



Thorium: Not a near-term commercial nuclear fuel

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Abstract

In the wake of the disaster at the Fukushima Daiichi Nuclear Power Station, opinion makers and policy makers, alike, have worked internationally to pique interest in thorium as a possible alternative fuel for commercial nuclear reactors. The key question posed has been: Could a thorium-based fuel provide advantages if deployed in current reactors? A full thorium-driven cycle used to produce and use uranium-233 for power generation has been understood to possess a range of benefits for many decades. To fully assess the practical utility of thorium use in existing light water reactors, it is necessary to critically dissect the promoted benefits of the thorium fuel cycle. The potential advantages of thorium are relatively small, the author writes, when viewed through the lens of current infrastructure and economic and political realities.

Keywords

light water reactors, nuclear fuel, thorium, thorium uranium dioxide

Thorium. In the popular press, this element has often been portrayed as a potential game changer. The *Atlantic's* Alexis Madrigal (2011) called thorium-fueled reactors, in concept, “a brilliant solution to our energy dilemma: They would be impervious to melt-downs, could be built faster and smaller than traditional nuclear plants, and cannot be used to produce radioactive material for nuclear weapons.” Articles in *Forbes* (Katusa, 2012) and the *Telegraph* (Evans-Pritchard, 2011) have similarly trumpeted the advantages of a commercial reactor fleet powered by thorium under the banner of vastly increased safety, far lower fuel costs and thus less expensive electricity,

and obsolescence of the problems of both nuclear waste and proliferation concerns.

Journalists are quick to point out that the most fundamental difference between a thorium fuel cycle and the conventional uranium fuel cycle, as currently used in industry, rests in the simple fact that thorium itself is not fissile. They quote experts who say this energy source is superior to existing conventional reactors in nearly every critical facet: safety, economics, proliferation resistance, and vastly reduced radioactive waste generation. But these articles are not solely the work of forward-thinking science journalists; in fact, they are largely inspired by various

international efforts. For decades, the International Atomic Energy Agency has maintained a global working group advocating advancement of thorium fuel-cycle research and development by member states (International Atomic Energy Agency, 2005). Both China and Great Britain have passed legislation this year directing funds for thorium fuel cycle and reactor technology research. In the United States, proposed legislation has sought to secure extensive support for thorium research and deployment (Thorium Energy Security Act of 2010).

The events that unfolded at the Fukushima Daiichi Nuclear Power Station in March 2011 convinced many American policy makers that the resources previously devoted to research of future systems would be better used to improve the technology of existing reactors. This change in focus stems from one question: If water-cooled, uranium dioxide-fueled reactors are fundamentally flawed from a safety standpoint, should the government and industry replace the conventional uranium dioxide fuel and zirconium cladding used in most commercial reactors—cladding that has an increased probability of inducing rapid corrosion, degradation, and ultimate failure during an accident—with an alternative that mitigates or even eliminates the possibility of a Fukushima-like accident?

Various interest groups in the coming years will advocate a range of possibilities to address this challenge, including metallic fuels, advanced cladding alloys, composite fuel systems, and other approaches.¹ Many will not withstand even a casual critique. But one contender for producing nuclear energy in the

United States very well could be thorium. In fact, debate has already begun on thorium's ability to produce nuclear power without the disadvantages associated with conventional uranium-driven light water reactors. However, as is often the case in translating the promoted benefits of any technology, it is critical to distinguish reality from hyperbole and address some important qualifiers to broad statements.

Near-term use of thorium must be evaluated according to two criteria: deployment within the existing fleet of reactors, and thorium use in an open fuel cycle.² But is it feasible to switch to thorium using the current fleet of reactors? Unlikely so. Close examination of the physical and economic realities strongly suggests that any benefits—whether in standard operations or in an accident scenario—would be either nonexistent or too small to encourage the plant operators to make the large investments required for, and accept the possible risks of, near-term conversion to thorium fuel.

An overview of thorium

The risks, costs, and benefits of using thorium in the current generation of commercial nuclear reactors must be carefully weighed to develop a critical prognosis for its near-term prospects as nuclear fuel. Any such analysis requires a clear understanding of the fundamentals of a thorium fuel cycle and how that cycle might be mapped onto an industry constructed upon 60 years of nearly exclusive reliance on uranium.

Thorium exists in nature predominantly as a single isotope, thorium-232. Thorium gained notoriety at the turn of

the 20th century, when its natural radioactivity was detected and reported by the Curies in one of their early works on the subject. Other than occasional interest from the nuclear community, thorium has been used only in scattered and specialized industrial applications, most notably in specialty filaments and ceramics requiring enhanced toughness. Thorium has one great difference from uranium: It is not fissile. A nuclear reactor fueled entirely with thorium would be as effective as a reactor filled with lead. Unlike lead and the vast majority of elements, however, thorium does possess the capability to transmute to a fissile isotope, if provided a neutron and the time required to navigate the decay chain. Under neutron irradiation, thorium-232 captures a neutron, transmuting first to protactinium and then to uranium-233, which can be used in a sustained fission reaction. Thus, a thorium fuel cycle may be fed by thorium, but relies upon bred uranium-233 to undergo fission, generate heat, and produce electricity in a reactor.

