ENCOURAGING NUCLEAR INNOVATION

WHAT SMALL MODULAR REACTORS CAN LEARN FROM NUCLEAR ATTACK SUBMARINE DEVELOPMENT

Master of Arts in Law and Diplomacy Capstone Project

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February 28th, 2014

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Abstract:

Small modular reactors (SMR) represent the most recent innovation by nuclear engineering firms in the United States, and thus are the subject of a great deal of optimism within the industry. SMR units are advanced reactors (Generation III+ or IV) that are miniaturized to a capacity less than 300 megawatts, that also feature enhanced siting flexibility, improved safety, advanced instrumentation, longer refueling intervals, and a shift to factory production. Nuclear power in the United States has struggled with diseconomies of scale as well as socio-political opposition in recent years, so much so that only two new site builds have been initiated since 1979. SMR is being touted as the answer to the woes of nuclear power, though even the best laid plans of SMR proponents leave many questions unanswered. The process of innovation in energy technologies faces systemic challenges, and policy interventions are needed for nascent developments like SMR to allow it to test the rigors of the commercial market. A potential model for SMR innovation to emulate is the success of a closely-related but often overlooked technology with strong energy-related ties: nuclear attack submarines. Naval Reactors has found tremendous innovation success through tightly knit networks of public-private partnerships that encourages the flow of information, funding, expertise, and a powerful safety culture to all participants. Additionally, nuclear submarine innovation had struggled with cost escalations similar to nuclear energy until a series of policy mechanisms were employed to stabilize submarine economics. The findings of this study point toward a potential model for the Department of Energy and the domestic nuclear industry to emulate in order to support innovation in nuclear energy technologies like SMR.

Introduction

Small modular reactors (SMR) represent the most recent innovation by nuclear engineering firms in the United States. These advanced Generation III+ or Generation IV reactors are intended to take advantage of standardized design and repeated production processes that make manufacturing in a factory setting economically efficient, a completely different approach to what nuclear energy has traditionally used. This transition is hailed by the industry as the answer to evolving electricity market landscapes that have left nuclear energy a relatively stagnant technology while natural gas captures increasing market shares and renewable energy sources advance rapidly. Improvements in safety, siting flexibility, instrumentation, controls, refueling intervals, as well as a number of new features are supposed to make SMR an attractive option for utilities, the United States government, or even foreign investors seeking to acquire the most advanced nuclear power plants on the planet.

Despite the optimism from the industry, the processes of innovation in nuclear energy are hindered by a number of obstacles. With massive amounts of government support available and a strong domestic industry, innovation in reactor technology should produce countless new designs, each successive idea better than the last. However, most original reactor designs never become realities, and this is a problem that demands a thorough explanation. If SMR is to be given a chance to test the rigors of the market, the processes of innovation in nuclear energy must be analyzed to find the reasons why innovative designs often remain "paper reactors" that never reach commercial production.

To highlight the failures of the nuclear innovation process and discover a potential model to follow for nuclear engineering going forward, a study was performed in an analogous industry: nuclear attack submarines. Submarines are powered by highly advanced, small reactors that must be at the cutting-edge of reactor advancements to maintain tactical superiority in ocean environments around the world. Naval propulsion development led to the commercial adoption of nuclear energy, as the latter was a spillover technology of the former. The parallels between the two industries are prevalent, as many industry representatives have cited nuclear shipbuilding as a reasonable comparison to the proposed strategy for SMR production. The purpose of this study is to explore the successes and failures in nuclear attack submarine innovation and discover how these lessons might be applied to enable innovation in SMR.

The study performed shows that submarine reactors do not struggle with the key points of innovation failure (Valleys of Death) that plague nuclear energy, and its development has proven the industry's capability to handle the systematic reduction of production costs. A primary mechanism that enables this is the powerful innovation network that has a singular goal of attack submarine development. Learning is one of the most powerful mechanisms in the innovation system, and the development and diffusion of knowledge must be the focus of the innovation network. The network benefits from substantial financial support at all stages of the innovation process, powerful feedback mechanisms, strong leadership in the innovation process, active knowledge creation, efficient diffusion of that knowledge, a predictable market, and the cultural legitimacy of the military in the political culture of the United States. Most importantly, however, nuclear attack submarine development is permeated by a high-reliability culture that prioritizes the safe operation of new reactors, an essential characteristic of any innovation system that promotes the development of complex technologies that possess a potential for catastrophic failure. In addition to systemic innovation processes, there are many lessons that can be learned from submarine production that are applicable to SMR. Policy mechanisms to incentivize parts standardization, industry infrastructure improvements, and federal purchases of plants can greatly assist in encouraging cost reductions associated with learning in the manufacturing process. The findings of this study point to a model that the United States nuclear industry and the Department of Energy can emulate to support SMR innovation and ultimately commercial deployment.

Impetus for this Study: The SMR Licensing and Technical Support Program & the Failures of Nuclear Innovation

What is SMR?

Small modular reactors are advanced reactor designs that have been miniaturized to enhance flexibility in applications, financing, transportability, and are further characterized by their incorporation of modular construction methods to reduce costs. These reactors can be based on any design using any type of coolant (heavy water, liquid sodium, gas cooled, etc.), so there is remarkable diversity in engineering to the myriad of commercial plants being developed globally. The small size of SMR units not only refers to the reduced physical dimensions of the reactors themselves, but also to the electrical generating capacity of the units. Definitions of vary, but it is generally agreed by organizations like the International Atomic Energy Agency (IAEA), Organization for Economic Cooperation and Development Nuclear Energy Agency (OCED NEA), and the United States Department of Energy (DOE), that the label of SMR typically applies to units that generate 300 megawatts electric (MWe) or less.[1] [2] [3] This reduced physical size of the units allows the entire power plant to be manufactured in a factory setting, then shipped to their installation sites via rail car, barge, or by truck. Factory-style production permits modular construction techniques, which is a strategy of prefabricating sections of a larger product and assembling them in a few large pieces on the final construction site. So while there may be great variation in core design, SMRs typically share the three basic characteristics of small size, transportability, and modularity.

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[1] Kuznetsov, Vladimir, and Alexey Lokhov. *Current Status, Technical Feasibility, and Economics of Small Nuclear Reactors*. Organisation of Economic Cooperation and Development. Nuclear Energy Agency Reports. June 2011. Accessed February 18, 2014. http://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf.

[2] *Status of Small and Medium Sized Reactor Designs: A Supplement to the IAEA Advanced Reactors Information System*. International Atomic Energy Agency. IAEA Nuclear Power: SMR. 2012: p. 1. Accessed August 13, 2013. http://www.iaea.org/NuclearPower/Downloadable/SMR/files/smr-status-sep-2012.pdf.

[3] Research reactors (typically 25 MWe or less) are not considered SMRs, as they are not built to produce electricity on a commercial basis.

On March 22, 2012, United States Secretary of Energy Steven Chu announced a public-private collaboration program worth $452 million designed to assist firms in designing and commercializing SMR.[4] This program, titled the Small Modular Reactor Licensing Technical Support program (Funding Opportunity Number DE-FOA-0000371, hereafter referred to as SMR LTS Program), is a cost-sharing agreement that would take place between the DOE and nuclear industry partners to facilitate the expensive design certification and licensing process of up to two SMR designs over a period of five years. The actual amount supplied by the DOE on an annual basis would be subject to Congressional appropriations, though the funding opportunity announcement (FOA) specifically states that the government's portion would not exceed $452 million, with industry covering at least 50% of the total costs.[5] The stated purpose of this program was to "promote the accelerated commercialization of SMR technologies that offer affordable, safe, secure, and robust sources of nuclear energy that can help meet the nation's economic, energy security and climate change objectives" and targeted a goal of SMR deployment by 2022.[6] In November, 2012, the Babcock and Wilcox Company (B&W) announced that its subsidiary, Babcock & Wilcox mPower Inc. had been selected as a winner of this grant.[7] On April 15, 2013, B&W mPower announced the details of the cooperative agreement signed with the DOE, which allocated $79 million for the project in the first year, and committed to providing at least $150 million over the course of five years.[8] The deal could be worth $226 million or more in total funding if certain conditions are met.

The SMR LTS Program goes beyond a simple partnership between the DOE and the nuclear industry, as it requires buy-in from a utility to purchase and operate the power plants. On June 16th, 2011, the Tennessee

[4] "Obama Administration Announces $450 Million to Design and Commercialize U.S. Small Modular Nuclear Reactors." Energy.gov. March 22, 2012. Accessed August 13, 2013. http://energy.gov/articles/obama-administration-announces-450-million-design-and-commercialize-us-small-modular.

[5] United States. Department of Energy. Idaho Operations Office. *Cost-Shared Industry Partnership Program for Small Modular Reactors.* Funding Opportunity Number: DE-FOA-0000371.March 22, 2012. Accessed August 13, 2013. http://www.grants.gov/web/grants/search-grants.html?keywords=modular reactors.

[6] US DOE *Cost-Shared Industry Partnership Program*, p. 1.

[7] "B&W Selected As Winner Of DOE's Small Modular Reactor Program." Babcock & Wilcox Company News Room: Press Releases. November 20, 2012. Accessed August 13, 2013. http://www.babcock.com/news_and_events/2012/20121120a.html

[8] "B&W, DOE Sign Cooperative Agreement for Small Modular Reactor Funding." Babcock & Wilcox Company News Room: Press Releases. April 15, 2013. Accessed August 13, 2013. http://www.babcock.com/news_and_events/2013/20130415a.html

Valley Authority (TVA) along with Bechtel agreed to fund a demonstration project for Babcock & Wilcox's mPower at the Clinch River site unit in Tennessee.[9] The deal is for at least 1 SMR module, with the option to purchase up to six.[10] On November 11th, 2013, B&W announced that it is seeking additional equity partners in the Clinch River project, which serves as another signal to the market that SMR technology is moving forward into the demonstration phase, and could become a commercial option within the decade. The partnerships between DOE, the nuclear industry, and a major utility are major steps in the progress toward commercialization of the mPower unit, as a demonstration project is needed to prove the viability of a new energy technology.

In March, 2013, the DOE announced a follow-on solicitation to the SMR LTS program, and began accepting applications under funding opportunity number DE-FOA-0000800.[11] This second round of funding for the LTS program targets the development of SMR plants for commercial deployment by 2025, specifically focused on assisting industry with design advancement and eventually certification. This is a slightly longer-term approach than the previous, nearly identical announcement, which targeted SMRs that could be deployed in the near term. Several firms have reportedly applied for these funds and for the opportunity to deploy demonstration units at the Savannah River Site in South Carolina, including Westinghouse, Holtec, NuScale, General Atomics, and Hybrid Power Technologies.[12]

The DOE's objectives in supporting SMR development are described in a document titled "A Strategic Framework for SMR Deployment", a draft paper outlining the goals of the SMR LTS Program.[13] The document outlines the role of the federal government in SMR development to "set national priorities for clean energy

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[9] "Generation MPower and TVA Sign Letter of Intent for B&W MPower™ Reactor Project." Bloomberg.com. June 16, 2011. Accessed February 05, 2014. http://www.bloomberg.com/apps/news?pid=newsarchive&sid=a7RU6bklIpjc
[10] "TVA Progresses with MPower Project." World Nuclear News. June 17, 2011. Accessed November 29, 2013. http://www.world-nuclear-news.org/NN-TVA_progresses_with_mPower_project-1706115.aspx
[11] United States. Department of Energy. Idaho Operations Office. *Cost-Shared Development of Innovative Small Modular Reactor Designs.* Funding Opportunity Number: DE-FOA-0000800.March 11, 2013. Accessed August 13 at www.grants.gov. http://www.grants.gov/web/grants/search-grants.html?keywords=modular reactors.
[12] "Small Modular Power Reactors." Small Nuclear Power Reactors. August 7, 2013. Accessed August 13, 2013. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/
[13] United States Department of Energy. "A Strategic Framework for SMR Deployment." Energy.gov. February 24, 2012. Accessed July 10, 2013. http://energy.gov/sites/prod/files/SMR%20Strategic%20Framework.pdf.

and national security and create incentives to achieve them."[14] The primary goals of supporting SMR development are twofold. First, the DOE wants the first SMRs to be deployed in the United States to establish United States leadership in safety and security standards for the technology. The idea is that this would not only provide leverage for United States-based preferences in international SMR development, but also provide an economic engine for domestic industrial growth. The second goal is to deploy upwards of 50 GW of SMR units to replace retiring coal plants, which currently are sources of high levels of pollution and carbon emissions. Many of these units are small-sized plants spread out in remote areas, and because baseload capacity for the grid must be maintained, SMR units are prime candidates to step in and fill the demand for electricity. President Barack Obama reiterated the need to retire these plants when he launched his Climate Action Plan in June of 2013, showing a commitment to a policy that could present an opportunity for SMR.[15] Whether or not this Strategic Framework becomes an official DOE program, it has provided insight into what the DOE has in mind for the SMR LTS program and the potential for SMR deployment in the United States.

Despite this seemingly optimistic start for SMR, innovations in energy technology face significant obstacles in their endeavor for commercialization. On November 13th, 2013, Babcock & Wilcox announced that it was seeking investors for the Clinch River Project, as it was attempting to reduce its stake to about 20%.[16] Is the SMR LTS Program and demonstration project enough to encourage private investment? If not, what support would be necessary to give SMR the opportunity to test the rigors of the market against large nuclear or other electricity generation options? How can the progress of this technology be measured? What pitfalls can SMR expect to face in its near and long term development?

The development of SMR also brings into focus the process of innovation in nuclear energy technology, as SMR represents the latest attempt in innovation and it could serve as a litmus test for why nuclear innovations have failed. Countless designs of brilliant reactors have been proposed over the years, each more powerful,

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[14] U.S. Department of Energy "A Strategic Framework", p. 1.
[15] *President Obama Speaks on Climate Change*. *The White House*. N.p., 25 June 2013. Web. 2 July 2013. <http://www.whitehouse.gov/photos-and-video/video/2013/06/25/president-obama-speaks-climate-change>.
[16] Downey, John. "Babcock & Wilcox to Sell Majority Stake in MPower Reactor Venture." The Charlotte Business Journal. November 13, 2013. Accessed February 05, 2014. http://www.bizjournals.com/charlotte/blog/power_city/2013/11/babcock-wilcox-looks-to-sell.html.

profitable, flexible, and proliferation resistant than the last. Despite all the genius in design, very few reactor designs have become commercial successes, which is a paradox that merits exploration. The problems of nuclear innovation bring to mind a quote from Admiral Hyman G. Rickover, a man who played a pivotal role in the very first innovation in nuclear energy: naval propulsion. The points Rickover made in this 1953 speech haunt the nuclear industry's theoretical reactor designs to this very day:

> "An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.
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> On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated."[17]

Many reactors look great on paper, but trying to make them a reality is a journey rife with many engineering and economic obstacles that hinder progress. This paper will therefore explore why nuclear energy innovation often fails by examining the development and deployment of SMRs.

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[17] *Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges*. Washington, D.C.: National Academies Press, 2009, p. 60. National Academies Press Online. http://www.nap.edu/openbook.php?record_id=12477.

Nuclear's Need for Innovation: The Rationale for SMR

SMR development has become a salient objective in global nuclear commerce as a means of reinvigorating the industry, and is a specific focus of United States-based firms. SMR is intended to overcome the numerous failings of a large-scale approach to nuclear, and represents the first major nuclear innovation to reach near-commercialization levels since the failed Clinch River Breeder Reactor Project of the 1970s and 80s.[18] Innovation is broadly defined as the processes by which new products, processes, or forms of organization are developed to exploit market opportunities. This can involve the invention of something radically new, or it can simply be the addition of new knowledge or practices to existing products or processes. The domestic nuclear industry in the United States has struggled through several decades of relative stagnation, and SMR is believed to be an attractive development in an era of changing electricity market conditions. The specific areas of improvement over the current fleet of nuclear power plants is addressed in the following sub-sections on Economics & Finance, Siting Flexibility, Nonproliferation, and Safety, among others.

To set the stage for the advantages of SMR, a brief introduction to the status of nuclear power in the United States is useful to understanding some of the core issues of the existing technology. Nuclear energy in the United States has a hardy but eroding position in the national electricity generating portfolio. As of February, 2014, there are 100 operational reactors with a total capacity of 98.9 gigawatts electric (GWe), generating 18.9% of the country's electricity.[19] However, until the combined construction and operating licenses (COLs) were issued for the Vogtle and Summer projects currently under construction in Georgia and

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[18] Katz, James E. "The Uses of Scientific Evidence in Congressional Policymaking: The Clinch River Breeder Reactor." *Science, Technology, & Human Values* 9, no. 1 (Winter 1984): 51-62. Accessed February 05, 2014. http://www.jstor.org/stable/688992. It is interesting to note the historical irony that the latest attempt at nuclear innovation (SMR) is being sited at the same location where the last attempt at a major change in nuclear technology failed.

[19] "Nuclear Power in the United States of America." World Nuclear Association. November 22, 2013. Accessed November 30, 2013. http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/USA--Nuclear-Power.

South Carolina, no new nuclear power plants had been ordered in the United States since 1978.[20] The only domestic growth in nuclear from 1978 to 2014 had been limited to the completion of the Watts Bar 1 plant for the Tennessee Valley Authority in 1996 (construction began in 1970), and the incremental generation output increases due to capacity expansion as well as increased operating efficiency at existing plants. Since 1978, more than 100 reactor orders have been canceled. In addition, many older plants in the United States are being retired due to weak economic performance and the need for costly repairs, including the San Onofre Nuclear Generating Station in California, as well as the Kewaunee Power Station in Wisconsin. [21] [22] [23] [24]

Nuclear power has struggled to compete against the rise of alternative electricity technologies, especially natural gas. Between 1990 and 2011, natural gas-fired power plants accounted for 77% of all electricity generation capacity additions in the United States. [25] The United States Energy Information Agency (EIA) projects that natural gas will continue to dominate the electricity market, accounting for an estimated 63% of all future grid capacity increases between 2012 and 2040.[26] A major reason for this switch is the low cost for producing electricity using natural gas following the hydraulic fracturing boom in recent years. The EIA calculates the average levelized cost of electricity production (in 2011 $/megawatt hour) for an advanced combined cycle natural-gas fired plant to be only $65.6 per MW hour, whereas advanced nuclear plants the

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[20] Holt, Mark. *Nuclear Energy Policy*. Congressional Research Service. The Federation of American Scientists. Accessed July 15, 2013. http://www.fas.org/sgp/crs/misc/RL33558.pdf.

[21] "Southern California Edison Announces Plans to Retire San Onofore Nuclear Generating Station." *Newsroom*. San Onofore Nuclear Generating Station Community, 7 June 2013. Web. 02 July 2013. http://www.songscommunity.com/news2013/news060713.asp.

[22] Sewell, Abby. "San Onofre Nuclear Power Plant to Be Closed Permanently." *Los Angeles Times*. N.p., 07 June 2013. Web. 02 July 2013. http://www.latimes.com/news/local/la-me-0608-san-onofre-20130608,0,3986075.story.

[23] "Dominion News." *Dominion Shuts Down Kewaunee Power Station Permanently*. Dominion Power, 7 May 2013. Web. 02 July 2013. http://dom.mediaroom.com/2013-05-07-Dominion-Shuts-Down-Kewaunee-Power-Station-Permanently.

[24] Wald, Matthew L. "Aging and Expensive, Reactors Face Mothballs." *The New York Times*. N.p., 23 Oct. 2012. Web. 2 July 2013. http://www.nytimes.com/2012/10/24/business/energy-environment/economics-forcing-some-nuclear-plants-into-retirement.html?_r=0.

[25] *Annual Energy Outlook 2013 with Projections to 2040*. U.S. Energy Information Administration. April 2013, p. 39. Accessed July 24, 2013. http://www.eia.gov/forecasts/aeo/pdf/0383(2013).pdf.

[26] "Annual Energy Outlook 2013." U.S. Energy Information Administration (EIA). April 15, 2013. Accessed February 05, 2014. http://www.eia.gov/forecasts/aeo/MT_electric.cfm#cap_addition.

cost is $108.4 per MW hour.[27] This huge cost disparity means that any utility seeking to add capacity will clearly choose a natural gas-fired plant over a new reactor.

Another factor in the struggles of the United States nuclear industry is the relatively weak electricity demand growth. The need for electricity generation capacity additions in the United States has slowed considerably since the heyday of nuclear expansion during the 1960s and 1970s, when demand increased by nearly 8% annually.[28] Large power plants were needed American's use of household electronics and appliance skyrocketed, but EIA projections today estimate only 0.7% electricity demand growth to 2040. Utilities have been forced to find alternatives to large power plants, and a "right-sized" approach utilizing smaller natural-gas fired plants (usually less than 300 MWe), renewable energy sources has been the preferred route, leaving nuclear power behind as a vestige of a bygone era.

In addition to the struggles at home, United States nuclear firms in foreign markets have been increasingly challenged by state-backed firms in France, the Republic of Korea, China, and the Russian Federation that have taken an ever-increasing market share of global nuclear commerce. According to a study performed by the Government Accountability Office (GAO), the United States' share in global nuclear commerce has declined substantially in recent years.[29] Between 1994 and 2008, the United States' share of global exports in nuclear reactors, major components & equipment, and minor reactor parts has declined from 11% to 7%. During this 14 year period, total global exports tripled from $1.5 billion in 1994 to $4.3 billion in 2008. Similarly, the United States' share in natural and enriched uranium has also declined: in 1994, United States-based firms exported $1.8 billion in reactor fuel out of a global market of $6.2 billion, but by 2008 these firms only accounted for $1.6 billion of a market that had grown to $16.1 billion. While the global market for

[27] "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013." U.S. Energy Information Administration (EIA). January 28, 2013. Accessed February 04, 2014. http://www.eia.gov/forecasts/aeo/electricity_generation.cfm.

[28] Smith, Rebecca. "United States Electricity Use on Wane." The Wall Street Journal. January 2, 2013. Accessed February 05, 2014. http://online.wsj.com/news/articles/SB10001424127887323689604578217831371436110.

[29] *Nuclear Commerce: Governmentwide Strategy Could Help Increase Commercial Benefits from U.S. Nuclear Cooperation Agreements with Other Countries*. Government Accountability Office. GAO.gov. November 2010, p. 3. Accessed July 16, 2013. http://www.gao.gov/new.items/d1136.pdf.

nuclear power plant equipment and fuel has grown substantially, the United States' industry has stagnated in global commerce, just like it has in domestic markets for electricity.

For these reasons, innovation in nuclear energy has been needed for some decades, and the industry has high hopes for SMR.

Economics & Finance

The nuclear industry had typically relied upon economies of scale (i.e. making larger and larger plants) to achieve efficient per MW cost efficiencies, however SMR permits the use of modularity to facilitate the benefits garnered from economies of mass manufacturing.[30] In the United States, the vast majority of nuclear builds have historically been site-specific, meaning that the plant designs were tailored to the particular topography of the site. Additionally, the balkanized nature of the United States utilities between regulated and deregulated electricity markets leads to a very disjointed approach to reactor diffusion that neutralizes the benefits that economies of scale might provide. This approach has proven ineffective, as the economics of nuclear energy in the United States show an energy technology that continually becomes more expensive over time, a clear departure from what one might expect with continual technological progress. The standardization of nuclear plant designs, repeated construction of these designs by the same firms, multi-reactor siting, and multiple reactors of the same design operated by the same utility have all proven to be more economically efficient approaches, as will be discussed later in this paper. Comprehensive analyses of the economic struggles of large-scale nuclear energy in the United States have been performed by Cooper on several occasions, and a common theme in his findings is that the nuclear industry greatly has a tendency to overestimate the benefits of economies of scale.[31] [32] Cooper's somewhat pessimistic approach toward nuclear

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[30] Rosner, Robert, and Stephen Goldberg. *Small Modular Reactors - Key to Future Nuclear Power Generation in the U.S.* Center for Strategic & International Studies. CSIS Past Events. December 1, 2011. Accessed August 13, 2013. https://csis.org/files/attachments/111129_SMR_White_Paper.pdf.

[31] Cooper, Mark. *Policy Challenges of Nuclear Reactor Construction, Cost Escalation and Crowding Out Alternatives*. University of Vermont Law School Publications. September 2010. Accessed February 8, 2014. http://www.vermontlaw.edu/Documents/IEE/20100909_cooperStudy.pdf.

economics is a necessary contrast to the optimism Rosner et al., as a thorough understanding of the failures of large nuclear are needed to provide SMR an opportunity to test the market.

The goal of SMR production is to shift away from economies of scale toward economies of mass manufacturing. Producing a higher volume of units in a factory setting provides the opportunity for the workforce to improve manufacturing techniques, thereby increasing efficiency and reducing the time it takes to complete a unit. These learning effects have been made famous by mass production specialists like Henry Ford, but also have utilized by industries closely associated with nuclear energy, such as nuclear submarine manufacturing.[33] Not only does the fabrication process become more streamlined, but materials are used more effectively, quality control can be maintained at a superior level, and regulatory impacts can be softened through the implementation of in-factory inspections. The idea is to capitalize on design standardization and repeated production leading to learning efficiencies that will improve cost performance. An additional challenge this approach is designed to solve is the issue of the maintenance of a highly skilled production workforce. Using modular construction techniques at a central factory would consolidate the workforce at one location and maximize the potential improvements of learning.[34] In effect, with SMR the industry intends to transition away from economies of scale toward economies of standardized mass production to enhance its ability to learn.

Mass production of smaller, modular reactors also can provide solve the problems faced by manufacturing the massive pressure vessels needed for large nuclear plants. The smaller size of SMR units permits domestic manufacturing, whereas large reactors require production facilities that no longer exist in the United States. Heavy forgings are needed to produce pressure vessels for large units like the

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[32] Cooper, Mark. *Renaissance in Reverse: Competition Pushes Aging U.S. Nuclear Reactors to the Brink of Economic Abandonment*. University of Vermont Law School. Illinois Public Media. July 18, 2013. Accessed February 8, 2014. http://will.illinois.edu/nfs/RenaissanceinReverse7.18.2013.pdf.

[33] U.S. Department of Energy "A Strategic Framework", p. 3.

[34] Sarkisov, A. A. "A New Direction for Development - Low-Capacity Nuclear Power." *Atomic Energy* 111, no. 5 (March 2012): 309-11. Accessed August 15, 2013. http://link.springer.com.ezproxy.library.tufts.edu/content/pdf/10.1007%2Fs10512-012-9494-9.pdf.

Westinghouse AP1000, which requires a 15,000 tonne press taking 350 tonne steel ignots.[35] Forgings of this type are rare, and are limited to a few foreign vendors, like Japan Steel Works and Doosan Heavy Industries in South Korea, which makes this area of the nuclear industry a "pinch point" that limits vendors' capabilities.[36] [37] But because SMR units do not require heavy forgings with this capability, they can be manufactured in the United States much more readily than their larger counterparts. Not only could they provide the domestic nuclear industry a much needed boost in productivity, but it would enable stronger learning feedbacks into the economy of mass manufacturing.

Because they are significantly smaller in capacity than their large-scale counterparts, SMRs require reduced amounts of upfront capital, and also have lower operating costs. Lower capital costs reduce the financial risks to utilities and governments looking to invest in nuclear. Currently under construction, units 3 & 4 at the Vogtle site in Georgia will cost in the range of $14 billion to complete, a massive sum by anyone's standards.[38] In the United States, even large utilities have limited market capitalization ($19 billion at most), making any investment in nuclear a "bet the farm" type of transaction.[39] The total cost of an SMR plant would be a fraction of this amount, making it a more attractive investment with lower risk. Large nuclear plants tend to face extensive construction delays that result in escalating costs due to re-planning, re-working, material shortages, labor, among many other sources. Shorter construction periods (24-36 months for SMR, at least 48 for large nuclear power plants) could also assist financing efforts by utilities, especially if the interest rates are high.[40] Because units can be built more quickly than larger plants, there is a more rapid return on investment,

[35] "Heavy Manufacturing of Power Plants." World Nuclear Association. August 2013. Accessed August 14, 2013. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Heavy-Manufacturing-of-Power-Plants/.

[36] United States Department of Commerce. "The Commercial Outlook for U.S. Small Modular Nuclear Reactors." U.S. Department of Commerce Online. February 2011, p. 2. Accessed July 10, 2013. http://www.trade.gov/publications/abstracts/the-commercial-outlook-for-us-small-modular-nuclear-reactors.asp..

