Investigation into the Unintended Consequences of Converting the U.S. Nuclear Naval Fleet from Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU)

Working paper for:
Independent Task Force on Naval Nuclear Propulsion: Assessing Benefits and Risks

Convened by:
The Federation of American Scientists
1725 DeSales St. NW, Suite 600
Washington, DC 20036

With funding from:
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Prepared by:
Jack Bell, Graduate Research Assistant
Nathan Roskoff, Graduate Research Assistant
Dr. Alireza Haghighat, Professor
Virginia Tech Transport Theory Group (VT^{3}G)
Nuclear Science and Engineering Laboratory (NSEL)
Nuclear Engineering Program
900 N. Glebe Rd.
Arlington, VA 22203

Consultant:
VADM (Ret.) Joe Leidig
Corbin A. McNeill Endowed Chair in Engineering
U.S. Naval Academy
121 Blake Rd.
Annapolis, MD 21402

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Executive Summary

From the birth of the United States Nuclear Navy until today, all nuclear-power ships have used highly enriched uranium (HEU) to fuel the onboard nuclear reactors. In the late 1970s, there began an initiative by the US Department of Energy to minimize the amount of HEU in civilian reactors by converting them to use low enriched uranium (LEU) fuel in an attempt to reduce the proliferation risks.

In 1995, at the request of Congress, the Office of Naval Reactors wrote a detailed report that addressed the potential to convert nuclear-powered ships to use LEU fuel in place of HEU. This document stated the conversion would be “technically feasible, but uneconomic and impractical.” In addition, that LEU as a fuel “offers no technical advantage to the Navy, provides no significant non-proliferation advantage, and is detrimental from environmental and cost perspectives.”

At the request of Congress, in early 2014 the Office of Naval Reactors issued another report on this issue. This report again states the conversion is technically feasible, but it is not economic or practical. However, the Navy offers that, “the potential exists to develop an advanced fuel system that could increase uranium loading,” so that LEU fuel could be utilized to meet the rigorous performance requirements; however, “it is not practical ... to work on an advanced fuel system without additional sources of funding.” Further, it is stated that “success is not ensured.”

This paper presents a thorough review and analysis of technical literature on the topic of using LEU for nuclear propulsion. It analyzes different technical issues and identifies a few that were not directly addressed by the Navy report. These include topics such as reactor control, fuel material properties and fuel cycle. A brief review of nuclear policies that influence any decision regarding nuclear materials or technologies is conducted. In particular, the Nuclear Non-Proliferation Treaty (NPT) is analyzed with an emphasis on Paragraph 14, a section, which authorizes a state to withdraw nuclear material from safeguards if it is being used for a “non-proscribed military activity.” In addition, an overview is provided of nuclear activities in key geographical regions including South America, Middle East, South Asia, and Northeast Asia.

The second half of this document addresses a number of “unintended consequences” of the conversion from HEU to LEU fuel for nuclear propulsion. These unintended consequences are split into two categories: technical and geopolitical. Technical unintended consequences are driven by the fundamental difficulties of using LEU fuel: decreased ^{235}U concentration and ^{238}U presence. Geopolitical unintended consequences represent the ways in which using LEU-fueled submarines may adversely affect the regional stability and power balance; these are broken down into high-level topics: easier access to LEU fuel, increased submarine range, use of nuclear submarines by non-democratic governments and possible “surrogate nuclear arms race.” For each unintended consequence discussed, a list of possible “future studies” is presented; these provide the reader with some concepts that have not yet been thoroughly investigated and should be addressed before action is taken toward conversion of the US Navy’s nuclear fleet.

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1. Introduction

This document investigates the implications of converting the United States Navy's nuclear fleet from highly enriched uranium (HEU) to low enriched uranium (LEU) fuel. The United States Congress, as well as foreign policy makers, has formally introduced the concept of conversion from HEU to LEU to address concerns of proliferation of HEU for weapons purposes to non-nuclear weapons states (NNWS), other nations outside of the NPT, and non-state actors. These concerns are based largely on the presence of a legal loophole in the NPT, which allows fissile material to be removed from IAEA monitoring for use in non-weapons military applications. This loophole has the potential to be abused as a front for weapons programs in NNWS. It is also considered that if the United States were to adopt the convention of using LEU instead of HEU for nuclear naval propulsion, it may pave the way toward an international norm against using HEU for naval propulsion. This could potentially help realize the goal of less stockpiled HEU worldwide.

Our goal in this paper is to consider and address possible "unintended consequences" that may arise from the potential switch from using HEU fueled naval reactors to LEU. In order to fully understand all of the issues at hand and the current climate of debate on the issue, Section 2 presents a review of all existing literature pertaining to the use of LEU in lieu of HEU for naval propulsion. Section 3 will identify unintended technical and geopolitical consequences.

2. Review of Existing Literature

Section 2.1 thoroughly reviews the technical issues associated with conversion of HEU fueled naval reactors to LEU fuel reactors. These main issues have been reiterated in numerous reports to Congress from the United States Navy. Section 2.2 reviews the international policies that regulate nuclear technologies, specifically the Nuclear Non-Proliferation Treaty (NPT) and geographically localized treaties, and how they address the issue of naval nuclear propulsion and development of such technologies in both nuclear weapons states (NWS) and non-nuclear weapons states (NNWS). This section also introduces some geographic regions, including South America, the Middle-East, South Asia, and Northeast Asia, that are currently of key importance to the discussion of naval nuclear propulsion, discusses their historical tensions, and how these regions may influence the geopolitical landscape with regard to naval nuclear propulsion.

2.1. Technical Considerations

Over the past 25 years, there have been several papers written which affect the climate of technical discussion on the topic of the use of LEU, instead of HEU, as fuel for naval reactors. In 1995, the Director of United States Naval Nuclear Propulsion submitted a report, as required by Section 1042 of the Fiscal Year 1995 Defense Authorization Act (Defense Authorization Act, 1995), to the Committees on Armed Services of the Senate and House Representatives which discussed the impacts of using LEU instead of HEU as fuel for naval nuclear propulsion (Office of Naval Reactors, 1995). This document officially states the United States Navy's position on the matter, which is that the conversion from HEU to LEU is "technically feasible, but uneconomical and impractical"; this sentiment is reiterated in a 2014 letter from the Office of Naval Reactors to Congress (Office of Naval Reactors, 2014). The 1995 Naval report has its limitations, but it provides a good starting point for analyzing the technical considerations associated with the use of LEU for naval nuclear propulsion systems.

To understand the issues associated with using LEU fuel for naval propulsion, it is first necessary to understand the functional requirements of a mobile nuclear power plant, or reactor, as designed for naval propulsion. The following list of essential design requirements for a naval nuclear reactor is taken from the 1995 Navy's report to Congress:

- **Compactness**: Reactor must be small enough to fit within space and weight constraints of a warship while still being able to provide adequate power to drive at necessary speeds for engagement or rapid transit.
- **Crew Protection**: The crew lives and works very close to the reactor for extended amounts of time.
- **Public Safety**: U.S. Navy ships use various ports around the world; it is a necessity that the safety of the general public at these ports be guaranteed so that our ships are continued to be welcomed.
- **Reliability**: The reactor must be able to continuously provide power and electricity to the ship to ensure a self-sufficient operational status in the most demanding environments.
- **Ruggedness**: The reactors must be able to tolerate extreme conditions of being at sea as well as severe shocks during battle conditions.
- **Maneuverability**: The reactor must be able to provide rapid and frequent power changes to support the ships' tactical maneuvering.
- **Endurance**: It is crucial that the reactor to be able to operate for many years before refueling, the best-case scenario is a lifetime core. This will maximize ship availability, minimize occupational exposure, minimize life-cycle cost, and minimize demand on the support infrastructure.
- **Quietness**: This is especially important for submarines so to minimize the threat of acoustic detection.

Failure to meet any one of the above requirements would jeopardize the operational status of the reactor, therefore compromising the ability of the ship to carry out its mission and potentially putting the crew in danger; such consequences are considered unacceptable. It is important to note that, over the last five decades, the Naval Nuclear Propulsion Program (NPP) has been continuously improving the design of naval nuclear reactors to best meet the aforementioned requirements. Though very few technical specifications of naval fuel and reactor design are unclassified, it is known that U.S. naval nuclear reactors use a fuel enriched to a minimum of 93% in ^{235}U and have achieved the "best-case scenario" for a reactor core endurance; the U.S. *Virginia*-class attack submarine (SSN) utilizes a reactor core that lasts for the lifetime of the ship, 33 years (Ma and von Hippel, 2001).

As a point of reference for a currently in-use LEU fueled naval reactor, let us consider a French Navy *Rubis*-class nuclear powered attack submarine, a submarine similar in *purpose* to the U.S. *Virginia*-class SSN. The *Rubis*-class SSN uses a reactor fueled with LEU enriched only to 7.5% ^{235}U. The *Rubis*-class SSN has a core life cycle of just 10 years and a maximum power of 48 MW compared to 33 years and 130 MW for the *Virginia*-class SSN (U.S Navy, 2014 and French Defense Ministry, 2014). The *Rubis* is a much smaller ship than the *Virginia,* (weighing in at 2,700 tons as opposed to 7,800 tons, with a diameter of 7.6

meters as opposed to 10.4 meters. Other noteworthy design differences include a more compact 'integral' reactor design, wherein the steam generator is incorporated into the reactor pressure vessel, and a large hatch for refueling. Table 1 provides a side-by-side comparison of selected performance parameters of the U.S. Virginia-class and French *Rubis*-class SSNs. The comparison provided shows that, while LEU fuel has been used in a naval reactor, it is in an application with significantly decreased core endurance.

