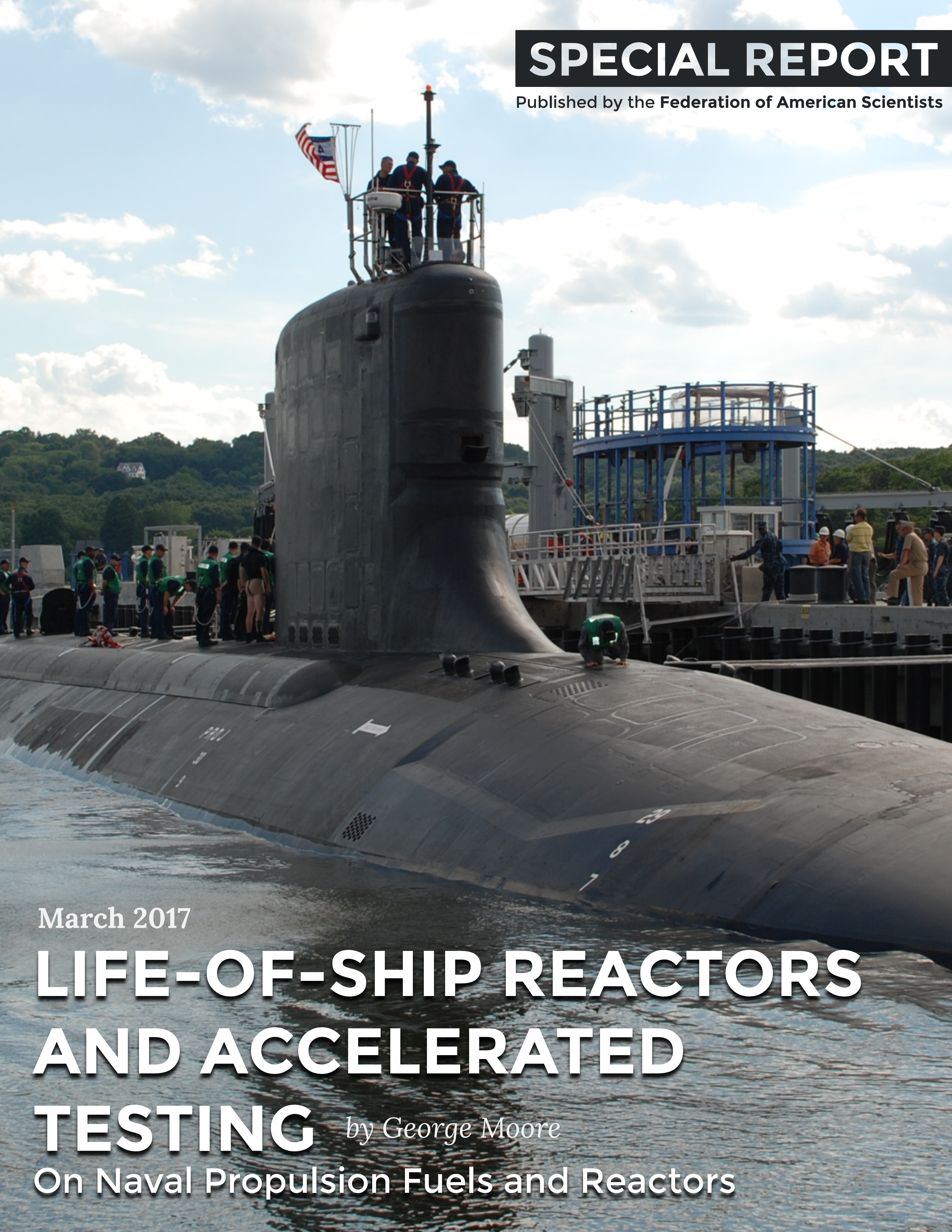

SPECIAL REPORT

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LIFE-OF-SHIP REACTORS AND ACCELERATED TESTING

by George Moore

On Naval Propulsion Fuels and Reactors

About FAS

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About the Author

Dr. George Moore is a scientist-in-residence at the Middlebury Institute of International Studies at Monterey (MIIS) and a CySec senior legal and technical fellow. He received a B.S. from the United States Naval Academy, an M.S. and Ph.D. in nuclear engineering from the University of California, Berkeley, and a J.D. from Berkeley. Dr. Moore is a former Fulbright Scholar (Netherlands) and former Atomic Energy Commission special fellow. He is a licensed professional engineer (nuclear) in California and was formerly an AEC-licensed research reactor operator. Prior to joining MIIS he served as a senior analyst in nuclear security at the International Atomic Energy Agency (IAEA) and was a staff member at Lawrence Livermore National Laboratory (LLNL). He is a member of the California and Colorado bars and is admitted to practice before various federal courts. Dr. Moore has authored a number of technical papers and legal articles and has been a speaker at numerous professional meetings and training activities throughout his career.

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Cover photo: The *Missouri* (SSN 780), a U.S. Navy *Virginia*-class submarine pre-commissioning unit.

