principles show up in your daily diet.

We, the technically enabled (politically correct rendition of ‘socially handicapped’), must remind ourselves that we are the exception. And, if we’re not at the table, we deprive ourselves not only of the opportunity to better understand the world that we and our industry must survive in but also of the ability to share our understanding and consequently increase our influence on that world.

> Engineers and engineering schools lament the waste caused by the movement of the technically trained into management, even while futilely seeking technical solutions to many engineering deficiencies that actually arise from the management system of which engineering is a part. Since the paramount problems in engineering have their origins in the management system, and since a preponderance of today's managers are not equipped to solve those problems, we should examine the possibility that the best engineers can serve engineering better by applying their engineering philosophy to the management interface that couples engineering to the needs of society[5].

System Dynamics Tools/Techniques

The basic building block for understanding dynamic behavior is a feedback loop. Thinking in circles requires a fundamental shift from the way we typically think about things. Our culture and our language condition us to what can be called a 'world is flat' perspective that is characteristic of a subject→verb→object 'period' approach. The systems view moves us toward a 'world is round' perspective. It omits not only the period but also the distinction between cause and effect.

Consider Figure 1, which is an example of a feedback loop that illustrates a familiar positive feedback mechanism. The commodities of interest, fissions and fission neutrons, are linked by arrows indicating causality. The '+' signs near the arrow points indicate that the commodities at each end of the arrow are positively correlated – meaning they move in the same direction. An increase (or decrease) in the precursor commodity causes an increase (or decrease) in the affected commodity.

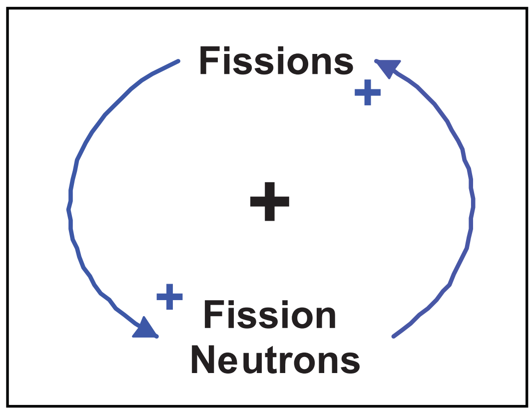

Figure 1. Positive Feedback Loop

A feedback loop, sometimes referred to as a causal loop diagram, may include virtually any commodity. And correlations between commodities may be either positively or negatively correlated. A negative correlation is a link indicating that an increase in the precursor commodity causes a decrease in the affected commodity, or vice-versa.

There are two fundamental kinds of feedback loops, positive and negative. Figure 1 is a positive feedback loop, as indicated by the '+' sign near the center of the loop. Whether the loop is a positive or a negative feedback loop is determined by counting the number of negative correlations around the loop. And, as in multiplication, an odd number of negative links results in a negative feedback loop. Figure 2 is a familiar negative feedback loop.

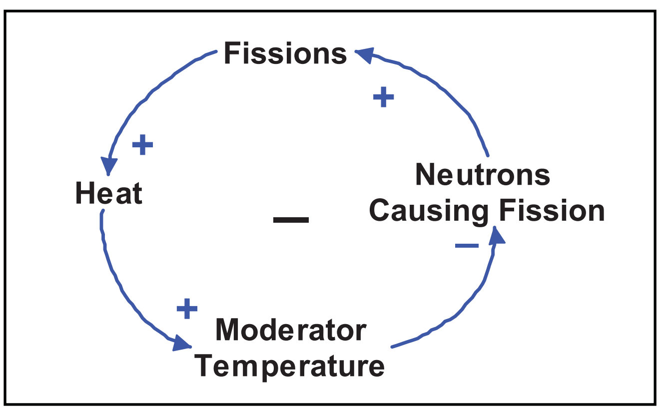

Figure 2. Negative Feedback Loop

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[5] Jay W Forrester, *Common Foundations Underlying Engineering and Management*, IEEE Spectrum 1, No. 9, Sept 1964.

Negative feedback loops are characterized by a thermostatic type goal-seeking behavior that resists change and helps ensure system stability. Positive feedback loops are naturally unstable. Left uncontrolled, a positive feedback loop will either asymptotically decay away or asymptotically increase until it runs out of fuel, self destructs, or bumps up against a limit imposed by another system in which it participates.

Loops may be nested and interconnected in many ways. Figure 3, illustrates how a positive and negative loop may be linked together to form a more complex system. System models typically contain many loops and are often referred to as spaghetti diagrams.