Table 1 – A comparision of various performance characteristics of the HEU-powered U.S. *Virgina*-class SSN and LEU-powered French *Rubis*-class SSN.

	U.S. *Virginia*-class[1]	**French *Rubis*-class**[2]	**Percent Change**
Enrichment, wt-% ^{235}U	93[3]	7.5	-92%
Core Power, MWt	130[4]	48	-63%
Core Lifetime, years	33	10[5]	-70%
Diameter, feet	33	25	-24%
Length, feet	377	241	-36%
Weight, tons	7,800	2,700	-65%
Estimated Volume[6], ft^3	322,448	118,301	-63%
Estimated Density[6], t/ft^3	0.0242	0.0228	-6%
Power to Weight Ratio, MW/t	0.0167	0.0178	+70%

[1] Data from www.navy.mil unless otherwise noted; [2] Data from www.defense.gouv.fr unless otherwise noted; [3] Assumed for comparison (actual value may be higher); [4] Value generally used for analysis (actual value not publically available); [5] Assumed value for analysis (actual value not publically available); [6] Estimated based on known exterior dimensions

The Navy's 1995 report was an attempt to assess the viability of using an LEU-fueled reactor; to do such an analysis it is necessary to make some limiting assumptions so that some results are actually obtainable. This being said, the Navy's assessment was guided by the aforementioned list of design requirements, and previously made engineering decisions in regard to choice of coolant, moderator, and fuel system materials and design features. More specifically the LEU naval reactor under consideration would:

i. be light water-cooled and light water-moderated,
ii. use the same plant temperature and pressure operating ranges as in current HEU naval cores, and
iii. use the same fuel element and fuel module design, materials, and fabrication methods as current HEU naval cores.

Regarding consideration (i), the use of a light water-cooled core is a good design standard: there will always be a limitless supply of makeup coolant; water has good heat transfer and neutron moderation properties; it is not hazardous or aggressively corrosive; and does not have violent chemical reactions with air or water, as does some other coolants, e.g., sodium. Regarding consideration (ii), there may exist alternative temperature and pressure operating ranges that allow an LEU core to be used more efficiently. Any detailed information on temperature and pressure operating ranges is classified information; therefore, analysis directly applied to a naval reactor by an outside party may be difficult. Investigation of consideration (iii)—fuel element design, materials, and fabrication methods--would also require a large amount of work, some of which has been conducted (Ippolito, 1990 and McCord, 2014). This should be addressed because the standard naval fuel type was decided based on an HEU core, and without the availability of some modern fuel materials knowledge. A further discussion on the topic of higher uranium loading fuel materials is presented in Section 2.1.2.

Considering the above limiting assumptions, the Navy, in its 1995 report to Congress, considers two alternative paths for proceeding with a LEU SSN design:

1. Keep the current ship design and replace the HEU fuel elements in the core with LEU fuel elements. Maintaining essentially the same volume of fuel, but with a lower ^{235}U content, less fissile loading which would *substantially decrease the core endurance*.
2. Completely redesign the ships to increase core volume, thus *overall size of the ship*, to maintain the fissile loading, i.e., maintain the total amount of energy that can be withdrawn from the core over its lifetime.

In Path 1, the Navy concludes that submarines of current design specifications could be retrofitted to accommodate 20% LEU fuel with the restriction of a 7.5 year refueling cycle. Technical disadvantages of this system are identified as (Office of Naval Reactors, 1995):

- Increased occupational exposure due to more refueling operations;
- Increased volume of radioactive waste;
- Need for more shipyard capacity;
- Need for 10% more ships in order to make up for increased downtime due to refueling;
- Increased annual cost; and
- Upfront investment needed to develop the new technology.

The report also suggests a desire by the Navy for longer, not shorter core lifetimes in the future. This desire is reinforced by the progress the Navy has made in increasing the core endurance; the original naval nuclear core, *Nautilus*-class SSN, had a lifetime of just two years and the most current core, for example the *Virginia*-class SSN, has a core lifetime of 33 years.

Considering Path 2, where the core is enlarged to increase the uranium loading to levels found in a current HEU core a complete ship redesign would be required. The Navy found that, using LEU fuel enriched to 20%, the core volume must be about 3 times larger to achieve the same core endurance as the current HEU core (Office of Naval Reactors, 1995). This increase in core volume is similar to that cited in the Ippolito thesis; Ippolito concluded that if 20% enriched LEU fuel is used, the core volume must be increased approximately 2.5 times (Ippolito, 1990). It appears that the primary difference in the factor of core size increase between these two studies is that the Navy will not vary their current fuel structure type while Ippolito chose to vary material type from the Naval ‘cermet’ type in his HEU core study to ‘Caramel’ fuel for his LEU core. The more uranium-dense French Caramel type fuel consists of uranium oxide ceramic clad in zirconium metal. (Schwartz, 1978 and White 2012). The Navy claims that such an increase in core volume will have a rippling effect throughout the reactor and ship, including a larger pressure vessel, larger steam generator, more shielding, more reactor piping, etc. (Office of Naval Reactors, 1995). This significantly increases not only size, but also weight, of the reactor compartment. Consequently, this weight increase means that the ship’s volume must be increased to add buoyancy to compensate. The impact of using 20% LEU fuel on the size of a Virginia-class SSN is presented in Table 2.

Table 2 –Impact of 20% LEU on a *Virginia*-class SSN (Office of Naval Reactors, 1995).

Attribute	**Current HEU Design**	**Proposed LEU Design**	**Change for a 20% LEU Core**
Core Lifetime[1], years	33	33	0%
Enrichment, wt-% ^{235}U	93	20	-78%
Core Volume[2], *relative*	1	3	+200%
Hull displacement, tons	7,800	8,736	+12%
Hull diameter, feet	33	36	+9%
Hull length, feet	377	367	-3%

[1]Base design criteria, [2]Proportional increase.

The bottom-line of this analysis is that an SSN redesigned for a 20% LEU core with a 33-year lifetime would be significantly heavier and larger, in diameter. These characteristics would increase ship cost, by approximately 26% (Office of Naval Reactors, 1995), as well possibly be detrimental to tactical capabilities; the ship may not be as maneuverable and would require a longer stopping distance. It would make sense that this increase in ship size would also require more power from the core to reach similar operating speeds and execute certain maneuvers.

2.1.1. Reactor Control Issues Not Considered in the Navy's Response

While reactor thermal-hydraulic performance is addressed in the 1995 Navy study, the effect of the change in the reactor physics, of the system due to LEU conversion does not appear to have been considered. There are two potential reactor physics issues that have since been identified: (i) Doppler broadening effect and (ii) Xenon poisoning.

The Doppler Broadening Effect – According to U.S. Naval Representative Paul Jorgensen, Naval reactor power is changed simply by a change in steam demand by the operator, without any further adjustments made to control moderator temperature (Ward, 2013). This is made possible due to inherent reactivity feedback mechanisms in a nuclear reactor. Nuclear reactors have two reactivity feedback mechanisms which are important for operation: (i) the moderator effect, where reactivity decreases as moderator temperature increases and (ii) the fuel (or Doppler broadening) effect, where reactivity decreases as fuel temperature increases (Duderstadt, 1976). Because of the extremely low ^{238}U content of an HEU reactor, the fuel effect is negligible and the moderator effect dominates. Figure 1 is a graphic representation of the reactivity feedback effects, which occur in both an HEU and LEU reactor. The sequence for power change in an HEU reactor is as follows: moderator temperature decreases with an increased steam demand, power increases with moderator temperature decrease, and, finally, moderator temperature increases back to effectively its original level. However, in an LEU reactor with greatly increased ^{238}U content, the sequence now goes: moderator temperature decreases with increased steam demand, power increases with moderator temperature decrease; however, next, fuel temperature increases and this decreases reactor power (though not as much as steam demand increases it) and this further decreases moderator temperature. The net effect is that, in an LEU reactor, moderator temperature naturally decreases with increased power level, so some operator action must be taken to avoid this (typically the withdrawal of control rods as power level is increased, in order to maintain moderator temperature.) This effect reduces the speed at which reactor power can be changed and relies on human intervention. Thus, reactor maneuverability is hampered.