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Executive Summary

The life-of-the-ship (LOS) reactor is, as the name implies, a reactor that is built to last without refueling for the operating life of a vessel. The U.S. Navy began implementing the LOS concept with the highly enriched uranium-fueled (HEU) *Virginia*-class attack submarines (SSNs) in the middle of the last decade. The Navy also currently plans to use HEU-fueled LOS reactors in the next generation of ballistic missile submarines (SSBNs). The SSNs are anticipated to have a service life of 33-plus years and the SSBNs a life of 40-plus years.

Elimination of reactor refueling is a great cost savings for the Navy, but the use of LOS reactors raises safety concerns and poses questions about the accelerated testing methods that may have been used for analysis of the LOS reactors' fuel and pressure vessels. Because details of naval fuel and reactors – and their testing – are generally classified, there has been little or no transparency about the original decision to adopt the LOS concept; nor has there been any public discussion of associated safety issues.

If the engineering assessments made in developing the LOS reactors do not prove to have been accurate, and some of the typical problems of accelerated testing have not been recognized and addressed, the potential economic and safety consequences could be severe. At the low end of the failure spectrum would be fuel leakage, where fission products would contaminate the primary coolant loop. Fuel leakage could have a range of consequences depending on its severity, but the consequences (ignoring the national security aspects of loss of operational use) would be economic in nature. Fuel might need to be replaced and the repair/replacement costs could be a significant fraction of the current $2.7 billion cost of a *Virginia*-class submarine. Should a pressure vessel fail, a far less likely event, the safety and economic consequences would be far more severe because this would probably be the worst-case reactor accident that might occur, including possible loss of life and off-ship contamination.

One disturbing aspect of the LOS concept is that sealing the reactor for 30-plus years may result in a loss of the ability to inspect the fuel and pressure vessel. Refueling offers the opportunity for in-depth inspection and analysis to assess the potential for failures. Refueling of commercial power reactors has, unfortunately, sometimes shown serious problems that could have led to serious later accidents. Whether the LOS concept would allow for any inspection that might detect failures due to aging, fatigue, etc., is unknown. However, a more serious concern with the LOS concept is whether it would be able to allow inspections to detect manufacturing defects that might be undetectable at the time of construction but appear in operation, or not.

Given the potential consequences of any failure in an LOS reactor, a transparent review of the LOS reactor decision and the testing that supported the decision would be in the nation's interests, as well as in the Navy's interest. In performing such a review, thought should also be given to comparing the LOS system's safety with the safety of the Navy's prior use of refueled reactors – and with examples of refueling as practiced by other navies. Of particular interest would be a comparative analysis that would include France's use of relatively rapidly refueled reactor systems that use proliferation-resistant low enriched uranium (LEU) fuel.

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Life-of-the-Ship (LOS) Reactors

Starting with the *Virginia*-class attack submarines (SSNs) in the first decade of the 21st century, the U.S. Navy began using life-of-the-ship (LOS) reactor cores. The current generation of LOS cores uses highly enriched uranium (HEU) and is designed to operate without refueling for the projected 33-plus year life of the vessel,[1] and the next generation ballistic missile submarines (SSBNs), the *Columbia*-class, will be built in the coming years and is designed for LOS cores with 40-plus years of reactor life.[2]

This special report considers whether the use of these LOS reactors by the U.S. Navy raises safety concerns and poses questions about the testing methods that may have been used for analysis of the reactors' fuel and pressure vessels. Note, however, that almost all aspects of naval reactor design and the testing of the LOS fuels and core components are classified.[3] Therefore, there has been little transparency about the original decision to adopt the LOS concept and thus no public discussion of associated safety issues.[4]

From the Navy's perspective, the LOS concept is an economic leap forward because the reactor will not be refueled during the life of the vessel. Historically, refueling –particularly submarine reactor refueling – has been a costly issue. Although it has typically been done in conjunction with other required overhaul periods (i.e. for weapon systems upgrades, etc.) in order to minimize the vessel's time out of service, the refueling requires the pressure hull of the submarine to be cut and re-welded in order to gain access to the reactor, a time-consuming process requiring extremely precise, non-destructive testing to ensure that the ship's hull could withstand the pressures it was originally designed for. Refueling outage times were a controlling factor in the length of the overhaul process, which might keep a vessel out of operational service for 18 months or more. [5]

Eliminating the costs of refueling and replacement core(s) considerably reduces the operating costs of each vessel.[6] Although cost comparisons are not available, the initial cost

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1 See: L. Thompson, "Five Reasons Virginia-Class Subs Are the Face of Future Warfare," Forbes online, May 2014. Available at: http://www.forbes.com/sites/lorenthompson/2014/05/06/five-reasons-virginia-class-subs-are-the-face-of-future-warfare/#3eab39da3e93.

2 See: R. O'Rourke, "Navy Columbia Class (Ohio Replacement) Ballistic Missile Submarine (SSBN[X]) Program: Background and Issues for Congress," Congressional Research Service, October 25, 2016. Available at: https://fas.org/sgp/crs/weapons/R41129.pdf.