[37] Ingersoll, D.T. "Deliberately Small Reactors and the Second Nuclear Era." *Progress in Nuclear Energy* 51.4-5 (2009): 589-603. *Science Direct*. 2009. Web. 4 Sept. 2013. http://www.sciencedirect.com/science/article/pii/S0149197009000171.

[38] Wald, Matthew L. "Atomic Power's Green Light or Red Flag." The New York Times: Energy and Environment. June 11, 2013. Accessed August 15, 2013. http://www.nytimes.com/2013/06/12/business/energy-environment/nuclear-powers-future-may-hinge-on-georgia-project.html?pagewanted=all&_r=0.

[39] *Statement of Peter Lyons Assistance Secretary for Nuclear Energy U.S. Department of Energy Before the Subcommittee on Energy and Water Development, and Related Agencies Committee on Appropriations*, US Senate Cong., 1-6 (2011) (testimony of Peter Lyons).

[40] Rosner, Goldberg & Hezir. *Small Modular Reactors - Key to Future Nuclear Power Generation,* p. 14.

and utilities can use income generated from the initial SMRs at a site to fund additional units that are added in parallel. Smaller plants also could require fewer operations and security personnel, thereby reducing costs even further.[41] Finally, some rather optimistic scholars have suggested that SMR could even become cost competitive with natural gas-fired electricity generation in the United States.[42] While it may be a stretch to anticipate that level of competitiveness today, it should certainly be a long-term goal for the technology. Should this be achieved, would make the technology a sound investment that many utilities might look into to diversify their electricity generation portfolios.

Siting Flexibility

Large nuclear plants also suffer from a profound siting inflexibility, which limits their applicability in the market. There are many factors that come into play in where a power plant can be built, including "not-in-my-backyard" (NIMBY) opposition, cooling water availability, accident planning, and the location of electricity demand. SMRs are being designed to be used in a variety of applications where a large power plant may not be necessary or even possible. Some of these niche markets targeted for these plants include areas that are remote or isolated, have low electricity demand requirements, experience slow demand growth, have high electricity generation costs, lack the necessary infrastructure for larger plants, installations where energy security is critical (military bases), or are areas where the heat and desalination capabilities of SMR are as valuable as the electricity that the plant would produce.[43] Transporting electricity or heat over great distance would incur unacceptable losses in remote areas, making long-range transmission uneconomic. Small nuclear units would also make attractive options for replacing retiring fossil fuel plants, potentially just adopting a "plug and go" policy that utilizes the existing electrical infrastructure and components left behind by the

[41] U.S. Department of Commerce, "The Commercial Outlook for U.S. Small Modular Nuclear Reactors" p. 3.
[42] Rosner, Goldberg & Hezir. *Small Modular Reactors - Key to Future Nuclear Power Generation,* p. 21.
[43] Alekseev, P. N., S. A. Subbotin, V. A. Stukalov, and T. D. Shchepetina. "System of Low-Capacity Nuclear Power Plants as a Strategic Direction for National Security." *Atomic Energy* 111, no. 5 (March 2012): 316-17. Accessed August 15, 2013. http://link.springer.com.ezproxy.library.tufts.edu/content/pdf/10.1007%2Fs10512-012-9496-7.pdf.

retired plant.[44][45] Finally, SMR could be useful in providing base-load electricity to supplement the intermittent electricity production of renewables, especially when a decentralized electrical grid approach is used.

Siting flexibility also would enable the addition of SMR units in parallel on an as-needed basis, so utilities can construct new units on a pace that matches demand growth. A single site could have anywhere from 1 to 12 units that require infrequent refueling, and incremental additions to capacity would make financing the plants easier as well. Additionally, SMRs also have lower heat exchange requirements of large nuclear plants, making it possible for the use of air cooling where large bodies of water are unavailable, which opens up more opportunities for deployment. With the enhanced safety characteristics discussed below, there is a possibility of reducing the emergency planning zones (EPZ) for SMRs to be a fraction of what large nuclear power plants currently require.[46] This would present the possibility of deploying units in closer proximity to industrial or residential areas, depending on the NIMBY interest of the local community. This would also reduce the costs of EPZ planning, which is a key point of SMR vendors who are looking to make their units competitive in energy markets. In these ways, the greater flexibility of SMR over large nuclear plants could engender interest from a wider range of markets than simply large-scale electricity production.

Safety

The issues raised by Fukushima make the safety of nuclear power plants a primary consideration in new reactor design and many SMRs has been specifically engineered to meet the challenge of enhancing reactor safety. SMR designs currently being developed are Generation III+ or Generation IV reactors, which are advanced design units that incorporate a variety of new safety features that are not present in many reactors operating today. Added emphasis is placed on the incorporation of passive safety characteristics that utilize gravity-driven or natural convection systems instead of pump-driven systems to supply backup cooling in unusual circumstances.[47] This means there are fewer pumps, valves, and systems required for maintaining

[44] US DOE, "Small Modular Nuclear Reactors".
[45] Kuznetsov & Lokhov, "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors", 25.
[46] Kuznetsov & Lokhov, "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors", 59.
[47] Rosner, Goldberg & Hezir. *Small Modular Reactors - Key to Future Nuclear Power Generation, p. 5.*

safety, thereby reducing the opportunities for equipment failures. Passive safety features also minimize the need for operator action during casualties, meaning there are fewer opportunities for human error, and should the control room need to be evacuated, the plant can provide cooling functions independently for an extended period of time. Most units are designed to be installed in underground containment structures and include other post-Fukushima safety modifications, thereby reducing the vulnerability of the plants to seismic events.

Small reactors also possess several other advantages in safety over conventional large nuclear power plants. The core damage frequencies (statistical likelihood for core damage resulting in a release of radioactivity) for SMR designs are considered comparable to or better than the frequencies for state-of-the-art large light water reactors.[48] Analysis of SMR designs indicate that large early release frequencies (LERFs) are even less likely, being one order of magnitude less likely than the core damage frequencies.[49] Source terms, which are defined as the types and amounts of radioactive or hazardous material that would be released to the environment following an accident, are smaller for SMR than large reactors, thus minimizing potential adverse consequences if an incident did occur.[50] SMR's also possess a larger surface-to-volume ratio, which facilitates easier decay heat removal in the event of an emergency shutdown. Furthermore, some SMR designs operate with reduced amounts of non-nuclear forms of energy (pressure, temperature, chemical), which reduces the possibility of the containment vessel failing and external damage occurring. Finally, some events that could initiate a fuel failure in older reactors have been completely eliminated by design.[51]

Nonproliferation

The development of SMR has also introduced new opportunities to mitigate proliferation concerns that arise from the spread of nuclear power plants. Some vendors are offering new fuel cycle options,

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48 Kuznetsov & Lokhov, "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors", 59.
49 Kuznetsov & Lokhov, "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors", 128.
50 *Design Features to Achieve Defense-in-Depth in Small and Medium Sized Reactors (SMRs)*. International Atomic Energy Agency. IAEA Scientific & Technical Publications. 2009: p. 7. Accessed August 15, 2013. http://www-pub.iaea.org/books/iaeabooks/8094/Design-Features-to-Achieve-Defence-in-Depth-in-Small-and-Medium-Sized-Reactors-SMRs.
51 Kuznetsov & Lokhov, "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors", 136.

including a “black-box” option where the unit is fueled by a nuclear battery.[52] This means that the unit is fueled at the manufacturing plant, shipped as a completed product to the site, and then shipped back to the same facility intact for decommissioning, meaning that the “battery” will remain sealed for the entire life of the reactor. This allows for the learning improvements mentioned previously, while also addressing security and nonproliferation concerns related to nuclear materials. Other units are designed with enough spent fuel pool space inside the containment structure to safely store the unit’s lifetime use of spent nuclear fuel, minimizing the amount of fuel transfers that might be hijacked or diverted for weapons purposes. Additionally, many SMR units are being designed to be constructed below grade, which reduces the points of access of the plant and also makes an external attack more challenging.[53] Finally, the majority of SMR designs being developed by United States-based vendors are of the light water variety which utilizes low-enriched uranium (LEU). While is not a perfect solution to preventing diversion of the fuel for weapons use, this does greatly diminishes the fuel’s weaponization potential.

Nonproliferation issues have played a critical role in the failure of nuclear innovations in the past, as the issues of spreading nuclear weapons technology undermined the nuclear industry’s attempts to advance an alternative to light-water reactor technology. An example of this in action is the Clinch River Breeder Reactor Project, a program initiated in 1970 to develop a sodium-cooled fast-neutron reactor that could be used to generate more reactor fuel than it consumed.[54] Concerns over long-term uranium availability during this period led to increased interest in nuclear fuel independence, and the unique design of a liquid-metal fast breeder reactor enabled it to produce material that could be reprocessed and used for fuel. However, the Indian nuclear weapon test of 1974 proved to be a nasty surprise for the United States in many ways, and led

[52] U.S. Department of Commerce, “The Commercial Outlook for U.S. Small Modular Nuclear Reactors” p. 4.
[53] US DOE, “Small Modular Nuclear Reactors”.
[54] Griffith, J. D., D. E. Thornton, P. Dastidar, L. E. Roberts, R. H. Allardice, and F. Penet. "The Fast-Neutron Breeder Fission Reactor: Development, Operational Experience, and Implications for Future Design in the United States [and Discussion]." *Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Scienes* 331, no. 1619 (June 28, 1990): 323-38. Accessed February 05, 2014. http://www.jstor.org/stable/53626.

to a period of intense scrutiny of the proliferation of nuclear technology. [55] It is important to note that United States SMR designs uses light-water reactor technology based on LEU, which while imperfect from a nonproliferation perspective, greatly limits the potential for any hijacked fuel from being transformed into weapons-grade material. So despite the grave security concerns about new developments in reactor technology, the SMR approach is one of the more benign designs and does not create additional proliferation risks.

Existing Benefits of Nuclear Energy

Nuclear energy has struggled in the face of strengthening competition in recent years from other sources of baseload electricity, but with some help from innovation, nuclear can attempt re-capitalize via SMR through some critical pre-existing advantages. Innovations in shale gas recovery have facilitated the rapid adoption of natural gas-fired plants in the United States, especially the highly efficient combined-cycle gas turbines.[56] According to the United States Energy Information Administration (EIA), 77% of domestic electricity generating capacity additions in the years between 1990 and 2011 were natural gas-fired plants, and this trend is projected to continue through 2040. Natural gas has vulnerabilities that can nuclear does not, such as fuel price instability, energy security issues, and greenhouse gas (GHG) emissions. The benefits of nuclear energy can be realized if SMR is successful in mitigating some of the problems the nuclear industry has created for itself.

Adding small nuclear to the energy portfolio can assist in a state's energy security, and help minimize the adverse economic impacts of fuel price fluctuations for utilities and consumers.[57] Energy security is a common goal for many states' energy policies, though a significant number of large economies lack the

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[55] Vine, Gary. *Abridged History of Reactor and Fuel Cycle Technologies Develpment: A White Paper for the Reactor and Fuel Cycle Technology Subcommittee of the Blue Ribbon Commission*. The Blue Ribbon Comission. UNT Libraries, p. 2. Accessed July 22, 2013. http://cybercemetery.unt.edu/archive/brc/20120621004807/http://brc.gov/sites/default/files/documents/vine_abridged_history_of_reactor_and_fuel_cycle_technologies_development_final.pdf.

[56] United States EIA*, Annual Energy Outlook 2013,* p. 39*.*

[57] Alekseev, et al., "System of Low-Capacity Nuclear Power Plants", p. 318.

domestic energy resources to achieve any degree of energy security. Japan needs to import 84% of its energy requirements, and the Republic of Korea is even more vulnerable to global fuel price shocks at 96%.[58 59] This is why both states have pursued nuclear as a major factor in the country's energy portfolio: to achieve some degree of stability in their economy that could otherwise be hamstrung by spiking fossil fuel prices.[60] The United States has a great supply of shale gas that has many claiming victory in the battle for energy security, but should the country opt to export this gas to foreign markets where prices are much higher, this could give SMR the opportunity that is needed for utilities to diversify their energy portfolios.

Emissions from nuclear energy are among the lowest of all energy resources.[61] Studies have shown that cumulative life-cycle GHG emissions from nuclear range between 2.8 and 24 grams of carbon dioxide equivalent per kilowatt hour equivalent (gCO_2e/kWh_e), which is close to wind and hydro (8-30 gCO_2e/kWh_e and 1-34 gCO_2e/kWh_e respectively) lower than solar photovoltaic (43-73 gCO_2e/kWh_e), biomass (35-99 gCO_2e/kWh_e), and significantly lower than natural gas (360-575 gCO_2e/kWh_e) and coal (950-1250 gCO_2e/kWh_e)[62] This argument in favor of nuclear energy has almost become a cliché, but given the growing importance of climate change in many country's energy policies, this characteristic alone keeps nuclear energy as a viable option in some states that may abandon it for safety and security concerns. Because of the intermittent nature of renewable technologies like wind and solar, SMR could be used to meet the small-scale electricity demand in areas that are poor in wind and solar energy resources, or even provide baseload stability where wind and solar are in high use. This would enable governments to meet their country's energy needs while simultaneously achieving their climate change mitigation agenda. In June of 2013, President Barack Obama announced his Climate Action Plan, which targeted the closure of ageing coal-fired power plants to

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[58] "Japan." IAEA PRIS. August 14, 2013. Accessed August 14, 2013. http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=JP
[59] OECD IEA, *The Republic of Korea 2012 Review*, p. 26.
[60] As a result of Fukushima, Japan's energy policy has experienced tremendous pressure to shift away from nuclear. But for the time being, the government may be forced to restart many plants just to meet electricity demand.
[61] Weisser, Daniel. "A Guide to Life-cycle Greenhouse Gas (GHG) Emissions from Electric Supply Technologies." *Energy* 32, no. 9 (September 2007): 1549. Accessed August 14, 2013. doi:10.1016/j.energy.2007.01.008.
[62] Weisser, "A Guide to Lifecycle Greenhouse Gas Emissions", p. 1543-1559

reduce GHG emissions.[63] While not explicitly stated in either the speech or subsequent White House publications, SMR could play a major role in supporting this policy action.

Other recent developments point to opportunities for nuclear to retake market share through innovation. Global health as it relates to energy use is a growing concern, and a study performed at the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies found that the use of nuclear energy has prevented an estimated 1.84 million deaths between 1971-2009 that otherwise would have occurred had nuclear energy production had been replaced by fossil fuels.[64] The study also found that nuclear had the fewest deaths per terawatt of baseload electricity generation methods, with nuclear only averaging 0.074 deaths per TWh (with a total of 4900 deaths attributed to nuclear) while coal caused 28.67 per TWh and natural gas 2.821 deaths per TWh. In China, coal was estimated to cause 77 deaths per TWh, an shockingly high number that demands a shift in energy policy. The NASA study also found that nuclear energy adoption has prevented approximately 64 gigatonnes of CO_2 equivalent, a victory for those concerned with the effects of climate change. In a separate study based in Northern China, it was found that air pollution from use of coal in fuel burners for heat reduced life expectancies for residents north of the Huai River by 5.5 years, resulting in the loss of 2.5 billion life years for the 500 million residents considered.[65] While these fuel burners were not used for electricity but for heat instead, the use of coal as an energy source has profound health implications, and electricity generated by nuclear can be used to produce heat.

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[63] *President Obama Speaks on Climate Change*, The White House

[64] Kherecha, Pushker A., and James E. Hansen. "Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power." *Environmental Science & Technology* 47 (March 15, 2013): 4889-895. Accessed June 11, 2013. doi:dx.doi.org/10.1021/es3051197.

[65] Chen, Y., A. Ebenstein, M. Greenstone, and H. Li. "Evidence on the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China's Huai River Policy." *Proceedings of the National Academy of Sciences* 110, no. 32 (2013): 12936-2941. Accessed February 8, 2014. doi:10.1073/pnas.1300018110.

Literature Review: Energy Technology Innovation System, the Valley of Death, and Studies in Nuclear Innovation

Previous Studies in Nuclear Innovation

Gallagher et al. (2006) noted that public R&D funding in energy technology is a key input metric of innovation policy.[66] This is one area where nuclear has no excuses for failing to innovate, as tremendous amounts of public funds have been allocated to national laboratories in the United States in the sixty-plus year history of nuclear industry. According to a study performed by the Congressional Research Service, nuclear has received an estimated 49.3% of all energy technology R&D funding from the Department of Energy between the years of 1948 and 2012 (see Figure 1).[67] Over that 65 year period nuclear has received a total of $95.69 billion in funding, double the combined funding toward all of fossil fuel energy resources (natural gas, petroleum, coal, etc.) and far more than any individual source. While the trend has shifted toward a much more balanced portfolio in recent years as evidenced by Figure 1, nuclear still receives the bulk of funding from the DOE.

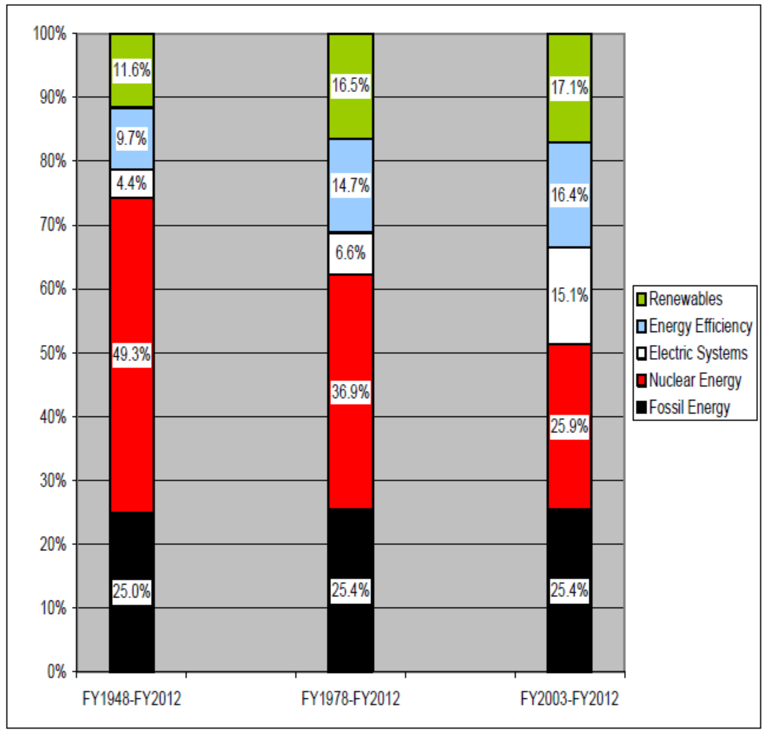

Figure 1: DOE Energy Technology Share of Funding, Comparison over Three Periods. Source: Sissine, Renewable Energy R&D Funding, p. 7.

[66] Gallagher, Kelly Sims, John P. Holdren, and Ambuj D. Sagar. "Energy-Technology Innovation." *Annual Review of Environment and Resources* 31, no. 1 (2006): 193-237. Accessed August 16, 2013. doi:10.1146/annurev.energy.30.050504.144321.

[67] Sissine, Fred. *Renewable Energy R&D Funding History: A Comparison with Funding for Nuclear Energy, Fossil Energy, and Energy Efficiency R&D*. Congressional Research Service. Federation of American Scientists. March 7, 2012. Accessed November 30, 2013. http://www.fas.org/sgp/crs/misc/RS22858.pdf.

In terms of outputs, a useful measure for determining the output of innovation efforts is the tracking of patents approved for an energy technology. Patent tracking is not a perfect metric, due to the value of some patents differing from others, but it can be used as a proxy for the relative private interest in a particular energy technology. Bettencourt, Trancik and Kaur found that while nuclear has received a high rate of public support, the rates of patent acquisition are strikingly low (see Figure 2).[68] This incongruity was attributed to slow market growth for nuclear, whereas rapidly growing markets for renewables has led to a surge in patent filing despite what the authors considered moderate public support. While the low rate of patents issued for nuclear energy technologies could be considered problematic for the United States' industry, the trend is global, suggesting that innovation has stalled with nuclear fission relative to other energy sources.

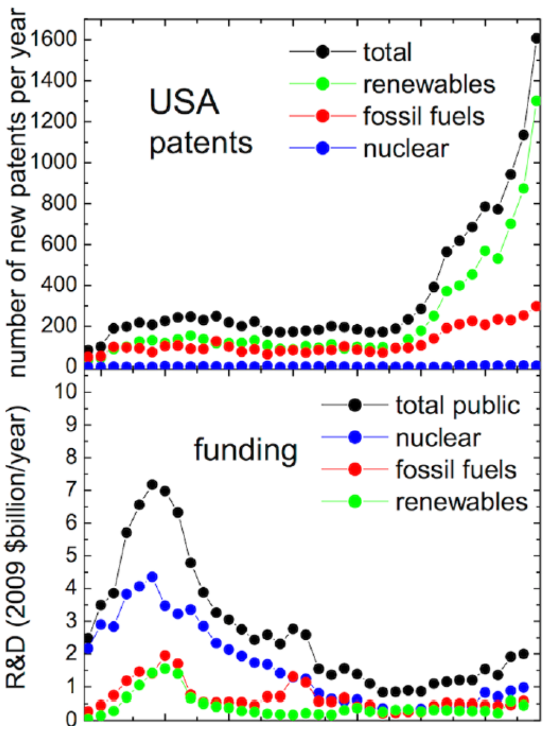

Figure 2: Temporal Trends in United States Energy Patents. Adapted from Bettencourt, Trancik, and Kaur.

The maturity of nuclear technology also plays a role in limiting the innovation potential, but can also prove to be a limiting factor in the direction in which innovation moves. A study performed by Winkel et al. found that because nuclear is considered a mature energy technology, the pathways for innovation have already been established, which serves as both a benefit and a hindrance.[69] Innovation can be supported through the substantial institutional, organizational, and financial resources that exist within industry and government, but also can be limited to incremental improvements that offer diminishing returns or inadequate responses to radically changing socio-economic contexts. This challenge was also noted by Cowan in his study on

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[68] Bettencourt L.M.A., Trancik J.E., Kaur J."Determinants of the Pace of Global Innovation in Energy Technologies." PLoS ONE 8(10), 2013. DOI:10.1371/journal.pone.0067864.

[69] Winkel, Mark, Nils Markusson, Henry Jeffrey, Chiara Candelise, Geoff Dutton, Paul Howarth, Sophie Jablonski, Christos Kalyvas, and David Ward. "Learning Pathways for Energy Supply Technologies: Bridging Between Innovation Studies and Learning Rates." *Technological Forecasting and Social Change*, 2013, 1-19. Accessed August 11, 2013. http://www.sciencedirect.com/science/article/pii/S0040162512002612.

technological lock-in of light water reactors (LWR) in the United States.[70] Cowan wrote that the commercial nuclear industry was built on the infrastructure laid by the aforementioned Admiral Rickover's nuclear Navy, thereby "locking" the nuclear industry into the same path. The long-lived nature of nuclear infrastructure compounds this problem, as old stock is slow to turnover as power plant lifetimes are extended.

Technological lock-in can extend beyond industrial production and infrastructure, as Cowan also noted its impact on the regulatory structure. Indeed, a great deal of discussion has taken place during pre-licensing meetings for SMR between the industry, the DOE, and the United States Nuclear Regulatory Commission (NRC) about the applicability of the NRC's licensing framework to even the light water-cooled SMR units.[71] [72] While the consensus is that the current framework is suitable, should any changes to existing regulations be required to safely license SMR units, bureaucratic inertia could create significant delays in the licensing process that could lead to project cost escalations and potentially the failure of an innovation. For example, a widely supported change in NRC regulations proposing the removal of hydrogen recombiners from the design basis of large pressurized water reactor (PWR) containments was initiated in 1992 and did not receive final approval until 2003.[73] With market conditions difficult to predict ten years into the future, the efficacy of attempts at innovation in nuclear could very well be vulnerable to regulatory delays that could render the technology obsolete by the time it is ready for the market.[74]

Lock-in on a large scale can also limit the pace of innovation, and the nuclear industry's emphasis on achieving economy of scale benefits may be hindering efforts at innovation. Trancik's study on innovation

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[70] Cowan, Robin. "Nuclear Power Reactors: A Study in Technological Lock-In." *The Journal of Economic History* 50.3 (1990): 541-67. *JSTOR*. Cambridge University Press. Web. 6 Sept. 2013. http://www.jstor.org.ezproxy.library.tufts.edu/stable/pdfplus/2122817.pdf?acceptTC=true.

[71] *Interim Report of the American Nuclear Society President's Special Committee on Small and Medium Sized Reactor (SMR) Generic Licensing Issues*. The American Nuclear Society: Publications Index. July 2010. Accessed July 15, 2013. http://www2.ans.org/pi/smr/ans-smr-report.pdf.

[72] United States Nuclear Regulatory Commission. *Report to Congress: Advanced Reactor Licensing*. NRC Document Collections. August 2012: p. 9. Accessed August 20, 2013. http://www.nrc.gov/reading-rm/doc-collections/congress-docs/correspondence/2012/frelinghuysen-08-22-2012.pdf.

[73] *Interim Report of the American Nuclear Society, p. 36.*

[74] For another informative example of regulatory delays hindering nuclear innovation, see Appendix A for the story of Offshore Power Systems, a radical innovation in nuclear energy that was stymied by market and geopolitical events that occurred while awaiting NRC approval for a manufacturing license.

rates in photovoltaics (PV) and nuclear fission found that the size of a particular energy technology directly affects its responsiveness to policy interventions.[75] This is a rather intuitive notion, as it is significantly less expensive to design and demonstrate a series of PV panels ranging between 100 W and 100 MW than a large 1000 MW-size nuclear power plant. While the article's conclusions were meant to prove that investments in PV systems were preferred to nuclear in the effort to mitigate climate change in a cost-effective manner, Trancik 's results imply that development in small scale reactors could enable the nuclear innovation process. However, Trancik also reiterates the challenges that nuclear faces in technological lock-in, so while smaller-scaled approaches through SMR may theoretically appear advantageous, overcoming the industrial inertia of the incumbent technology and regulatory framework is still problematic.

Technological lock-in is especially problematic in the United States, because the number of variations in the LWR technology that dominates the market reduces learning effects that would otherwise provide economic benefits. Learning effects or learning-by-doing is the capability of workers to improve their productivity by performing a task repeatedly, improving their economic efficiency through practice and minor innovations, and is most famously discussed by Arrow.[76] Because the nuclear industry in the United States constructs each nuclear power plant for the specific topography of the site where the plant is to be built, there is little repetition in the process. A study performed by McCabe found that the variations in nuclear plant design were sufficient in reducing the learning, especially when the work was contracted out to different principals.[77] Site-customized nuclear power plant builds mean that the same plant will never be constructed again, and often subsequent plants use different workers, which further reduces the learning potential that could improve the economics of the plants.

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[75] Trancik, J. E. "Scale and Innovation in the Energy Sector: A Focus on Photovoltaics and Nuclear Fission." *Environmental Research Letters* 1, no. 1 (2006): 014009. Accessed October 29, 2013. http://iopscience.iop.org/1748-9326/1/1/014009.
[76] Arrow, Kenneth J. "The Economic Implications of Learning by Doing." *The Review of Economic Studies* 29.3 (1962): 155-73. *Social Science Research Network*. Web. 30 Nov. 2013. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1506343.
[77] McCabe, Mark J. "Principals, Agents, and the Learning Curve: The Case of Steam-Electric Power Plant Design and Construction." *The Journal of Industrial Economics* 44, no. 4 (December 1996): 357-75. Accessed September 10, 2013. http://www.mccabe.people.si.umich.edu/JIE.pdf.