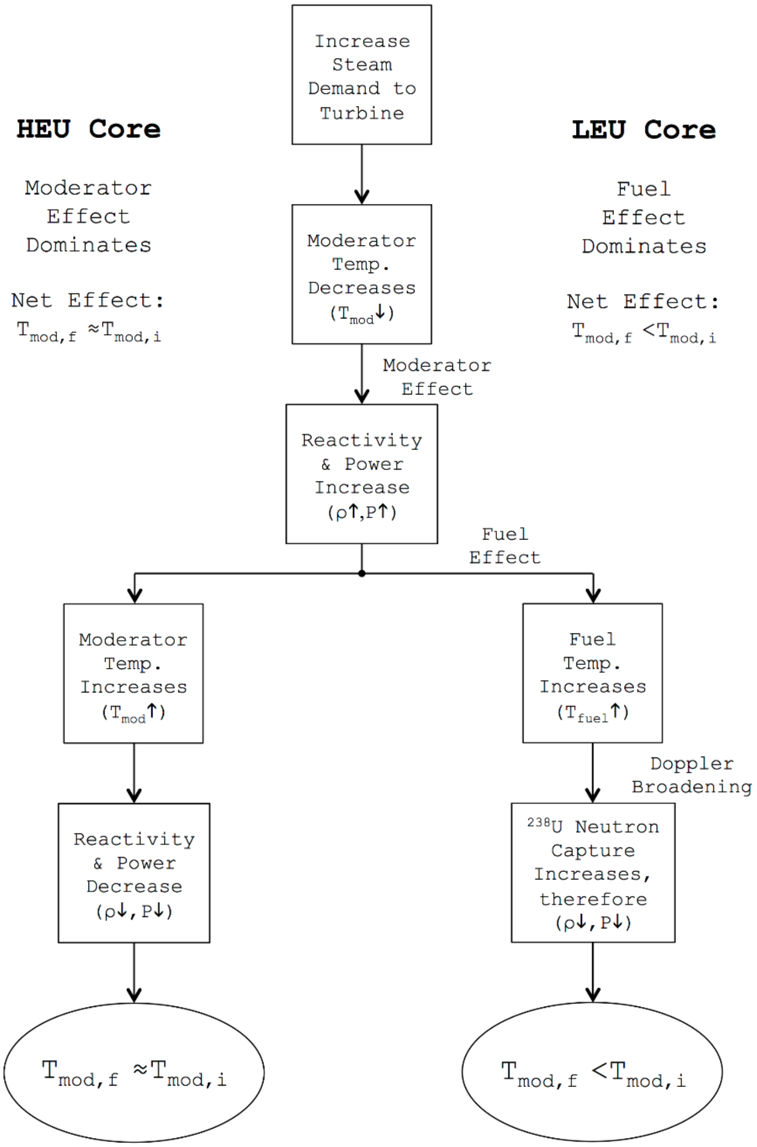

Figure 1 – Reactor core feedback effect as realized in a HEU and LEU cores. T_{mod} is the moderator temperature, T_{fuel} is the fuel temperature (note that the f and i subscripts represent final and initial temperatures, respectively), P is the power, and ρ is core reactivity.

Xenon Poisoning – A 2014 MIT thesis by Cameron McCord identifies overcoming the reactivity issue of Xenon poisoning as one of the primary challenges to practicality of an LEU Naval core (McCord, 2014); specifically, this has the potential to be an issue at high burnups. Xenon poisoning is a phenomenon wherein the fission product ^{135}Xe adds negative reactivity to a core because of its large neutron absorption cross-section;[1] this effect is actually maximized hours after the core has switched from operating at a higher power level to a lower power level or shut down (Duderstadt, 1976). In the event that a core's power must be increased rapidly several hours after a power decrease or shutdown, an instance where ^{135}Xe inventory in the core would be high, the operator must be able to 'burn through,' or overcome, the negative reactivity of the Xenon by adding a sufficient amount of positive reactivity; this is customarily done by partial withdrawal of control rods. In order to overcome this Xenon poisoning the core must contain an adequate amount of excess reactivity; this is of particular concern at the core end-of-life when the fuel has diminished excess reactivity. This is a challenging requirement for an LEU core to meet.

2.1.2. Materials Concerns

The Navy's 2014 report concentrates primarily on fuel structure and material type as a barrier to naval reactor LEU conversion. It is indicated that fuel material type is the principal reason why conversion is impractical; it is stated that "naval fuels must satisfy very high standards for fuel integrity" and that they have to "reliably retain the fission products under extremes of operating conditions." Additionally, "naval fuel elements and modules are rigid and tough, able to withstand the extreme shock loads that might occur in a collision or an attack without losing integrity or compromising the ability to operate the reactor. The design shock loads for naval fuel are more than 10 times greater than seismic loading assumed for land-based reactors." (Office of Naval Reactors, 1995). There is a potential to develop an advanced fuel system; however, development of such an advanced fuel system would take time and investment and the report states that "success is not assured."

The current naval fuel, while classified, is widely believed to be of a plate-type 'cermet' design, meaning it is a combined metal-ceramic dispersion material. The metal in this case is zirconium and the ceramic is uranium dioxide, UO_2. The fuel elements themselves are manufactured by mixing metal and UO_2 particles into one homogeneous substance, which is compressed and coextruded to form the cermet fuel element (Burgess, 1968). This design, in comparison to others, offers a high level of structural integrity that is particularly important in this application. In contrast to cermet fuel, many nuclear fuel structures commonly employ a pure ceramic, which is coated in a thin metal layer, generally referred to as uranium oxide fuel. U.S. power reactors use zirconium pins filled with ceramic UO_2 pellets and the French Navy's Caramel fuel uses plates of UO_2 coated with zirconium. The Caramel fuel type has the advantage of a higher uranium density than cermet, or dispersion type, fuels, and is the fuel type investigated by Ippolito in his thesis. However, while Ippolito finds that use of this fuel type reduces core size in general, the reduction is not enough to allow a 20% enriched LEU core to be made as small as a comparable HEU (~97%) core (Ippolito, 1990).

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[1] It should be noted that there are other poisoning effects that occur in a reactor core following power level reduction or shutdown. Samarium-149 is one such isotope which accumulates following the fission process and two subsequent beta decays. The negative reactivity that ^{149}Sm creates is approximately one order of magnitude less than that due to ^{135}Xe and therefore its effect on reactor startup is less severe.

The cermet fuel has a major structural advantage over more common uranium oxide fuel in that it is highly resistant to leakage of fission products upon structural damage. Consider a circumstance in which the fuel elements are met with a challenging operational condition, for example, they encounter an extreme shock load as the Navy consistently states is a critical design requirement. Uranium oxide fuel could become structurally compromised and, if the cladding is breached, radioactive particles such as fission products could be released into the coolant causing a potentially serious safety hazard. Alternatively, cermet fuel would retain radioactive fission products in the structure, because it is manufactured as a combined metal-ceramic fuel dispersion material. The obvious disadvantage of cermet fuel is the lower uranium density; this is because more metal is needed relative to the amount of uranium ceramic when using metal as an integral part of the fuel structure, as opposed to just a thin cladding.

Cermet and Caramel are two fuel types currently used in naval reactors around the world. However, new options for fuels with higher uranium loadings have been and will continue to be explored. While Ippolito settles on the use of Caramel uranium oxide fuel for his study, he considers a number of other options: metallic uranium fuel, metallic uranium rich alloy fuel, uranium aluminide - aluminum dispersion fuel, uranium silicide - aluminum dispersion fuel, uranium oxide - aluminum dispersion fuel, and uranium carbide and uranium nitride fuels. All of these potential alternatives are found to have significant drawbacks (Ippolito, 1990). $U^{10}Mo$ ceramic in an aluminum dispersion has been recently considered by McCord and others due to its high uranium density (McCord, 2014). Initial results from qualification of $U^{10}Mo$ show that a core using $U^{10}Mo$ fuel, enriched to 20%, can likely be designed to be smaller than a current HEU cermet design (McCord, 2014). However, one significant drawback of $U^{10}Mo$ fuel is that it exhibits unpredictable fuel swelling, particularly at higher burnups (Rest, 2006). While further research and development into $U^{10}Mo$ could potentially yield a solution, it is not a feasible fuel type at this time.

2.1.3. Discussion of Fuel Cycle Risk

Fresh HEU and LEU fuels are stored securely based on internationally agreed upon safeguards protocol. It is expected that the HEU fuel has a higher degree of safeguards requirement.

After the fuel is burned in a reactor, either HEU or LEU fuel cannot be accessed easily because of high level of radioactivity caused by fission products and actinides. So, both fuels are equally toxic, while both contain weapon-grade materials, i.e., ^{235}U in HEU and ^{239}Pu in LEU. These isotopes can be separated from the rest of fuel via chemical processing or pyroprocessing.

Making HEU requires significant investment in an enrichment facility and a large amount of resources, while plutonium can be easily made in any reactor by placement of depleted or low-enriched fuel in the periphery of the reactor.

2.1.4. Conclusions from Technical Investigation

Upon review of the various publicly available documents addressing the technical feasibility of a conversion from HEU to LEU fueled naval nuclear reactors, we have identified two fundamental technical effects regarding fuel composition. These fundamental fuel effects are: (i) a lower concentration of ^{235}U and (ii) a higher concentration of ^{238}U. These effects come with technical disadvantages from which a number of practical consequences regarding ship performance or design are realized. Figure 2 presents a summary of the cause and effect linkage from the fundamental technical effects to practical consequences.