3 Whether the extent of classification is justified or is a vestige of Cold War thinking and the influences of Admiral Hyman Rickover, the "Father" of the U.S. Navy's nuclear propulsion program, will be discussed further below.

4 This lack of transparency contrasts sharply with the reviews of designs for nuclear power plants (NPPs). Although naval reactors are typically an order of magnitude less powerful (NPPs are typically on the order of 3000 Megawatts thermal whereas naval plants for submarines are on the order of 300 Megawatts thermal or less), the naval plants may be operating closer to population centers both in their domestic homeports and in foreign ports and any reactor accident could have potentially serious political, environmental, and economic consequences.

5 It is also costly for surface vessels (currently aircraft carriers and previously smaller combatant cruiser designs) but doesn't involve hull integrity as it does in submarines.

6 S. Magnuson, "Nuclear Power Plants on New Submarines May Last 40-Plus Years," National Defense online ed. February, 2015. Available at: http://www.nationaldefensemagazine.org/archive/2015/February/Pages/NuclearPowerPlantsonNewSubmarinesMayLast40PlusYears.aspx. In this article, the administrator of the National Nuclear Security Administration, retired General Frank G. Klotz, is quoted as saying, "It is extraordinarily important on cost because one of of an LOS core would have to exceed the price of two cores (new and replacement core), plus the cost of refueling in order for costs to be at all comparable. Thus, undoubtedly, the cost savings of an LOS reactor are significant and, without such savings, the already expensive *Virginia*-class would be even more expensive.[7] A less obvious cost benefit of eliminating refueling is that the time saved means that fewer vessels are required to be built in order to maintain the same at-sea presence because each vessel has more available time at sea throughout its lifetime.

Despite these economic advantages of LOS reactors, it is reasonable to ask whether the LOS concept involves more safety risks than using refueled reactors. Is an LOS reactor as safe as a series of refueled cores?[8] How has the safety of the LOS core been assured, or is the LOS concept essentially a large-scale *proof of concept* with uncertainties involved? Should the engineering assessments made in developing the LOS reactors not be proven in practice – and problems develop in the LOS cores – what are the potential economic and safety consequences? These and other questions are posed in this special report because little is known about the actual construction and testing of the Navy's reactors.

It is assumed that the Navy's engineering design contractors and their engineering efforts are of the highest quality and that they are dedicated to the safety of their products. They have obviously performed the design and safety work to the best of their ability, but are the risks such that the LOS decision should be reexamined in a more transparent context, a practice that would allow a broader base of analysis and review? Should the design and testing of naval reactors be effectively exempt from open public review by classification issues or should the decisions already made be subject to review, involving a transparent analysis of the Navy's efforts to date?

In addition to safety issues, the LOS concept also has an impact on the decision to potentially use low enriched uranium (LEU) fuel to replace the HEU fuel currently used by the U.S. Navy. One of the Navy's main objections to the use of LEU fuel historically has been that LEU use in current hull designs would require more refueling and that the costs involved both in the refueling and the need for more vessels to maintain the same level of at-sea operations are prohibitive.[9] However, current Navy discussions of the use of LEU

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the largest elements of the total operational cost of a submarine over its life has been replacing the core when that has come due. It is very expensive." Cost of aircraft or refueling is also high See, J. Bender, "The Pentagon wants $678 million refuel a single aircraft," Business Insider February 2, 2015.

7 The *Virginia*-class construction costs are currently approximately $2.7 billion per vessel. See: R. O'Rourke, "Navy Virginia (SSN-474) Class Attack Submarine Procurement: Background and Issues for Congress," Congressional Research Service RL32418, October 25, 2016, available at: https://fas.org/sgp/crs/weapons/RL32418.pdf.

8 It should be noted that there are risks associated with refueling. The pressure hull is cut and welded back together under the current U.S. Navy refueling practice for submarines. This practice adds an additional risk of hull failure, which is not addressed in this paper. Note that, as mentioned later in this paper, French submarines refuel without cutting the pressure hull. This is accomplished by using a large refueling hatch referred to as *brèche* in French. See, A.Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion-Why Low-Enriched Uranium Was Chosen," Federation of American Scientists Special Report, December 2016. Available at: https://fas.org/wp-content/uploads/2016/12/Frances-Choice-for-Naval-Nuclear-Propulsion.pdf.

9 See: "Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion June, 1995" have also considered the use of LEU-LOS concepts, so the LOS decision and risks are not only a topic for retrospective discussion but also part of future decision making regardless of whether cores are LEU- or HEU-fueled.[10]

The Navy anticipates that the *Ohio* future replacement ballistic missile submarine (SSBN), most recently dubbed the *Columbia*-class, will have LOS reactors, whereas the newest *Ford*-class aircraft carriers already have similar long-lived reactors with about a 25-year lifetime that allow them to be refueled only once in their lifetime of about 50 years.[11] The Navy's apparent commitment to future LOS cores makes it essential that any transparent review of the LOS concept be done promptly. Should a review disclose problems or unacceptable risks, future programs, such as the *Ohio* replacement, would need to be reconsidered.