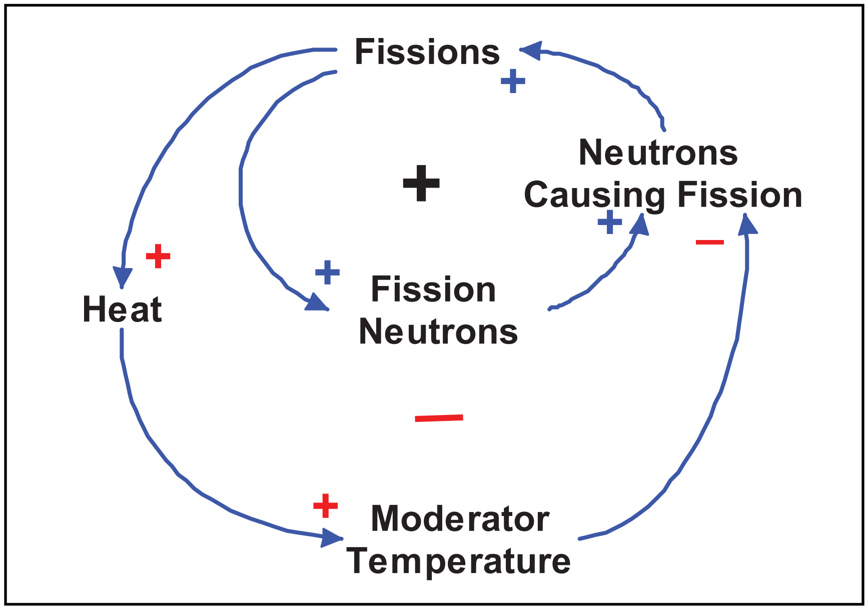

Figure 3. Combined Feedback Loops

The response of a system is determined by its structure and is often complex and counterintuitive. With an understanding of how a system's structure affects its behavior, a system designer may employ a positive loop as an engine for growth or an agent for change. Similarly, negative loops are employed to apply desired controls and ensure stability.

A sub-discipline of system dynamics, commonly known as 'systems thinking' has evolved and is widely discussed and applied by a variety of institutions seeking to better understand and guide policy development. The principles and language of systems thinking are intended to help uncover the bases for differing mental models underlying the positions of various stakeholders and thereby develop a more complete and effective model of the system. With a more complete model of the system, policies can be designed to be consistent with anticipated system responses, unanticipated responses are more easily and quickly recognized; and, when needed, effective and timely interventions are made possible. In short, by participating and making explicit our mental models in ways that constituents and policy makers (i.e. politicians) can understand, we have the possibility to be more than just passengers aboard 'The System'. We can help navigate.

Applications

So, how might these principles be applied to help provide useful perspective on the political issues relevant to our industry? In the beginning of the nuclear industry, there was great, almost euphoric, hope that the power within the atom would prove to be an abundant source of economical, clean power that would transform the world's standard of living – as noted in Atomic Energy Commissioner Lewis L Strauss' 1954 speech where he stated, "It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter…." The prevailing mental model at the time was something like that shown in Figure 4, a positive loop that would fuel growth of an industry to provide virtually unlimited electrical power.

But, as shown by Figure 5, this was clearly an incomplete model that missed some very important connections – which resulted in the public acceptance turned negative. Rather than driving industry growth, the positive feedback loop then served not to drive growth of the industry but to accelerate its decline. And, it did this despite the public benefits derived from nuclear technologies. What happened?