Studies performed on the learning effects for nuclear technology showed early benefits from learning, but on a long enough timeline, learning is typically negative, meaning costs go up. A study conducted from 1960-1979, Ostwald and Reisdorft reported early learning rates of 18.7% to 21.7% in nuclear plant construction in the United States, but the evolution of plant cost shows discontinuity, where they found a -29.4% learning rate for plant construction after 1973.[78] [79] A study by Zimmerman in 1982 showed a strong correlation with positive learning-by-doing, where the second nuclear plant built had a cost reduction of 11.4% from the first, and the third plant cost reduction would be about 4% from the second.[80] However, Zimmerman also found that learning in nuclear might reduce diffusion of the technology, as it would permit more accurate cost estimates which would deter many utilities from purchasing the increasingly costly nuclear plants. In terms of plant operation, Joskow and Rozanski found that learning-by-doing was a significant factor in improving plant reliability and operating capacity of nuclear power plants in the United States, but they also found that nuclear energy faced diseconomies of scale, meaning that the larger the plants the more costly they were per MW after a certain power level.[81] Finally, in a study performed by Grübler on French nuclear learning, it was found that the learning effects in both countries was negative, although the French were far more effective in mitigating cost escalations by using standardized plants, multi-unit siting, and maximizing inter-reactor learning (see Figure 3).[82]

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[78] Ostwald, Phillip F., and John B. Reisdorft. "Measurement of Technology Progress and Capital Cost for Nuclear, Coal-Fired, and Gas-Fired Plants Using the Learning Curve." *Engineering and Process Economics* 4, no. 4 (December 1979): 435-54. Accessed October 28, 2013. http://www.sciencedirect.com/science/article/pii/0377841X79900020.

[79] A 10% learning rate means that costs are reduced by 10% for each doubling of number of modules or plants. A negative learning rate implies that costs actually increase as cumulative production of the plants increases.

[80] Zimmerman, Martin B. "Learning Effects and the Commercialization of New Energy Technologies: The Case of Nuclear Power." *The Bell Journal of Economics* 13, no. 2 (1982): 297-310. Accessed October 28, 2013. http://www.jstor.org/stable/3003455.

[81] Joskow, Paul L., and George A. Rozanski. *The Effects of Learning By Doing on Nuclear Plant Operating Reliability*. Massachusetts Institute of Technology. September 1977. Accessed October 28, 2013. http://dspace.mit.edu/bitstream/handle/1721.1/63590/effectsoflearnin00josk.pdf?sequence=1.

[82] Grübler, Arnulf. "The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing." *Energy Policy* 38, no. 9 (May 2, 2010): 5174-188. Accessed September 2, 2013. doi:10.1016/j.enpol.2010.05.003.

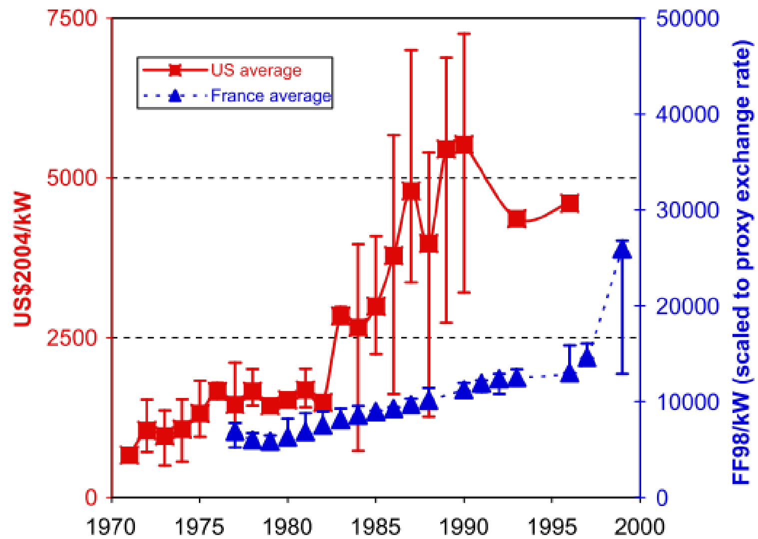

Figure 3: Comparison of French and United States nuclear construction costs, average and minimum/maximum per reactor completion year. Adapted from Grübler "The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing".

The results in international studies of nuclear learning were generally more positive, though again point to problems when introducing new plants. The Japanese experience in rapid nuclear deployment was more efficient than what occurred in the United States due to having greater numbers of multi-unit sites, information sharing networks, standardized designs which led to economic efficiencies through inter-reactor learning.[83] Favorable regulatory structure and reduced siting costs also contributed to limiting cost escalation. Comparisons between France and the United States by Lester & McCabe, as well as Grübler echoed these findings, as the studies found that the high level of standardization, centralized decision making, increased multi-unit siting, and inter-reactor learning from these practices assisted the French industry in limiting the cost escalations that have plagued the industry in the United States.[84] [85] However, despite the relative success in the cases of Japan and France compared to the struggles in the United States, these studies emphasized that negative learning invariably occurred over time.

There are presently no studies on the learning rates achieved for SMR production as they have yet to become commercialized. One paper utilizes projected learning rates for SMR production in the United States

[83] Navarro, Peter. "Comparative Energy Policy: The Economics of Nuclear Power in Japan and the United States." *The Energy Journal* 9, no. 4 (1988): 1-15. Accessed October 29, 2013. http://web.merage.uci.edu/~navarro/Vita05/JA%2029%20Comparative%20Energy%20Policy,%20The%20Economics.pdf.
[84] Grübler, "The Costs of the French Nuclear Scale-up", p. 5185.
[85] Lester, Richard K., and Mark J. McCabe. "The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation." *The RAND Journal of Economics* 24, no. 3 (1993): 418. Accessed October 29, 2013. http://mccabe.people.si.umich.edu/rand.pdf.

as part of a business plan for SMR commercialization. In a White Paper written for the Energy Policy Institute at Chicago (EPIC), Rosner, Goldberg & Hezir use learning rates to project cost reductions for SMR units to determine their commercial feasibility compared to natural gas-fired plants.[86] While Rosner et al. discuss various issues surrounding SMR, such as safety, licensing, design & engineering, and economics, their business plan for an SMR economy is the central focus of the paper. They created a hypothetical 100 MW SMR module as a basis for projecting costs, and found that the overnight cost estimate of LEAD plant (6 x 100 MW modules) would be in the range of $7,000-11,500 per kW, a very high price for a power plant. With the economic benefits of learning, they found that the best achievable overnight cost estimate for the nth-of-a-kind (NOAK) SMR plant to be $4770 per kW when 6 modules configured as a 600 MW plant. Total cost of such a project would be $3 billion, which would be similar in cost to a new 1,000 MW advanced pulverized coal power plant. This estimate is based on a 10% learning rate for capital (fixed) costs and a 2-3% learning rate for variable costs (operations & maintenance). Rosner et al. based these estimates on two key assumptions: learning rates would be equivalent to naval shipbuilding at Huntington Ingalls Industries' Newport News shipbuilding, and the SMR industry would receive sufficient orders that the industry could attract private investment for a SMR production factory (costing roughly $300 million). The rate of production needed to justify the construction of such a facility was estimated to be of a quantity of one 100 MW module per month for 54 months, which would allow the SMR industry to achieve the maximum effects of learning (see Figure 4).

[86] Rosner, Goldberg & Hezir. *Small Modular Reactors - Key to Future Nuclear Power Generation,* p. 14.

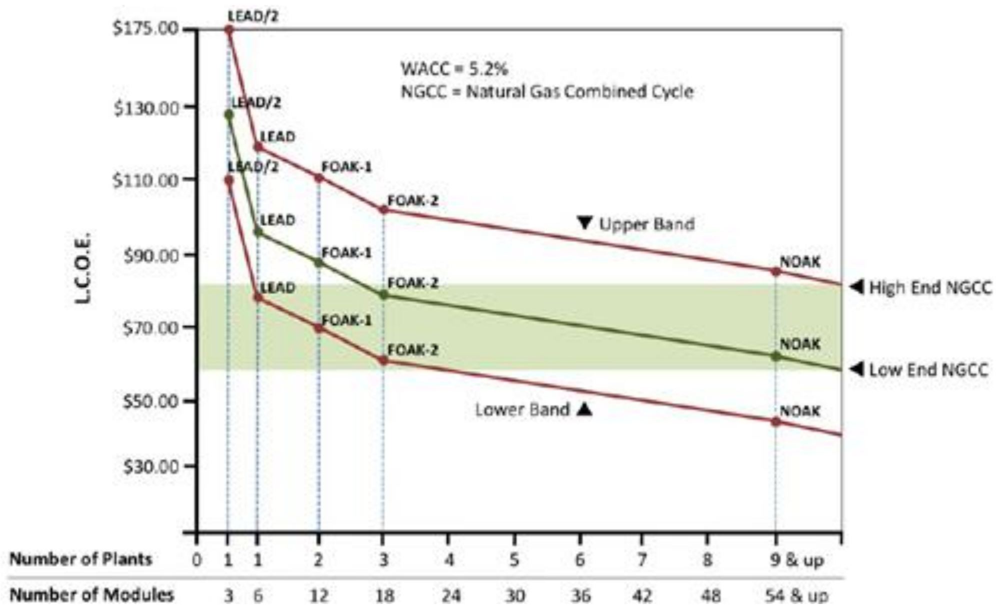

Figure 4: Levelized Costs of LEAD and Learning plants ($/MWh), adapted from Rosner et al., p. 21

Figure 4 was adapted from the EPIC White Paper to show how SMR would supposedly become competitive with natural gas combined cycle electricity generation with various learning rates. The tan band in the center reflects Rosner, Goldberg, & Hezir's projected natural gas levelized cost of electricity (LCOE) range, and the three descending parameters reflect the SMR LCOE based on learning rates of 3% (most pessimistic), 7% (moderate), and 10% (most optimistic). As evidenced by Figure 4, the scholars expect SMR to be cost competitive on a LCOE basis with natural gas if a 7% or greater learning rate is achieved.

The business plan for a SMR economy was outlined by Rosner et al. as having the five following stages:[87]

1. "Detailed design & engineering (DD&E)": This stage assumes a $1 billion price tag for developing a single SMR design and designing a manufacturing facility. For this stage, the authors recommend a 50-50 cost share with the federal government. The DOE's SMR LTS program as it relates to B&W's mPower unit fits the bill as such a mechanism, thus enabling the industry to complete this stage.
2. "LEAD Commercial Deployment": The LEAD plant, or the first-of-a-kind (FOAK) plant, must be deployed as a demonstration. The authors recommend a production tax credit to facilitate the higher

[87] Rosner, Goldberg & Hezir. *Small Modular Reactors - Key to Future Nuclear Power Generation,* p. 33-36.

costs of such a unit. This stage is partially accounted for by TVA's purchase of 1-6 mPower units, though no electricity generation incentives for SMR currently exist.

3. "SMR Manufacturing Facility": At this stage, an "order book" of sufficient quantity must be accumulated for the nuclear industry to justify construction of a $300 million facility where SMR modules can be mass produced. There are significant disincentives to be an early adopter of SMR, as the early plants will cost substantially more than those produced later. Furthermore, how early adoption of SMR to fill the order book is not addressed by Rosner et al. other than suggesting a production tax credit and represents a significant gap in the business plan.
4. "SMR Commercial Learning Deployment": This is where the learning rates come into play. Maximum learning rates must be achieved while production of the units is in progress to make the SMR plants competitive with natural gas. How the facility is to achieve the maximum learning rate of 10% is not discussed, except that such a rate is possible is a comparable industry (shipbuilding).
5. "Fully Commercial, Competitive SMR Industry": This stage is achieved when SMR achieves widespread diffusion into the market and orders for plants are continuous.

The two key points of contention that this writer has with the SMR business model are the processes by which an order book is developed, and how exactly a maximum learning rate could be achieved.

Literature Review: Conclusion

The lessons from the literature review must be reiterated going forward, as the findings of the scholars will be echoed in the analysis on submarine innovation to come. The economics of nuclear energy prove to be a limitation in the innovation process, and will likely be the major obstacle to the United States nuclear industry's attempt to commercialize SMR. Despite high R&D support in the United States, costs are persistently high and uncompetitive. Also, the prevailing theory of economies of scale seems to have been proven ineffective using the current approach by the nuclear industry. While nuclear is a mature technology that should theoretically benefit from having paths of innovation established, the ineffectiveness of the nuclear industry's current approach being "locked in" on the large scale, light-water reactor technology may inhibit its ability to radically innovate. From the literature it is clear that standardization of plant designs, repeated construction of these plants, inter-reactor learning, and a fleet-wide support network are critical factors in limiting cost escalations. These are the lessons that must be brought forward for SMR, if new reactor innovations are to avoid the cost escalations that have stymied nuclear expansion in the last few decades. Furthermore, these practices should be incorporated as part of the SMR Business Plan advocated by Rosner et al. It is likely that the SMR approach targeting economies of mass manufacturing recognize that the approach used by the French and Japanese is more efficient than that used by the United States, so the next topic to be addressed is how to turn this approach into something embraced by all involved in the processes of innovating nuclear technologies. The cases of France and Japan point to a very tightly knit network that operated in close synchronization to create a systematic process for commercializing reactor technology. The topic of innovation systems is a relatively new field, especially in relation to energy technologies, so this paper will now turn to develop a greater understanding on how innovation processes work and how they can be enhanced.

Innovation and Energy Technology

In recent years a great amount of progress has been made in academic circles on understanding ways in which innovation occurs in energy technologies, but significant gaps remain, especially in how these systems relate to nuclear and SMR. Common conceptions of innovation assume that a technology follows a predetermined linear life-cycle that moves sequentially from invention, develops into a mature technology over time, and then ultimately falls into decline as "better" technologies are developed. In reality, innovation is a much more dynamic and decidedly non-linear process. It has been described as an "…interactive process involving a network of firms and other economic agents that, together with the institutions and policies that influence their innovative behavior and performance, bring new products, processes, and forms of organization into economic use", making an argument that innovation is not merely a single action leading to a known result, but a series of processes that are susceptible to a wide variety of inputs that continually influence the path a particular technology follows. [88] Instead of a unidirectional movement toward an inevitable product, innovation is a process of matching technical possibilities to market opportunities, involving multiple layers of interaction that is affected by processes of learning. .[89] [90] Taking this idea to the next level, an innovation *system* is considered "the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge" which adds another layer in our thinking on how technology is developed. [91] A system is what is necessary for SMR to overcome the obstacles the nuclear industry has created for itself.

The process of energy technology innovation required an even more specific approach than a typical innovation system, as energy technologies in general face much higher capital costs than most technological innovations, and also represent a major focus of governments in terms of policy. An innovation systems

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[88] Johansson, Thomas B., and Arnulf Grübler. "Policies for the Energy Technology Innovation System." In *Global Energy Assessment (GEA)*, 1665-743. Cambridge: Cambridge University Press, 2012.
[89] Freeman, Christopher, and Luc Soete. *The Economics of Industrial Innovation.* Cambridge, MA: MIT Press, 1997.
[90] Kline, S. J., N. Rosenberg, and N. Rosenberg. "An Overview of Innovation." In *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, edited by R. Landau, 275-306. Washington DC: National Academy Press, 1986. Accessed September 29, 2013. www.nap.edu/openbook.php?record_id=612&page=275.
[91] Lundvall, Bengt-Åke. *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*. London: Pinter Publishers, 1992.

approach focuses on the interaction of factors and actors that drive and direct the processes of innovation.[92] Many different models have been proposed to analyze how innovation occurs across various technologies, including national systems, technological systems, and socio-technical systems, among others.[93] [94] [95] [96] [97] This writer's research has pointed that the most applicable system for SMR is the Energy Technology Innovation System (ETIS) as described in the 2012 Global Energy Assessment.[98] Energy Technology Innovation is described by Gallagher, Holdren, and Sagar as a set of processes through which energy technologies are improved, refined, or even replaced through a series of stages that are chain-linked and are further connected through a series of feedbacks.[99] The stages are defined as fundamental research, applied research, development, demonstration, pre-commercial & niche deployment, and diffusion. This system is incorporates the aforementioned innovation systems approach but with the specific focus toward energy technology that Gallagher et al. also advocated (see Figure 5). The stages are described as follows:[100]

Research & Development (R&D): The processes through which knowledge is generated, either to develop new technologies or to improve pre-existing ones.

Demonstration: The construction of a prototype to demonstrate the viability of the technology.

Market Formation: The utilization of a comparative advantage the technology possesses to exploit niche markets, or using government incentives to encourage early adoption in a limited market. The process of

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[92] *GEA 2012*, p. 1676.
[93] Freeman, Christopher. *Technology, Policy, and Economic Performance: Lessons from Japan*. London: Pinter Publishers, 1987
[94] Nelson, Richard R. *National Innovation Systems: A Comparative Analysis*. New York: Oxford University Press, 1993.
[95] *National Innovation Systems*. Organisation of Economic Cooperation and Development. OECD Innovation in Science, Technology, and Industry. Accessed October 14, 2013. http://www.oecd.org/science/inno/2101733.pdf.
[96] Geels, Frank W. "From Sectoral Systems of Innovation to Socio-technical Systems." *Research Policy* 33, no. 6-7 (September 2004): 897-920. Accessed October 14, 2013. http://www.sciencedirect.com/science/article/pii/S0048733304000496.
[97] Carlsson, B., and R. Stankiewicz. "On the Nature, Function and Composition of Technological Systems." *Journal of Evolutionary Economics* 1, no. 2 (1991): 93-118. Accessed September 19, 2013. http://link.springer.com/article/10.1007%2FBF01224915#.
[98] *GEA 2012*, p. 1665-1743.
[99] Gallagher, Holdren & Sagar, "Energy Technology Innovation", p. 194-196.
[100] *GEA* 2012, p. 1673.

niche market formation has been described as crucial for the success of an innovation.[101]

Diffusion: Widespread adoption of the technology; could also be thought of as commercialization.

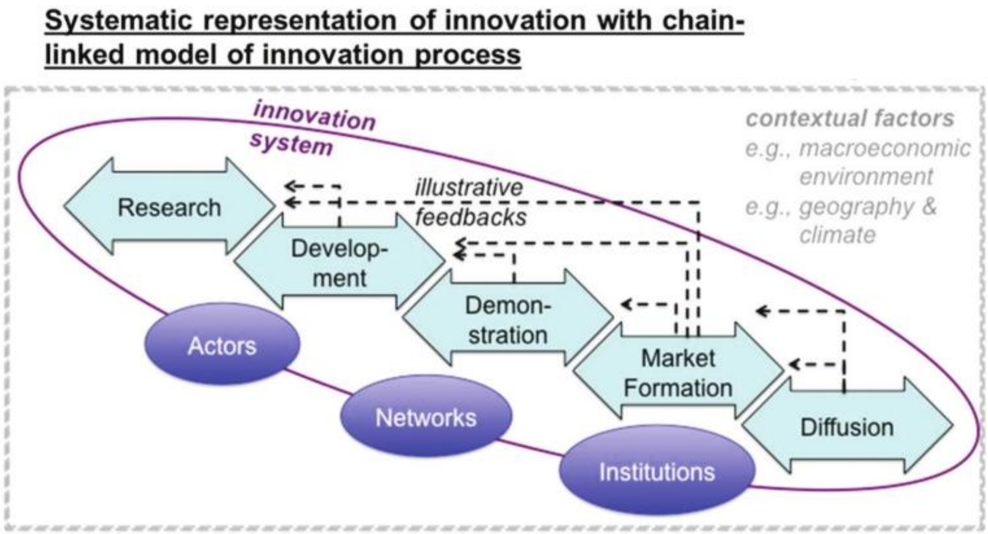

Figure 5: The Energy Technology Innovation System (chain linked model), adapted from the 2012 Global Energy Assessment.

An effective ETIS has seven functions that are essential for the innovation process. These functions are described in another piece by Gallagher, Grübler, Kuhl, Nemet, and Wilson, hereafter noted as Gallagher et al. (2012).[102] The first is entrepreneurial activities, where businesspersons take risks. The second function is knowledge development, which relates to R&D. The third is the diffusion of knowledge through innovation networks, including information exchanges and spillovers. Another necessary function within ETIS is the guidance of the search for new energy technology applications, where industrial or government leadership directs the focus of limited resources. Market formation, as described in the paragraph above, is both a stage in ETIS as well as a function of it. Resource mobilization is another critical role an innovation system plays, as

[101] Kemp, René, Johan Schot, and Remco Hoogma. "Regime Shifts to Sustainability through Processes of Niche Formation: The Approach of Strategic Niche Management." *Technology Analysis & Strategic Management* 10.2 (1998): 175-98. *Collaboration of Sustainable Energy Governance*. Florida Statue University. Web. 5 Oct. 2013. http://seg.fsu.edu/Library/Regime%20Shifts%20to%20Sustainability%20Through%20Processes%20of%20Niche%20Formation_%20The%20Approach%20of%20Strategic%20Niche%20Management.pdf.

[102] Gallagher, Kelly Sims, Arnulf Grübler, Laura Kuhl, Gregory Nemet, and Charlie Wilson. "The Energy Technology Innovation System." *Annual Review of Environment and Resources* 37 (July 31, 2012): 137-62. Accessed October 15, 2013. http://www.annualreviews.org/doi/abs/10.1146/annurev-environ-060311-133915.

both human and financial resources must be allocated to specific tasks to ensure development. Finally, the creation of legitimacy and counteraction to the resistance of incumbent technologies is the last function of innovation systems. The seven functions of ETIS will be important in the study, as strengthening these mechanisms for innovation in nuclear energy will be critical for the success or failure of SMR.

In addition to functions meant to facilitate the effectiveness of innovation systems, the energy technology innovation process contains two "Valleys of Death" that hinder the innovation process and may cause technologies to fail altogether. The Valley of Death derives its name from the phase in a technology's development just before market introduction where uncertainties about its commercial viability are coupled with high investment costs, thus often causing an innovation to languish in a pre-commercial state, revert back to the R&D phase, or fail altogether.[103] Avato and Coony describe the Valley of Death as the gap in funding that occurs in product development when government R&D support is reduced (due to R&D successes) but private investment is lacking due to high capital costs and perceived risks associated with expensive new technology (see Figure 6).[104] This scholarly interpretation of the problems of energy technologies accurately reflects the problems associated with the

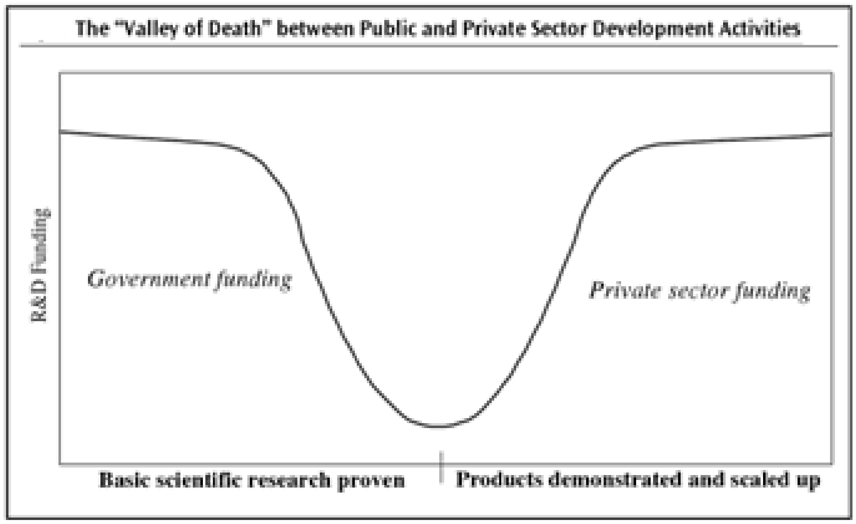

Figure 6: Adapted from Avato & Coony Accelerating Clean Energy Technology Research, Development, and Deployment p. 7-14.

[103] Negro, Simona O., Floortje Alkemade, and Marko P. Hekkert. "Why Does Renewable Energy Diffuse So Slowly? A Review of Innovation System Problems." *Renewable and Sustainable Energy Reviews* 16 (April 30, 2012): 3836-846. Accessed November 1, 2013. http://www.sciencedirect.com/science/article/pii/S1364032112002262.

[104] Avato, Patrick, and Jonathan Coony. *Accelerating Clean Energy Technology Research, Development, and Deployment: Lessons from Non-energy Sectors*. Washington, D.C.: World Bank, 2008. Accessed October 23, 2013. https://openknowledge.worldbank.org/bitstream/handle/10986/6528/443820REVISED0134057B0June010102008.pdf?sequence=1.

SMR business plan promoted by Rosner et al. in that high FOAK costs can deter the initial private investment needed to start production.

This high FOAK cost for SMR and other innovations in energy technology has been referred to as the "Mountain of Death", and represents a significant portion of the problem presented by the Valley of Death.[105] Once a new technology is developed, all the newly designed components in a plant must be integrated into a system. This initial integration of all new equipment will lead to the highest per-unit cost that the developers will face, as described in Figure 7. Again, because it has only ever been constructed as a prototype, the FOAK commercial plant will not benefit from any learning effects, which is why the FOAK SMR unit described by Rosner et al. is substantially more expensive than the NOAK units produced later (FOAK or LEAD at $7,000-11,500 versus the NOAK at $4,770).

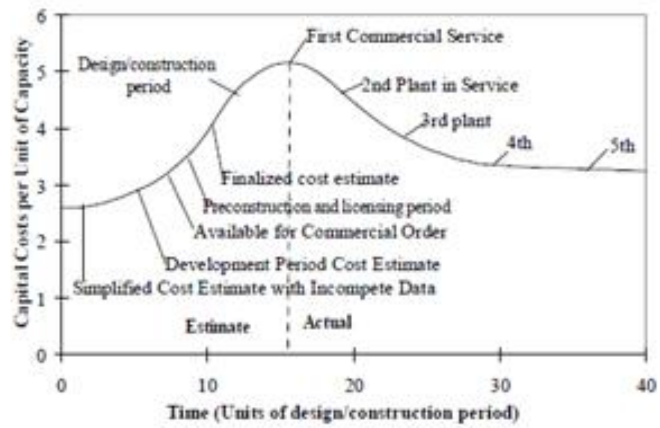

Figure 7: The Mountain of Death, adapted from Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-First Century, p. 7-15.

Understanding the location of the two Valleys of Death within the ETIS and the mechanisms that create them is critical for supporting innovation. The first Valley that innovations encounter is located between the development and demonstration phases, where technologies are too expensive or too difficult to scale up on a commercial scale and private investment is difficult to acquire.[106] The second Valley of Death is between the demonstration and diffusion stages, which is why a market formation stage is needed in the ETIS. The reasons technologies often struggle to move toward diffusion from this point are numerous: the

[105] Avato & Coony, *Accelerating Clean Energy Technology Research*, p. 7-15.
[106] Gallagher, Kelly Sims, Laura Diaz Anadon, Ruud Kempener, and Charlie Wilson. "Trends in Investments in Global Energy Research, Development, and Demonstration." *Wiley Interdisciplinary Reviews; Climate Change* 2.3 (2011): 373-96. *Wiley Online Library*. 18 Apr. 2011. Web. 23 Sept. 2013. http://onlinelibrary.wiley.com.ezproxy.library.tufts.edu/doi/10.1002/wcc.112/pdf.

technology may be too risky from an economic perspective, it may be uncompetitive against alternatives, regulatory hurdles can hinder development, there may not be sufficient incentives to adopt it, or substantial market barriers like technological lock-in, unfair subsidization of competitors, or infrastructure lock-in can prevent it from reaching the diffusion stage.

The Valleys of Death are evident in Rosner, Goldberg & Hezir's business plan for SMR, and while the first may have been successfully bridged, the second looms as a threat to undermine the development of SMR. The first Valley between the development and demonstration phases has largely been overcome with the help of government support in the DOE's SMR Licensing and Technical Support Program. This cost-sharing agreement is providing the financial support needed to get a handful of SMR designs through the final stages of engineering as well as the licensing process with the NRC, and as noted by the EPIC White Paper, can be an extraordinarily expensive progression. The demonstration at Clinch River with TVA represents the LEAD or FOAK deployment. The business plan for SMR noted that this type of 50-50 cost sharing agreement with the government could be very helpful to meet this end. Unfortunately the business plan does not delineate a clear path to completely bridge the second Valley of Death, as the authors only recommend the implementation of a production tax credit to assist in market formation. How SMR is to reduce costs of production and descend the Mountain of Death is not readily apparent, especially when nuclear innovation has a track record of cost escalation. This is the gap in knowledge that this study intends to address.