How is the Navy able to ensure that LOS reactors will operate safely throughout their anticipated lifetimes? The Navy's method of certifying these reactors has not been disclosed in detail, but it is clear that "accelerated testing" must play a major role in assuring the Navy that they have overcome all fuel and other problems that they might encounter over a 33-plus-year operating history.[12]

Accelerated Testing

Although the LOS design and testing protocols are unknown, the Navy has not operated individual reactors without refueling for the LOS periods of 33-plus years.[13] We know that the Navy has used "accelerated testing" of the fuel for the LOS reactor and accelerated testing must have been a major underpinning for studies to ensure the safety of these reactors.[14] Accelerated testing is a process by which designers attempt to simulate – in a relatively short time – the operating environment that a part, component, assembly, or an entire system (perhaps a complete aircraft) will experience throughout its anticipated service life. The science and engineering aspects of accelerating testing are highly developed and used over a wide range of newly designed products. Accelerated testing is necessary when a product is designed with materials that have not been used in practice over the anticipated life of the product, or known materials are being used in an environment that they have not previously been exposed to.

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by Director, Naval Nuclear Propulsion (1995), hereinafter 1995 Report. See, also, "Report on Low Enriched Uranium for Naval Reactor Cores: Report to Congress January 2014"by Office of Naval Reactors (2014).

10 "Conceptual Research and Development Plan for Low-and Enriched Uranium Naval Fuel: Report to Congress (July 2016)," National Nuclear Security Administration (NNSA), United States Department of Energy, Washington, DC 20585. Available at: http://fissilematerials.org/library/doe16.pdf.

11 Ronald O'Rourke, "Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress," Congressional Research Service Report, May 27, 2016, available at https://fas.org/sgp/crs/weapons/RS20643.pdf.

12 NNSA Report (July 2016), *supra*, with the discussion of accelerated testing at pp. 5-6.

13 Although the stated service life of the *Virginia*-class is 33 years, peacetime experiences of the U.S. Navy have been that vessels are often kept in service long after their initially anticipated lifetimes due to inflated new construction costs, operational needs, etc. Whether the LOS cores would have a definite "drop dead" date or would be pushed for extended service life past the initial estimated lifetimes is, at least from open sources, an unknown issue.

14 "Conceptual Research and Development Plan for Low-and Enriched Uranium Naval Fuel: Report to Congress (July 2016)," *supra*.

Accelerated testing may have various purposes and may employ various methodologies. For example, one method is to accelerate the aging of a part or system until that system fails. In order for this type of test to ensure safety, the part or system should survive past its anticipated lifetime by x safety factor to account for uncertainty in the testing, variations in parts, etc. Another method used in accelerated testing is to similarly accelerate a part or system for a period of time that is x safety factor longer than what is anticipated for the part or system, with the part or system "passing" if it survives without failure. Although somewhat similar in concept, the two methods may have different capacities to accurately ensure safety depending on how well the failure modes of the part or system are known and, therefore, how well the mechanism of acceleration simulates the actual operational history of the part or system.

As stated above, we do not know any details of the Navy's testing of fuel; there is also a lack of open-source material on accelerated testing for naval fuels. However, the testing of fuel elements is only one aspect of testing necessary to ensure the lifelong safety of an LOS reactor. Given the confined space for a reactor aboard a submarine, we assume that fuel elements and components within the pressure vessel of an LOS reactor cannot be removed without cutting into the reactor compartment.[15] The Navy must have developed a reliable accelerated testing program for all reactor components: fuel, pressure vessel, etc. Furthermore, it is essential that the Navy must have dealt with accelerated testing in at least two significant areas of reactor design: the fuel elements themselves and the reactor pressure vessel. We will discuss the fuel testing and pressure vessel testing separately below.

Fuel Testing

Accelerated testing of new nuclear fuels is a far more complicated process than normal accelerated testing for a number of reasons.[16] Whereas the regular, non-nuclear part may see varied temperatures and a stressful regime over its life, the material from which the part is made is subject only to what we might consider to be "normal" aging of the material.[17] This type of aging involves oxidation, embrittlement, chemical changes to the grain boundaries of metal parts, etc., in ways that have been studied over time and, though perhaps not fully understood, have been understood to the extent that accelerated models have been developed to address most, if not all, of these issues.

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15 This assumption may be incorrect and some components might be removable, but this seems unlikely due to space limitations. However, control rod drives and other reactor components external to the pressure vessel are probably able to be serviced, removed and replaced since these would probably not be anticipated to last for the life of the ship.

16 "Accelerated Fuel Qualification-Sustainable Nuclear Power Initiative Focus Area Fact Sheet," Pacific Northwest National Laboratory, PNNL-SA-59834, Revision 2_11/09.