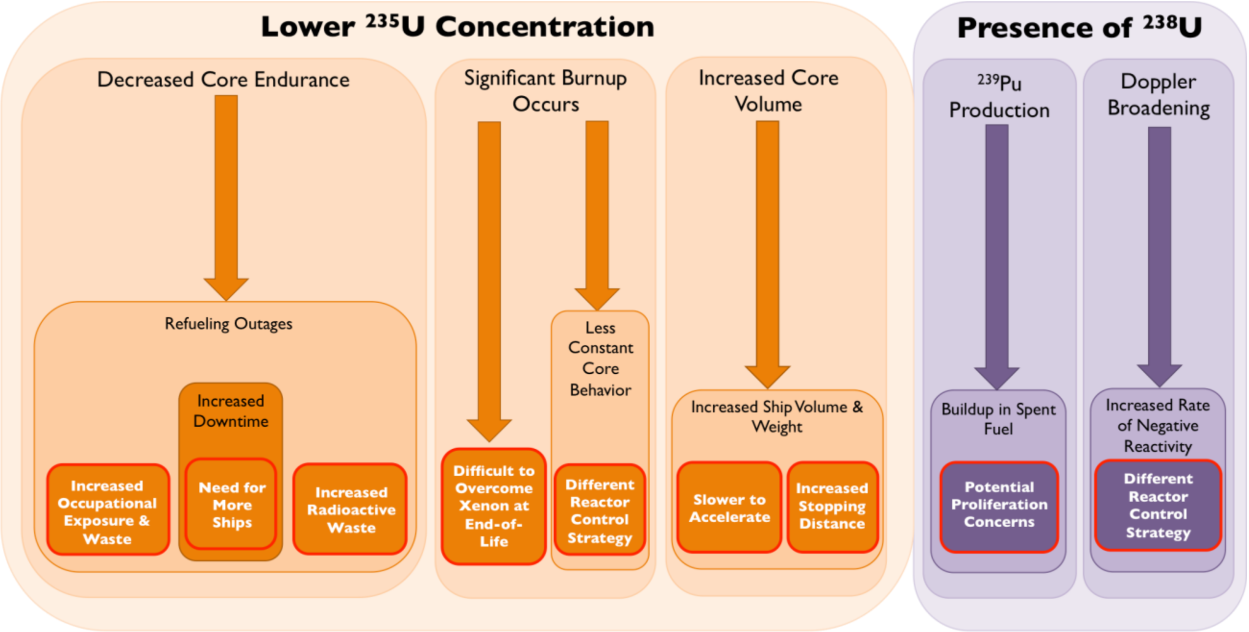

Figure 2 – Summary of technical consequences from the conversion from HEU to LEU fueled nuclear propulsion reactor on a submarine.

2.2. Nuclear Policy Historical Review and Current Status

Desires to look toward LEU for naval propulsion are driven in large part by the framework of the Non-Proliferation Treaty (NPT). This international treaty, which entered force in 1970, is interpreted as having three main goals: nonproliferation, eventual disarmament, and promotion of peaceful use of nuclear energy. Parties to the treaty are designated as nuclear weapons states (NWS) or non-nuclear weapons states (NNWS). The five NWS are the United States, United Kingdom, Russia, China, and France. Among the 184 NNWS are Brazil, Argentina, Afghanistan, and Iran. Non-parties to the treaty are India, Israel, North Korea, Pakistan, and South Sudan. The NPT is enforced by the International Atomic Energy Agency (IAEA).

One of the largest among a number of loopholes that have been discovered in the Comprehensive Safeguards Agreement (IAEA, 1972), which non-nuclear weapons states' parties to the NPT are required to sign, is Paragraph 14, a provision that allows fissile material to be removed from IAEA monitoring for use in non-weapons military applications. This could, for instance, allow a NNWS to enrich uranium to weapons-grade levels and then declare that the uranium is to be used in a nuclear naval reactor, thereby removing the material from the purview of the IAEA with no verification that the material is being used as claimed. While this loophole has never been invoked before, it is postulated that it could allow a NNWS to use a nuclear naval propulsion program as a front to acquire nuclear weapons. Fears exist that a country with nuclear aspirations and future potential for large shifts in balance of power, such as Iran, could exploit this system. Several countries have argued that the United States could mitigate the potential consequences of this loophole by helping to build an international norm of LEU use for naval reactors (Harvey, 2010 and Guimaraes, 1999). Such a norm could give NNWS one less viable reason to embark on programs for production of HEU.

However, one well-known historical decision by the United States government casts serious doubt on the claim that the United States could influence other countries by abandoning the use of some nuclear technology. In 1977, U.S. President Jimmy Carter banned commercial reprocessing of used nuclear fuel. The goal of this ban was to prevent the proliferation risks associated with plutonium being separated out from the commercial fuel cycle, but perhaps more importantly, to encourage other nations to follow the example set by the United States However, this has apparently had little or no bearing on the choices of other countries to reprocess fuel--France, the UK, Russia, Japan, and India have all had longstanding operations to reprocess civilian nuclear fuel.

The Fissile Material Cutoff Treaty (FMCT) is a proposed binding convention, which has been envisioned but never fully drafted and ratified. The FMCT is defined as a treaty that bans production of fissile material for nuclear weapons purposes. Currently, the FMCT is considered attractive by the United States and the other NWS[2]. Current U.S. stockpiles of weapons-grade plutonium and HEU are at a comfortable level—there is currently enough HEU to power the nuclear navy for the foreseeable future and the United States has declared a significant portion of the remaining HEU and Pu stockpiles as excess to defense needs (Office of Naval Reactors, 1995). The only states still producing fissile material for nuclear weapons are India and Pakistan, and possibly Israel and North Korea, (Reif, 2013) which are all outside of the NPT. A successfully implemented FMCT could end the progression of the nuclear arms race in these countries and stop others from joining.

There is no clear, immediate future for the FMCT. Talks have been stalled for years due to the following significant barriers. One challenge is getting all of the relevant states to be party to the FMCT. For example, India, Israel, N. Korea, and Pakistan all have strong reservations about the treaty. And unless all of these states are party to the treaty, Russia has expressed that it will not sign. China has also linked the FMCT to negotiation of a Treaty on Prevention of Arms Races in Outer Space. Additionally, there are disagreements on the details of the treaty. In general, the NWS, unlike the NNWS, want the FMCT to have the same loophole as the NPT, wherein there is no ban on HEU production for non-weapons military purposes such as naval propulsion. As currently conceived, the FMCT would contain

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[2] Note that, China has not officially confirmed that it has stopped producing fissile material for weapons purposes.

this loophole. Another point of contention is whether or not to employ a verification regime for the FMCT—the United States, Russia, and China are all concerned about the intrusiveness of verification (Reif, 2013).

2.2.1. South America – Brazil and Argentina

Two countries currently working toward acquiring nuclear naval propulsion are South American neighbors, Argentina and Brazil.

These countries are regarded as relatively peaceful, rarely engaging in military conflict. Argentina and Brazil both have nuclear energy programs and both are members of the NPT as of 1995 and 1998, respectively. This dispelled earlier concerns that they might have been developing and potentially selling nuclear materials and related equipment, which Argentina had a minor track record of doing (IAEA, 1988 and Burr, 2013). Additionally, both countries are members of the nuclear safeguards agency ABACC (Argentine-Brazil Agency for Accounting and Control of nuclear materials) as of 1991 (Alvim, 1997).

ABACC is a binational nuclear safeguards agency which verifies the peaceful use of nuclear materials in Argentina and Brazil, ensuring that no nuclear weapons are derived from their nuclear programs and that a nuclear arms race does not develop between them. In 1994, Argentina, Brazil, the IAEA, and ABACC entered the Quadripartite Agreement, a full scope agreement on the application of safeguards in these countries (NTI, "Brazilian-Argentine Agency," 2014).

While these two countries are parties to the NPT, they have not signed the INFCIRC/153 comprehensive safeguards agreement with the IAEA (IAEA, "The Structure and Content," 1972 and Phillipe, 2014). In lieu of INFCIRC/153, the Quadripartite Agreement covers all safeguards for Argentina and Brazil (IAEA, "Agreement of 13 December 1991," 1991). The non-application of safeguards portion of INFCIRC/153—Paragraph 14, also known as 'the loophole'—is replicated in Article 13 of the Quadripartite Agreement, albeit in a stricter form. In the case of Article 13 of the Quadripartite Agreement, nuclear material may only be exempt from "special procedures" while it is in an operating submarine. Unlike Paragraph 14, Article 13 implies that the fuel must be safeguarded during fabrication, storage, and disposal (Phillipe, 2014).

Brazil is further along in the process of acquiring nuclear naval technology than Argentina. Brazil is now firmly committed to gaining nuclear submarines according to the 2008 Brazilian National Defense Strategy (NDS) (Ministry of Defense, 2008). Since then, Brazil has signed an agreement with France wherein France will sell Brazil the technology to build the hull and 'conventional part' of a nuclear submarine and help co-develop the sub (Muxgato, 2009 and Taylor, 2009). However, the nuclear reactor and plant side of the project will be developed entirely by Brazil, which wants its reactor technology to be exclusively for Brazilian use (Diehl, 2009).

The NDS cites the 2007 discovery of vast oil fields within Brazil's territorial waters as a key motivation for acquiring a nuclear submarine. Analysts estimate the size of the fields at 33 billion barrels—enough to make Brazil one of the world's largest oil producers. With these newfound reserves, Brazil claims nuclear submarines are needed for protection. (Diehl, 2009)

Skeptics, however, are not convinced that use for oil field defense justifies the high cost of a nuclear naval program, and see Brazil's desires to obtain a nuclear submarine as largely symbolic (Taylor, 2009 and Miller, 1992). A nuclear submarine could be seen a "nuclear weapon surrogate" for a NNWS in terms of military prestige, indicating that while they have the ability to create sophisticated nuclear military technology, they are committed to obeying international treaties (Miller, 1992). A nuclear submarine may also be attractive to Brazil because it has desired a permanent seat on the U.N. Security Council for some time, and it is known that all current permanent members have nuclear submarines (Diehl, 2009 and Taylor, 2009). During the 2013 inauguration of a new Brazilian naval shipyard, President Dilma Roussef declared, "We are entering the select club of countries with nuclear submarines—The United States, Russia, France, Britain, and China" (Phillipe, 2014). In March of last year, Brazil's Defense Ministry announced that its first nuclear submarine would be commissioned in 2023.

Argentina's plans to pursue nuclear naval propulsion are more recent and less developed than Brazil's. In 2010, Argentina's Minister of Defense announced a plan to develop naval nuclear propulsion; however, Argentina has stated that it does not know yet whether this technology will be used for a submarine or an icebreaker (NTI, "Country Profile: Argentina," 2014). Due to this announcement coming not long after Brazil's decision to pursue a nuclear navy, it is possible that Argentina's decision is reactionary.