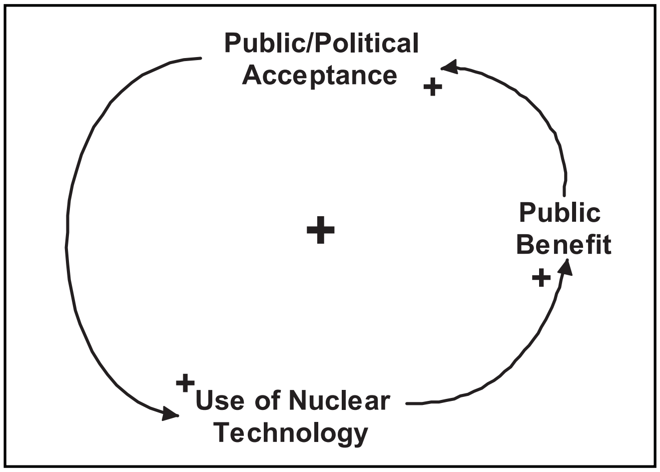

Figure 4. Nuclear Optimism

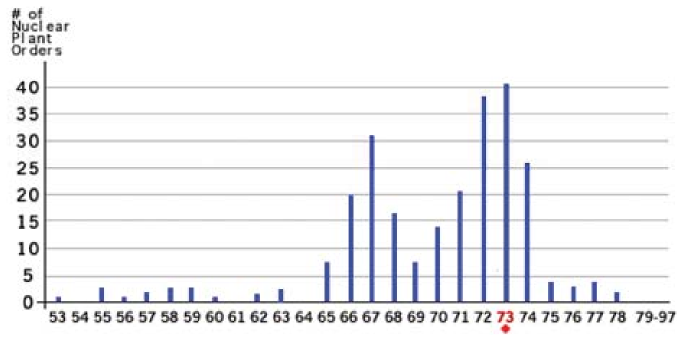

Figure 5. U.S. Nuclear Plant Orders by Year

From the 'world is flat' perspective, the symptom was diagnosed as an irrational fear of nuclear technologies based primarily on a lack of understanding. And the prescription was to educate consumers and to provide increased opportunities for public participation – along with rigorous regulations to provide assurance of nuclear safety. Over thirty years has gone by – with tremendous investment in public education and participation, and we have yet to start construction of another nuclear plant. Perhaps we failed to properly understand and characterize the problem. Expanding the model to look beneath the issue, a different picture emerges (see Figure 6).

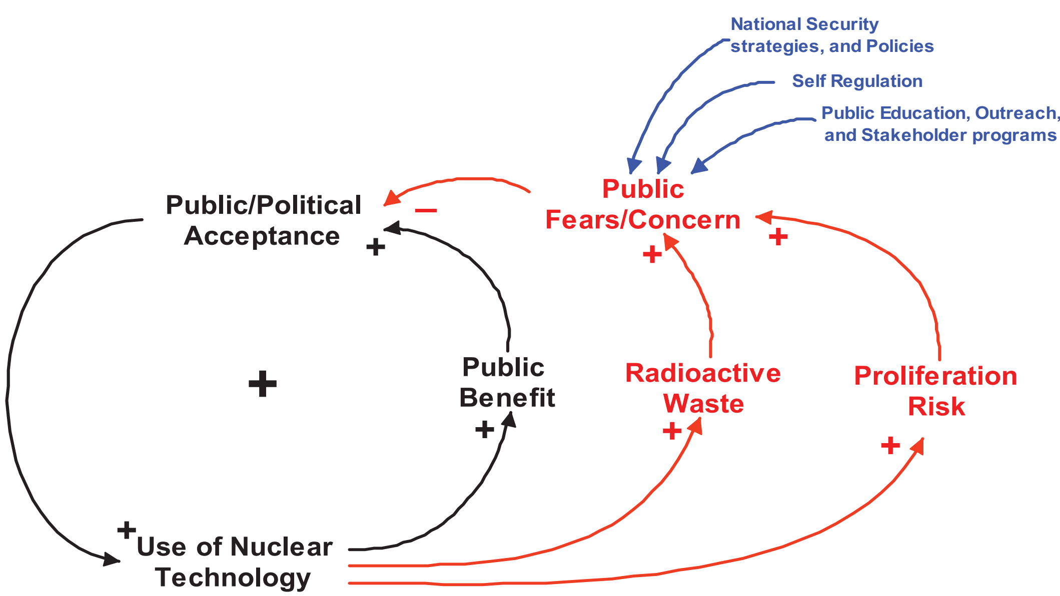

Figure 6. Nuclear Reality

One sees that the causes underlying public concern (shown in red) are positively correlated with use of nuclear technology. With this broader perspective, it becomes clear that efforts to directly affect public confidence are destined to fail as long as underlying issues remain unresolved. Alternatively, this model also shows that an increase in the public benefit derived from nuclear power would also allow some growth. Accordingly, increased awareness and concern over the effects of CO_2 emissions and the specter of carbon limits and carbon taxes has resulted in increased acceptance of nuclear energy. However, the structure of the above model indicates that, although this may provide some relief, the underlying issues remain and can be expected to continue to limit growth.

Disposal of high level radioactive waste and proliferation risk are difficult issues with potentially far-reaching consequences. Yet an acceptable solution appears to be crucial in order to gain the public acceptance needed to enable the industry to move forward.