17 A general view of failure rates versus time for a complex system can be described by a "bathtub curve," which divides a part or system's life into three phases. In the first phase failure is due to early production defects, in the second phase there are random failures, and in the final phase failures are due to wearout; the bathtub shape comes from the pattern of failures in that the early and late phases typically have much more failures than the second phase. See, D. H. Collins, et al., "Accelerated Test Methods for Reliability Prediction," Los Alamos National Laboratory report LA-UR 12-20429 at pages 134-135.

The nuclear fission process, however, introduces several entirely new regimes that must be accounted for in the accelerated testing of nuclear fuel elements. In addition to the significant release of energy that is locally deposited in the fuel itself, once the nuclear fission process has started, elements of the fuel are subject to several types of changes. The fission fragments created in the fission process are totally different chemical elements from what had existed in the fuel material prior to irradiation.

Other elements of the fuel exposed to neutrons are changed to new isotopes of the same element initially, and then many of these radioactively decay to other elements. Because many of the decay chains that develop in the fuel have long half-lives, it is doubtful that accelerated testing can account for the late time production in changing chemical elements that appear in the fuel as a function of fuel life. Simply put, several lifetimes' worth of neutron exposure in a short time does not allow the decay chains to develop properly. How much of a factor this can be in accelerated testing of the LOS reactors is not known but should be part of a transparent discussion of the accelerated testing that the Navy has done to ensure safety of the LOS reactors.

In addition to the neutron-induced changes in materials in the reactor fuel, other structures are subject to damage due to the release of high-energy gamma rays, X-rays, and other charged particles that originate either directly from the fission process, or from the radioactive decay of fission products or activation products.

Typically, the most damaging fission products for the fuel are the noble gases, krypton and xenon. Because these elements are essentially chemically inert, they attempt to work themselves out of the fuel. Power reactor fuel elements typically account for noble gases with a plenum designed to provide expansion of space for the noble gases without rupturing the fuel cladding. Because the details of naval propulsion reactor fuels are not publicly available, we are not sure how the U.S. Navy and its engineers deal with these factors.

At an INMM Technical Meeting on Nuclear Energy and Cyber Security held in Annapolis, Maryland in April 2016, the director of naval reactors, Vice Admiral J. Frank Caldwell, in response to a question about testing of the LOS cores, stated that he had seen fuel coupons tested in reactors at the test facility at Idaho National Laboratory and was impressed by the process. Subsequently, as part of the Navy's new (July 2016) report to Congress on the potential for developing LEU fuel for new propulsion,[18] the method used by the Navy for development of naval propulsion fuels was described.

The Navy's 2016 report described that the process involves manufacturing and testing small specimens that "evaluate different aspects of fuel performance."[19] According to the Navy, "Irradiation testing is essential. Nuclear fuel can fail in ways that can only be found

18 "Conceptual Research and Development Plan for Low-and Enriched Uranium Naval Fuel: Report to Congress (July 2016)," *supra.*

19 Id. at page 5.

through irradiation testing."[20] In the same report, the Navy described the irradiation testing as follows: [21]

- Fuel test specimens are fabricated, usually iterating on several processing steps to achieve the desired properties and create manufacturing techniques that can be scaled up to factory production. Once the desired characteristics can be manufactured, small fuel specimens are fabricated for testing. This typically requires two to three years when new, developmental manufacturing methods are involved.

- Fuel performance is demonstrated through accelerated testing of these small fueled specimens in a test reactor. The Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) is the only domestic test reactor available that can perform these fuel tests. Specimens are irradiated for up to 10 years to simulate the effects of aging through the life of the ship.

- Specimens are periodically removed from the ATR and transported to the Expended Core Facility at the Naval Reactors Facility at INL, where they undergo interim examinations before being returned to the ATR for additional testing. The interim examinations verify fuel performance and provide data used to develop performance limitations for the fuel system.

- Near the end of their irradiation time, some specimens undergo a series of severe tests which simulate rapid power changes to provide assurance that the fuel system can perform under worst-case operating conditions.

- When the specimens have been fully irradiated, they are shipped to the Knolls Atomic Power Laboratory for examination in hot cell facilities that can remotely examine highly radioactive materials. The examination process typically requires approximately two years to complete. The above process is typically repeated in multiple overlapping phases within a 10-15 year period. Interim examination results from the first specimens, supplemented by fuel analysis models, provide confidence to proceed with subsequent test iterations. Initial test results are also used to improve fuel system design and construction of subsequent test iterations. These initial specimens are built with small scale laboratory equipment, usually not representative of factory equipment. Factory fabrication methods are developed in parallel and can be used to make specimens for follow-on fuel tests. The result of this stepwise development is a fuel system that the program has high confidence can be successfully deployed in a reactor.

Thus, it appears that the accelerated testing for the 33-plus years of anticipated life has been done over a maximum of 10-15 years. The Advanced Test Reactor (ATR) at Idaho Na-

20 Id.

21 Id. The following bullet points appear at pages 5-6.

tional Laboratory was used in the testing. However, it should be noted that the operating conditions of the ATR are at a pressure of 360 psi and temperature of 160°F, which are probably significantly below the operating pressure and temperature in a naval propulsion reactor.[22]

In addition to accelerated test results, the Navy should have data on prior reactor fuel and pressure vessel experiences. Although these may not be exactly the same fuel elements and/or operating temperatures and experiences, the data should provide the Navy with additional data points not available in the open literature upon which to base their analysis of accelerated testing results.