Rationale, Objectives, and Methods of this Study

This study intends to explore the mechanisms behind nuclear attack submarine (SSN) innovation and how the lessons from an analogous industry can be applied to the nuclear innovation of SMR. An in-depth exploration of nuclear submarine manufacturing should assist the nuclear industry in finding a path toward stabilization of costs over time through theoretical approaches to innovation, policy measures to encourage cost reduction, and practical "best practices" to manage innovation and construction in complex systems. Nuclear submarines incorporate small reactors and are already constructed in modular form, and represent a suitable proxy for a SMR plant. Submarines also incorporate highly advanced weapons systems, sonar, and cutting-edge technologies to give the United States Navy every possible edge in military operations, which not only require constant innovation to stay ahead but are tremendously expensive. Because of the unique nature of nuclear technology, a catastrophic failure in either a submarine or a deployed SMR unit could have disastrous consequences for the government, industry, and the people in the vicinity of the reactor, so the constraints of high reliability and safety must be similarly accounted for in any analysis.

A study of this nature has been recommended directly or indirectly by several scholars, though to this point no comprehensive analysis has been attempted. Countless SMR studies have commented on how the United States' SMR industry could use submarine manufacturing as a foundation for labor, expertise, materials, R&D, etc. [107] [108] [109] As previously noted, Rosner et al. used the learning rates of nuclear submarine production at the Huntington Ingalls Newport News Shipyard as a basis for their projected learning rates of SMR, citing the shipbuilding industry as analogous to SMR production. [110] [111] A study in busbar costs for United States nuclear power plants performed by Koomey and Hultman suggested that a study in nuclear powered ship construction was needed to determine how the learning rates in nuclear energy might be affected by variations in organizational structure. [112] Other studies have described the interrelatedness of the two industries, citing that innovation in the nuclear submarine industry created spillover effects into the nuclear power sector. [113] [114] An obvious reason why this study is needed is because some SMR designs globally are naval reactor platforms being re-applied to commercial markets. One example of this spillover is the Flexblue

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[107] U.S. Department of Commerce "The Commercial Outlook for U.S. Small Modular Nuclear Reactors", p. 2.
[108] Alekseev et al., "System of Low-Capacity Nuclear Power Plants", p. 316-321.
[109] Domenici, Pete, and Warren F. Miller. *Maintaining U.S. Leadership in Global Nuclear Energy Markets: A Report of the Bipartisam Policy Center's Nuclear Initiative*. Bipartisan Policy Center. Accessed July 11, 2013. http://bipartisanpolicy.org/library/report/maintaining-us-leadership-global-nuclear-energy-markets
[110] Rosner, Goldberg & Hezir. *Small Modular Reactors - Key to Future Nuclear Power Generation,* p. 17, 56.
[111] "Who We Are." Huntington Ingalls Newport News Shipbuilding. Accessed November 04, 2013. http://nns.huntingtoningalls.com/about/index.
[112] Koomey, Jonathan, and Nathan E. Hultman. "A Reactor-level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005." *Energy Policy* 35, no. 11 (July 31, 2007): 5630-642. Accessed August 29, 2013. http://www.sciencedirect.com/science/article/pii/S0301421507002558.
[113] Kessides, Ioannis N., and Vladimir Kuznetsov. "Small Modular Reactors for Enhancing Energy Security in Developing Countries." *Sustainability* 4 (August 14, 2012): 1806-832. doi:10.3390/su4081806.
[114] Trancik, "Scale and Innovation", p. 5.

nuclear plant currently being designed by DCNS in France that will be deployed offshore and under the sea to supply coastal towns with NIMBY concerns. A second is the Russian KLT-40S reactor that had been developed for nuclear icebreaking ships that is now being installed on barges to supply power to isolated ports in the Far East of Russia.[115] [116] As evidenced by these reasons and many others that will be addressed later in this paper, innovation in nuclear submarines is directly applicable to SMR, so a study of what facilitates the former can greatly assist the latter.

The primary objective of this study is to discover enables innovation as well as cost stabilization in nuclear attack submarines and ascertain whether these methods can be applied to innovation in SMR. Prior to launching the study, this author was aware that the latest attack submarine program in the United States, the *Seawolf* and *Virginia* Class submarines, had initially struggled with cost escalations and delayed deliveries, similar to the issues the nuclear industry has faced with the recent construction efforts at the Vogtle and Summer sites. The difference with the *Virginia* class submarines, however, is that the costs were eventually stabilized, and eventually reduced as the effects of learning-by-doing seemingly generated the economic benefits that SMR so desperately needs to bridge the Valley of Death. Specific focus is given to the submarine reactors themselves wherever possible, however due to the sensitive nature of the technology, detailed data is not entirely available. The initial objective of this study was to focus only on submarine reactor innovation; however the categorization of production and design data for nuclear attack submarines is classified. Because of this, submarine reactor innovation has been broadened to include the entire attack submarine, which is a complicated series of systems in itself that incorporates advanced reactor technology, thus making it a suitable proxy for a nuclear innovation. The fact that the submarine is produced in a factory setting like SMR plants will be adds to the parallels between nuclear shipbuilding and SMR production. The mechanisms for what facilitates innovation and cost stabilization in modern attack submarines is addressed below.

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115 "Flexblue." DCNS. Accessed December 01, 2013. http://en.dcnsgroup.com/energy/civil-nuclear-engineering/flexblue.
116 Kiger, Patrick J. "Russia Floats Plan for Nuclear Power Plants at Sea." National Geographic. October 23, 2013. Accessed December 01, 2013. http://news.nationalgeographic.com/news/energy/2013/10/131023-russia-floating-nuclear-power-plants.

Nuclear Attack Submarine (SSN) Innovation Network

Introduction

In the following sections, the innovation system in place for developing naval reactors will be assessed in terms of the ETIS discussed earlier in this paper. Typically, government support is limited to targeting a few key points in the ETIS process, but the development of nuclear propulsion incorporates massive government intervention at every stage of the process from Research through Diffusion. This is a result of the military application of this particular energy technology, as nuclear propulsion has epitomized the definition of a military-industrial complex since its very inception. Note that this writer is not using the ETIS comparison to advocate for titanic public support for SMR development, but to show that the limitations of nuclear energy are not technologically based. If reactor technology can be developed without the per-unit cost of the plants escalating, then the stumbling blocks that hinder nuclear's evolution are policy-related. Therefore, policy can support innovation in nuclear energy and SMR can theoretically overcome the boundaries of economics achieve commercialization.

The study performed shows that submarine reactors do not struggle with the Valleys of Death that plague nuclear innovations, and its development has proven the industry's capability to handle the Mountain of Death by reducing and stabilizing costs of production. The seven functions of innovation systems are satisfied by the network available for nuclear attack submarines. The unique position of Naval Reactors at the center of a powerful innovation network empowers the office to be the guiding hand in developing submarine reactor technology, with the Navy providing clear direction for technology to follow and policy to support. The relationships between industries, government agencies, the legislature, along with the military are remarkably strong, which supplies Naval Reactors with high levels of sustained government support at every stage of the innovation process. Critical feedback mechanisms allow the system to refine SSN technology and its management practices. Finally, the SSN innovation system is permeated by a culture of high reliability with a special focus on safety, which is essential when managing the development of complex technologies that have a potential for catastrophe. The findings points to a potential path for SMR to follow in the process of innovation of that technology.

The SSN Development Network

Nuclear attack submarines are produced at the nexus of a far-reaching system that incorporates bureaucracies, technical systems, national security policy, and industry. In this way, the submarines themselves are only the tip of the iceberg of a vast network responsible for their production. Naval reactor development benefits from a robust network that integrates the major actors necessary to facilitate an effective system for innovation in nuclear propulsion as well as military hardware. The office of Naval Reactors is situated at the nexus of military and energy technology, which is advantageous in the United States due to the massive military budget for both R&D and for procurement of military hardware. This position also serves as a powerful intersection of knowledge and expertise between major actors, which empowers Naval Reactors to direct the pathways of innovation and manage the end-result technologies through monitoring feedback from the fleet. The processes of innovation are sustained by the culture of the Naval Reactors program, which is heavily focused on safety to reduce the potential for catastrophic nuclear disasters that might otherwise undermine the public support of the program.

Naval Reactors (also called the Naval Nuclear Propulsion Program) is comprised of both civilian as well as military personnel with a comprehensive control over all aspects of naval nuclear propulsion.[117] The authority for Naval Reactors to perform these duties is delineated in several locations, including Presidential Order 12344, Public Law 98-525 (42 USC 7158) and Public Law 106-65 (50 USC 2406).[118] [119] [120] The office is a

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[117] "Powering the Nuclear Navy | National Nuclear Security Administration." NNSA. Accessed December 23, 2013. http://nnsa.energy.gov/ourmission/poweringnavy.
[118] "Executive Order 12344 - Naval Nuclear Propulsion Program." United States National Archives - Federal Registrar. Accessed December 23, 2013. http://www.archives.gov/federal-register/codification/executive-order/12344.html.
[119] "42 U.S.C. 7158 - Naval Reactor and Military Application Programs." United States Government Printing Office. January 7, 2011. Accessed December 23, 2013. http://www.gpo.gov/fdsys/granule/USCODE-2010-title42/USCODE-2010-title42-chap84-subchapIII-sec7158/content-detail.html.
[120] "50 USC § 2406 - Deputy Administrator for Naval Reactors." Legal Information Institute - Cornell University Law School. Accessed December 23, 2013. http://www.law.cornell.edu/uscode/text/50/2406.

responsible for the research, development, design, operation, maintenance, and safe management of nuclear powered vessels and their associated support facilities. These facilities include all nuclear-certified naval shipyards, support laboratories, submarine tenders, and training facilities like the Naval Nuclear Power Training Command. The Office also works with national laboratories to train personnel as well as test prototype reactors that will inevitably be used for undersea warfare.

Despite the military focus of the program, Naval Reactors actually is a division of the DOE. As previously noted, because the DOE possess the legal authority to develop and test reactor technology, the Naval Nuclear Propulsion Program must be under their authoritative umbrella and not the Department of Defense (DOD). Naval Reactors is an office within the National Nuclear Security Administration (NNSA) which is under the authority of the Under Secretary for Nuclear Security, who then reports to the Secretary of Energy.[121] The office itself is managed by both civilian officials and Navy officers, which is important to reiterate before moving forward into the network that nuclear submarines have at their disposal. The DOD and the Navy still have control over the overall development of the submarine itself, but the DOE gives Naval Reactors the authority to develop and regulate the submarine's energy source.

SSN Network: Initial Formation

While the Navy's interest in nuclear fission for submarine propulsion began prior to the Manhattan Project, the nuclear weapons program ultimately led to nuclear naval propulsion becoming a salient innovation priority. On March 17th, 1939, Enrico Fermi met with members of the Navy's Bureaus of Engineering, Ordnance, Construction & Repair, the Army's Ordnance Department, and the Naval Research Laboratory (NRL) to present his idea that fission could be utilized to create an atomic weapon.[122] This presentation convinced Ross Gunn, a research physicist and technical advisor to the NRL who was present at the meeting, of the

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[121] "DOE Organization Chart - June 6, 2013." United States Department of Energy. June 6, 2013. Accessed December 23, 2013. http://energy.gov/downloads/doe-organization-chart-june-6-2013.

[122] Ahern, Joseph - James. ""We Had the Hose Turned on Us!": Ross Gunn and the Naval Research Laboratory's Early Research into Nuclear Propulsion, 1939-1946." *Historical Studies in the Physical and Biological Sciences* 33, no. 2 (2003): 217-36. doi:10.1525/hsps.2003.33.2.217.

feasibility of using fission to power a submarine. The NRL launched several studies into this theory, but World War II led to Manhattan Project being prioritized under the Army Corps of Engineers, thus leading to submarine propulsion research being deferred until after the war. The Atomic Energy Act of 1946 turned over control of the Manhattan Project and all of its laboratories to civilian authorities under the newly formed Atomic Energy Commission (AEC). The AEC was awarded the exclusive legal right of conducting R&D on nuclear fission for energy purposes, and was also responsible for regulating nuclear safety.[123] The advent of atomic weapons led the Navy to renew their interest in submarine propulsion as a delivery mechanism for warheads, but the Atomic Energy Act prevented them from independently pursuing nuclear energy. In order to develop nuclear propulsion, the Navy needed to gain access to the AEC's network of national laboratories, uranium enrichment facilities, and nuclear expertise.

The Navy's integration into the network of nuclear innovation was championed by Hyman G. Rickover, and his leadership provided the catalyst needed for both submarine innovation and for commercial nuclear power. Rickover, who was at the time a Captain, quickly became a convert to the idea of nuclear propulsion when he served as an advisory to the Navy's Bureau of Ships while working at the Oak Ridge Laboratory in Tennessee in 1947. He quickly recognized the Navy's need to manage naval nuclear propulsion development as a series of closely related functions: R&D, detailed design, procurement, maintenance, personnel training, etc. All of these processes needed to occur in a tightly grouped mutually-reinforcing system that enabled the Navy to pursue its own specific agenda outside the auspices of the AEC.[124] Rickover navigated the bureaucracies of the Navy and the AEC with remarkable political savvy to create an independent office that had a powerful, singular mandate of developing nuclear fission for naval purposes. The Naval Nuclear Propulsion Program was established with a tremendous amount of freedom to develop nuclear powered

[123] Crawford, John W., and Steven L. Krahn. "The Naval Nuclear Propulsion Program: A Brief Study in Institutional Constancy." *Public Administration Review* 58, no. 2 (March/April 1998): 159-66. Accessed September 18, 2013. http://www.jstor.org/stable/976363. At this point in history, there was no United States Department of Energy. The AEC was the precursor to the Nuclear Regulatory Commission (NRC), which at the time was responsible for all nuclear technology.
[124] Crawford & Krahn, "The Naval Nuclear Propulsion Program", p. 160.

vessels outside of the Navy's standard system of naval innovation, was free of the oversight of the AEC, but had the resources of both at its disposal.

At this juncture in history, it is useful to point out that naval nuclear propulsion is the epitome of a radical innovation which not only led to the creation of advanced submarines but also spawned the civil nuclear energy industry. The very first nuclear reactor to supply electricity to civilians was the Shippingport Atomic Power Station in Pennsylvania, a scaled-up submarine design which was built as a demonstration project under the auspices of Admiral Rickover himself.[125] The plant first produced electrical power on December 18th, 1957, nearly four years after the first nuclear powered submarine (the *USS Nautilus*, SSN-571) was launched.[126] As discussed earlier in this paper, the implications of Naval Reactor involvement had far-reaching consequences, as it put nuclear energy in the United States on a path for technological lock-in on light water reactor technology. For better or worse, it was only natural for Naval Reactors to lead the way on civil nuclear energy projects

[125] "Atoms for Peace in Pennsylvania." Pennsylvania Historical & Museum Commission - History. Accessed December 27, 2013. http://www.portal.state.pa.us/portal/server.pt/community/history/4569/it_happened_here/471309.

[126] "Nautilus (SSN 571)." History of the United States Navy. Accessed January 08, 2014. http://www.history.navy.mil/danfs/n2/nautilus-iv.htm.

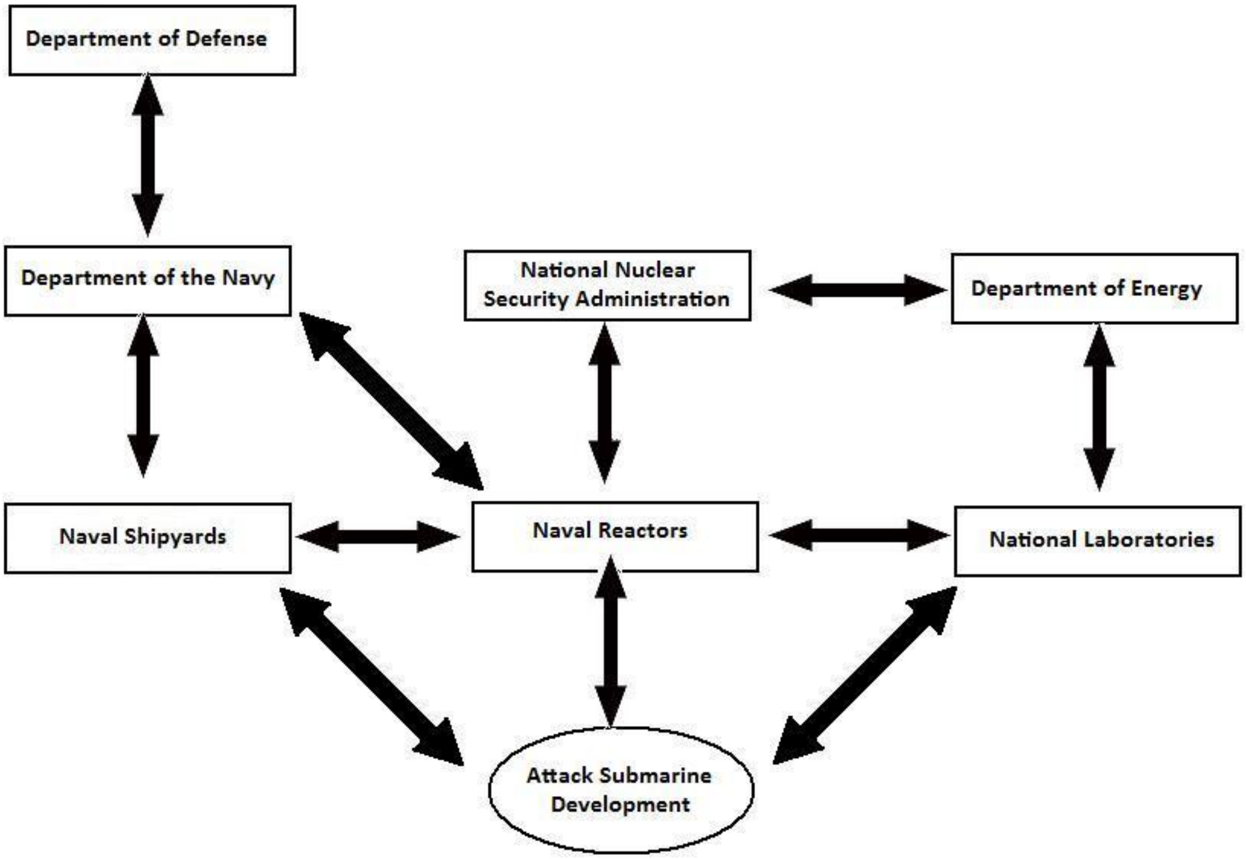

Figure 8: United States Government Support Network for SSN Development

Admiral Rickover's efforts to situate Naval Reactors in a unique managerial position had a tremendous effect in the efficacy of the program and the network available to developments in nuclear propulsion. As shown in Figure 8, the location of Naval Reactors places the office in a situation where they can benefit from flows of knowledge and funding from more locations than standard military or energy technology, represented by the arrows. These actors include major federally funded actors with substantial expertise and funding at their disposal, including the DOD, DOE, national laboratories, and shipyards, all of which have tremendous ties to myriad private industries that all funnel their expertise toward a singular goal of nuclear propulsion development.

National laboratories are a major source of knowledge generation for Naval Reactors. Both the Bettis Atomic Power Laboratory (BAPL) and the Knolls Atomic Power Laboratory (KAPL) is a federally funded national laboratory operated by private industry that has a sole purpose of developing nuclear marine propulsion.[127] [128] In association with Bechtel Marine Propulsion Corporation, BAPL and KAPL perform basic R&D, train engineers, train plant operators, provide fleet support during ship maintenance, manage projects for nuclear plant component production with contractors, and perform environmental monitoring for the Naval Nuclear Propulsion Program. Naval Reactors also is connected to the Idaho National Laboratory (INL), which formerly performed similar support tasks as BAPL as well as KAPL and even housed several prototype submarine reactors. Today, INL focuses more heavily on the DOE's missions for nuclear energy R&D, but the work done there still benefits the knowledge generation of the SSN innovation network. In general, national laboratories are the foundation for R&D, as well as hosts for prototype demonstration projects that are needed for the development, evaluation, and testing of naval nuclear reactors.

The nuclear-certified shipyards are central participants to the processes of SSN innovation, as they are the locations where learning acquired through construction experience is generated and relayed to Naval Reactors. There are only two privately owned yards in the United States that are certified to build nuclear propelled vessels: General Dynamics Electric Boat (GDEB) in Groton, Connecticut, and the Huntington Ingalls Newport News Shipyard (referred to as NNSY in this paper) in Virginia.[129] There are also four public yards that GDEB, NNSY, and the Navy contract out to for support, which include the Norfolk Naval Shipyard, Pearl Harbor Naval Shipyard, the Portsmouth Naval Shipyard, as well as the Puget Sound Naval Shipyard and Intermediate Maintenance Facility. The construction process is important for learning effects built up through repeated ship production and will play an important part in the analysis of the cost reductions in submarine manufacturing later in this paper. While GDEB and NNSY are privately owned companies, their substantial long-term high-volume contracting with the Navy essentially makes them a government supported industry, as the very

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[127] "Our Mission." Knolls Atomic Power Laboratory. Accessed December 26, 2013. http://www.knollslab.com/mission.html.
[128] "What We Do." Bettis Atomic Power Laboratory. Accessed December 26, 2013. http://www.bettislab.com/whatwedo.html.
[129] O'Rourke, Ronald. *Navy Virginia (SSN-774) Class Submarine Procurement: Background and Issues for Congress*. Congressional Research Service. Federation of American Scientists. September 27, 2013: p. 5-6. Accessed July 22, 2013. http://www.fas.org/sgp/crs/weapons/RL32418.pdf.

existence of the yards is dependent on the Navy's need for nuclear powered warships. Also, the Navy supports these shipyards through infrastructure development grants and placing orders for new submarine designs (that may never be used) to keep the design skills of the shipyards intact over long periods of time.[130] For this reason, the shipyards have been included as part of the public support network.

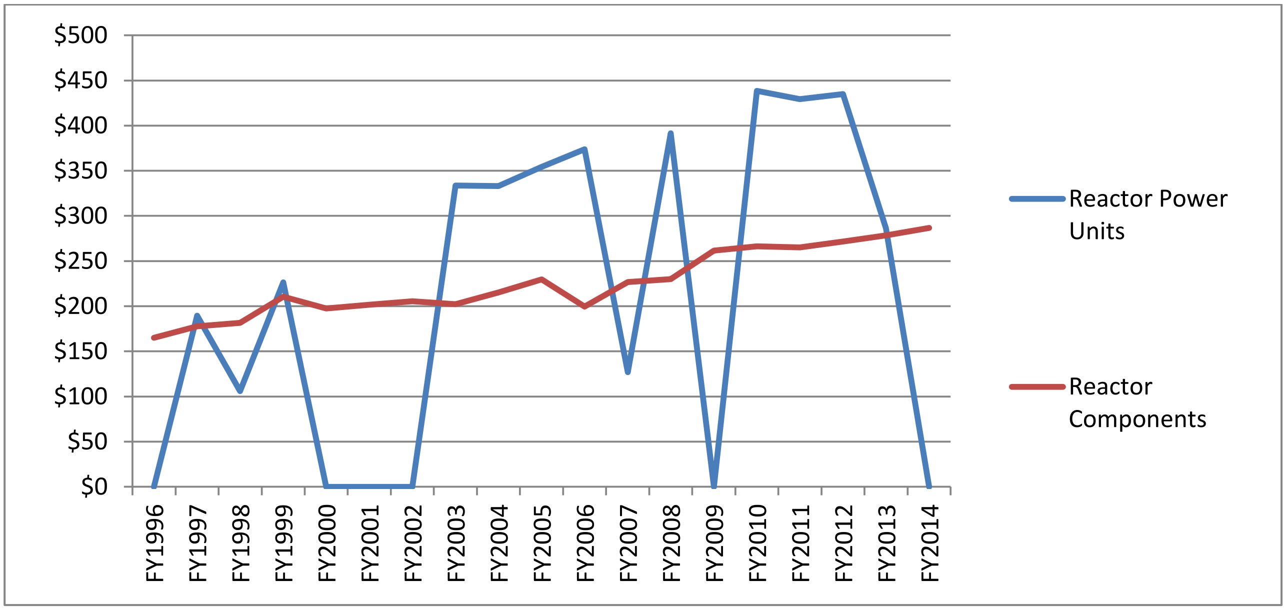

Figure 9: The United States Navy's Annual Budget for Procurement for Reactor Power Plants and Reactor Plant Components, FY1996 to FY2014 (in millions $)[131]

The influence of major government agencies like the DOD and DOE within the submarine innovation network is more financial than knowledge oriented, though their role in defining the missions of submarines is also a critical factor in leading the innovation process. The DOE supplies R&D funding to Naval Reactors through the NNSA, and the DOD provides funding through the Department of the Navy. The DOD and Navy also serve as the "market" for submarine purchases, as they contract directly with the shipyards for specific quantities of boats ordered in "blocks" so the shipyards can plan their material and workforce acquisition

[130] Schank, John F., Cesse Ip, Frank W. Lacroix, Robert E. Murphy, Mark V. Arena, Kristy N. Kamarck, and Gordon T. Lee. "Learning from Experience Volume II: Lessons from the U.S. Navy's Ohio, Seawolf, and Virginia Submarine Programs." Rand National Defense Research Institute. Accessed July 23, 2013. http://www.rand.org/pubs/monographs/MG1128z2.html.

[131] United States. Department of Defense. Office of the Under Secretary of Defense (Comptroller). *RDT&E Programs (R-1): Department of Defense Budget for Fiscal Years 1998-2014.* Accessed December 18, 2013. http://comptroller.defense.gov/Budget2014.html. Data collected from each annual report issued by DOD Comptroller on this website for the years of 1998 through 2014 for the production of the Figure 9.

strategies in advance of the Navy's need for new vessels.[132] Figure 9 provides a window in the Navy budget for reactors and nuclear power plant components. While it appears that reactor power unit purchases are inconsistent, the rate of purchase is actually contractually determined by an agreement with the shipyards, so the industry can plan their economies accordingly. The relative increase in reactor power purchases over the years reflects the decline of the *Seawolf* class submarine program during the 1990s and subsequent increase in purchases with the *Virginia* class in the late 2000s.

In addition to serving as the "market" for nuclear units and components, the DOD defines the missions for which the submarines must be designed and built. This means that the DOD's national security objectives dictate the Navy's mission planning, which then relays to Naval Reactors on what capabilities the submarines must be designed for. This leadership is an important driver of the innovation process, and is just as important as the financial connections that connect these agencies to the innovation network.

[132] O'Rourke, Ronald, and Moshe Schwartz. *Multiyear Procurement (MYP) and Block Buy Contracting in Defense Acquisition: Background and Issues for Congress*. Congressional Research Service. Federation of American Scientists. October 29, 2013. Accessed November 18, 2013. http://www.fas.org/sgp/crs/natsec/R41909.pdf. The policy of block buy contracting is an important one for achieving cost reductions in series productions of submarines, and will be addressed later in this paper.