> Thank you, Mr. Chairman. I guess I in also taking off a point from Commissioner Meserve, there may not be a scientific crisis. And I, too, am not an expert on the science of these issues. But to the extent there is a crisis of confidence, I think there exists. If we agree that nuclear power should continue to be a viable part of the supply portfolio in this country, our inability to address this issue is an impediment in my mind. If we want to grow domestically vendors who will construct nuclear plants. If we want students to enroll in nuclear specialties, I think is an issue that if we are serious about the growth of nuclear power that we have to address. As a former state and federal regulator, we often found ourselves on the front lines of decision making. And as state commissions make resource decisions and commit rate payers to meet the supply needs in their state and as the industry makes resource commitments and financial commitments, they need confidence that there is a direction in place for managing the end of the nuclear fuel cycle, one that gives clarity and one that gives certainty. This is how I believe we show that we are serious about promoting the growth of nuclear power in this country.[6]

The U.S. is not alone in its struggle to identify an acceptable solution. Some countries, however, appear to be having more success moving toward the goal. Finland and Sweden have selected repository sites, with high public acceptance, and expect to be emplacing spent fuel within ~12 years. The Netherlands is operating a storage facility designed to provide 'at least' 100 years storage for its used nuclear fuel.

Each of these success stories shares some common themes. First, the waste forms are retrievable – such that the decision does not necessarily preclude future alternatives. Second, each shared broad local public and political support. And third, each facility was sited at or near an existing nuclear facility. From these commonalities, there appear to be at least two key lessons:

- People who have had a chance to get to know the nuclear industry first hand, are much more comfortable with it[7].
- Deciding on a path is much easier when not saddled with the burden of irreversibility.

These lessons have been adopted and applied in Canada in an approach called Adaptive Phased Management which lays out a slow and deliberate path which, over the course of ~120 years, will conclude by siting a repository at a location that will likely have existing nuclear facilities and will leave decisions related to final sealing and closure of the repository to future generations[8].

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[6] Hon Vickie Bailey, Opening remarks at Blue Ribbon Commission on America's Nuclear Future, March 25, 2010.
[7] This conclusion is supported by polls conducted during the site selection process employed in Sweden where six localities neighboring each of two candidate sites were also surveyed in 2008 and, while the ~80% of residents were in favor of a final repository in the neighboring municipalities, support diminished as distance from ongoing nuclear power operations increased. http://www.world-nuclear.org/info/inf42.html
[8] *Choosing a Way Forward, The Future Management of Canada's Nuclear Fuel, A Summary;* http://www.nwmo.ca/uploads_managed/MediaFiles/342_NWMO_Final_Study_Summary_E.pdf

Addressing concerns relative to proliferation risk is a challenging task primarily due to the wide range of concerns and theories relative not only to what constitutes a threat but also as to the effectiveness of various strategies for managing these threats. The existing risk management approach is built around the Non-Proliferation Treaty (NPT). Yet the effectiveness of the NPT is increasingly questioned. Underlying the NPT are presumptions that, left uncontrolled, nuclear weapons would proliferate and that proliferation would be a bad thing. A simple model of this dynamic is illustrated in the black portion of Figure 7.

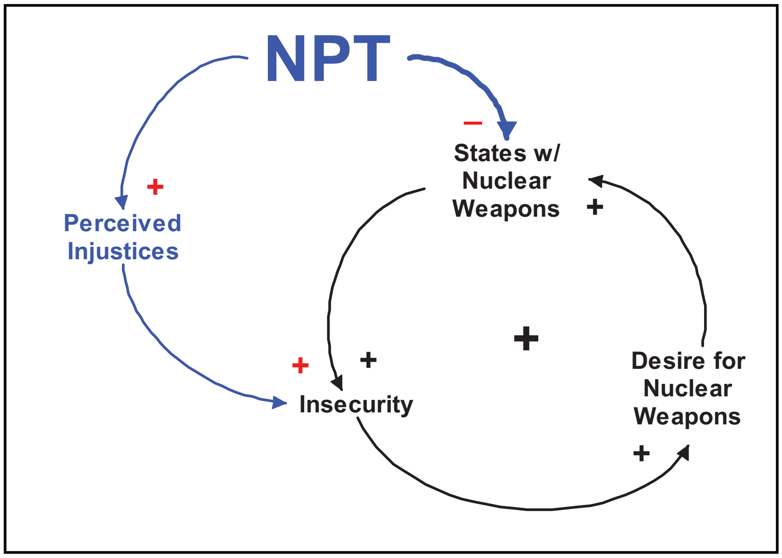

Figure 7. NPT Unintended Consequences

The NPT was imposed as a control to oppose the buildup of nuclear weapons feared to result from this dynamic. However, several other system dynamics are present. One example, shown in the blue portion of the figure, is based on perceived injustices within the framework of the NPT[9].