While accelerated testing of the fuel is probably the primary focus of testing for the LOS reactors, testing of the pressure vessel and other in-core structural components is also essential.

Pressure Vessel Testing

Testing and certifying the pressure vessel is also an essential safety aspect for the LOS reactors. Pressure vessels are typically thick-walled steel cast parts that must always contain the primary coolant/moderator. While the reactor is operating (and even to some extent after reactor shutdown) the pressure vessel is subject to neutron- and gamma ray-induced damage. In a large commercial nuclear power plant, this damage is tracked by positioning removable test coupons of the pressure vessel material on the inner wall of the vessel. Some of these coupons are removed during refueling and analyzed to estimate damage.

It is assumed that the LOS reactor pressure vessel will not be opened during the life of the ship.[23] Therefore, the Navy must be assured that the vessel itself will not be compromised during its 33-plus years of operation. Presumably, the Navy has studied reactor pressure vessels that have been removed from its submarines in the past and it may have very good data on pressure vessel aging so that the Navy feels comfortable that induced damage will not be a problem with the LOS reactor. However, another concern with pressure vessels is that there may be manufacturing defects that are not detected by nondestructive testing methods during manufacture. Unfortunately, these undetected defects may become an is-

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22 C. Schultz and J. Campbell, "Advanced Test Reactor-Meeting international nuclear energy research challenges," Idaho National Laboratory 08-GA 50044 – 27 R7-16. Available at: http://www4vip.inl.gov/research/advanced-test-reactor/d/advanced-test-reactor.pdf. Although we do not know the exact operating temperatures and pressures of Naval propulsion reactors, conventional power PWRs operate at approximately 2200 psi and 600°F, while BWRs operate at approximately one half that pressure. It is possible that the Navy created an in core increased pressure system at the ATR to use in testing. In their 2016 Report to Congress the Navy mentions the need to reestablish a test loop to use for LEU testing. It is possible the prior test procedures used a loop running at operational pressure and temperature. See, "Conceptual Research and Development Plan for Low-and Enriched Uranium Naval Fuel: Report to Congress (July 2016)," *supra* at page 8.

23 Like the removal of the fuel rods mentioned above, there would probably be little or no ability to remove the pressure vessel, or even to access the interior. Limited access to the interior might be available by removing the control rod drives, or a special access port might be available, but it is not anticipated that such access would allow significant levels of inspection of the pressure vessel and/or the removal of any type of test material placed in the reactor to potentially study aging.

sue during the operational life of the reactor. Sealing the pressure vessel for 33-plus years without the ability to conduct inspections may lead to a failure in detecting the development of pressure vessel problems.

While the U.S. Navy's safety record is unblemished and there are no indications of pressure vessel problems with Navy reactors in the open literature, this has not been true for commercial nuclear power plants. Pressure vessels in commercial nuclear power plants have experienced embrittlement and, in particular, cracking of areas around the nozzles in the upper portion of the pressure vessel. One particularly serious incident was severe damage to the reactor pressure vessel head in the Davis-Besse reactor in Ohio that was discovered in the early 2000s.[24] Fortunately, none of the defects found in commercial power plant pressure vessels have led to a serious incident or accident, but this is because the problems have been detected during inspections that occur every two years or so during refueling outages.

Extensive corrosion of the reactor pressure vessel head of the Davis-Besse nuclear reactor.

Photo/Nuclear Regulatory Commission

The commercial nuclear power plant pressure vessel problems, while not directly applicable to the U.S. Navy's propulsion reactors, do indicate the necessity for accelerated testing and/or surveillance of the pressure vessels.

Problems with Accelerated Testing

There are, unfortunately, some general problem areas associated with accelerated testing. One major concern is that an accelerated testing program may not be testing the appropriate factors that may lead to failure. Another concern is that overcycling or overloading a part over a short period cannot adequately predict the performance of the part as it naturally "ages." Examples of this problem in other areas of design are attempts to accelerate fatigue tests by placing a part or design in far more situations than it is expected to see over its lifetime. Thus, airplane components that might be expected to see, for example, 10,000 fatigue cycles over a 20-year lifespan may be exposed to 20,000 or 30,000 cycles over a few months. Fatigue failures have been observed even though accelerated testing of this nature has been successfully carried out. Simply, the "fresh" metal is not the same as the metal at 20 years into its life when grain boundary issues have made it more susceptible to fatigue.

Although we do not know any of the specifics of the Navy's accelerated test program, it is fair to state that the materials involved in nuclear reactors are subject to far harsher

[24] "Backgrounder on Reactor Pressure Vessel Issues," US Nuclear Regulatory Commission (February 2016). Available at: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/prv.html

environments over their life than aircraft parts. Unique failure modes such as radiation damage, hydrogen embrittlement, etc. are all factors that must be adequately accounted for in the accelerated test program for LOS fuel, pressure vessel, and components. A transparent review of the Navy's program will hopefully show that all these factors have been properly accounted for.