Brazil and Argentina both have a good track record as peaceful countries, despite some military competition between themselves. In fact, aside from a minor instance of fighting alongside the United States in WWII, Brazil has not engaged militarily with another country in well over one hundred years (Taylor, 2009). Aside from military practices, both countries have had commercial nuclear power for over 30 years with no proliferation or nuclear-arms-race activity.

2.2.2. Middle East –Iran and Israel

Iran – The Shah of Iran conceived Iran's initial nuclear program in the 1950s and, with help from the United States under the Atoms for Peace program, built a research reactor for Tehran University (Peters, 1953). In 1968 Iran signed the NPT (FAS, 1993). The Shah established the Iran Atomic Energy Organization in 1974 with the hopes to spread the use of nuclear energy in the country and construct two power reactors at Bushehr. The 1979 Iranian Revolution led to the fall of the Shah of Iran and the nuclear program was halted, because West Germany terminated its contract for building the Bushehr's power plant, and no other country was willing to help.

Further, the United States cut off support to Iran's nuclear program and would no longer supply HEU for the Tehran Nuclear Research Center, which forced the reactor to be shut down for years. In 1987, Iran signed an agreement with Argentina's National Atomic Energy Commission in order to help Iran convert its research reactor to LEU. Argentina supplied Iran with the necessary fuel in 1993 in accordance to an agreement signed in

1988 by both countries (IAEA, 1988). In the early 1980s, the IAEA was intent on helping Iran continue to pursue nuclear technologies for peaceful purposes, but the U.S. government "directly intervened" to discourage this assistance (Hibbs, 2003). Iran then turned to China for help, but this was also quickly dissolved due to pressure from the United States. Then, during the Iran-Iraq war, between 1980 and 1988 Iran's two Bushehr reactors were damaged by multiple Iraqi airstrikes and Iran's nuclear program again came to a halt.

The Iranian government finally decided to finish the Bushehr project in 1995 with help from Russia, under IAEA safeguards (NTI, "Country Profile: Iran," 2014). There was a clear push in the early 1990s for a full nuclear fuel cycle with interest in improving and developing the necessary technologies in mining, processing, and enrichment; the United States successfully halted the Russians in helping with enrichment facilities associated with the Bushehr project. There still exists a strong desire in the international community to steer Iran away from enrichment and reprocessing activities. In fact, the UN Security Council has passed resolutions calling for Iran to halt all such activities. The P5+1 have, however, recently indicated that Iran may have limited enrichment capability.

Arab nations have expressed discontent with United States's apparent double standard in criticizing Iran's nuclear program while seemingly ignoring Israel's possession of nuclear weapons (Pincus, 2005, "Israeli-Arab spat," 2005, and "IAEA conference urges," 2007). The Arab League has stated that its member states will withdraw from the NPT if Israel admits to having nuclear weapons but refuses to open its facilities to international inspections ("Arab League vows," 2008).

In 2012, Iran announced that it was in the early stages of building a nuclear submarine program. Iranian officials have discussed 60% as a target enrichment level for these ships and in 2012, Iran threatened that should its discussions with the P5+1 on nuclear technology break down, Iran would embark on this 60% enrichment program (White, 2012).

Currently Iran has a significant nuclear infrastructure including uranium mining, milling, conversion, and enrichment capabilities, the latter of which is the most controversial in the international community (ISIS, 2014). The Iranian Navy has three Russian designed, conventional diesel-electric powered *Kilo*-class submarines (U.S. Office of Naval Intelligence, 2009).

Israel – Israel is widely believed to have nuclear weapons. This makes Israel the sixth country to acquire nuclear weapons. Israel is one of four countries which possess nuclear weapons but have not signed the NPT; the others being India, North Korea, and Pakistan. Israel has vowed to practice a policy of *amimut* or "nuclear opacity," meaning that it will not publically reveal that it has nuclear weapon capabilities. Israel has also reiterated over the years that it will "not be the first" country to "introduce" nuclear weapons in the Middle East; this language goes back to the 1965 Eshkol-Comer memorandum of understanding between the United States and Israel, in which Israel committed to such an agreement (Department of State, 1965). Yitzhak Rabin informed the United States that "introduction" of a weapon implied they would be tested and publically declared, while just possessing them did not count as "introducing" them to the region (Cohen, 2006 and Kissinger, 1969).

It is believed that Israel has produced roughly 300kg of HEU[3] and 840kg of weapons-grade plutonium to date (International Panel on Fissile Materials, 2013). This correlates to a capability of producing between 100-200 nuclear warheads though it is currently believed that Israel possesses 80 warheads (International Panel on Fissile Materials, 2013). Israel has the capabilities to deliver these warheads via ballistic missiles (both medium-range and intercontinental), aircraft, and submarine-launched cruise missiles (NTI, "Country Profile: Israel," 2014).

The Israeli Navy operates four modern German-built *Dolphin*-class diesel-electric submarines. These submarines are the most expensive vehicles in the Israel Defensive Forces and are considered to be the world's most sophisticated and capable conventionally-powered submarines according to a commander of the Israel Defense Forces (IDF) Navy's submarine school ("Spy Tool," 2013). In June 2009, an Israeli Dolphin-class submarine sailed from the Mediterranean Sea to the Red Sea via the Suez Canal to demonstrate that it could access the Indian Ocean and the Persian Gulf. This demonstration may be seen as threat to Iran and the Persian Gulf nations, as Israel is showing its strength in the region ("Israeli nuclear submarine," 2009).

Israel is determined to maintain its nuclear superiority in the Middle East. In 1979, agents of Mossad, the Israeli national intelligence agency, damaged two reactor cores designed for Iraqi reactors and were implicated in the assassination of an Egyptian nuclear engineer and two Iraqi engineers, all of whom were working for the Iraqi nuclear program (Reiter, 2005). In 1981, Israel preemptively destroyed an Iraqi breeder reactor via airstrike ("Israel bombs Baghdad reactor," 1981). In 2007, Israel launched an airstrike in the Deir ez-Zor region of Syria; though Israel declined to comment on the attack, U.S. intelligence states that Israel had reasons to believe that Syria and North Korea were cooperating to build some sort of nuclear facility. After an investigation in 2011, the IAEA concluded that the destroyed facility was "very likely" an undeclared nuclear reactor (Brannen, 2011). In 2010, Iranian enrichment facilities at Natanz were attacked with the Stuxnet malware, which destroyed nearly 10% of Iran's centrifuges (Melman, 2010); it is widely believed that Mossad was responsible for the attack, though this has never been verified by Israeli officials (Stark, 2011). It is believed that because of this attack, Iranians have improved their centrifuge technology (Blaustein, 2013).

2.2.3. South Asia – India and Pakistan

India – India's nuclear energy program began in 1948 and currently has a very active nuclear energy program with nuclear power being the fourth largest contributor to the country's energy demand. India currently operates 21 nuclear reactors with six new reactors currently under construction (NPCIL, 2011). India is also supporting research on

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[3] Based on 90% ^{235}U enriched equivalent.

thorium-based fuel cycles and is working construction of an operational prototype advanced heavy water reactor using thorium and LEU (International Thorium Energy Organization, 2009).

India has refused to sign the NPT on the same grounds as most other non-signatories--that the Treaty provides an unfair advantage to the NWS over the NNWS. Aside from the NPT, India has taken steps to join a broader nonproliferation regime including the Partial Test Ban Treaty (PTBT). India's nuclear weapons program began in 1964, followed by a successful "peaceful nuclear explosion" in 1974, and India became a self-declared nuclear weapons state in 1998. In 2005, India and the United States reached a nuclear cooperative agreement that would allow India to participate in international nuclear trade (Office of the Press Secretary, 2005), so long as it approved a limited safeguards agreement with the IAEA (IAEA, 2008); this cooperation was fully realized in 2008 when India and the United States signed the '123' nuclear cooperation agreement (Council on Foreign Relations, 2008).

It is estimated that India's nuclear arsenal consists of between 90 and 100 warheads (Wolfsthal, 2005). According to best estimates, India has a stockpile of about 2.4 tons of HEU and 230 kg of weapons-grade plutonium (NTI, "Country Profile: India," 2014), and has short and intermediate range ballistic missiles which are believed to be nuclear capable. India's primary vehicle of payload delivery is aircraft, though it is believed that they are also pursuing intercontinental ballistic missile (ICBM) and submarine-launched ballistic missile (SLBM) technologies. India fist tested its SLBM capabilities from a docked barge in 2008 (Bedi, 2008), but in 2014 it demonstrated its *Arihant*-class nuclear submarine's capabilities to deploy nuclear tipped missiles ("Strategic Weapons Systems," 2014).

The *Arihant*-class ballistic missile submarine is an Indian designed nuclear submarine that was originally launched in 2009; it is the first nuclear submarine to be developed by a country that is not one of the five permanent members of the UN Security Council, and the first developed by a country that is not an NPT-member NWS. The vessel is powered by an 83MW pressurized water reactor fueled with 40% HEU fuel (Pandit, 2009 and "INS is Indian design," 2009).