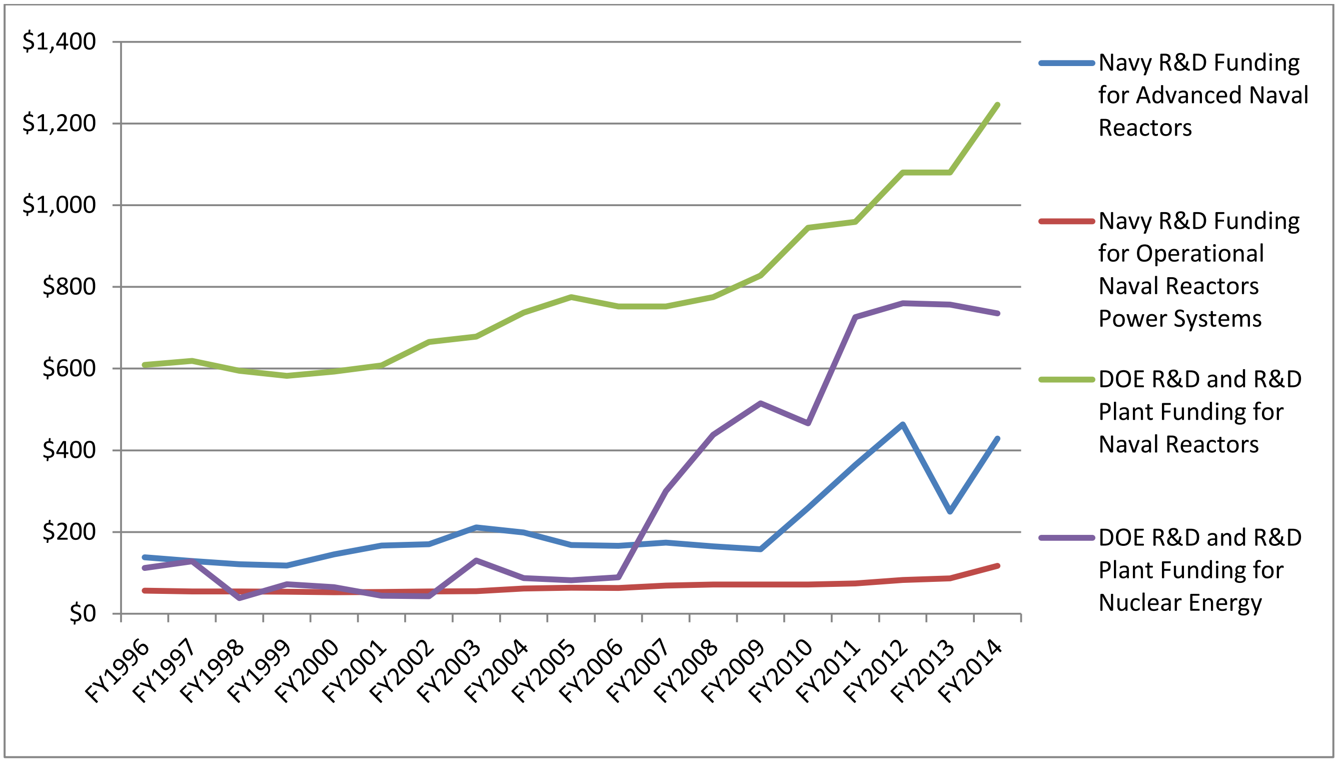

Figure 10: DOE and Navy Research, Development, Testing & Evaluation Funding for Nuclear Technologies (in millions $, not adjusted for inflation.)[133]

The most remarkable aspect of Naval Reactor's position within the SSN innovation network is the vast amounts of R&D funding available for both energy and military hardware. In the Fiscal Year 2014 Department of Defense Research, Development, Testing and Evaluation (RDT&E) budget, the DOD base appropriations was at $67.5 billion, and Navy was allotted a $15.9 billion of that amount for R&D purposes.[134] A deeper look into the Navy's R&D budget shows that a substantial portion of those funds goes toward designing, improving, and testing reactors for nuclear propulsion. As shown in Figure 10, Navy R&D funding for Advanced and also for Operational Nuclear Power Systems is consistent and considerable. The Navy invests far more in R&D for their warships' reactors than the DOE does for commercial nuclear energy, although recently the disparity has lessened. What is even more striking about this graph is the DOE's investment in R&D and R&D Plant funding

[133]DOD, Office of the Under Secretary of Defense (Comptroller). *RDT&E Programs (R-1): Department of Defense Budget for Fiscal Years 1998-2014.* R&D and R&D plant includes standard assessments of R&D, plus the costs of R&D facilities as reactors, wind tunnels, or particle accelerators or the construction, repair, or alteration of such facilities. Data collected from each annual report issued by DOD Comptroller on this website for the years of 1998 through 2014 for the production of the Figure 10.
[134] United States. Department of Defense. Office of the Under Secretary of Defense (Comptroller). *Department of Defense Budget Fiscal Year 2014: RDT&E Programs.* April 2013. Accessed December 26, 2013. http://comptroller.defense.gov/defbudget/fy2014/fy2014_r1.pdf.

for Naval Reactors, which in recent history is substantially more than their R&D funding in civil nuclear programs. Because nuclear submarines are at the nexus between DOD and DOE, they are the ultimate benefactor of funding from both agencies. Note that this graph does not include the hundreds of millions of dollars in the Navy R&D budget marked for innovation in submarine weapons, navigation, sonar, materials, and communication systems, which also empower Naval Reactors to design and manage the most advanced and reliable submarine fleet in the world. Consistent, predictable, and substantial R&D funding is a key driver of innovation. While nuclear energy receives a significant amount in terms of volume, the recent inconsistency of this funding sends mixed signals to the private market. Naval Reactors has high-volume and high-stability R&D funding available on an annual basis to improve reactor technology, which greatly enhances the office's ability to lead innovation within the submarine innovation network.

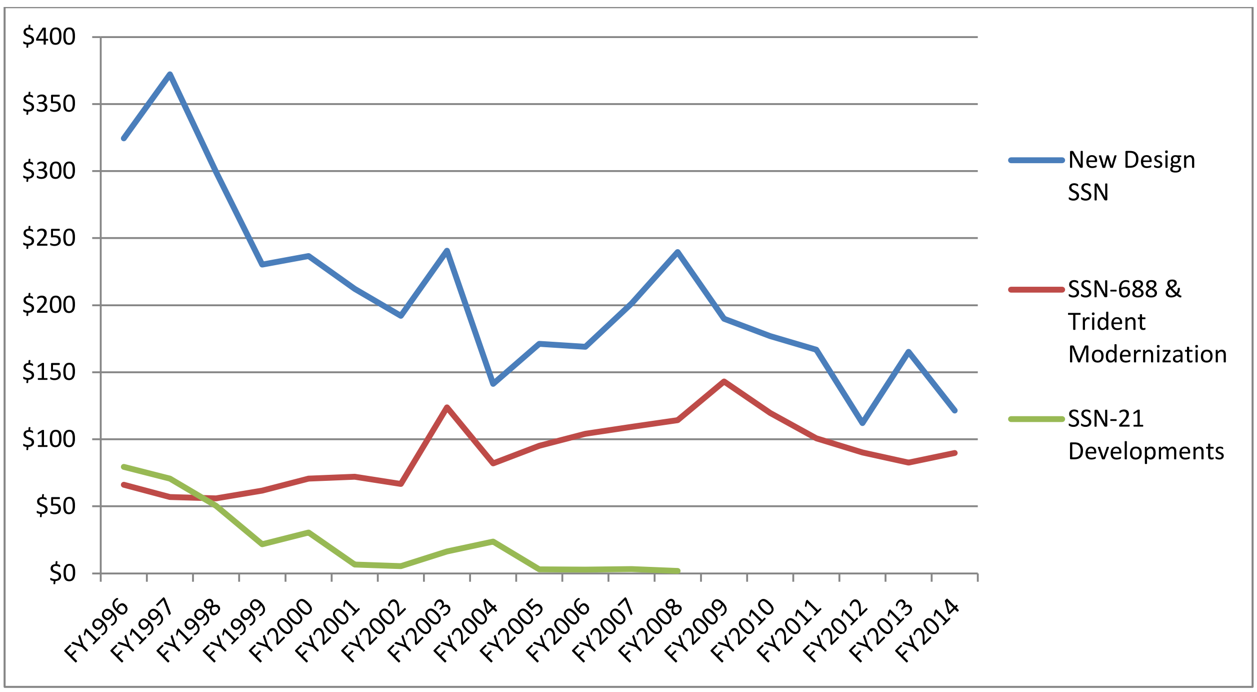

Figure 11: United States Navy's RDT&E Budget for Pre-Existing Submarine Modernization, Development, and Advancement of New Submarine Designs (in millions $)[135]

The Navy's budget also supplies RDT&E funding for continuing improvements in the existing fleet while supporting design of the next submarine, which is another benefit of the feedbacks within the system for

[135] DOD, Office of the Under Secretary of Defense (Comptroller). *RDT&E Programs (R-1): Department of Defense Budget for Fiscal Years 1998-2014.*

innovation. Designing a nuclear submarine can take 12-15 years and cost hundreds of millions of dollars, but the Navy plans ahead for future mission needs by continuously challenging naval architects to develop new designs and improve the existing fleet. This funding is shown in Figure 11. Funding for the "New Design SSN", which in this case was the *Virginia* class submarine, received substantial funding annually, though this amount decreased over time. Construction of the first Virginia class boat began in 1998, and at that point the Navy began to wean the designers from funds that were then only needed for design changes.[136] The other subs listed in the graph are pre-existing vessels that received upgrades as improvements to various systems were implemented across the entire class of vessels. The SSN-21 Development funding was eventually cut off, as this class of vessel (*Seawolf*) is only made up of three boats while the SSN-688 design (*Los Angeles* class) and the Trident (*Ohio* class) has 42 and 18 commissioned boats at present time. It should be noted that the *Ohio* class boats are nuclear powered ballistic missile submarines (SSBNs) that do not represent the core focus of this study, but the *Ohio* class and SSN-688 class were grouped as a single item on the DOD Comptroller's RDT&E budget. The ongoing effort by the Navy to modernize weapons, sonar, or other systems is an example of the knowledge generated from feedbacks being relayed to the network leadership to continuously innovate on a small scale, and has proven effective at keeping United States submarines at the top in terms of performance.

Organizational Culture

The development of an institutional culture of high reliability became critical to the Naval Reactor's success, as any catastrophic accident could be an existential threat to Rickover's program and end the processes of innovation. Due to the accident potential of nuclear fission, Rickover recognized the necessity of maximizing safety, as any accident would undermine the public support needed for his program. History has seen this occur with the events at Three Mile Island, Chernobyl, Fukushima, as well as Russian naval reactor accidents. Catastrophic events leading to fission product release inevitably results in strong public opposition

[136] "Virginia Class." General Dynamics Electric Boat. Accessed December 27, 2013. http://www.gdeb.com/about/oursubmarines/virginia.

to nuclear energy. If sufficiently powerful, this opposition in a democracy could greatly diminish or even destroy the system created for nuclear submarine innovation. Rickover's prioritization on safety is a key component of the ability of Naval Reactors to continue to operate without the yolk of additional government oversight and regulation.

The emphasis on safety and reliability permeated Naval Reactors from top to bottom, incorporating Admirals at Naval Reactor headquarters down to the lowest-ranked enlisted reactor plant operator. A study performed by Bierly & Spender found that naval nuclear propulsion is successful in the United States due to the tightly-knit network of organizations (with Naval Reactors at the center) that worked together to prioritized safety.[137]   They argued that the United States' nuclear submarine program illustrated how culture can interact with bureaucracy to create a higher lever system of knowledge that is capable of transforming a high-risk technology into a high-reliability one. This system was created by the centralization of authority over nuclear propulsion in Naval Reactors, which acts as the nexus for information flows and can effectively prioritize safety.

Bierly & Spender also claimed that this system that emphasizes safety also allows for tremendously effective knowledge diffusion across the network, as formalized networking was enabled between submarines. Safety in the organizational culture of Naval Reactors is maintained through feedback mechanisms that communicate learning across the SSN innovation network. Incident reports are generated as well as fact-finding investigations are launched when even minor plant casualties occur, and these are distributed throughout the fleet to inform commanders of potential operational hazards or equipment deficiencies. Additionally, various continuous inspection programs like the Operational Reactor Safeguards Examination (ORSE) and the Navy's Board of Inspection and Survey (INSURV) ensure that reactor plant equipment is in

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[137] Bierly, P. E. "Culture and High Reliability Organizations: The Case of the Nuclear Submarine." *Journal of Management* 21, no. 4 (1995): 639-56. Accessed August 8, 2013. doi:10.1177/014920639502100403.

prime working order and that operators are highly trained.[138] Plant operators participate in a daily training regimen that is highlighted by continuous examination of the knowledge of the crew. Also, personnel are transferred between vessels as part of a rotation to bring best-practices and expertise from one boat to another, which serves as a reinforcement mechanism for maintaining a high reliability safety culture. The results from the training and examinations are relayed directly to Naval Reactors, which can then adapt its focus to researching new processes, developing new technologies, or applying new knowledge to remedy safety issues. From this central location in the network, Naval Reactors can then communicate these issues to the entire fleet, thereby maintaining a fleet-wide culture of safety. As discussed with the ETIS in Figure 5, feedbacks from operators are critical elements to continuously improving nuclear submarine operations, maintenance, and technology development.

The prioritization of communication in an organization's culture also can be a sustaining element of that network's success over long periods of time. The culture of Naval Reactors benefits from what LaPorte & Keller describe as "institutional constancy". [139] This means that the nuclear Navy has exhibited unwavering adherence to safe management techniques of dangerous technology over several generations, and has been effective in doing so. Crawford & Krahn build on this idea by claiming that Naval Reactors has achieved institutional constancy by demonstrating trustworthiness that has enabled its autonomy from additional federal oversight or regulation. [140] A key factor in demonstrating trustworthiness is the internal communication network that Naval Reactors has created that maximizes the knowledge diffusion through the network.

As seen with past case studies in French and Japanese nuclear energy, inter-reactor and cross-network communication can greatly enhance learning effects, which are critical to the innovation process. Knowledge

[138] Krahn, Steven L. "Naval Reactors (NR): A Potential Model for Improved Personnel Management in the Department of Energy (DOE)." Federation of American Scientists. Accessed January 08, 2014. http://www.fas.org/man/dod-101/sys/ship/eng/appndx-c.htm.
[139] LaPorte, Todd R., and Ann Keller. "Assuring Institutional Constancy: Requisite for Managing Long-Lived Hazards." *Public Administration Review* 56, no. 6 (November/December 1996): 535-44. Accessed January 8, 2014. http://www.jstor.org/stable/977252.
[140] Crawford & Krahn, "The Naval Nuclear Propulsion Program", p. 163.

diffusion is a key function of any innovation system, and Naval Reactors has been tremendously effective at managing the flows of information while ensuring that potential safety issues are well-documented and understood across the entire nuclear attack submarine network. But Naval Reactors also has the responsibility of participating in the design process of the submarines themselves, where knowledge generation and diffusion are directed through leadership functions that are necessary in any innovation system.

Where Culture Meets Design

The safety culture established in Naval Reactors plays a significant role in the direction innovation takes, as reliability is emphasized in the design of propulsion plants technologies. Innovation in this system is characterized by minimizing the application of untested technologies, simplification of design wherever possible, designing reactors to prevent accidents instead of mitigating the consequences with those that occur, and ensuring the safety systems possessed redundancy.[141] All new reactors are initially produced as land-based prototypes that would be subject to rigorous testing to best simulate the arduous conditions and demanding requirements that submarine operations dictate. These prototypes are evaluated at national laboratories, and then later are used as training platforms for reactor operators moving through Naval Reactor's training pipeline.

Because of the prioritization of safety and centralized authority within Naval Reactors, Bierly, Gallagher, & Spender (hereafter Bierly et al.) argue that naval reactors development has developed as a group of "high reliability organizations" (HROs).[142] A HRO is defined as a group that is tasked with managing sophisticated technologies that could suffer catastrophes due to the complex nature of the technology and the inefficacies of human management. HROs typically share several characteristics, including the potential for catastrophic failure of equipment, tightly coupled systems, complex interconnections between subsystems,

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[141] Duncan, Francis. *Rickover and the Nuclear Navy: The Discipline of Technology*. Annapolis, MD: Naval Institute Press, 1990.

[142] Bierly, III, Paul E., Scott Gallagher, and J. C. Spender. "Innovation and Learning in High-Reliability Organizations: A Case Study of United States and Russian Nuclear Attack Submarines, 1970–2000." *IEEE Transactions on Engineering Management* 55, no. 3 (2008): 393-408. Accessed July 22, 2013. doi:10.1109/TEM.2008.922643.

and the accountability of the employees in the organization to any failures that occur. Much of HRO theory is based on the work of Charles Perrow on accident prevention, who cites nuclear energy as a high risk technology.[143] Nuclear submarines might be considered a double threat, due to the potential of the weapons systems or hull of the submarine to fail catastrophically in addition to the reactor.

Innovation in a HRO is especially challenging because military capabilities must be balanced against safety, but the United States' nuclear submarine industry has developed a very effective approach to maintaining reliability while maximizing innovation potential. Bierly et al. found that the use of platforms as a basis for design has enabled innovation to occur while simultaneously reinforcing the safe and reliable operation of nuclear attack submarines.[144] A platform for a product is described by Meyer and Lehnerd as a set of "subsystems and interfaces that form a common structure for which a stream of derivative products can be efficiently developed and produced," which essentially means that a platform is a series of components or practices that can be shared across multiple products.[145] A platform approach promotes modular innovation, because as components are improved they can be readily implemented as part of a new module that can replace the outdated version.

As products (or submarines) grow in complexity, modularity is a useful means to manage large systems that have complex interdependencies. [146] Modular innovation allows for maximization of the rates of innovation at the component level, because it permits open system architecture. This translates to continuous implementation of improved components to the platform as they are developed without waiting for the next major submarine design to be developed. Theoretically this should also improve the cost effectiveness of a series of products, because it builds on a foundation of a pre-existing product that now can be improved without wholesale redesign. A platform approach using modular innovation can also preserve the safety of the

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[143] Perrow, Charles. *Normal Accidents: Living with High-risk Technologies*. New York: Basic Books, 1984
[144] Bierly et al., "Innovation and Learning in High Reliability Organizations".
[145] Meyer, Marc H., and Alvin P. Lehnerd. *The Power of Product Platforms: Building Value and Cost Leadership*. New York: Free Press, 1997, p. xii.
[146] Ethiraj, Sendil K., and Daniel Levinthal. "Modularity and Innovation in Complex Systems." *Management Science* 50, no. 2 (2004): 159-73. doi:10.1287/mnsc.1030.0145

product because these modular innovations can be added incrementally when thorough testing has been completed. Modularity also allows for increased quality control and learning effects, as more work is performed in a manufacturing environment where it is inherently more efficient. Finally, a platform approach can improve the safety of a product over time because innovations in safety can be used to upgrade the existing fleet when submarines have shipyard availabilities. Modularity is of course the strategy being employed by SMR designers, so the investigation into SSN development is justified.

Another important feature of a platform approach in a system for innovation is the impact it has on learning. As previously noted, the culture of an organization is the body of shared knowledge that is built up through learning. In another study performed by the same Bierly & Spender (this time without Gallagher) they found that United States naval nuclear propulsion is successful due to the tightly-knit network that prioritized safety.[147] But because this learning is system-wide, the knowledge accrued within this network also facilitates increased economic efficiency in production. Shipyards are able to streamline their processes as a platform is produced in large quantities. Bierly et al. determined that the *Los Angeles* class submarine platform was the most cost-effective attack submarines built during the Cold War by either the United States or the Soviet Union.[148] The success of this class was facilitated by the platform approach that enabled system-wide learning that preserved reliability as well as improved the economics of production.

There are disadvantages to using a platform approach, as it inhibits radical innovation. A platform is typically based on the dominant design within the industry, which relates to the concept of technological lock-in that Cowan discussed for nuclear energy. In the case of nuclear propulsion, this means that innovations will be limited within the realm of light water reactor technology, as any other variety of plant would call for a completely new submarine platform. This is a familiar problem, as radical innovation is also limited in SMR development. While platforms enable modular innovation, which provides a firm with the flexibility to change components within a system, it also prevents the firm from innovating the system's architecture. This means

[147] Bierly, "Culture and High Reliability Organizations", p. 639-656.
[148] Bierly, Gallagher, & Spender, "Innovation and Learning in High Reliability Organizations", p. 404.

that while reactor plant equipment can be upgraded, the reactor's systems on the whole cannot be replaced with improved versions due to the complex interconnectivity between modules of the submarine. Finally, because the platform approach builds-in the ability to innovate in a modular fashion from the original design of the product, there are much higher upfront development costs as well as continuing costs to upgrade the entire fleet when new innovations are developed.

Platforms in the United States Navy

The Navy's platform approach was manifested by sustained development of only few attack submarine classes, and producing each design sequentially, building on the successes of past platforms. A class is most easily thought of as a platform, and this approach to innovation was initiated by the development of the *Los Angeles* class attack submarine. The *Los Angeles* class submarine was the first class to incorporate a modular innovation strategy with open source architecture that permitted the continuous component-level innovation described above, and the success the United States Navy had with this vessel on several levels inspired its continued application with the *Improved Los Angeles*, the *Seawolf*, and the *Virginia* classes.

Table 1: United States Navy's Modern Nuclear Attack Submarine Platform Evolution[149] [150] [151] [152]

Class (Platform)	# Built	Years Built	Submerged Displacement (tons)	Length (feet)	Reactor Design, Power, and Shaft Horse Power (shp)[A]	Core Life	Diving Depth (feet)	Maximum Submerged Speed (knots)	Other
Los Angeles	39	1976-1989	6900	360	**S6G, 26.1 MWe, 30,000 shp**	**10-13 years**	1475	32	Reactor power twice that of previous reactor design (S5W), increasing speed. Significantly quieter, enhanced sonar and weapons control, later in series (after-SSN 718) have 12 vertical launch tubes for Tomahawk missiles and an upgraded reactor core.
Improved Los Angeles	23	1988-1996	7100	360	**S6G, 26.1 MWe, 35,000 shp**	**10-13 years**	1475	32	Quieter, advanced sonar, mine laying capability than *Los Angeles* class, diving planes moved from sail to bow, under-ice capability
Seawolf[B]	3	1997-2005	9150	353	**S6W, 38.8 MWe, 52,000 shp**	**13 years**	1600-2000	35-39	Higher tactical speed than *Los Angeles* class, quieter, 8 torpedo tubes (*Los Angeles* has only 4), enhanced sail, under-ice operation capable, high pressure steel hull to increase diving depth (first submarine to use HY-100 steel), enhanced communications, modular design
Virginia	11 [C]	2002-Present	7800	277	**S9G, 29.8 MWe, 40,000 shp**	**33 years**	800+ [D]	25+ [D]	Designed to be a "low-cost" attack submarine. Less expensive than *Seawolf*, but similar quiet acoustic signature. Better in littoral seas than *Seawolf* or *Los Angeles* classes, also more upgradable over time. Boat is an all-electric ship, has open system architecture, modular masts, mission-reconfigurable torpedo room, enhanced special warfare capabilities. Possess 12 vertical launch tubes (without Virginia Payload Module) and four torpedo tubes.

Table Notes

A: Reactor design codes: First digit represents the reactor's application, S = Submarine, A = Aircraft carrier, D = Destroyer. The second digit is the design generation of that reactor's application, so fifth generation design is a 5, sixth generation is a 6, etc. The third digit represents the manufacturer of the reactor, W = Westinghouse, G = General Electric.

B: USS *Jimmy Carter* is one of the three *Seawolf* class submarines, but it has been outfitted for special operations. It has 453 feet long with a displacement of 12,140 tons, has enhanced missile launch and special warfare capabilities. It is based on the same platform as the other two Seawolf vessels, which shows the versatility of platforms in allowing boats to be lengthened.

C: There are currently 11 commissioned Virginia class submarines, but two are currently under construction and a total of 30 boats are planned to be built in this class.

D: The maximum diving depth and top speed of the Virginia class submarine is classified.

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149 Bierly et al., "Innovation and Learning in High Reliability Organizations", p. 398.

150 Ma, Chunyan, and Frank Von Hippel. "Ending the Production of Highly Enriched Uranium for Naval Reactors." *The Nonproliferation Review* 8, no. 1 (2001): 86-101. Accessed January 9, 2014. doi:10.1080/10736700108436841.

151 Cochran, Thomas B. *Nuclear Weapons Databook.* Cambridge, MA: Ballinger/Harper & Row, 1983.

152 Polmar, Norman. *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet*. Annapolis, MD: Naval Institute, 2005.

As shown in Table I, the United States only produced a single attack submarine platform at a time, and typically planned to build a large number of each design. There is some slight overlap between the *Seawolf* and *Virginia* platforms, which was due to the sudden cancelation of the *Seawolf* program alongside severe construction delays for the three *Seawolf* class boats that were built. Because many of the innovations on military hardware are classified, metrics of innovation are difficult to quantify, and often the literature is limited to broad statements about general improvements to systems. Table I only includes modern attack submarines that utilized a platform approach, beginning with the *Los Angeles* class, and is by no means a comprehensive tabulation of innovation results. However, it does represent a useful visual for the evolution of nuclear attack submarines and will help the reader in understanding the submarine designs that are discussed at length in the following sections of this paper.

The *Los Angeles* class represented a conservative platform approach to modular innovation, and experienced three phases of platform development. The boat was designed as a 'jack-of-all trades' attack submarine that could be adapted to shifting mission requirements over the long term development of the platform. The first phase was the result of major innovations in nuclear propulsion, as the S6G was significantly more powerful and quieter than the S5W plant that had been used on the preceding *Skipjack*, *Thresher*, and *Sturgeon* class attack submarines (11.2 MW, 15,000 shaft-horsepower for the S5W versus 26.1 MW, 35,000 shp for the S6G).[153] The second phase of the *Los Angeles* class incorporated 12 vertical launch tubes for Tomahawk cruise missiles, an innovation that enabled an attack submarine to reach inland shore targets for the first time.[154] Finally, the third phase or the *Improved Los Angeles* class upgraded weapons control to a BSY-1 sonar suite combat system, and also had the ability to lay mines through the torpedo tubes,

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[153] Ragheb, Magdi. "Nuclear Naval Propulsion." Edited by Pavel Tsvetkov. In *Nuclear Power - Deployment, Operation and Sustainability*, 3-32. Accessed January 9, 2014. http://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Nuclear%20Marine%20Propulsion.pdfhttp://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Nuclear%20Marine%20Propulsion.pdf.

[154] "SSN-688 Los Angeles-class." Navy Ships - Federation of American Scientists. February 14, 2000. Accessed December 31, 2013. http://www.fas.org/man/dod-101/sys/ship/ssn-688.htm.

among a few other improvements. However, due to the limiting nature of platform-oriented strategies of innovation, Soviet innovation had caught up to the Los Angeles classes and even began to surpass them in speed, diving depth, or stealth.[155] By the 1980s, the Navy had exhausted the modular innovation capability of the *Los Angeles* classes.

The *Seawolf* was the answer to regaining dominance under the seas, but the platform's early termination resulted from pivoting national security interests and tighter budgets. The *Seawolf* class was the most capable submarine ever built, as evidenced by the powerful S6W reactor that could maximize submerged speeds and provide electrical power for all the other advanced systems on board. Additionally the *Seawolf* was the first United States submarine to have its hull constructed with HY-100 steel, which represented an innovation in materials and steel welding techniques that would enable the boat to dive substantially deeper than *Los Angeles* submarines.[156] *Seawolf* submarines also had a cutting-edge weapons system in the AN/BSY-2, which was a computer-based combat system that controlled targeting, settings, and navigation of mines, torpedoes, and missiles.[157] These innovations, among many others, greatly increased the classes' capabilities in warfare, though at a tremendous cost. Development of the AN/BSY-2 system alone cost roughly $1 billion.[158] But when the Soviet threat disappeared, these advances proved less applicable to new security threats and were abandoned, along with the costly *Seawolf* platform that had been designed specifically to counter Soviet submarine innovations. Only three boats in this class were ever built.

As a result of the inapplicability of the *Seawolf* class' innovations, the *Virginia* class vessels were designed with different missions in mind with cost-effectiveness being a primary consideration.[159] The specifics

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[155] Friedman, Norman. *U.S. Submarines Since 1945: An Illustrated Design History*. 1st ed. N.p.: Naval Institute, 1994. Print, p. 214.
[156] Schank et al., "Learning from Experience Volume II", p. 54.
[157] "AN/BSY-2 Combat System." Federation of American Scientists. January 8, 2000. Accessed December 31, 2013. http://www.fas.org/man/dod-101/sys/ship/weaps/an-bsy-2.htm.
[158] United States. General Accounting Office. *Navy Ships: Problems Continue to Plague the Seawolf Submarine Program GAO/NSIAD-93-171*. Washington DC, 1993. Accessed December 31, 2013. http://www.gao.gov/assets/160/153587.pdf.
[159] Jones, Mike, Kevin Dehoff, and Eric Kronenberg. *ISSR: What Drives (Your) Program Costs? Achieving Step-Change Cost Reducation on Department of Defense Platforms*. Booz Allen Hamilton. 2008. Accessed December 31, 2013. http://www.boozallen.com/media/file/vb-west2011-ISSR.pdf.

about the capabilities of the *Virginia* class are classified, so maximum speed and diving depth are listed as rather innocuous numbers to mask the sub's true capabilities. The platform's innovations include the use of a photonics mast that replaces the traditional periscope. This is an important development, because not only does this new mast include high-tech infrared sensors, laser range-finders, and other tools transmitted through fiber optic cables, but the elimination of a periscope permits changes to the platform's architecture that enables flexibility in modular design. Additionally, *Virginia* class submarines possess a command and control systems module that permits touch-screen monitoring of every system on the boat from a central location. The *Virginia* class boats also have the AN/BYG-1 combat system, which is an upgraded version of the AN/BSY-1 and AN/BSY-2 systems installed on *Seawolf* and Los *Angeles* vessels. (This new combat control system is also being implemented on *Los Angeles* and *Seawolf* class submarines as part of the modular innovation system the Navy uses to keep submarines updated and to create some cohesion across platforms.[160]) Like the Seawolf before it, the hulls of Virginia class submarines use HY-100 steel to enable deeper dives.[161] In terms of electrical power and propulsion, the S9G reactor is not as powerful as the S6W on the *Seawolf*, but the core life is substantially longer, matching the expected lifetime of the boat. This means that the reactor should never require refueling, which greatly reduces operations and maintenance costs as well as increasing the boat's availability for deployment. Finally, the overarching theme in design for the *Virginia* class was affordability. The Navy faces a submarine shortage in the coming years, but has to balance the costs of advanced capabilities against the tighter budgets the Navy has struggled with in recent years. These innovations are only a few highlights of an entirely new submarine platform: a more comprehensive list of innovations for the Virginia class is located in Appendix 2 for additional information.