Consequences of Inadequate Testing

Fuel Element Failure

What are the consequences for a naval propulsion reactor if the accelerated testing does not adequately predict problems that might occur in the LOS cores? The most probable event would be leakage from a fuel element into the primary coolant without serious mechanical compromise of the fuel element. Although this would not be described as a reactor accident, it would create a situation in which the core would probably need to have the fuel element replaced (depending on where in the lifecycle this occurred) – a situation that would bring about a refueling-like process, probably requiring the pressure hull to be cut open and portions of the core removed.[25] Because refueling has not been anticipated for the LOS vessels, such repairs would be a major economic setback.

The next most likely failure would be a mechanical failure of a fuel element. Without knowing the core design, one can only say that this would probably create a situation where a submarine would essentially be out of service until the core or the damaged component is replaced. Whether a mechanical failure of the fuel element would lead to an incident that could further damage the core beyond the fuel element itself is speculation. Like a badly leaking fuel element, this incident would require the same level of reactor access as refueling.

In any event, fuel element failures would probably not lead to any loss of containment of radioactive materials. The primary coolant loop would have residual radiation; repairs would probably have to be made; and there would be a large costs (perhaps major fractions of $1 billion) to correct the problems because, as discussed above, the reactor core would need to be opened, the pressure vessel cut, new core or parts purchased, etc.

Pressure Vessel Failure

Failure of the primary containment (pressure vessel and associated piping) would be a significant reactor accident. Has testing been done to ensure this cannot happen? Once again, we have no data on tests the Navy may have done on pressure vessels in prior service or on the pressure vessels used in the LOS reactors. We are unsure as to whether with prior submarines and surface vessels the pressure vessel is removed with the fuel on refueling. For commercial nuclear power plants, the fuel is removed from the pressure vessel (the pressure vessel head is removed and then replaced), but naval reactors are physically much smaller. Moreover, the Navy may have removed the pressure vessel along

[25] There would, of course, also probably be an option to continue to operate the reactor if the leakage rate was low enough not to substantially increase the dose rate to personnel who might have to enter the normally unmanned reactor compartment. Continued operation would have to be considered on a case-by-case basis.

with the fuel during refueling. Whatever the case, the Navy has had an opportunity to examine aging pressure vessels that have seen about one-half the service life that LOS core pressure vessels will see.

If the pressure vessels were left in place during the refueling of the naval reactors, then the Navy would have a very good measure of the safety of LOS core pressure vessels as they have operated throughout the life of prior naval reactors. Thus, the Navy would not need to rely significantly on accelerated testing results assuming the operating conditions of the older cores to be roughly the same as with the LOS cores. Then, perhaps the Navy would only need to account for the higher power levels in newer reactors.

In contrast to a failed or leaking fuel element, a ruptured pressure vessel would probably be the most serious accident imaginable for a naval propulsion reactor. Regardless of whether or not there was off-vessel release of radioactivity, it would be a disaster for the Navy's nuclear power program and a tragic end to an unblemished safety record.

Risks versus Benefits and Considering the French Example

Regardless of the need for accelerated testing, another question arises with the LOS concept. Assuming the best state-of-the-art accelerated testing, and the best quality control over production, is it a good idea to seal up a nuclear reactor for 33-plus years without inspection? The experience with commercial nuclear power reactors indicates that refueling outages have sometimes detected problems in both the fuel and pressure vessel. Has the Navy provided for some type of periodic inspection of the LOS cores, or, as the name indicates, are these reactors designed to be sealed up and operated for the useful life of the ship?

The risks of being wrong in choosing the LOS concept are significant. At the low end there would be increased economic cost and loss of operational capability if the LOS fuel does not perform as anticipated, and at the high-end there would be a serious reactor accident with economic and potential life-threatening consequences were a pressure vessel to fail.

Without a complete understanding of how the Navy has implemented the LOS concept, it appears that continuing to travel down the LOS path is essentially foregoing any developments that may occur in the next 30-40 years in terms of nondestructive testing and better understanding of failure mechanisms and reactor fuel and components.

Compounding these issues is the risk that, as mentioned above, LOS reactors in operation without periodic *in situ* inspections may not be able to detect manufacturing defects that were not detected by pre-operational testing. While the Navy's use of frequent chemical analysis of primary water will certainly detect some types of problems, it is probably not a replacement for *in situ* inspections.[26] Water analysis should detect leaking fuel once leaks occur, but the onset of fatigue or fracture failure in the fuel or pressure vessel may be more problematic for chemical analysis

[26] We assume that the Navy's testing of primary water is very frequent and is at least as good as that of the commercial power industry. For a general description of water chemistry programs see, for example: "Primary Water chemistry Guidelines," Electric Power Research Institute Technical Report, TR-105714-V1R4, 1999. Available at: http://www.miroslavgregoric.com/wp-content/uploads/2013/10/PWR-Primary-Water-Chemistry-Guidelines-Volume-1-Revision-4-

Maintenance on the nuclear propulsion plant for the French SSBN, *Le Terrible*.

to detect since it depends on what material(s) might enter the primary water prior to failure.