In his 2006 book, *The Psychology of Nonproliferation,* Jacques E.C. Hymans concludes that, "the common idea that the non-proliferation regime is the most successful arms control treaty in history is based on a basic misunderstanding of the dynamics of proliferation. The non-proliferation regime has had great utility in monitoring the pace of nuclear technological diffusion, but it has not been the proverbial finger in the dike blocking a flood of new weapons states. Tough non-proliferation policies are unlikely to change the minds of those who really want the bomb, while they are likely to anger and offend many of those who do not. As I will argue below, this is not a reason to abandon the NPT regime but it is a reason to second guess the continual urge to "strengthen" it with ever-heavier supply-side controls." [10]

In other words, a more comprehensive model of the system would not only provide new methods for strengthening nonproliferation objectives, but could also change our understanding of proliferation risks and have a corresponding influence on their role in the public/political acceptance of nuclear technologies.

Conclusion

On February 16, 2010, the Connect U.S. Fund, the Rockefeller Brother and Global Systems Initiatives convened a one-day conversation on *U.S. Global Engagement in the Age of Interconnectedness: An Inquiry into a Systems Approach to Policy-Making*. The day was a series of roundtable discussions engaging leaders from the current administration, the non-governmental

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[9] http://www.japanfocus.org/-China-Hand/2749, http://www.npec-web.org/files/20070410-Goldbemberg-ErosionOfNPT.pdf

[10] *The Psychology of Nuclear Proliferation*, Jacques E.C. Hymans, Cambridge University Press, 2006; p 216

community, funders, and systems experts in an inquiry process that sought to identify specific ideas and proposals for how policy makers and those who seek to influence them can usefully apply systems thinking to difficult global challenges. The approximately 35 participants addressed the issues of climate change, food security, and nuclear non-proliferation from a multi-disciplinary perspective, looking especially at how a systems lens might add value to the policy process[11].

The following is an excerpt from a keynote address delivered to meeting participants by a respected particle physicist, Dr. Fritjof Capra[12].

> For example, the statement that nuclear power does not emit CO2 reflects a narrow, linear view. When we consider the entire (nonlinear!) nuclear fuel cycle, we find that the operation of nuclear power plants emits about 27% of the CO2 emitted from coal-fired plants. Moreover, worldwide uranium supplies are limited. As the mining and refining of less concentrated uranium ores becomes more and more difficult, the energy required for these processes will increase, together with the resulting CO2 emissions, until, within just one or two decades, the generation of nuclear power will emit as much CO2 as coal-fired plants, and will produce no net energy. So, systems thinking - without even talking about the inherent health risks - makes it evident that nuclear electricity has no future, and that investing in nuclear power today is non-productive, diverting money from much more effective and less problematic investments in renewable energy sources and energy conservation.
>
> A systems thinker would also be aware of the fact that, historically as well as technically, nuclear power and nuclear weapons are inextricably linked. All nuclear power plants are potential bomb factories. From a systemic perspective, our government's concern about nuclear proliferation is at variance with the active promotion and encouragement of the dissemination of nuclear technology and expertise.
>
> Systems thinking means being able to see how the major problems of our time - energy, environment, economy, health, security - are all interconnected. It means being able to "connect the dots," to use a popular phrase.

Systems approaches include many powerful techniques for understanding complexity. And it is currently employed by several non-governmental organizations working to influence constituents and their elected officials by helping them to 'connect the dots'[13]. But, if we are not present and conversant in the language, many key dots will be absent.

Consider the more complete model shown in Figure 8. The dynamic pointed out by Dr. Capra is present (red text) and was, in principle, correctly described in his remarks. However, the more complete model produces an entirely different behavior.