A noteworthy example of the mid-production modular innovation capability of the Virginia class is the case of the Virginia Payload Module (VPM). The VPM is a mid-body section addition that can be used to store

[160] United States. Department of Defense. Office of the Director, Operational Test and Evaluation. *AN/BYG-1 Combat Control System.* 2011. Accessed December 31, 2013. http://www.dote.osd.mil/pub/reports/FY2011/pdf/navy/2011anbyg-1.pdf.
[161] Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet*, p. 76.

and launch additional Tomahawk missiles or other payloads, like unmanned underwater vehicles (UUVs).[162] This section could permit the boats to carry up to seven more Tomahawk missiles, which broadens the mission scope of the submarines to compensate for the retirement of *Ohio* class guided missile submarines (SSGN). While the VPM adds to the length of the boat, the platform approach makes this a relatively simple change that is a relatively low-cost solution to bridging the SSGN shortage gap instead of building new submarines. The VPM will be implemented on Block V vessels, which is planned to be the final group of boats purchased by the Navy on the *Virginia* platform.

While the list of innovations appears impressive on paper, the ultimate test of an innovation's success is its performance in the market. In the case of nuclear attack submarines, this translates to efficacy in warfare. In a comparison study on the innovation strategies of the United States and the Soviet Union's attack submarine industry from 1970 until 2000, Bierly et al. rated the nuclear submarines of each country using three categories: speed, stealth, and attack capability.[163] As previously noted, the authors found that the *Los Angeles* class was the most economically efficient of all Cold War attack submarines. Bierly et al. also determined that while the Soviets would occasionally develop a radical design that would out-perform United States vessels in one of the three categories, they never developed a submarine that was superior in all three. United States submarines were all-around high performers that always had an overall edge in capability. The reasons stated by Bierly et al. for this sustained success was a profoundly different innovation system as well as the aforementioned commitment to a platform approach that emphasized safety.

The Soviet process of innovation was strikingly autocratic, a stark contrast to a process of negotiation used in the United States. For example, a man named Igor Spassky dominated the direction of submarine design for decades, but his control went beyond that of his American counterpart, Admiral Rickover.[164] While the network described for the United States placed Naval Reactors at the very center of the innovation

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[162] O'Rourke, *Navy Virginia (SSN-774) Class Submarine Procurement,* p. 6.
[163] Bierly et al., "Innovation and Learning in High Reliability Organizations", p. 396.
[164] Polmar, Norman, and Kenneth J. Moore. *Cold War Submarines: The Design and Construction of U.S. and Soviet Submarines*. Washington, D.C.: Brassey's, 2004.

process, the office still had to negotiate design proposals with the Navy and the shipyards, which led to a number of compromises that ultimately resulted in a rather conservative design that only incorporated a few well-tested innovations in a new platform.[165] The Soviet system allowed very little negotiation between network participants. This type of process is more open to radical ideas of those in charge, who might be overly eager to implement breakthrough technologies without thorough testing after the R&D phase or even by skipping the demonstration stage altogether. This is how the Russians were able to achieve superiority in a single phase (stealth, speed, weapons) very rapidly. The early negotiation between the shipyards, Navy, and Naval Reactors is a key mechanism that enables feedbacks necessary in the innovation process, as it keeps the major players in constant communication which enhances learning during the initial stages of R&D. In the Soviet Union, the autocratic nature of their nuclear submarine innovation network reduced communications, thereby blocking feedbacks that are essential to the innovation process.

A second issue with the autocratic nature of the Russian network was the lack of emphasis placed on the reliability of the submarines. This issue of network culture was the primary difference between the United States and Soviet nuclear submarine development network. While the authoritarian regime of the Soviet Union enabled massive funding for military technology advancement, the regime was not accountable to the public for the mistakes of the military. As noted previously, Rickover was well aware that the stability of his program was tied to the reliability of his innovations, as a single reactor accident could undermine public and congressional support for Naval Reactors. Soviet nuclear propulsion would continue to receive unhindered government funding regardless of their safety record, because the jobs of key officials hinged upon the submarines' ability to outperform those of the United States and not democratic elections.

While the official safety record of Soviet/Russian nuclear submarines is rather opaque, a tabulation of what is known shows remarkable failure to prioritize safety. A survey performed by this author on accidents involving United States and Russian nuclear submarines is shown in Table II.[166] [167] [168] [169] [170] [171] [172] [173] [174] [175] The

[165] Bierly et al., "Innovation and Learning in High Reliability Organizations", p. 405.
[166] Higgins, Chris. *Nuclear Submarine Disasters*. Philadelphia: Chelsea House Publishers, 2002.

survey shows that the Soviets suffered repeated failures in reactor safety which resulted in the losses of several submarines and hundreds of lives. In contrast, the United States' incidents typically are limited to collisions, which while serious, have considerably less grim consequences.

Table 2: Soviet and United States Navy Nuclear Submarine Incidents (next page). Reactor incidents highlighted in yellow.

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[167] Bierly, Gallagher, & Spender, "Innovation and Learning in High Reliability Organizations", p. 401-402.

[168] Miller, David. *Submarine Disasters*. Guilford, CT: Lyons Press, 2006

[169] "Project 659 / Echo I Project 675 / Echo II- Russian / Soviet Nuclear Forces." Federation of American Scientists. Accessed January 09, 2014. http://www.fas.org/nuke/guide/russia/theater/659.htm.

[170] Cutler, David. "Timeline: Worst Nuclear Submarine Accidents." Reuters. December 30, 2011. Accessed January 9, 2014. http://www.reuters.com/article/2011/12/30/us-russia-submarine-accidents-idUSTRE7BT0DJ20111230.

[171] Sarkisov, A. A., and Alain Tournyol Du Clos. *Scientific and Technical Issues in the Management of Spent Fuel of Decommissioned Nuclear Submarines*. Dordrecht: Springer, 2006.

[172] "The Last Accident of Soviet Nuclear Fleet." English Pravda.ru. September 28, 2011. Accessed January 09, 2014. http://english.pravda.ru/history/28-09-2011/119172-soviet_nuclear_fleet-0/.

[173] "Two Killed in Russian Sub Blaze." BBC News. July 09, 2006. Accessed January 09, 2014. http://news.bbc.co.uk/2/hi/europe/5322474.stm.

[174] "Fire Breaks Out on Russian Nuclear Submarine." Reuters. September 16, 2013. Accessed January 9, 2014. http://www.reuters.com/article/2013/09/16/us-russia-submarine-fire-idUSBRE98F02620130916.

[175] Parfitt, Tom. "Nuclear Leak Feared as a Second Russian Sub Is Lost with Nine Crew." The Telegraph. August 31, 2003. Accessed January 09, 2014. http://www.telegraph.co.uk/news/worldnews/europe/russia/1440224/Nuclear-leak-feared-as-a-second-Russian-sub-is-lost-with-nine-crew.html.

Soviet Navy			
Incident Date	**Hull Number**	**Class**	**Details**
October 13th, 1960	K-8	November	Primary coolant leak, no casualties but 3 crew members suffered from radiation poisoning
July 4th, 1961	K-19	Hotel	Leak in reactor coolant system, 9 deaths
February 12th, 1965	K-11 (later renamed K-116)	Echo II	Severe reactor accident, casualties unknown
September 8th, 1967	K-3	November	Fire in hydraulic system, 39 deaths
May 24th, 1968	K-27	November	Unknown reactor accident, 9 deaths
November 15th, 1969	K-19	Hotel	Collision with *USS Gato*
April 8th, 1970	K-8	November	Fire damaged boat, then sank while being towed to port. 52 deaths
June 20th, 1970	K-108	Echo II	Collision with *USS Tautog*
1970	K-320	Charlie I	Reactor accident, unknown outcome
February 24th, 1972	K-19	Hotel	Fire, 28 deaths
1972	K-377	Alfa	Reactor accident (metal coolant froze) during sea trials
June 13th, 1973	K-56	Echo II	Major reactor accident after collision with a research vessel, 27 deaths
August 28th, 1976	K-22	Echo II	Collision with *USS Voge* (destroyer), no casualties
September 26th, 1976	K-47	Echo II	Fire, 8 deaths
August 19th, 1978	K-116	Echo II	Unknown reactor accident, towed home, unknown casualties
August 21st, 1980	K-122	Echo II	Fire, 9 deaths
August 8th, 1982	K-123	Alfa	Primary coolant leak, required 8 year overhaul
June 24th, 1983	K-429	Charlie I	Sank in 1983, salvaged, refitted, then sank again in 1985, killing 16.
August 21st, 1983	K-122	Echo I	Fire, 9 deaths
June 18th, 1984	K-131	Echo II	Fire, 13 deaths
August 10th, 1985	K-431	Echo II	Reactivity event leading to steam explosion while refueling in Chazhma Bay, Vladivostok. 10 deaths
1985	K-313	Charlie I	Primary coolant leak
October 6th, 1986	K-219	Yankee	Missile explosion, fires, 4 deaths
1986	K-463	Alfa	Reactor accident, then decommissioned
April 7th, 1989	K-278	Mike	Electrical fire, explosion, 42 deaths
June 25th, 1989	K-192	Echo II	Reactor accident, unknown outcome
September 27th, 1991	TK-17	Typhoon	Missile explosion, casualties unknown
February 11th, 1992	K-276	Sierra I	Collision with SSN-689 *USS Baton Rouge*
August 12th, 2000	K-141	Oscar II	Torpedo room explosion after boat sank, 118 deaths.
August 30th, 2003	K-159	November	Boat was already decommissioned and was being towed to another port when it sprang a leak and sunk, killing 9.

September 6th, 2006	K-414	Victor III	Fire, two deaths
November 8th, 2008	K-152	Akula II	Fire system failure releases toxic gas, 20 deaths
December 29th, 2011	K-84	Delta IV	Fire in dry-dock, partially sunk. No casualties.
September 16th, 2013	K-150	Oscar II	Caught fire in shipyard, no casualties
United States Navy			
Incident Date	**Hull Number/ Vessel Name**	**Class**	**Details**
April 10th, 1963	SSN-593 *(USS Thresher)*	Permit	Seawater system piping failure during diving trials led to boat sinking below crush depth, 129 deaths.
May 21st, 1968	SSN-589 *(USS Scorpion)*	Skipjack	Sank, cause unknown, 99 deaths.
November 15th, 1969	SSN-615 *(USS Gato)*	Permit	Collision with K-19
June 20th, 1970	SSN-639 *(USS Tautog)*	Sturgeon	Collision with K-108
August 11th, 1984	SSBN-636 *(USS Nathanael Greene)*	James Madison	Lost propeller, able to return to Holy Loch using standby propulsion
October 20th, 1986	SSN-710 (USS Augusta)	Los Angeles	Collision with unknown Russian submarine, remained operational
February 11th, 1992	SSN 689 *(USS Baton Rouge)*	Los Angeles	Collision with K-276, but remained operational
March 19th, 1998	SSBN-737 *(USS Kentucky)*	Ohio	Collision with USS San Juan, remained operational
March 19th, 1998	SSN 751 *(USS San Juan)*	Improved Los Angeles	Collision with *USS Kentucky*, remained operational
February 9th, 2001	SSN-774 *(USS Greenville)*	Los Angeles	Collision with Japanese fishing vessel, killed 9 fishermen
January 9th, 2005	SSN-711 *(USS San Francisco)*	Los Angeles	Boat ran aground, 1 death
March 20th, 2009	SSN-768 *(USS Hartford)*	Los Angeles	Collision with *USS New Orleans*, an amphibious transport vessel, no casualties.

The United States does have two incidents that stand out, that being the cases of the *Thresher* and the *Scorpion.* The *Thresher* incident was believed to have been caused by the failure of silver-brazed piping joints that led to flooding in the engine room, subsequently causing short-circuits in electrical equipment forcing an emergency shutdown of the reactor.[176] Without propulsion, the boat sank below crush depth and imploded. What happened on the *Scorpion* is still undetermined. Following these incidents, safety was re-prioritized by

[176] "50 Years of Steely Purpose - USS Thresher Remembered." Naval Sea Systems Command (NAVSEA) - United States Navy. April 10, 2013. Accessed January 01, 2014. http://www.navsea.navy.mil/NewsView.aspx?nw=NewsWires.

Rickover and the Navy beyond what importance had already been placed upon it, and since the *Scorpion* no severe submarine incident has occurred. For the purposes of this study, it is important to note that a reactor accident did not cause the sinking of the *Thresher,* nor was believed to be the cause of the sinking of the *Scorpion*. On the other hand, the Russian experience with naval reactors is marked by repeated catastrophic failures in safety, as shown in the table above.

The combination of superior overall performance with high reliability were hallmarks of the United States' Navy's approach toward innovation. The advances in nuclear technology were remarkable: the program's first submarine reactor had a core endurance of 62,000 miles, and today the cores can last for more than 30 years and travel over one million miles.[177] The innovation system that developed around Naval Reactors provided the substantial and predictable funds necessary to perform R&D, while the guaranteed contracts assured the shipyards that whatever they produced would be purchased by the Navy. The safety culture prevalent in this system has been sustained by a series of feedback mechanisms, and has served to keep Naval Reactors as an autonomous office for over sixty years that has some freedom to lead innovation in reactor technology. Performance of the submarines has not sacrificed to a great degree due to the platform approach. Platforms support modularity, which in turn facilitates incremental innovations at the expense of more radical developments. The end result was history of safe, high-performance nuclear attack submarines that have always remained ahead of the competition in their efforts to innovate in critical mission areas. But a critical aspect of the SSN innovation system that was only touched upon was the effects of learning within the system. Since learning effects are so critical to the SMR business plan, a deeper look into how the SSN innovation network learns is needed to discover how its benefits can be maximized. This topic is addressed in the following section.

[177] NNSA, "Powering the Nuclear Navy".

Learning Effects in SSN Development

In addition to the benefits of safety, there have been substantial economic improvements in the production process that are a product of learning. Let us recall that in the literature review section of this paper, learning effects were defined as improvements to productivity during repetitious tasks through streamlining processes and minor innovations, leading to greater economic efficiencies of production. The business plan advocated by Rosner et al. for SMR is dependent on this increased efficiency to achieve cost reductions necessary for small-scale nuclear to be competitive with natural gas-fired plants. The experience curves referenced by the SMR business plan show that learning effects have indeed occurred in naval shipbuilding, but a closer look into that process is necessary to gauge the applicability of these curves to SMR. The study performed by this author on the nuclear attack submarine innovation system showed that the industry was plagued by cost escalations and delivery delays when new submarine platforms were introduced, similar to what we see in nuclear power plant construction today. However, with the help of some policy incentives and Navy leadership, the industry was able to achieve the economic benefits necessary to make the Virginia class submarine a success.

The following analysis focuses on the Navy's transition from the *Los Angeles* platform to the *Seawolf*, and then to the *Virginia* class attack submarines. The *Seawolf* and *Virginia* platforms were the most recent attempts at innovation, and data for these boats is more readily available than for older platforms. Also, the *Seawolf* to *Virginia* transition is particularly interesting for this study because it shows how the SSN innovation network adapted from a platform designed to maximize capability having rapidly escalating costs (*Seawolf*) to prioritizing affordability without sacrificing significant performance (*Virginia*). The problems the nuclear energy industry faces with escalating costs and their transition to mass-produced SMR makes this a very useful case that will likely yield some interesting points for SMR production.

Problems with Seawolf

The *Seawolf* platform was planned to be the most capable nuclear attack submarine ever built, but cost escalations and a shifting budgetary environment ultimately led to the program's demise. Early concept design of the platform began in 1982 during a period of intense competition with the Soviet Union for undersea supremacy. The Navy originally planned to build 29 boats in the class at an estimated cost of $38 billion, but by 1999 the program had reached a $16 billion price tag for only three boats.[178] The first-in-class *Seawolf* submarine, aptly named the *USS Seawolf*, was delivered 25 months late, required 79% more man-hours than planned, and altogether ran 45% over cost.[179] The collapse of the Soviet Union in 1991 resulted in hundreds of former-Soviet submarines being mothballed as the Russian Navy could not financially support the massive fleet, which meant the attack submarines being built to counter the Soviet threat no longer were prioritized in the United States' federal budget. The changing national security and budget landscape combined with the cost escalations to limit the production of *Seawolf*-class boats to only three.

The causes of the *Seawolf* platform's cost escalations and construction delays were partially the fault of miscommunications within the SSN innovation network, and also caused by the integration of immature innovations. The detailed design drawings for the *Seawolf* were only 5% complete when construction started, and only 65% complete three years into construction.[180] When the details of a complex piece of military hardware are not communicated to all participants in the production process, errors will undoubtedly occur.

Failure to communicate standards across the network led to costly delays and rework. The AN/BSY-2 weapons system, which was being developed concurrently, experienced similar communication breakdowns. Not only was the weapons system delivered a year late, but technical specifications were not relayed to the shipyard, leading to significant redesign being needed in order to mate the system with the platform. By 1992, over 800 design changes had increased the costs of development by $180 million. Over the entire life of the

[178] Schank et al., "Learning from Experience Volume II", p. 55.
[179] "Costs, Delays Surface Again for New Attack Submarines ." National Defense Magazine. September 2004. Accessed January 02, 2014. http://www.nationaldefensemagazine.org/archive/2004/September/Pages/Costs_Delays3416.aspx.
[180] Schank et al., "Learning from Experience Volume II", p. 80.

program, the *Seawolf* platform had registered some 70,000 design changes that led to extensive delays and increased costs.[181]

Other issues implementing innovations were just as costly. Welding techniques for the innovative HY-100 steel hulls were immature, leading to cracks from failed welds that required substantial re-work. The innovation in materials that enabled the platform to achieve new diving depths ultimately added $68.6 million in costs and a one year delay in delivery.[182] The implementation of HY-100 steel in the hull would have benefitted from additional testing and development. The Navy had believed at the time that this technology was mature enough to apply to the world's most advanced submarine, which points to a breakdown in the feedbacks within the SSN innovation network that would have informed key decision-makers that there were still issues to resolve with welding techniques.

New systems and components had many new parts, and due to a lack of network communication, the *Seawolf* platform suffered from a problem of parts proliferation.[183] While earlier platforms like the *Los Angeles* class submarine had an inventory of 29,000 parts, the *Seawolf* platform ballooned to 45,000 parts, which greatly added to the cost of production. Many of these parts were duplicates made by the two design yards, as there were no established standards or criteria across the network to ensure that this would not occur. A DOD effort to standardize parts production in military platforms found that there was an average cost of $20,000 related to adding a single new part to a platform's inventory due to the costs of engineering, design, testing, manufacturing, inventory, and logistics support.[184] By the DOD's estimations, an increase by 16,000 parts to the Seawolf's inventory over previous SSN designs added approximately $320 million to the design of the boat.

[181] Schank et al., "Learning from Experience Volume II", p. 80.
[182] Schank et al., "Learning from Experience Volume II", p. 54.
[183] United States. Department of Defense. Defense Standardization Office. *Case Study: The Virginia Class Submarine Program.* Accessed January 2, 2014. http://quicksearch.dla.mil/docimages/A/0000/0027/5846/000000606477_000000206462_CTDQWXETWC.PDF?CFID=928538&CFTOKEN=65490622&jsessionid=583021923ae4e2e7db3f9331c37b75586d18.
[184] United States. Department of Defense. The Parts Standardization and Management Committee. *Reduce Program Costs Through Parts Management.* Accessed January 2, 2014. http://www.dsp.dla.mil/APP_UIL/content/documents/partsmgt.pdf.

Parts proliferation, immature innovations, and the subsequent cost escalations in the *Seawolf* platform were primarily the result of a breakdown in inter-network communications. The consequences for the program were severe, as Congressional oversight began to exert pressure on the process and ultimately the program was canceled. But the Navy needed new attack submarines to replace the ageing Los Angeles class vessels, so the next SSN was designed with the lessons of *Seawolf* fresh in mind. Parts proliferation could be considered a serious issue in nuclear energy as well, as every plant is designed to be site-specific, meaning that there are substantial differences in detailed design and engineering, even among reactors of the same fundamental design. The problems in the *Seawolf* platform were addressed in the subsequent attack submarine, the *Virginia* class, and the lessons learned there are similarly applicable to nuclear energy.

The Virginia Class Platform

While the *Seawolf* program floundered in negative learning, leading to construction delays and cost overruns, the *Virginia* program had a rough start but is largely considered a success. Figure 12 shows that the end-item recurring flyaway costs of submarines built on the *Virginia* platform show that over the life of the program, the per-unit cost of each submarine has generally decreased following the construction of SSN-775 (the *USS Texas*). The term "recurring flyaway cost" is a generic term mean to describe the per-unit cost of producing a usable end-item.[185] In this case it refers to a submarine (typically the term is used for aircraft, hence "flyaway"), and it includes the cost of the "recurring" equipment items that are standard on the platform like reactor plant equipment, weapons systems, etc. This makes the recurring flyaway cost a useful metric for assessing the overall cost of a submarine after it is delivered to the Navy. As shown in Figure 12, the end-item recurring flyaway cost of a Virginia class submarine started between $2.2-2.4 billion for SSN-774 and 775 (the *USS Virginia* and the *USS Texas*), but quickly dropped and stabilized to around $1.8 billion per submarine by the time SSN-778 (*USS New Hampshire*) was produced. This graph uses 1995 as a base year, so all costs are stabilized to 1995 dollars. Today, the real cost (adjusted for inflation) of a Virginia class submarine

[185] Department of Defense Financial Management Regulation "Budget Formulation and Presentation", Volume 2B 4-31 § 4 (United States Deparment of Defense 2010). http://comptroller.defense.gov/fmr/current/02b/Volume_02b.pdf.

is roughly $2.4-$2.6 billion. Additionally, it should be noted that as of the writing of this paper only the first 11 submarines have been built, and the remaining 19 are the Navy's projections. With or without projections, what this graph shows is that learning is evident in the production of the latest nuclear attacks submarine. Costs of production were reduced and ultimately stabilized.

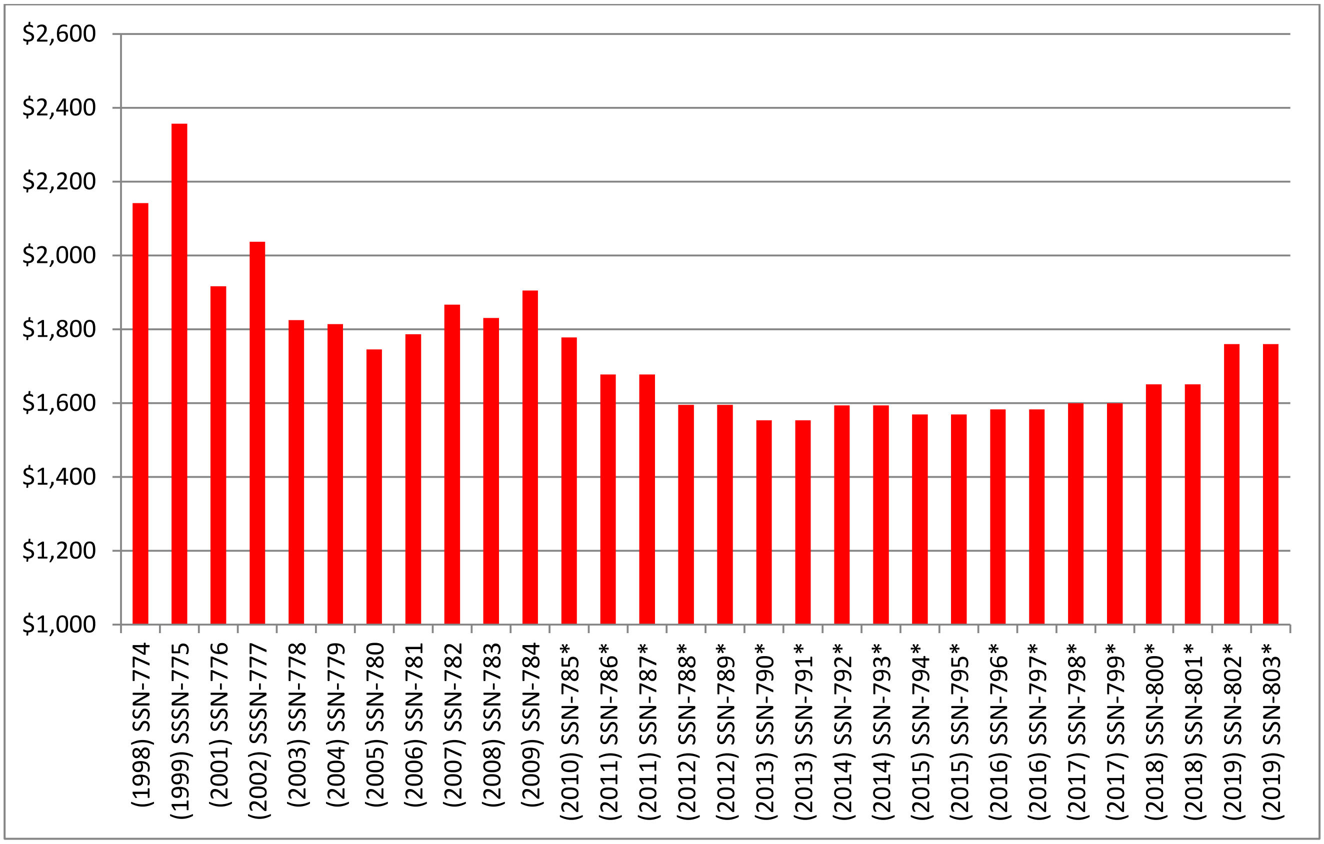

Figure 12: *Virginia* Class Submarine End-Item Recurring Flyaway Cost (in millions of 1995 $)[186]

Another useful metric to evaluate learning is the rate at which submarines are produced. Learning effects show increased efficiency as processes become streamlined and reduced amounts of construction time shows that learning is taking place. Figure 13 shows the delivery rates for the first 11 *Virginia* class

[186] United States. Department of Defense. Virginia Submarine Program Office. *Selected Acquisition Report (SAR): SSN 774 Virginia Class Submarine - Defense Acquisition Management Information Retrieval.* By David Goggins. December 31, 2012. Accessed January 9, 2014. http://www.dod.mil/pubs/foi/logistics_material_readiness/acq_bud_fin/SARs/2012-sars/13-F-0884_SARs_as_of_Dec_2012/Navy/SSN_774_December_2012_SAR.pdf.

submarines.[187] [188] [189] (Note: * indicates that SSN-784 is projected for delivery within 59 months.) The first-of-a-kind SSN-774 was 4 months late on delivery, while the second (SSN-775) was roughly a year late.[190] However, by the third boat the submarines were being delivered on-schedule or early. SSN-777 was on-time, SSN-778 was 8 months early, SSN-782 and 783 was built nearly a year ahead of schedule.