Pakistan – Pakistan has a fairly strong history with nuclear technology. The country has peacefully operated nuclear power plants for electricity generation since 1972 (IAEA, "KANUPP-I," 2014) using imported reactor technologies. It has also built a research reactor using indigenous technology. It has been indicated that Pakistan has been capable of producing a nuclear weapon since the mid-1980s ("Interview with Abdul," 1998); it successfully tested nuclear arms and declared itself a nuclear weapon state in 1998. This made it the first Muslim-governed country with nuclear weapons. Pakistan is not a signatory to the NPT; however, it is a member of the IAEA, who has provided assurances of the security of Pakistan's nuclear power program (UN Press Release, 2012). Its nuclear stockpile, which is comparable to India's, is currently estimated at about 3 tons of HEU and about 140 kg of weapons-grade plutonium (IPFM "Countries: Pakistan," 2013).

There is a long history of power struggles, including several wars, between India and Pakistan. Perhaps the most significant of these conflicts is the 1971 Indo-Pakistani war, which India won, establishing itself as the dominant force (NTI, "Country Profile: Pakistan," 2014). The regional balance of power between these two countries is key to understanding the trajectory of Pakistan's nuclear technology. Parallels between the nuclear policies of the two countries became particularly pronounced in the 1990s; each state became a self-declared NWS in 1998. In 1990, Pakistan began negotiations with China to lease a nuclear submarine after learning that India had possession of a nuclear submarine, which was leased from Russia. However, Pakistan abandoned its nuclear naval ambitions in 1991 upon learning that India had returned the submarine to Russia ("Nuclear Deal on Han," 1990). Since then, India has launched an indigenously-developed nuclear submarine in 2009 (Pandit, 2009).

In 2012, Pakistan declared that it intends to acquire nuclear submarines, likely in response to India (Ansari, 2012). However, earlier this year, officials stated that Pakistan and China were on track to sign an agreement by the end of 2014 for China to sell six conventional submarines to Pakistan (Bokhari, 2014). This may suggest a possible future progression to nuclear powered ships; Pakistan's defense planners are conscious of its current disadvantage to India in this regard (Bokhari, 2014).

2.2.4. Northeast Asia – China, Japan, Russia, and South Korea

China – As of 2014, China has 22 operational nuclear power plants that supply approximately 2% of the country's electricity (IAEA "Nuclear Share," 2014) along with 26 reactors under construction (WNA "Nuclear Power in China," 2014). China has a nuclear weapon program, which started in 1955 and achieved detonation by 1964. In 1992, China acceded to the NPT as an NWS and is thought to have approximately 250 nuclear warheads (Kristensen, 2013). China also became the first NWS to ratify the IAEA Additional Protocol. The People's Liberation Army (PLA) Navy currently has a total of 63 submarines; 10 of which are nuclear powered (4 SSBN and 6 SSN) while the remainder are conventional diesel-electric powered attack submarines.

Japan – Japan has a very strong history in nuclear energy, with its first commercial nuclear power reactor coming online in 1956. Prior to the Fukushima Daiichi disaster in the spring of 2011, approximately 30% of the country's electricity was supplied from 54 nuclear power reactors and this number was anticipated to increase to 40% by 2017 (WNA "Nuclear Power in Japan," 2014). The last of Japan's nuclear reactors were offline by the spring of 2012 ("Japan shuts down," 2012), leaving the country with no electricity supplied from nuclear power plants.

Following World War II, Japan renounced its right to use force, or the threat of, to resolve disputes (U.S. Library of Congress, 2010). Therefore the island nation has a non-military naval fleet known as the Japan Maritime Self-Defense Force (JMSDF), which is, in fact, one of the world's largest navies. The JMSDF currently has 16 active diesel-electric powered attack submarines.

During WWII, Japan unsuccessfully tried to develop a nuclear weapon. Experts believe that, should the political decision be made, nuclear weapons could be quickly produced, due to the fact that Japan is the only NNWS signatory to the NPT with full nuclear fuel cycle facilities. These nuclear capabilities, along with its significant stocks of plutonium, ~9.3 tons held within the country (IPFM, 2013), strike some controversy in the international community regarding Japan's commitment to nonproliferation and disarmament.

Russia – The Russian Federation is one of the most prominent nuclear weapons states. It first successfully tested a nuclear weapon in 1949 and is a NWS signatory to the NPT. While embroiled in the Cold War with the United States in the second half of the 20th century as the USSR, Russia acquired a massive stockpile of nuclear warheads (NTI, "Country Profile: Russia," 2014). This stockpile has been decreasing since its peak in 1986 due to disarmament treaties, but is still the world's largest (IPFM, 2013).

In additions to weapons history, Russia has long had notable capabilities in the nuclear power, nuclear research, and nuclear navy sectors. About 16% of Russia's electricity is derived from nuclear power (IEA, 2014), which is slightly lower than the percentage of electricity from nuclear in the United States. Russia's nuclear naval fleet is second largest only to that of the United States in size, see Table 3. This owes to the fact that geopolitically, Russia has traditionally been more of a land power while the United States has been more of a sea power.

Russia's nuclear navy may be of particular importance in the Northeast Asia region. Japan and South Korea, two countries who currently do not have a nuclear navy, have both expressed interest in further development and export of their nuclear technologies and could potentially become interested in acquiring a nuclear navy.

South Korea –South Korea has been a NNWS signatory since 1975, largely due to pressure from its ally, the United States. Prior to this, however, South Korea had been pursuing a nuclear weapons program (Pinkston, 2004).

The Korean peninsula has had a tumultuous history since the mid-20th century. Military tensions between North and South Korea is still prominent. North Korea is no longer a party to the NPT, and has conducted three nuclear weapons tests, beginning in 2006 ("North Korea's Nuclear Tests," 2013).

South Korea has peacefully used nuclear technology for power and research for decades; its first research reactor came online in 1962; its first power reactor in 1978 (Pinkston, 2004). Over a quarter of South Korea's electricity comes from nuclear energy ("Nuclear to Remain North Korean Mainstay," 2013). However, due to various agreements with the United States and with North Korea, South Korea may not enrich or reprocess fuel. This makes South Korea's nuclear power industry dependent on fuel imports. South Korea has expressed a desire for fuel cycle independence, and successfully conducted experiments to enrich laboratory-scale quantities of uranium in 2000 (Pinkston, 2004).

South Korea's navy has never had nuclear-powered ships. However, in the 2003-04 timeframe, South Korean officials were reportedly examining the possibility of developing a nuclear submarine. While South Korea's conventionally powered fleet is adequate for protection against North Korea, tensions with China are considered to be the primary motivation for South Korea's consideration of a nuclear navy (Globalsecurity.org, 2014).

2.2.5. Global Submarine Inventories

This section provides a summary table of each aforementioned country's operational submarines. For each of the geographical regions discussed in Section 2.2, as well as the United States, Table 3 provides the number of operational submarines, type (nuclear or conventional, diesel-electric), and notes regarding origin of the ship design for each country.

Table 3 – Regional submarine inventories.

Region	Country	Type	Number	Notes
North America	USA	Nuclear	72	54 SSN, 14 SSBN, and 4 SSGN
South America	Argentina	Conventional	3	German design, TR-1700 & Type 209
	Brazil	Conventional	5	German design, Type 209
Middle East	Iran	Conventional	4	3 Russian design, 1 indigenous design (undergoing sea trials)
	Israel	Conventional	5	German design, Type 212
South Asia	India	Nuclear	2	1 Russian designed (on lease), 1 indigenous design (expected commission 2014)
		Conventional	12	8 Russian design (Kilo-class), 4 German design (Type 209)
	Pakistan	Conventional	5	French design (Agosta & Agosta 90B class)
Northeast Asia	China	Nuclear	10	4 SSBN and 6 SSN
		Conventional	53	2 SSB and remainder SS, 12 Russia design (Kilo-class)
	Japan	Conventional	16	2 are currently used as training submarines
	Russia	Nuclear	39	
		Conventional	16	2 more expected by 2015
	South Korea	Conventional	12	German design, Types 214 and 209

Data obtained from www.globalsecurity.org. Note that only full-sized submarines are included, i.e., midget-class or smaller submarines are not included.

3. Unintended Consequences of LEU Conversion

This section presents our group's specific contributions in the identification of "unintended consequences" of the conversion of the U.S. Naval submarine fleet from HEU to LEU. Each consequence is listed with a reference to its fundamental causes and an explanation of the net unforeseen effect on the submarine. A description of possible future studies for assessing risks associated with each consequence is also included.

3.1. Technical

Considering our review of technical concerns of a conversion from HEU to LEU in Section 2.1, this section will address a number of unforeseen technical consequences which have not been mentioned previously.

3.1.1. Limited Access to Confined Spaces

To maintain the current core lifetime in an LEU submarine, the volume of the ship must be increased, as was previously discussed in Section 2.1. This increased volume may limit the ship's ability to effectively maneuver both tactically and for safe navigation. If the additional volume limits the tactical capabilities of U.S. ships then it may not be a viable option.

Future Studies:

- Identify the limiting "tight spaces" and ensure that the proposed ship size is not restrictive to the ship's ability to carry out its mission.

3.1.2. Limited Maximum Diving Depth

A conversion to LEU wherein ship volume is unchanged would require that the core lifetime be reduced significantly, as is discussed in Section 2.1; this obviously will require the reactor to be refueled during the ship's lifetime. A refueling operation requires that the reactor compartment be accessed from outside the ship; this may require that an external hatch opening into the reactor compartment be incorporated into the ship's hull. The installation of such a large hatch would likely limit the allowable diving depth because it would decrease the crushing depth—the depth that a submarine may reach without imploding due to water pressure. The hatch would be the weak point in the hull of the ship and would act as a limiting factor when determining the maximum diving depth. A decreased allowable diving depth may compromise the ship's ability to effectively search for, hide from, or otherwise out-maneuver enemies.