One would hope that any defects in reactor components would be inadvertent both in the origin of the defect and in the failure to detect a defect through quality assurance testing procedures during the vessels' construction. However, this may not be the case. The current saga of the USS *Minnesota* (SSN –783), a *Virginia*-class attack submarine, raises some concerns. Press reports indicate that the *Minnesota* has been unusable for over two years due to what may have been intentionally improper welding procedures on piping in the reactor compartment.[27] This problem may also exist in other *Virginia*-class submarines.[28]

While it can be assumed that the U.S. Navy's testing was done to state-of-the-art standards, all accelerated testing is somewhat suspect until the tested product has actually survived the operating environment for its full life. Therefore, it is reasonable to ask whether the cost savings of LOS reactors are worth the risk, albeit small, that accelerated testing cannot adequately predict success of the LOS designs. Is it as safe as the alternative of refueling reactor cores as the U.S. Navy has done in the past and as France does? Although many of the problems, such as manufacturing defects, may also exist in any new non-LOS reactors requiring refueling, using refueling with either HEU or LEU cores may be a conservative and safer, but more expensive, alternative.

The decision about refueling is not unique to the U.S. Navy. The French Navy uses LEU fuel and regularly refuels its submarines and aircraft carrier. France's nuclear safety regulations require the inspection of reactors and their components at least every 10 years. No exemption is granted to the military. Therefore, even if the French wanted to use LOS reactors, they could not. By

EPRI-1999-TR-105714-V1R4.pdf.

27 D. Larter, "Secret weld: How shoddy parts disabled a $2.7 billion submarine," Navy Times online March 27, 2016. Available at: https://www.navytimes.com/story/military/2016/03/27/minnesota-two-years-in-the-yards-virginia-class-attack-sub/81600432/.

28 B. Lendon, "Unauthorized repairs found on Navy's three newest subs," CNN politics August 6, 2015. Available at: http://www.cnn.com/2015/08/06/politics/navy-submarine-unauthorized-repairs/.

regulation, they would have to open the reactor compartment and examine the pressure vessel's interior and the fuel.[29] The French, therefore, are committed to refueling and have developed automated refueling procedures that allow refueling to be done at a small fraction of the time that U.S. Navy refueling has historically taken.[30] The rapid refueling capability results from incorporation of refueling into the submarine designs by using refueling hatches that allow access to the reactor compartment by automated refueling equipment.[31]

Whether the French approach, using LEU fuel with refueling, is safer than the LOS concept can be debated. However, one distinct advantage to the French approach is that it would certainly appear to allow for the detection of defects that emerge or develop during operation, defects that the inability to thoroughly inspect the LOS reactors in operation might not be revealed. The French experience also is a strong argument that LEU fuel can be used and refueling can be done without the impact that the Navy feels it would cause in the U.S. program. Has the U.S. Navy thoroughly evaluated the French experience? It is interesting to note that none of the reports to the U.S. Congress on the potential for LEU use in naval propulsion reactors have mentioned France's use of refueled LEU reactors.[32]

Conclusions

The U.S. Navy has used accelerated testing to ensure the safety of the Navy's extensions beyond known experience with the LOS reactor concept. Therefore, to some extent, the LOS reactors must be viewed as testing a concept. Hopefully the U.S. Navy's decision to implement an LOS reactor concept will prove to be as safe as the impeccable prior history of U.S. Navy reactor operations. However, the Navy's decision appears to be one that might, to some extent, trade safety for economic advantage.

In all probability, should there be fuel problems with the LOS reactors, the consequences would be economic, albeit probably very expensive to repair. The far less likely prospect of a pressure vessel failure would, however, have the potential to be a serious reactor accident with far-reaching impact.

Given the potential consequences of any failure in an LOS reactor it certainly seems reasonable that a transparent review of the LOS reactor decision, and the testing that supported the decision, would be in the national interests as well as in the Navy's interest. In performing such a review thought should also be given to comparing the LOS system's safety with the safety of the Navy's prior use of refueled reactors and with the French example of reactor refueling and use of LEU fuel.[33]

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29 A.Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion-Why Low-Enriched Uranium Was Chosen," *supra.*

30 This ability to relatively rapidly refuel makes the use of LEU, as the French have done, a far more viable option.

31 A.Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion-Why Low-Enriched Uranium Was Chosen," *supra.*

32 The 1995, 2014, and 2016 reports to Congress. *supra.* Although little is known of the Chinese experience with LEU fuel there is also no mention of Chinese use of LEU powered reactors in these reports.

33 The advantages for nonproliferation and counterterrorism of using LEU fuel and eliminating the large naval propulsion stock of HEU have been discussed by this author and others (e.g. Dr. Frank von Hippel, Princeton Univ.) and in other FAS publications.

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