First, known reserves of uranium have not decreased over the past ~60 years that it has been being actively mined.[14] Uranium is indeed a finite resource and, eventually, we may be pushed to using lower and lower ore grades as Capra suggests. However, historical data indicate that this is not in the foreseeable future. This is explained, in part, by the fact that investment in exploration is made only as needed to justify a sufficient supply to meet foreseeable needs. In other words, it is not

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[11] http://www.connectusfund.org/blogs/us-global-engagement-age-interconnectedness-inquiry-systems-approach-policy-making

[12] http://www.connectusfund.org/blogs/policy-making-interconnected-world

[13] The more complete model shown in Figure 8. offers a different perspective on the underlying dynamics of the system. Additionally, the sources of the data provided in Capra's remarks are not provided but they coincide with data shown in sources whose assumptions and methods show an extreme bias against nuclear power. Capra also fails to acknowledge the potential of thorium as a nuclear fuel or of the role of advanced fuel cycles both for extending the available fuel supplies and for addressing nuclear proliferation concerns.

[14] *Forty Years of Uranium Resources, Production and Demand in Perspective*, Nuclear Energy Agency Organization for Economic Co-operation and Development, 2006.

reasonable to assume that reported Uranium reserves will be depleted at the same rate that uranium is mined. This effect is shown in the diagram (brown text). **Second**, the operation of the power reactor itself is virtually carbon free. The carbon footprint associated with the life cycle assessment of nuclear power is primarily the result of electrical energy consumed in the front-end of the fuel cycle (i.e. mining, milling, conversion, and enrichment). CO_2 emissions from these processes result from the fact that electricity from the current grid is largely produced from carbon-based fuels. However, as shown in the figure (green text), an increase in the use of nuclear power not only benefits the public by reducing the CO2 footprint of electricity in general, it also reduces the emissions from the front end of the nuclear fuel cycle. By the operation of this imbedded positive feedback loop, one can envision moving toward nuclear-generated electricity with a near zero life-cycle carbon footprint (i.e. power consumed for front and back end fuel processes is electricity generated from carbon free electricity).

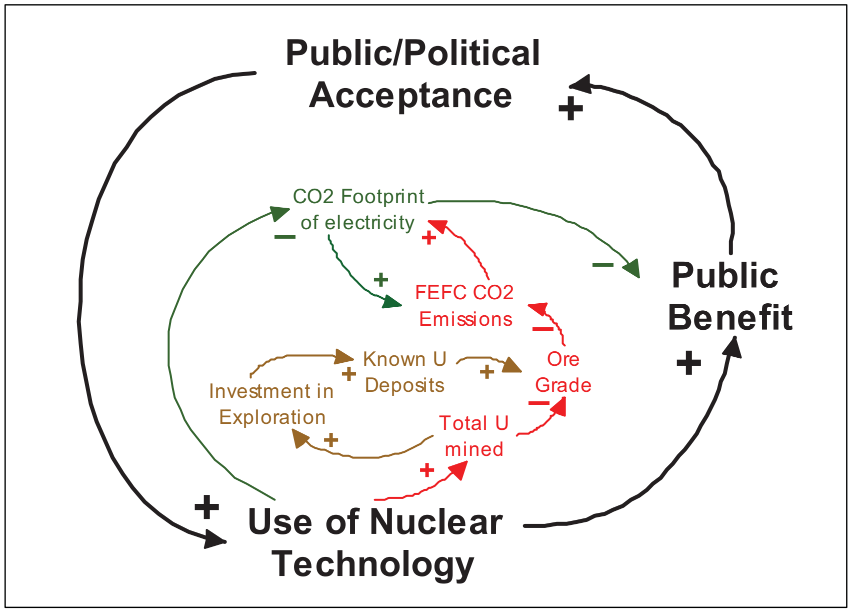

Figure 8 Carbon Footprint of Nuclear Power

So, what is the point of this rambling exposé that bounced through a bit of the industry's history, gave a whirlwind introduction to the discipline of system dynamics, provided a few feedback loops illustrating phenomenon of which we are all already painfully aware, and then rubbed some salt in an open wound?

The objective is, in the words of another respected particle physicist, Richard Feynman, to encourage you to refuse to allow science to be irrelevant[15].

> "I want to answer the question as to why people can remain so woefully ignorant and not get into difficulties in modern society. The answer is that science is irrelevant. …. and I believe that science has remained irrelevant because we wait until somebody asks us questions …. So I suggest, maybe incorrectly and perhaps wrongly, that we are too polite."

We need to be 'at the table' and we need to be able to participate in the discussion in ways that help build shared understanding. Our industry is at a critical juncture. And the path we choose will be crucial to winning the battle for the hearts and minds of the public and, ultimately, for the future of our society.

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[15] Richard P. Feynman, excerpt from *What Is and What Should Be the Role of Scientific Culture in Modern Society*, Lecture given at the Galileo Symposium in Italy, 1964;