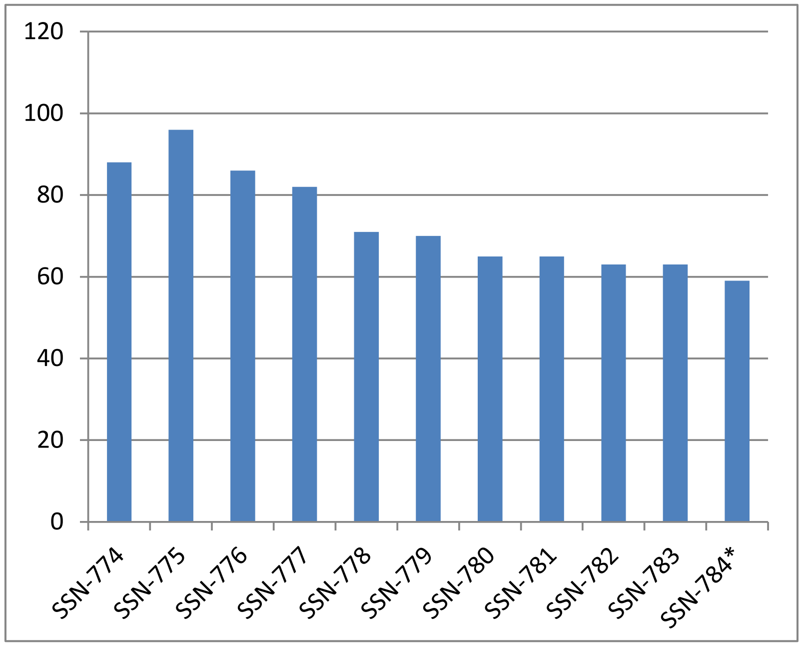

Figure 13: Delivery Rates for Virginia Class Submarines

The Navy initially scheduled each submarine to take 84 months for Block I subs (SSN-774 through 777) and intended the schedule to be reduced to 60 months by Block III (SSN-784 through 791).[191] The first Block III submarine (SSN-784) is projected to be completed in roughly 59 months (delivery date is expected to be January of 2014), putting it on schedule and showing a remarkable ability by the SSN innovation network to reach some ambitious cost reduction and time reduction targets.

[187] Goggins, David. *Virginia Class Submarine Program Status: Sea Air Space Symposium 2013*. United States Navy. Naval Sea Systems Command (NAVSEA). April 9, 2013. Accessed January 9, 2014. http://www.navsea.navy.mil/Media/SAS2013/3.%20VA-Class.pdf.
[188] "PCU Minnesota (SSN-783) Delivers Ahead of Schedule, Achieves Highest Readiness Scores of the Class." PCU Minnesota (SSN 783) Delivers Ahead of Schedule, Achieves Highest Readiness Scores of the Class. June 07, 2013. Accessed January 09, 2014. http://www.navy.mil/submit/display.asp?story_id=74695.
[189] "Photographs and Facts." USS North Dakota. Accessed January 09, 2014. http://ussnd.com/photographs-and-facts/.
[190] Schank et al., "Learning from Experience Volume II", p. 87.
[191] Johnson, David C., George M. Drakeley, and George M. Smith. *Engineering the Solution: Virginia Class Submarine Cost Reduction*. American Society of Naval Engineers, p. 2. Accessed July 22, 2013. https://www.navalengineers.org/SiteCollectionDocuments/2008%20Proceedings%20Documents/ETS%202008/VA%20Class%20ASNE%20Paper%20FINAL.pdf.

The quality of the work performed is another critical factor in measuring the effectiveness of learning. As quality goes up, less re-work is needed, thereby reducing delays and costs. As discussed earlier, the SSN innovation network uses a number of feedback mechanisms to facilitate network-wide learning, one of these mechanisms being the Navy's Board of Inspection and Survey, or INSURV. This inspection group performs annual inspections of all the Navy's warships, and the initial inspections on the Virginia class submarines after their construction are very informative about the learning process for new platforms. Figure 15 shows the INSURV results for its initial readiness assessment of delivered submarines, and it is clear that with each boat produced, the number of unsatisfactory or degraded scores decreased over time.[192] (The reason the total number of graded areas went up over time is that the Navy added new categories to be scored.) Along the same lines, Figure 14 shows the average overall INSURV readiness scores for the same inspections, which also went up with each succeeding *Virginia* class submarine. (Note: An average score considered satisfactory by the INSURV board is between 0.8 and 1.0, a score considered "degraded" is between 0.6 and 0.79, and an unsatisfactory score is between 0.0 and 0.59.) This means that the quality of workmanship was increasing at the same time the delivery rates were improving, all while costs on a per-submarine basis were being reduced.

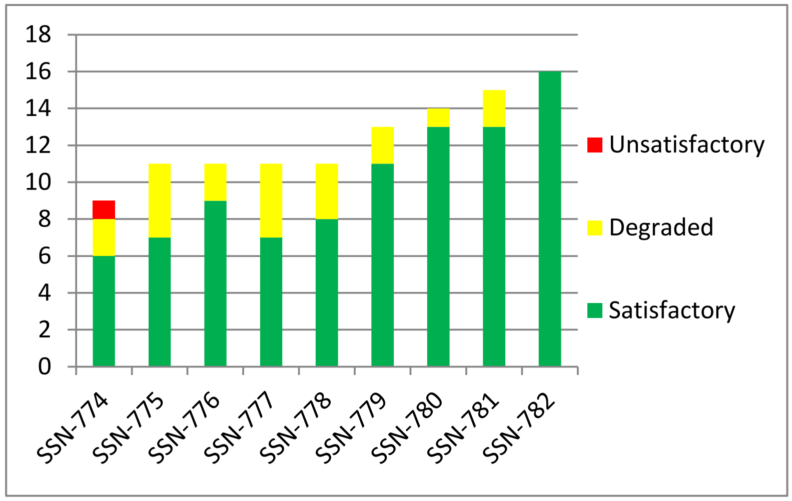

Figure 15: INSURV Readiness Results for Delivered *Virginia* Class Submarines

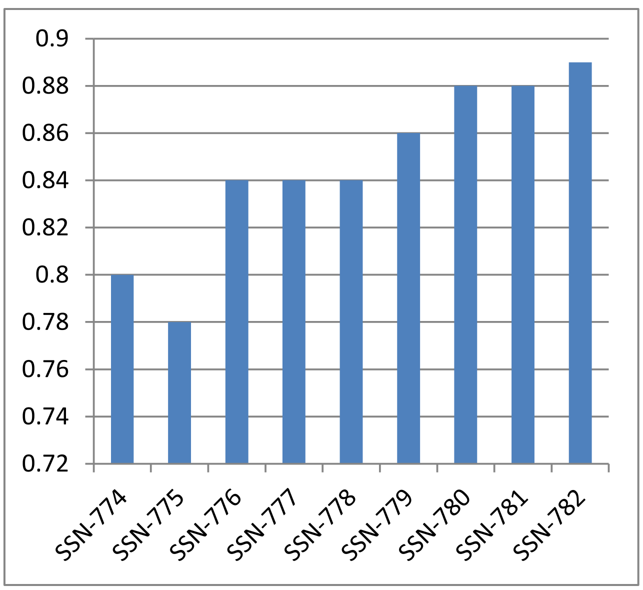

Figure 14: Average Initial INSURV Readiness Scores for *Virginia* Class Submarines

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192 Goggins, *Virginia Class Submarine Program Status,* slide 4.

The first step for the SSN innovation network in approaching the *Virginia* class was to correct the failures of the *Seawolf* debacle. First, the Navy returned to a policy of introducing innovations incrementally instead of all at once with a new platform, as the incorporation of several immature technologies led to delays and cost escalations with the *Seawolf*.[193] The design process involved greater cooperation and less competition between shipyards, thus increasing the communication across the network. [194] [195] Lead ship construction would wait until the designs were sufficiently mature, which meant detailed design drawings were 99% complete for the *Virginia* class where they were only 65% complete for *Seawolf* class.[196] In complex systems like submarines, roughly 80% of all costs are built in to the first 20% of the design process, so a complete and thoroughly planned design is critical to keeping initial costs low.[197] The strategy of early completion of designs led to significantly fewer errors, as the *Virginia* platform only needed roughly 12,000 changes compared to the *Seawolf* platform's 70,000. [198] Finally, early design completion enabled parts standardization, as the Virginia platform only required only 17,963 parts, avoiding approximately $789 million in additional costs.[199]

Despite these early efforts to limit cost escalations and enhance learning in the system, overruns and delays occurred. The massive reduction in submarine orders following the end of the Cold War and the subsequent termination of the *Seawolf* program led to a great deal of knowledge depreciation in the nuclear submarine industry.[200] Additionally, many vendors of high-tech equipment left the submarine industry following the termination of the *Seawolf* platform to pursue commercial products, which greatly raised the price of the highly-specialized submarine warfare components they no longer manufactured in large numbers.[201] However, the most heinous contributors to cost growth were found by a United States

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[193] Schank et. al "Learning from Experience Volume II", p. 64.
[194] Johnson, Drakeley, & Smith, *Engineering the Solution*, p. 2.
[195] Schank et al., "Learning from Experience Volume II", p. 81.
[196] Schank et al., "Learning from Experience Volume II", p. 80.
[197] Eccles, Thomas J., and Henry Marcus. "Integrating Design and Production: A Case Study of the Naval Submarine Program." *International Journal of Production Economics* 28, no. 1 (November 1992): 107-26. Accessed October 19, 2013. http://www.sciencedirect.com/science/article/pii/092552739290116O.
[198] Schank et al., "Learning from Experience Volume II", p. 80.
[199] Defense Standardization Office. *Case Study: The Virginia Class Submarine Program,* p. 6.
[200] Schank et. al "Learning from Experience Volume II", p. xv.
[201] GAO, *Defense Acquisitions*, p. 68.

Government Accountability Office (GAO) study that showed that 83% of the cost growth on SSN-774 and SSN-775 were related to labor and materials acquisition.[202] SSN-774 alone saw 3.4 million more man-hours of labor than was expected, and rising costs of shipbuilding materials led to $350 million in additional costs for both boats combined.

These cost overruns combined with new budgetary constraints led the Navy to take drastic action. On December 23, 2004, the DOD issued Program Budget Decision (PBD) 753 which cut the funding to the *Virginia* class program by $5.27 billion.[203] In early 2005, the Chief of Naval Operations challenged the program to cut per-ship costs by 20% to a price of roughly $2 billion per submarine (in FY 2005 dollars), or the Navy would cut boats from the contract. Any military program that experiences a 15% or greater increase in costs is known as a Nunn-McCurdy Breach, a dubious designation that mandates immediate Congressional investigation into the program.[204] The fear of increased Congressional oversight and the further reduction of funding proved to be a valuable motivator for the Navy. The Navy also was motivated by an intermediate-term submarine shortage in their force levels, which also was an issue for the shipyards that were already struggling from reduced nuclear warship orders. Necessity is a powerful motivator, and in this case it led to collaboration within the SSN network. This collaboration is known as the Virginia Class Cost Reduction Program.

In order to identify the causes of submarine cost escalations, the SSN production network reached out to consulting groups to generate knowledge about their inefficiencies. Groups like the PA Consulting Group and Booz Allen Hamilton were contracted to improve management of the Virginia program and find areas to reduce costs.[205] [206] Numerous reports were published by the Government Accountability Office detailing the cost overrun problems of the Navy, and the Navy launched several studies of its own into the problem. Knowledge generated from these reports was shared across the network and served as feedback mechanisms

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[202] GAO, *Defense Acquisitions*, p. 65.
[203] Johnson, Drakeley, & Smith, *Engineering the Solution*, p. 1.
[204] United States. Department of Defense. News. *Nunn-McCurdy (NM) Unit Cost Breaches.* May 2002. Accessed February 8, 2014. http://www.defense.gov/news/May2002/d20020502nmc.pdf.
[205] Jones & Dehoff, ISSR, p. 1-10.
[206] Johnson, Drakeley, & Smith, *Engineering the Solution*, p. 1.

that allowed participants to learn from their mistakes and correct the underlying issues causing the escalations in the *Virginia* and *Seawolf* platforms.

Armed with the new information, the Navy targeted material and labor costs by implementing a procurement strategy created economies of scale. The use of a multi-year procurement strategy gave contracts to the shipyards for periods of two to five years instead of a single year deal, which allowed them to contract labor well in advance and acquire materials in larger quantities, thereby reducing costs. By the completion of SSN-780, this strategy was saving the Navy roughly $115 million per boat, and total program costs had been reduced by $805 million.[207] The Navy also launched what was called a "2 for 4 in 12" program, meant to motivate the SSN production network to improve economic efficiencies.[208] The idea was that the Navy would buy two boats per year for a price of $4 billion starting in 2012 if costs of production were reduced to $2 billion per boat (in 2005 dollars). If costs were not reduced, the Navy would only buy a single boat per year. The SSN network was able to achieve the targeted goal, and referring back to Figure 12, starting in 2011 the Navy began purchasing two Virginia class boats per year. This increase in demand allowed the shipyards to spread fixed costs and improve learning rates, reducing the per-unit cost of the submarines by between $200 and $400 million.[209]

The Navy also found other ways to reduce costs through infrastructure investment programs. One such program is called the Capital Expenditures incentive fee program, or CAPEX. The CAPEX program provides nuclear-certified shipyards with funding from the Navy so that they can improve their infrastructure to increase production efficiency. The shipyards approach the Navy with a business plan, and if the plan is approved, the Navy will supply half the cost of the improvements upfront, paying for the rest of the costs after improvements are completed. If the project fails to improve efficiency, the Navy charges the shipyard the

[207] "Multiyear Procurement Authority for the Virginia Class Submarine Program." Paul L. Francis to Jerry Lewis, Chairman of the Subcommittee on Defense, Committee on Appropirations, House of Representatives. June 23, 2003. Accessed January 4, 2014. http://www.gpo.gov/fdsys/pkg/GAOREPORTS-GAO-03-895R/pdf/GAOREPORTS-GAO-03-895R.pdf.
[208] O'Rourke, *Navy Virginia (SSN-774) Class Submarine Procurement,* p. 5.
[209] O'Rourke, *Navy Virginia (SSN-774) Class Submarine Procurement,* p. 6.

entire cost of the program, so there is a measure of protection on the investment.[210] An example of this program in action is the Quonset Point Coating Facility built by Electric Boat, which improves the hull coating process of submarine manufacturing. An investment by the Navy of $9.4 million reduces the labor per boat by 1,306 man-hours, and will ultimately save the Navy $71 million over the course of producing 30 *Virginia* class boats.[211] Through FY 2020, it is estimated that a total of $63 million in CAPEX program investments will saved the Navy roughly $422 million, yielding a 7:1 return on investment.[212]

A similar CAPEX-like program that incorporates an up-front investment by the Navy in parts standardization has also been beneficial. This program was referenced previously as one of the lessons-learned from the *Seawolf*, but further explanation is needed. The Navy invested $27 million in the parts standardization program, which has led to $789 million in cost avoidance for the *Virginia* class program.[213] Additionally, the Navy is incorporating many of the Virginia platform's parts into other parts standardization programs for other submarine platforms. The *USS Jimmy Carter*, a highly specialized *Seawolf* class boat, is reusing roughly 4,000 parts from the Virginia program, which will save $72 million. The new guided missile submarine (SSGN) under development will re-use 4,447 parts from the Virginia platform, avoiding another $80 million in costs. In essence, the Navy is forcing some degree of integration across platforms, strengthening relationships across the entire submarine development network.

Learning Effects: Conclusion

What is evident from the experience of learning in the SSN innovation network is that it cannot be taken for granted, and requires substantial effort by all participants to achieve maximum benefit. The standardization programs required forward-thinking and cooperation between the Navy, Naval Reactors, and

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[210] United States. Government Accountability Office. Defense Acquisitions. *Guidance Needed on Navy's Use of Investment Incentives at Private Shipyards.* July 2010. Accessed January 4, 2014. http://www.gao.gov/assets/310/307645.pdf.
[211] Johnson, Dave, and Dustin Muniz. "More for Less: The Navy's Plan to Reduce Costs on Virginia Class." United States Navy: Undersea Warfare. Winter 2007. Accessed January 04, 2014. http://www.navy.mil/navydata/cno/n87/usw/issue_33/more.html.
[212] Johnson, Drakeley, & Smith, *Engineering the Solution*, p. 10.
[213] DOD Defense Standardization Office, *Case Study: The Virginia Class Submarine Program,* p.6

the shipyards. CAPEX programs relied on the creativity by those at the shipyard level to innovate new processes to reduce production costs. Everyone in the system was under substantial pressure to innovate cost reduction techniques rapidly, lest the Navy cut back its contract or Congress cut further funding. Any further reduction in the contract would exacerbate the already rising costs in materials acquisition and labor, as benefits economies of scale would be reduced. The “2 for 4 in 12” target proved to be a powerful motivator for the network, which otherwise might suffer continued knowledge depreciation that already was occurring following the end of the Cold War and termination of the *Seawolf* program. The stability of multi-year procurement contracts gave the system a strong foundation to plan for, as guaranteed military purchases reduced the risk for the industry. All of these measures enable learning effects that make innovation cost-effective.

The next step for this paper is to apply the lessons learned from the SSN innovation network to SMR development. How can an approach used for military technology be applied to a energy technology that faces strong market competition? Does the military-industrial complex make innovation inevitable? If a complex platform like a nuclear submarine can experience learning and benefit from economies of mass production, can some of the mechanisms for enhancing learning be applicable to commercial nuclear energy as well? The relevance of SSN innovation system mechanisms to SMR will be discussed in the following section.

Lessons from the SSN Network: Enabling the Key Functions of Innovation Systems

The purpose of the Discussion section of this paper is to put SMR innovation in the context provided by the submarine study. This means drawing parallels between lessons from the nuclear attack submarine study and energy technology innovation theory, then using these ideas to enable success in the development of SMR. The goal of innovation networks is to minimize the adverse economic and political costs of a technology, which can be accomplished through efficient implementation of the seven key functions of innovation systems. The

SSN system has been able to optimize these functions to overcome the challenges faced by the Valleys of Death and the Mountain of Death. Can a similar approach be used for SMR?

Recall that the first Valley of Death occurs between the development and demonstration phases of the innovation process, where technologies are too expensive to scale up or private investment in demonstration projects is otherwise difficult to acquire. These issues are minimized in the SSN innovation system through the effective functionality of the network. The scale-up costs of a new reactor are not an obstacle, since the Navy, DOD, and DOE supply funding for demonstration projects at national laboratories. Not only do prototype reactors have a guaranteed demonstration project, the projects themselves reinforce the learning within the network, learning that must be maximized for innovation to take place.

The second Valley of Death is essentially non-existent in the SSN innovation system. As discussed previously, energy technologies tend to fail between the demonstration and diffusion stages due to the riskiness of new technology in the market, thus the necessity of the Market Formation stage in ETIS. But for nuclear attack submarines and their associated reactors, the Navy guarantees purchase of a large quantity of these items after a successful demonstration and testing period. The market for this new technology is predetermined by the DOD and the Navy, which provides market predictability for private industry partners which reduces their risk. With multi-year procurement and block-buy contracts, the Navy determines its shipbuilding needs decades in advance which allows the entire network to plan the submarine production economy.

The Mountain of Death, a contributor to the second Valley of Death, also has been managed well with the *Virginia* platform. With multi-year procurement and block buy contracts from the Navy, shipyards can plan materials procurement and labor contracts that otherwise would be primary contributors to cost escalations. Large orders allow for repetition in the manufacturing process, giving ample opportunities for shipyards to learn and improve their practices. Finally, the yards are incentivized through CAPEX programs and the "2 for 4 in 12" program, as both of these policy initiatives involve increased investment from the Navy if processes are improved and costs of production reduced. These efforts combine to facilitate cost stabilization by encouraging the learning process.

With the Valleys of Death bridged, the SSN innovation system also accomplishes all seven functions of an innovation system. Knowledge development is accomplished through R&D, as well as the numerous feedbacks from the fleet. Knowledge diffusion has been perfected by the placement of Naval Reactors in a central position, where it communicates feedbacks and perpetuates the prioritization of safety. From this position Naval Reactors can also assist in guiding the search, but the leadership role in the innovation process is also filled by the DOD and the Navy. By defining national security objectives and mission capability criteria, the military not only leads but also creates legitimacy of the new technology and counteracts resistance to change. Incumbent technology is replaced, and political obstacles to submarine innovation are navigated at the highest levels through the military procurement process. The Navy and DOD also combine to negotiate with Congress for the market formation for nuclear attack submarines through long-term fleet planning; multi-year procurement and block buy contracts. This allows the shipyards to mobilize resources in advanced economy planning. Finally, shipyards also engage in entrepreneurial activities by developing business plans to cut costs and earn larger contracts from the Navy.

In the nuclear attack submarine study, much was made of the learning that was evident, but the effects of learning must be placed in their proper context. In the SMR business plan proposed by Rosner et al., the projected learning rate for SMR (based on naval shipbuilding) was between 3% and 10%. In a parallel study, Professor Geoffrey Rothwell of Stanford University performed a cost-benefit analysis that determined that the net benefits of a SMR business plan would require a 5.4% learning rate over the manufacture of the first 8-9 plants to yield a positive net benefit.[214] It is tempting to take the results from the Virginia platform learning and forecast the LCOE for SMR based on cumulative production of units; however, scholars warm against this

[214] Rothwell, Geoffrey. *Keys to Deploying U.S. Small Modular Reactors (SMRs)*. *Platts McGraw Hill Financial*. N.p., 21 May 2012. Web. 15 Jan. 2014. http://www.platts.com/IM.Platts.Content/ProductsServices/ConferenceandEvents/2012/pc230/presentations/Geoffrey_Rothwell.pdf.

practice. Learning curves are meant to be descriptive, and cannot with any accuracy be used to predict how new energy technologies may perform in the market.[215] Forecasting learning curves can lead to "buying down" approaches to policy that focus on demand-pull policies without the needed supply push.[216] Learning also does not necessarily lead to cost reductions. An improvement in manufacturing quality alone may occur, which was evident in the *Virginia* platform. To facilitate SMR's ability to test the rigors of the market, a balanced policy approach that addresses all aspects of the innovation process is needed.

A fairly obvious reason for the success of the SSN innovation process is the planned submarine economy and massive government spending, so this clearly cannot be the complete answer for the questions raised by the SMR business plan. Nuclear attack submarines face no market competition and have a single guaranteed buyer (the United States DOD) in what amounts to a nearly monopsony on nuclear submarine technology. The economics of submarine production are also somewhat skewed by the fact that there are only two shipyards competing for the DOD's contracts (GDEB and NNSY), especially now that the two yards are collaborating more on the *Virginia* platform and competing less for projects. The market for SMR will likely start as government owned utilities like TVA, and then branch out to other domestic utilities while the rules for export of SMR technology are worked out between the NRC, DOE, State Department, and private industry. These potential buyers lack the market capitalization of the DOD, are more sensitive to high costs, and therefore will be difficult to persuade to invest in SMR.

Another related difference between SSN innovation and SMR is that nuclear must compete against other electricity generation sources in balkanized electricity market. Nuclear energy must compete against other sources of electricity across vastly differentiated electricity markets, some regulated, some unregulated. The selection process of utilities looking into purchasing a new power plant must incorporate NIMBY concerns, local policy constraints, and short term earnings targets, among countless other criteria. There are many more options for electricity generation than there are varieties of nuclear attack submarines. This means that the

[215] Gallagher et al. (2006), "Energy Technology Innovation", p. 205.
[216] Gallagher et al. (2012), "The Energy Technology Innovation System", p. 142.

order book development described by Rosner et al. in the SMR business plan is still problematic; there are no guarantees from the market that investors will place orders for plants, especially when inexpensive natural gas is a more attractive alternative. In unregulated markets this is especially risky for utilities.

Another major difference between SMR and SSN innovation is in the nuclear engineering of the plants themselves. Naval reactors are ill-suited to be dedicated electricity generators for commercial use, so spillovers between the two technologies will not be directly related to reactor design. Land-based reactors are fueled with 3-5% LEU, whereas plants for nuclear propulsion contain 93-97% HEU.[217] This level of enrichment is weapons grade, and would engender severe proliferation concerns and therefore is absolutely inapplicable for commercial purposes. In the United States, submarines are designed with high-density cores to permit smaller reactor vessels to enhance transportability and enable long core lives. Additionally, the use of HEU provides enough reactivity to overcome the effects of xenon poisoning that occur with frequent power transients that can otherwise force a reactor shutdown.[218] The approach used by Afrikantov OKB Mechanical Engineering (OKBM) in Russia with their KLT-40S plant might be feasible if United States SMR vendors were designing a barge-mounted SMR meant for use by coastal communities or industrial applications at sea, like by the petroleum industry. The fuel would have to be modified, though this may be possible by using nonproliferation-supportive “caramel” fuels that the French have been adapting for their nuclear submarines.[219] But in general it is viewed in the near to intermediate term that United States SMR vendors cannot collaborate with BAPL or KAPL and start producing naval reactors for commercial sale.

A major factor that may influence or hinder the processes of nuclear innovation is the regulatory environment, which is profoundly different between submarines and SMR in the United States. The safety of reactors operated by the Navy is the responsibility of Naval Reactors, whereas civilian nuclear power plants are regulated by the NRC. In recent years there has been a great deal of debate about the applicability of NRC

[217] Ma & Von Hippel. "Ending the Production of Highly Enriched Uranium for Naval Reactors." p. 87.
[218] Ragheb, "Nuclear Naval Propulsion." p. 13.
[219] Heinonen, Olli. ""Nuclear Submarine Program Surfaces in Iran"" The Harvard Belfer Center for Science and International Affairs. July 23, 2012. Accessed February 09, 2014. http://belfercenter.ksg.harvard.edu/publication/22207/nuclear_submarine_program_surfaces_in_iran.html.

standards for SMR due to the smaller source term, concerns over EPZs, operator staffing, security requirements, manufacturing practices, among many issues.[220] [221] [222] Some scholars have recommended slight modifications to NRC licensing requirements to facilitate effective management of a new technology. [223] [224] Innovations in reactor technology are exacerbated by the NRC's lack of familiarity with the new designs, especially those that are not based on light-water reactor technology. [225] Regulatory changes during plant construction can also create construction delays and increased costs. [226] These issues combine to unintentionally hinder the diffusion of new reactor technologies in the name of safety, something that SSN innovation does not struggle with because development and regulation go hand-in-hand.

However, it should be noted that a regulatory environment that supports innovation and safety simultaneously may not be an effective solution for SMR development. Recent events have shown that for civil purposes, the separation of the two may be necessary for safe operation of nuclear power plants. Wang & Chen argue that within Japan's Ministry of Economy, Trade, and Industry (METI), the responsibilities of endorsing and regulating the use of nuclear energy were confused, which led to relaxed safety standards that contributed to the accidents at Fukushima. [227] Additionally, the promoter-regulator conflict combined with what Charles Perrow described as a "nuclear village" of rotating professionals between private and public positions further exacerbated the safety problem.[228] In fact, so many professionals from the private industry had transferred into the regulatory sphere that Wang & Chen labeled the situation "regulatory capture". This eliminated whatever safety culture existed in Japan, as concerns over the costs of upgrading the seawall at

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[220] *Interim Report of the American Nuclear,* 1-114.
[221] Kuznetsov & Lokhov, "Current Status, Technical Feasibility and Economics of Small Nuclear Reactors", 25.
[222] NEI, *SMR Pre-Application Engagement*, p. 9.
[223] Rosner et al., p. 48-52.
[224] *Interim Report of the American Nuclear Society*, p. 51.
[225] *Interim Report of the American Nuclear Society*, p. 36.
[226] Koomey & Hultman, "A Reactor Level Analysis of Busbar Costs", p. 5632.
[227] Wang, Qjang, and Xi Chen. "Regulatory Failures for Nuclear Safety - The Bad Example of Japan - Implication for the Rest of the World." *Renewable and Sustainable Energy Reviews* 16 (2012): 2610-617. *ScienceDirect*. 20 Mar. 2012. Web. 23 Nov. 2012. http://ac.els-cdn.com.ezproxy.library.tufts.edu/S1364032112000342/1-s2.0-S1364032112000342-main.pdf?_tid=daa8cbe8-357c-11e2-9028-00000aab0f26&acdnat=1353682293_a8727800535e2f0698e29c204a5724e8.
[228] Perrow, Charles. "Fukushima and the Inevitability of Accidents." *Bulletin of the Atomic Scientists* 67.6 (2011): 44-52. Print.