Future Studies:

- Investigate the structural effects of the addition of a refueling hatch on a submarine.
- Is it possible to design a refueling hatch, or alternative, such that it would not adversely impact the maximum diving depth of the vessel?

3.1.3. Decreased Ability to Withstand Battleshock

It is mentioned in Section 2.1.2 that the Navy did not consider using other fuel material types when considering an LEU-fueled reactor. The Navy has suggested that alternative fuel materials and types may not meet its ruggedness criteria. It is likely that the metal clad ceramic fuel, i.e., French Caramel design, would not hold up and contain radioactive fission products under severe damage as well as the current Navy dispersion fuel design.

Future Studies:

- Is it possible to fabricate an LEU fuel structure and material type that would satisfy the ruggedness criteria of the U.S. Navy while increasing uranium density?

3.1.4. Increased Shielding Requirements

As has been discussed in Section 2.1.1, the 1995 Navy report failed to mention some reactor physics concerns associated with using LEU, which would affect reactor operation and control. Below, we introduce another reactor physics concern that has not been addressed in any of the literature that has been reviewed pertaining to LEU naval reactors: the hardening of the neutron spectrum emitted from the LEU core.

Ensuring that crewmembers receive minimal radiation exposure is a prominent design criterion; of primary concern is neutron radiation because it is the most difficult to shield. A conversion from HEU to LEU would result in a harder, i.e., shifted toward higher energies, neutron energy spectrum emitted from the reactor. The harder neutron spectrum in a LEU core is due to the increased production of plutonium due to the higher ^{238}U content in a LEU core as compared to a HEU core. This shift in neutron spectrum has been observed in research reactors that have been converted from HEU to LEU cores (Keller, 2009). In order to ensure the crew is not exposed to more radiation than with a HEU reactor, two options may be implemented: 1) place more shielding around the reactor compartment or 2) locate the crew living and operating quarters farther away from the reactor. Either option would have an adverse effect on current ship design. Option 1 would increase the weight of the ship, which would require a proportional increase in volume to maintain buoyancy. Option 2 would require that the crew not occupy ship compartments that are near the reactor; this would limit the number of crewmembers able to fit aboard the vessel or result in a larger ship volume. Neither of these options are appealing to ship designers trying to design a safe, compact vessel.

Future Studies:

- Determine the amount of neutron spectrum hardening, and its impact on the crew dose for different shield designs

3.1.5. More Complicated Reactor Control

We have mentioned some of the already known reactor physics effects of conversion from HEU to LEU in Section 2.1.1; namely the Doppler Broadening effect and Xenon poisoning issues. Designing a reactor control system that takes into account these reactor physics effects is not inherently difficult in land-based reactors--commercial power reactors manage these effects quite effectively. However, the high stress environment of a naval reactor, in terms of both power density and rapid changes in power demand, present more rigorous challenges with regard to reactor control. More actions must be taken to adequately control an LEU reactor, see Doppler Broadening Section 2.1.1. This is associated with a need for more operators, more operator training, and additional passive safety reactor control systems.

Another concern that has not yet been addressed is how the production of ^{239}Pu affects the control of the reactor towards the reactor's end-of-life (EOL). In an LEU core, a substantial amount of the ^{238}U which is present may transmute to ^{239}Pu, adding to the fissile material in the core. Because ^{239}Pu is produced in substantial amounts as a by-product of ^{238}U in an LEU-fueled reactor, a non-negligible amount of the energy produced in the reactor comes from fission of plutonium and not uranium (WNA

“Plutonium,” 2014 and Makhijani, 1996). Concentrations of ^{239}Pu in a standard power reactor are highest at the end of the core’s life (i.e., directly prior to refueling).

In addition to spectral hardening mentioned above, one challenge posed by the presence of ^{239}Pu is the fact that a smaller fraction of neutrons produced by ^{239}Pu are delayed in comparison to neutrons produced by ^{235}U (Keepin, 1965). This has very important effects with regard to reactor kinetics (or time-dependent behavior) and reactor control. Additional operator training or passive safety systems may be necessary, and potentially even greater restrictions on how quickly a submarine may change power.

Future Studies:

- Investigate the effect of LEU fuel on the reactor control including change of power, restart, and end-of-life (EOF) operation.
- Conduct accident analysis studies for the proposed LEU core design.
- Assess the impact on the training of reactor operators and restructuring of the Power School curriculum.

3.1.6. Increased Risk of Refueling-Related Accidents

A decrease in core lifetime means that the ship must be refueled a number of times during its lifetime. Several previously known consequences of this are addressed in Section 2.1 of this report. The more frequent refueling of an LEU ship means that more time is spent handling the used fuel by workers; increased fuel handling operations increase the risk of a refueling-related accident. Clearly, this risk is most easily avoided by reducing the number of refueling outages necessary--the current U.S. submarine reactor is designed to last the entire lifetime of the ship. The proposed LEU core (wherein current ship volume is maintained) will only last a maximum of seven years, which correlates to approximately 4-5 refueling operations per ship lifetime. This corresponds to a marked increase in the amount of time spent by workers handling and transporting used nuclear fuel.

Future Studies:

- Identify ways to reduce the risks associated with refueling operations.

3.1.7. Summary of technical consequences

This section has discussed a number of unforeseen issues stemming from technical concerns associated with the conversion from HEU to LEU for naval propulsion. Figure 3 presents a summary of these technical unintended consequences; this shows the “cause and effect” progression of how each technical issue, not mentioned in reviewed literature, is realized as an unintended consequence.

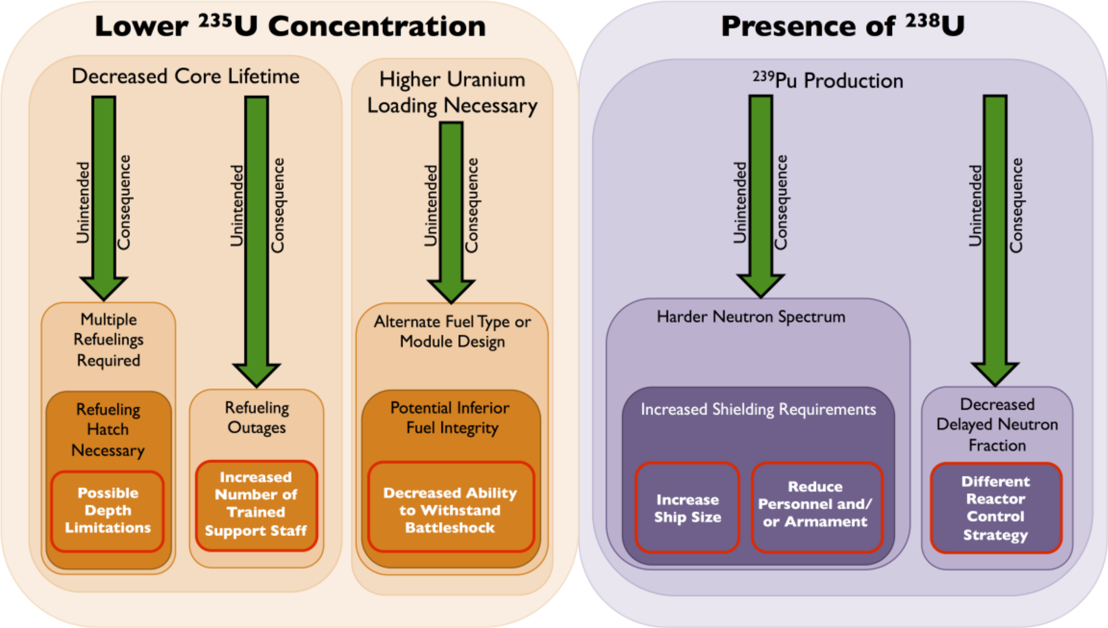

Figure 3 – Summary of technical unintended consequences of the conversion of submarines to LEU.

3.2. Geopolitical

Considering our review of policy issues in Section 2.2, this section will address a number of unforeseen consequences not mentioned in previously released literature on the universal conversion from HEU to LEU for nuclear propulsion.

3.2.1. Increased Accessibility to Nuclear Submarines

Currently, there is an exclusive "nuclear submarine club"; membership includes China, France, Great Britain, India, Russia, and the United States (note that the only nuclear submarine nation that has not signed the NPT is India). It is possible that an effort to push for LEU fueled submarines would give other countries the desire to pursue nuclear submarines, i.e., join the nuclear submarine club, as the technology would appear more accessible. This would mean that, upon development and implementation of the ships, there would be a larger number of these submarines operating in the world's oceans.

Future Studies:

- What would be the political and operational impact of increased submarine traffic?
- What is the implication of increased access/availability of nuclear fuels?

3.2.2. Shift of Balance of Power

Currently, NWS are controlling the world's waterways. However, the increased access to nuclear submarines will change this picture. This is especially important for strategic regions such as the Persian Gulf. For example, currently the U.S. naval fleet controls the commercial shipping through the Gulf, which supplies about 20% of the world's oil supply. Iran, which has a long shoreline along the Persian Gulf, has had significant interest in protecting its resources and its regional influence. With its three dieselpowered submarines and numerous surface ships, Iran has tried to control the Strait of Hormuz with limited success. But, this picture may change if Iran and/or other Gulf nations have access to nuclear submarines. Additionally, this could lead to increased tensions in the region, which would obviously impact oil production and export and thus send a global economic shock to the nations which depend on energy from oil.

Future Studies:

- What would be the impact of greater submarine presence on a regional power structure, e.g., in the Persian Gulf region?
- Investigate the vulnerability of the global oil trade to tension in the Persian Gulf.

3.2.3. Increased Operational Range of Hostile Countries

Submarines are designed to be nearly undetectable, which make them an ideal vessel for espionage and to carry out covert attack missions. A submarine's range is limited by either fuel supply or crew sustainability; diesel-electric submarines are limited by the former, while nuclear powered submarines are limited by the latter. Because the United States is somewhat isolated by oceans from many of the hostile counties in the world, the current threat on the United States of espionage and/or covert attack by submarine is limited to only a few countries that have the required range, i.e., nuclear powered submarines. There are numerous countries that possess standard diesel-electric submarines; some of these countries are listed in Sections 2.2.1 and 2.2.3. If these countries suddenly obtain nuclear powered submarines, because of the international shift to LEU-fueled reactors, the number of countries which have access to U.S. shores could potentially increase, therefore increasing the threat of espionage and/or covert attack on our country.

Future Studies:

- Identify which countries may pose a threat to the United States if they obtained nuclear propulsion capabilities and evaluate the level of risk.

3.2.4. Proliferation Risks Associated with LEU Enrichment Facilities

If a once-through LEU fuel cycle for nuclear submarines were to become an international norm, it is likely that the fuel for these naval reactors will be enriched in an unsafeguarded, indigenous plant. Such a plant, which may be used for other purposes such as power reactor fuel enrichment, may not be as highly safeguarded as a military-specific HEU enrichment plant. This is troublesome because of the relative lack of technical difficulty associated with increasing the level of enrichment of a plant's final product. It is conceivable that a plant prescribed to produce LEU submarine reactor fuel outside of the purview of IAEA inspectors could be upgraded to produce HEU rather easily. Figure 4 shows the relative lack of effort necessary to move from LEU to HEU fuel, as opposed to the amount of effort needed to obtain LEU from natural uranium.

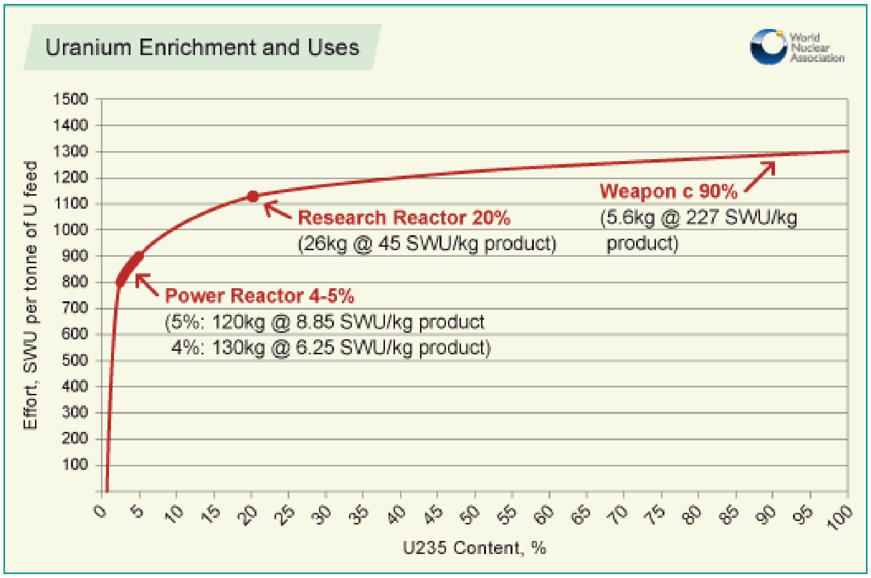

Figure 4 – Effort required, in SWU per ton of natural uranium feed, to enrich natural uranium to a given percentage of ^{235}U (“Uranium Enrichment,” 2014).

Future Studies:

- Investigate the security of currently operating, indigenous LEU plants.
- Quantify the risk associated with the potential upgrade of current LEU enrichment facilities to HEU.

3.2.5. Increased Potential for Naval Accidents

Throughout the history of their nuclear navies, the United States and Russia have experienced a number of accidents related to nuclear submarines. The United States has lost two nuclear submarines, but due to the high operating standards and strict concern for reactor safety in the U.S. Navy’s Nuclear Propulsion Program, neither were lost due to a reactor accident. Russia, including initial Soviet Union submarine development, has lost a recorded seven submarines, some of which had two reactor cores onboard. Note that one of these submarines sank due to reactor failure. This means that there are at least nine naval nuclear reactors that sit on the ocean floor; such sunken nuclear fuel could potentially present an environmental risk.

If the number of nuclear submarines increase in militaries around the world, it is possible that more accidents and sunken submarines will occur leading to a greater risk of potential environmental and public health risk. This possibility increases with a nation that is a relatively new to nuclear submarine operations, with little operational experience.

Future Studies:

- Investigate the environmental impact due to the sunken nuclear ships.
- Investigate how to mitigate the impact due to a sunken nuclear naval reactor.
- Investigate the development of a program for creation of safety culture in new nuclear countries

3.2.6. Non-Democratic Countries

As has been mentioned in Section 2.2.3, many of the governments in the Middle East do not have a robust democratic system, and therefore are vulnerable to uprisings and unrest. Additionally, there is no guarantee that currently peaceful, democratic governments will not one day change to an authoritarian regime. Such countries have more potential for losing control of their nuclear assets.

Future Studies:

- Investigate the potential threat of a terrorist organization obtaining a nuclear submarine.
- Investigate development of a safeguards program that prevents access by terrorist groups to nuclear submarines.

3.2.7. Surrogate Nuclear Arms Race

The use of LEU as a nuclear propulsion fuel may promote a "surrogate nuclear arms race," akin to the Cold War era (Guimarães, 1999 and Miller, 1992). If LEU submarines become the accepted norm, the potential for acquiring nuclear-powered vessels becomes easier. As examples, Persian Gulf or South America, if one country acquires nuclear submarine it may provoke others in the region to acquire one. This could alter the regional stability and balance of power that may affect the U.S. national security.

Future Studies:

- Assess the potential of new countries initiating the development of nuclear submarines.
- Evaluate the impact on the regional stability and power balance.

3.2.8. Summary of Geopolitical Consequences

This section has discussed numerous unforeseen geopolitical consequences associated with the conversion of naval propulsion reactors to LEU. Figure 5 presents a summary of these geopolitical unintended consequences; this diagram shows how the HEU to LEU conversion policy may result in unintended consequences.

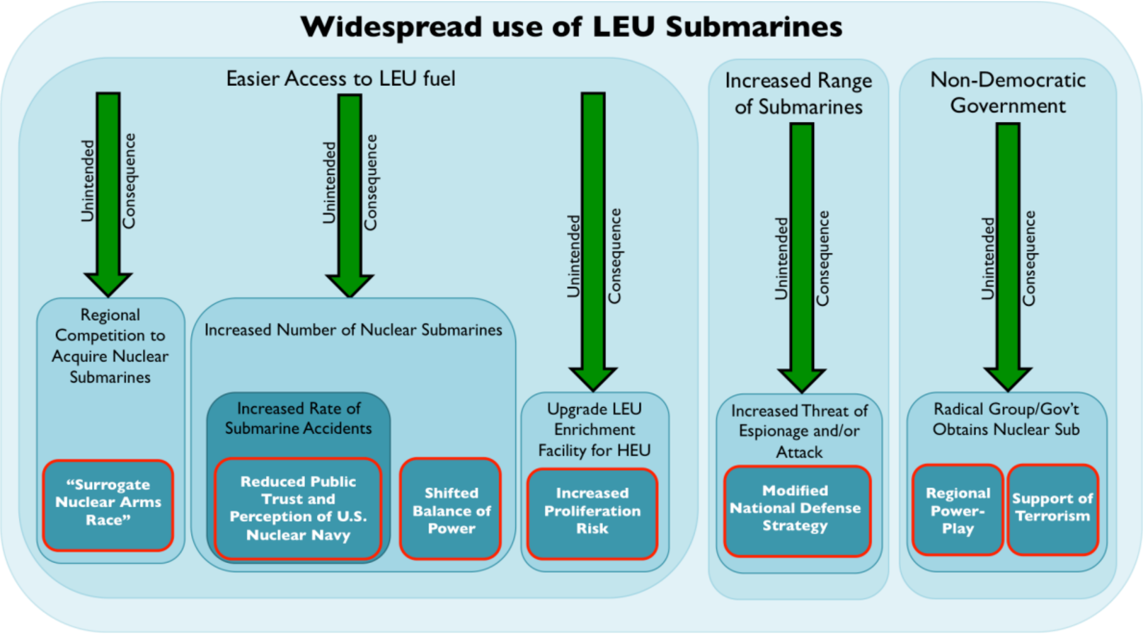

Figure 5 – Summary of the possible geopolitical unintended consequences of the conversion to LEU fuel.

4. Remarks

This report summarizes past studies by other researchers, and by analyzing these studies identifies new issues both technical and geopolitical. It also attempts to identify and analyze potential unintended consequences in case of the use of LEU fuel by the U.S. Nuclear Navy.

More specifically, the technical unintended consequences are driven by the fundamental difficulties of using LEU fuel: decreased ^{235}U concentration and ^{238}U presence, and the geopolitical unintended consequences represent the ways in which using LEU-fueled submarines may adversely affect the regional stability and power balance. These include topics such as easier access to LEU fuel, increased submarine range, use of nuclear submarines by non-democratic governments, and possible "surrogate nuclear arms race." For each unintended consequence discussed, a list of possible "future studies" is presented.

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