Fukushima superseded the concerns over new studies on tsunami potential.[229] In the United States, there is a clear division between the responsibilities of the NRC (safety enforcement) and the DOE (promotion of nuclear energy). The SSN innovation system was successful in part due to the emphasis on safety, but for this very reason the idea of a regulatory body also promoting the use of nuclear energy is therefore not recommended as part of an innovation network.

The final major differences between SMR and SSN innovation is the concept of cultural acceptance of the technology and therefore its legitimacy. Nuclear energy faces a unique NIMBY struggle that other electricity generation sources do not, and public opposition to nuclear power plants has played a key part in stymieing the advancement of new reactor technology. In a case study on the Dutch nuclear energy industry, Geels and Verhees found that in any "innovation journey", nuclear energy is wholly dependent on public acceptance to proliferate.[230] Nuclear attack submarines, however, are not substantially hindered by this problem. Culture in the United States is very supportive of the military, and this carries into the political realm as SSN development has strong bipartisan support. Because nuclear propulsion is framed as a military technology, it faces little in the way of public opposition; something that nuclear energy has struggled with in the wake of Fukushima.

[229] Acton, James M., and Mark Hibbs. *Why Fukushima Was Preventable*. *The Carnegie Papers*. Carnegie Endowment, Mar. 2012. Web. 15 Jan. 2014. http://carnegieendowment.org/files/fukushima.pdf.

[230] Geels, F. W., and B. Verhees. "Cultural Legitimacy and Framing Struggles in Innovation Journeys: A Cultural-Performative Perspective and a Case Study of Dutch Nuclear Energy (1945-1986)." *Technological Forecasting and Social Change* 78 (2011): 910-30. *Science Direct*. Web. 12 Oct. 2013. http://www.sciencedirect.com/science/article/pii/S0040162510002878.

Recommendations

Network Strengthening

The major theme of success for the SSN innovation system was the tightly knit network of players that worked toward a singular goal of nuclear attack submarine production, which suggests that a similar approach could be advantageous for SMR development. The functions provided by this network include knowledge generation, knowledge diffusion, communication, leadership, mitigation of knowledge depreciation, and the funneling of resources toward SSN production. The lessons from the SSN innovation system echo the findings in academic literature regarding the relative success of the French and Japanese nuclear programs that were built on the principles of inter-reactor learning and system-wide diffusion of information regarding the reactors. The current balkanized approach used in the United States is self-defeating. The present innovation network of the United States nuclear industry must be mapped, and armed with this information the linkages between nodes can be strengthened.

Additional research into establishing successful public-private partnerships is essential in understanding how such a system might be created in the United States. The network centered on Naval Reactors is heavily public-oriented, especially when considering that GDEB and NNSY are essentially government-supported industries. An example that merits further investigation in this area is that of SEMATECH, a non-profit consortium of private industry, universities, and government agenciesthat performs R&D on microchips as well as semiconductors.[231] The success of SEMATECH has been cited by several authors

[231] "Accelerating the next Technology Revolution." SEMATEC. Accessed February 09, 2014. http://www.sematech.org.

as a path to follow for energy technology innovation, and by nuclear energy in particular.[232] [233] Additionally, the government can strengthen the Advanced Research Projects Agency – Energy (ARPA-E), an agency tasked with accelerating technological advances in energy projects. The NRC must be increasingly involved as well without promoting regulatory capture or a conflict of interests between safety and promotion of new nuclear technology. The NRC must stay ahead of new reactor development to continually reinforce their engineering expertise to facilitate reasonable rates of design certification and licensing while maintaining a high degree of safety.

A truly ambitious approach to establishing an efficient public-private partnership would be to maneuver the innovation network for nuclear energy to create more linkages between it and the network for SSN innovation. How this might be accomplished is certainly a daunting task and is beyond the scope of this paper, though it seems that in the cases of nuclear energy and nuclear attack submarines, the DOE as well as its national laboratories are the key nexus points where the two technologies might intersect. Spillovers might abound if these networks could collaborate more extensively. The classified nature of advanced military technologies makes this type of linkage problematic, although in a post-Cold War world where undersea warfare is not an international competition for supremacy, perhaps some areas of classification might be re-evaluated.

Policy Incentives

The network created for the SMR innovation system must have leadership to guide the search and policy mechanisms at every stage of the process, functions that can be provided by increased involvement by the DOE. The initial investment in SMR technology via the SMR LTS Program should not be wasted, meaning that

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[232] Hayward, Steven F., Mark Muro, Ted Nordhaus, and Michael Shellenberger. *Post-Partisan Power: How a Limited and Direct Approach to Energy Innovation Can Deliver Clean, Cheap Energy, Economic Productivity and National Prosperity*. TheBreakthrough.org. October 2010. Accessed February 9, 2014. http://thebreakthrough.org/blog/Post-Partisan%20Power.pdf.

[233] Diaz Anadon, Laura, Kelly Sims Gallagher, Matthew Bunn, and Charles Jones. *Tackling U.S. Energy Challenges and Opportunities*. *Belfer Center for Science and International Affairs*. John F. Kennedy School of Government at Harvard University, 18 Feb. 2009. Web. 2 Oct. 2013. http://belfercenter.ksg.harvard.edu/files/ERD3_Energy_Report_Final.pdf.

the DOE should ensure that their venture has the best chance of success. A few lessons that could be applied from the SSN innovation system would be to offer CAPEX Program incentives to SMR vendors seeking to start reactor production, including a parts standardization program. A project that might mirror the SMR LTS Program could be a DOE cost-sharing agreement with SMR vendors to assist in the construction of the SMR manufacturing facility, should widespread commercialization of the units take place. The DOE must establish long-term signals to the market that SMR will be supported to some degree throughout the development process, which would encourage private firms to invest in demonstration projects or FOAK plants. Additionally, it is up to the DOE to ensure that communication between the national laboratories, private industry, itself, and other government agencies is free-flowing, and that information critical to the innovation process is relayed to all players in the network.

Alongside the efforts from the DOE, Congress can assist in establishing long-term market signals through the implementation of policies. Like DOE programs, these policies must target key points of failure for energy technologies to provide support where it is needed most, such as the Valleys and Mountain of Death. An example of this might be extending some incentives for new nuclear plants found in the Energy Policy Act of 2005 (EPA 2005) for SMR, including production tax credits for advanced reactor designs, loan guarantees, among others.[234] To receive the benefits of this policy, the license application must have been submitted by the end-of-the-year 2008, and since SMR vendors like Babcock & Wilcox have yet to even apply for design certification with the NRC, they cannot participate. Even if the incentives of EPA 2005 are not extended, some form of policy benefit should be established for the short to intermediate term to encourage private interest in SMR.

Another policy mechanism that could be implemented is federal procurement of SMR units for military installations, national laboratories, or other federal facilities. Many United States military bases are overly dependent on the fragile civilian electrical grid both at home and abroad, and having energy independence

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[234] Holt, *Nuclear Energy Policy*, p. 20-25.

could add a much needed dimension of security.[235] National laboratories or other federal installations could also benefit from having an independent electricity supply. Federal procurement would provide additional demonstration of SMR performance outside of the demonstration projects at the Clinch River or Savannah River sites, and help SMR vendors by giving them an opportunity to learn by producing more units. The United States Army has periodically shown interest in small reactors to enhance their energy security, having had their own reactor program during the 1960s into the 1970s.[236] More recently, the DOD called for a study in the feasibility of SMR at military bases in the 2009 National Defense Authorization Act. The regulations around federal purchases of electricity and generation facilities are difficult to navigate, so additional research into federal procurement of SMR is required.

SMR Design

Because nuclear attack submarines incorporate variants of small modular reactor designs, and the entire submarine is built in a modular platform, some basic elements of design are applicable to SMR. Majority of costs built-in during initial design phases, so to avoid the cost escalations that plague the current nuclear industry, SMR vendors must be as forward-thinking as possible.[237] Submarines are designed through a process of negotiation across the network with a wide range of contributors, ultimately leading to conservative platform approaches that incorporate a few well-tested innovations. This approach emphasizes safety, which is critical to any innovation in nuclear energy. This emphasis must be maintained in SMR, though this is already a high priority given the timing of the events at Fukushima in relation to SMR development. The negotiation process is already underway for SMR vendors like Babcock & Wilcox mPower, which is working with the NRC to ensure that their initial designs meet the NRC's stringent safety criteria. Whether or not the

[235] Andres, Richard B., and Hanna L. Breetz. *Small Nuclear Reactors for Military Installations: Capabilities, Costs, and Technological Implications*. National Defense University. Strategic Forum. February 26, 2011, p. 1. Accessed July 11, 2013. http://www.ndu.edu/inss/docuploaded/SF%20262%20Andres.pdf.

[236] *Highly Enriched Uranium: Striking a Balance*. United States Department of Energy. National Nuclear Security Administration Office of the Deputy Administrator for Defense Programs. Accessed in CURIE Database: Centralized Used Fuel Resource for Information Exchange, p. 146. Accessed July 22, 2013. http://curie.ornl.gov/content/highly-enriched-uranium-striking-balance-rev-1.

[237] Jones, Kronenberg, and Scherer. *ISSR: What Drives (Your) Program Costs,* p. 2-4.

mPower units are designed as platforms is difficult to say at this point, as the details of the reactor are a trade secret of the firm. For SMR units still in development, it stands to reason that following in the Navy's wake is certainly worth exploration.

A few practical lessons from submarine production are also important going forward. The DD&E should be as complete as possible prior to beginning production, as design changes became a major source of cost escalation in the SSN experience. The standardized approach of submarine production that allowed for repeated construction points to the potential for learning in SMR production, and many of the construction processes and techniques might also be spillovers that SMR could benefit from. The majority of submarine cost issues outside of design changes resulted from the acquisition of materials and labor, which, however, will be difficult to plan for until a SMR economy becomes a reality. One suggestion that might be helpful would be to locate SMR manufacturing facilities near nuclear naval shipyards like GDEB and NNSY, as the two industries could benefit from the other's success. Naval shipbuilding has struggled with a post-Cold War reduction in boat orders from the Navy, but if there was a degree of personnel transfer between the two industries, the highly skilled workers needed for nuclear shipbuilding and SMR production would have a place to keep their skills sharp and in high demand. The feasibility of this is beyond the current scope of this paper, but would certainly warrant some exploration.

Cultural Legitimacy

New technology can struggle with social acceptance, and this could be exceptionally problematic for advances in nuclear energy. Concerns over NIMBY are certainly a factor, but the concept of developing cultural legitimacy for SMR goes beyond siting. Recall that Geels & Verhees found that innovation journeys for nuclear energy demand public acceptance.[238] In In order to pass policy that is supportive of SMR, there has to be social and political buy-in, which is an issue following Fukushima. Submarines face no such issue in the United States, as the military is highly valued both socially as well as politically, and the reactors have a

[238] Geels & Verhees. "Cultural Legitimacy and Framing Struggles in Innovation Journeys", p. 910-912.

flawless record of safe performance. Once again we find that safety is paramount for SMR development, but more may be required. Public advocacy, lobbying, or other public-relations efforts might be needed to repair the image of nuclear energy as frightening or inherently dangerous in order for public acceptance to increase and for SMR innovation to occur.

International Markets for SMR

In order to develop the order book called for in Rosner et al.'s business plan for SMR, international orders will likely be necessary. Currently, the United States nuclear industry is struggling to compete against state-supported nuclear firms like AREVA, Rosatom, and KEPCO E&C, who are each acquiring larger and larger shares of the international market while United States-based vendors business has not kept pace.[239] The Government Accountability Office issued a report in 2010 calling for an integrated government-wide approach to facilitating nuclear exports, claiming that the current legal framework was restricting the United States' ability to compete in the growing global nuclear industry.[240] The framework for nuclear exports in the United States is difficult to navigate, as it incorporates regulations from the NRC, DOE, and the Executive branch of government. Export controls also involve diplomacy, therefore including the State Department in the process, as the United States must have a pre-existing 123 Agreement with the target country of export to allow any nuclear export license to be issued. Streamlining this process would be a powerful facilitator for SMR adoption internationally and thereby also assisting in solving the problem of developing the order book. Additional work is needed in this area to determine how efficient and secure transactions could be enabled in the future.

Future Work on Naval Reactors

A core objective of this study was to discover how innovation occurred in the nuclear attack submarine network with a special focus on the reactor themselves. Information regarding the propulsion systems of the Navy's submarines is generally highly classified, and the data regarding the technical development and

[239] Andres & Breetz, *Small Nuclear Reactors for Military Installations*, p. 1.
[240] GAO*, Nuclear Commerce,* p. 28-29.

economics of naval reactors was difficult to find. Because unclassified information on the reactors themselves was difficult to find, this paper's focus was broadened to include the entire submarine, to be used as a proxy for a nuclear power plant. For the purposes of SMR development, additional research could be advantageous, especially any cost data on the production of each iteration of submarine reactor that BAPL, KAP, General Electric, or Westinghouse might possess.

Conclusion

The Navy's success in continually improving the performance of their submarines and achieving affordability with the *Virginia* platform has countless lessons for the innovation processes of SMR. The tightly knit innovation network, CAPEX investments, standardization programs, platform design, and emphasis on safety are all significant themes that should be incorporated in Rosner et. al's business plan going forward. While it is true that it would be poor policy to support SMR in the way nuclear attack submarines are, the mechanisms that enhance learning and reinforce safety should be incorporated in a joint-venture fashion similar to what was achieved in SEMATECH. They key for SMR is to bridge the Valleys of Death and descend the Mountain of Death so as to not languish and fail without getting a chance to really evaluate the performance of innovative SMR designs. Lessons from the academic literature on past nuclear innovation strategies and on the ETIS are also critical for SMR, as they provide a strong theoretical foundation for which new innovations can build upon.

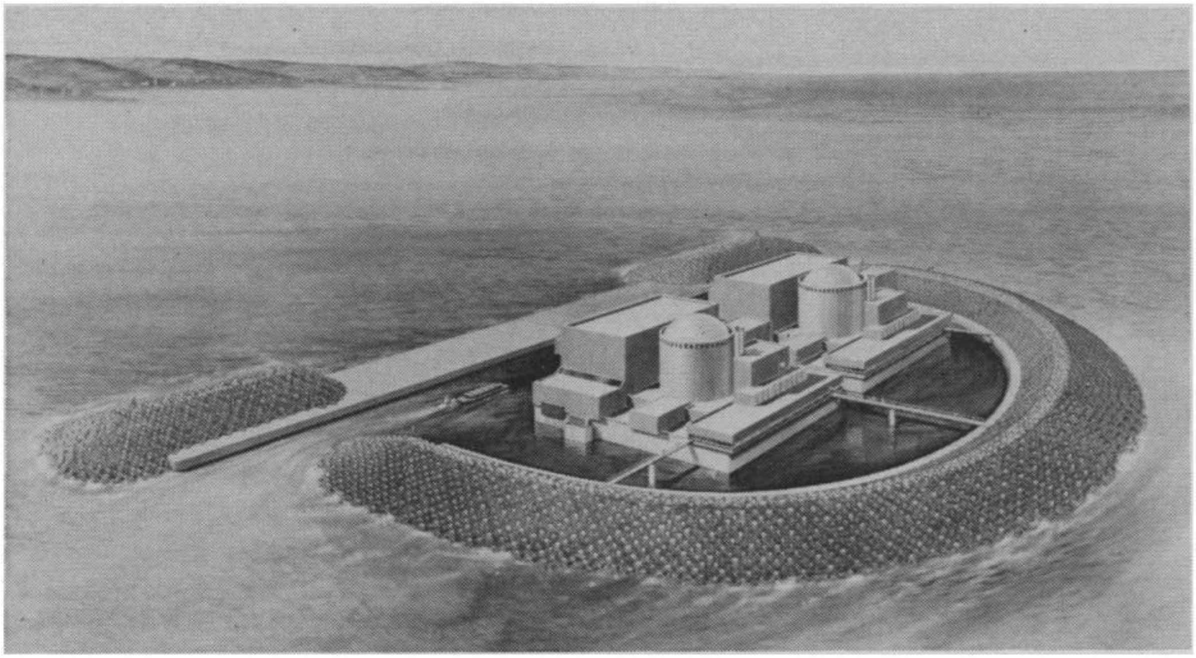
Will SMR become the commercial success in the United States that the nuclear industry claims it can be? Even with the lessons-learned from the nuclear attack submarine innovation system, there remain some gaps in the SMR business plan that would have to be filled before SMR could get a real chance at competing against natural gas. While learning was evident in submarine production, direct application of specific learning rates to project cost estimates for SMR might lead to an imprudent policy approach to buy-down the costs of SMR to encourage their adoption. As with the *Virginia* class, the reception of any policy incentive for a new technology should be contingent upon the performance of the technology in terms of economics and safety.

The nuclear industry's recent track record with cost escalations, construction delays, and socio-political opposition must be addressed before SMR can be given an opportunity to succeed. Some might interpret the recommendation advocated in this paper to strengthen the innovation network for SMR as a type of industry reform. In a sense, reform is exactly what is needed for nuclear. Nuclear energy is a complex technology, rife with political and economic concerns, that is situated in the balkanized electricity market of the United States. Change at some level is needed to encourage its success, whether within the industry or varying levels of government. Nuclear may very well be necessary for mitigating climate change, preserving public health, and managing energy security in the long-run. Given that the pace of nuclear technology is measured in decades rather than years, it follows that change is necessary sooner rather than later if the technology intends to remain a viable option.

Appendix A: Offshore Power Systems

Escalating costs of large site-specific nuclear plants in the 1970s combined with issues of siting inflexibility led the industry to attempt modular innovation with a Westinghouse venture called "Offshore Power Systems". The idea for such a concept was first floated to Westinghouse by the New Jersey Public Service Electricity and Gas Company (PSE&G) in 1970 to solve a number of issues facing the utility in the electric sector. [241] Electricity demand skyrocketed during the 1960s, so there was a call for large scale new nuclear builds to meet this growth. Newly introduced environmental policies like the National Environmental Policy Act of 1969 and the Water Quality Act of 1970 made it more difficult for power plants to obtain permits that would be located near heavily populated areas or encroach on coastal habitats where they would degrade water quality and impact wildlife. There also was the problem of siting large plants, as the densely populated East Coast made it difficult to find sites close but not too close to the population to keep transmission costs low while still meeting legal safety requirements for EPZs. Because of the factory based manufacturing of these units, and their sea-based operating characteristics that is reminiscent of the KLT-40S and the FlexBlue plants, a comparison of Offshore Power Systems to SMR development is an interesting one to ponder. Engineers are at their most innovative when presented with technical obstacles, and these new approaches to nuclear power plant were met with great enthusiasm from the nuclear industry, much like with SMR today.

[241] Carter, L. J. "Floating Nuclear Plants: Power from the Assembly Line." *Science* 183, no. 4129 (1974): 1063-065. Accessed August 23, 2013. doi:10.1126/science.183.4129.1063.



Artists' rendition of how a functioning 1200 MWe Offshore Power Systems' plant might look. The escalating costs of the massive breakwater seen in the drawing were one of the major factors that ultimately led to the failure of this attempt at innovation.

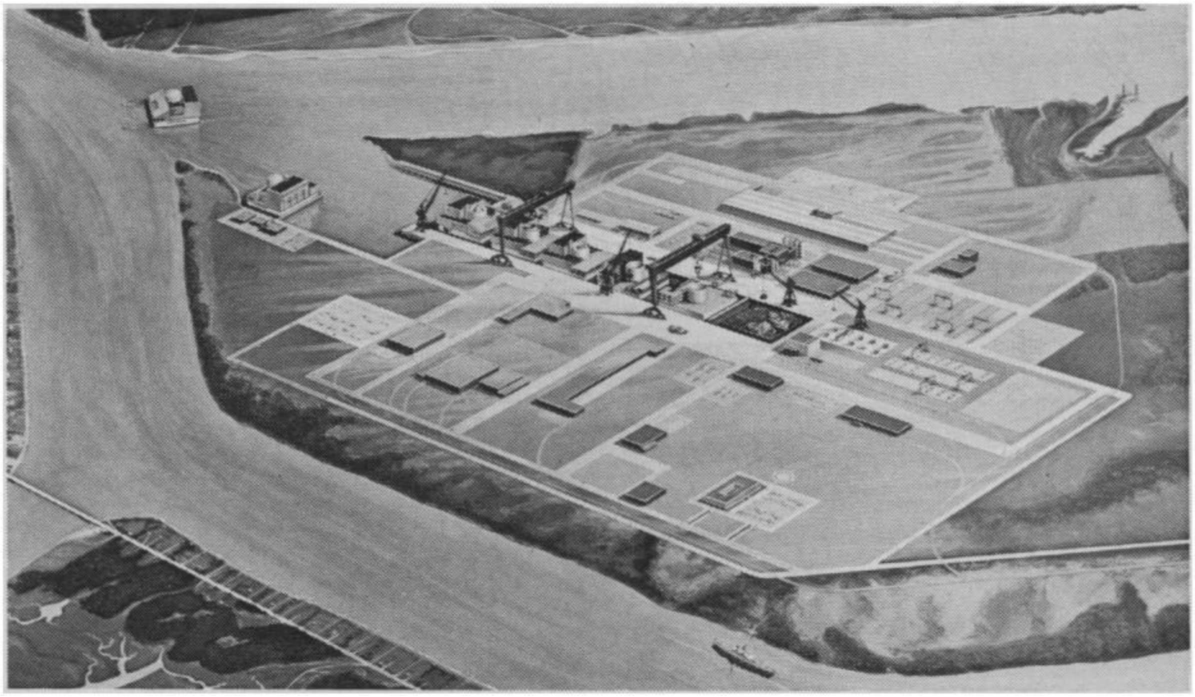
In December of 1970, Westinghouse concluded that floating nuclear plants were a plausible option, and combined forces with Tenneco Incorporated to start a joint venture to manufacture these plants on a large scale. The plants would be built as massive offshore artificial islands surrounded by an expansive breakwater, with each plant having a capacity of 1,200 MWe and a lifetime of 40 years.[242] Offshore Power Systems anticipated manufacturing these plants on a large scale, so in 1972 the company announced that a massive construction yard would be built on Blount Island near Jacksonville, Florida, where complete plants would be built and shipped out by barge. In 1973, PSE&G submitted a letter of intent to purchase the first two units produced, and intended to moor them 2.8 miles of the New Jersey coast, roughly 12 miles northeast of Atlantic City.[243] Atlantic 1 & 2, as they were designated, would cost nearly $1 billion to construct when built with their associated breakwater. Clearly, the industry saw this as the next big thing in nuclear energy, and

[242] *Coast Effects of Offshore Energy Systems: An Assessment of Oil and Gas Systems, Deepwater Ports, and Nuclear Powerplants Off the Coast of New Jersey and Delaware*. United States Congress Office of Technology Assessment. Office of Technology Assessment Archive - Federation of American Scientists. November 1976, p. 198. Accessed July 22, 2013. http://ota-cdn.fas.org/reports/7615.pdf.
[243] U.S. Congress Office of Technology Assessment *Coast Effects*, p. 201.

committed itself wholeheartedly to developing an innovative new electricity generation platform that could solve a number of issues.

This optimism may seem familiar, because many of the same arguments for Offshore Power Systems are being made today for SMR. Economies of mass manufacturing, innovation through learning, standardization, having a centralized and highly trained workforce were all touted as advantages to a new approach to nuclear plant construction. [244] The total costs for these plants was expected to be comparable to a large land-sited plant, despite the added expenses of having to construct a massive breakwater, living spaces for the crew, and the added costs of building an off-shore platform. The standardized plant design would not have to be adapted to a particular site, thus making manufacturing more efficient, and also simplifying the NRC's job of safety inspections. While it was projected that the FOAK plant would take 50 months to complete, Westinghouse believed that experience gained through learning would enable the process to be accelerated to 26 months per unit, greatly reducing costs associated with construction. Offshore plants were also expected to benefit from having reducing NIMBY opposition, reduced costs of site preparation, reduced investments needed in transmission, and having access to a high volume of cooling water. [245] So what went wrong?

[244] U.S. Congress Office of Technology Assessment *Coast Effects*, p. 203.
[245] Orr, R., and C. Dotson. "Offshore Nuclear Power Plants." *Nuclear Engineering and Design* 25, no. 3 (April 6, 1973): 334-49. Accessed August 23, 2013. doi:10.1016/0029-5493(73)90030-7



Artists' rendition of Westinghouse's proposed reactor manufacturing plant that was planned for Blount Island, near Jacksonville in Florida. While never built, this plant would have used modular techniques to enable higher learning rates to reduce nuclear energy's escalating costs of construction.

A combination of market conditions and geopolitical events ultimately led to the failure of Offshore Power Systems. First, the 1973 oil crisis led to a flattening in electricity growth, thus undermining the need for new capacity for the electric grid. Oil refineries also were expected to be major sources of electricity demand growth, and with the downturn of oil this growth was never realized.[246] Tenneco pulled out due to the increasing costs and delays that were engendered by the uncertainty in the market, and in 1978 PSE&G finally canceled their plant orders. During this period Offshore Power Systems had been working with the NRC to acquire the manufacturing license to build 8 plants, but this application would not be approved until 1982. By that point, any hope of penetrating the weakened electricity market was already lost and the venture was soon terminated, only to remain a dark legacy that forever shadows the nuclear industry's hopes for innovative new ideas.

[246] Dowdall, Mark, and William J.F. Standring. *Floating Nuclear Power Plants and Associated Technologies in the Northern Areas*. Norweigan Radiation Protection Authority. Nrpa.no. 2008, p. 10. Accessed July 22, 2013. http://www.nrpa.no/dav/0e1f312fc9.pdf.

Appendix B: Innovations Specific to *Virginia Class* Submarines[247]

The following items are technology initiatives (innovations) that were identified as key changes from the *Seawolf* class to be implemented in the *Virginia* class. Because the mission areas for attack submarines had changed following the Cold War, the Joint Chiefs of Staff adjusted the mission focus of the Virginia class to include: covert strike warfare, anti-submarine warfare, covert surveillance, electronic warfare, anti-surface ship warfare, special warfare, covert mine warfare, battle group support, and affordability of the platform. These innovations are listed in Part 2 of Appendix B of the *Secretary of Defense Report on Nuclear Attack Submarine Procurement and Submarine Technology*, and are briefly listed here.

1. Advanced display system
2. Advanced submarine tactical electronic warfare support measures combat system and integrated electronics mast
3. Advanced two operation ship control
4. Air turbine pump
5. Battery electrolyte agitation blower
6. Brushless direct current motors for towed array handling systems
7. Doppler sonar velocity log
8. Electromagnetic Silencing system
9. Fiber optic cable system
10. High data rate communications antennae
11. High frequency arrays
12. High speed direct current SSTG
13. High speed EDG
14. Hovering system components
15. Hull penetrators (fewer?
16. Impressed current cathodic protection system
17. Integrated interior communications system
18. Integrated low pressure oxygen generating plant
19. Isolated deck structures
20. Lightweight wide aperture array
21. Main propulsion unit
22. Main Shaft Seal
23. Main storage battery and automatic battery monitoring system
24. Main thrust bearing
25. Mechanically attached fittings

[247] United States. Department of Defense. Office of the Secretary of Defense. *Secretary of Defense Report on Nuclear Attack Submarine Procurement and Submarine Technology*. Accessed December 31, 2013. http://www.dod.mil/pubs/foi/logistics_material_readiness/acq_bud_fin/862.pdf.

26. Navigation sensor system interface
27. New design electric plant
28. Non-tactical data processing
29. Onboard team trainer
30. Open System architecture computer resources
31. Photonoics Mast imaging
32. Propulsion plant
33. Propulsion shaft
34. Propulsor
35. Quiet electro-mechanical actuator
36. Quiet non-ozone depleting air conditioning and refrigeration
37. Quieted torpedo tubes
38. Reconfigurable weapons shipping and handling module
39. Reverse osmosis desalination plant
40. Ring laser gyro navigator
41. Single Element Hangers
42. Sonar Signal processing
43. Structurally integrated enclosures
44. Submarine communications support system
45. Submarine defensive warfare system
46. Total ship monitoring system
47. Undermatched welding (advanced welding process)
48. Universal modular masts
49. Vacuum sanitary and quiet sanitary blow
50. Variable speed secondary propulsion motor

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