This facet of the thorium fuel cycle has a critical implication. Thorium requires a source of neutrons to begin the transmutation process; that is to say, a fissile element must be present in the reactor core at start-up. The two most likely possibilities would be either the familiar uranium or uranium-233 separated from thorium that has been transmuted previously.³ Although this distinction may seem insignificant, as the two are chemically identical, a number of important consequences stem from the decision of which fissile isotope will drive breeding of uranium-233 from thorium.

One of the primary benefits attributed to a thorium fuel cycle is reduced waste

generation. The reason behind this lies in the isotopic inventory of the fuel; if the isotopes present in the fuel at any point in its lifetime are principally thorium-232, protactinium-233, and uranium-233, which subsequently fissions into much lighter isotopes, the radioactive waste generation will be largely limited to those fission products. In most cases, these daughter isotopes decay substantially following only a few hundred years. Conversely, the isotopic population of low-enriched uranium as used currently consists of just below 5 percent uranium-235, with the balance being primarily uranium-238. The latter isotope contributes negligibly to fission but is responsible for the generation of long-lived transuranic elements such as neptunium, plutonium, and americium that are long-term disposal challenges and create proliferation concerns.

Realization of the waste-reduction benefits of a thorium fuel cycle thus requires the use of uranium-233 for fission. As a reactor fueled by thorium operates, uranium-233 will be bred as described above. But the source of neutrons for the first several weeks of operation before uranium-233 begins to accumulate significantly in-pile must also be uranium-233. The only means of producing a constant source of uranium-233 on the scale necessary to drive a commercial reactor loaded with thorium at start-up would be a massive separations installation where spent fuel previously used in the reactor would undergo a process to extract bred uranium-233. Neither the political support nor financing for such infrastructure is likely to be available in coming decades.

The only alternative to such a massive investment is to provide neutrons to thorium through conventional

low-enriched uranium, thus negating the reduction in long-term waste production offered by a full thorium cycle.

Considerations in commercial deployment of thorium

Given its negligible advantage in regard to waste reduction, thorium would only be attractive to current nuclear plant operators if it could be shown to produce performance benefits. These could, for example, come in the form of improved reactor responses during accident conditions or direct contribution to reactor output or economics.

There are several such benefits that thorium might, in theory, provide. Enhanced thermal conductivity would reduce fuel temperatures and provide a greater time interval for restorative action before the core is damaged during a loss of active cooling. More robust mechanical properties could maintain superior integrity of fuel pellets.⁴ From a commercial perspective, the inherent attribute of the thorium fuel cycle—a continuous breeding of fissile uranium-233—might offer the possibility of extending fuel use beyond the standard 18-month to 24-month cycles and, thereby, increase profits. Any of these demonstrated or potential advantages must, however, be weighed against the established performance metrics of the industry.

In considering what properties or performance gains thorium might offer to the current generation of commercial reactors, the first question to be addressed involves form. Thorium could be fabricated as any number of metal alloys or ceramic compounds for use as solid fuel. The only two forms of thorium that have received consistent

attention from the nuclear community are pure thorium in its metallic form and thorium dioxide, a ceramic.⁵

Choosing between these two plausible options is straightforward. If thorium is to be used in today's commercial reactors, it must be fully compatible with both the geometric constraints of the reactor cores and the water coolant that transfers heat generated by fission to produce electricity.

The nuclear fuel used in commercial reactors is assembled in a relatively standardized manner, with only minor differences dictated by fuel vendor and reactor type. Uranium dioxide fuel pellets, containing roughly 5 percent uranium-235, are first fabricated into approximately 10-millimeter right cylinders. These pellets are then loaded into zirconium-alloy cladding, sized to allow a very small pellet-to-cladding gap. The total length of the cladding tubes measures several meters. The cladding is then backfilled with helium and welded shut to obtain a hermetic seal. Depending on the specific reactor and design, anywhere from just under 100 to roughly 250 fuel rods are then gathered to construct assemblies, or bundles. A complete reactor core measuring several meters across consists of several hundred such assemblies.

Although described above on only a cursory level, the precise dimensions and orientation of the fuel pellets, cladding, rods, and assemblies critically influence reactor performance. It may be theoretically possible to completely redesign the core geometry to use a smaller or larger pellet diameter, a tighter or looser spacing of the rods within an assembly, or an entirely different fuel, but not without greatly increasing cost and risk because of other impacts on

reactor operation. A campaign to bring about such design changes is unlikely to succeed, barring a revolutionary fuel that comes with a drastic economic incentive to the utilities and vendors who would fund development. If thorium is to be deployed in existing reactors, then, it must be interchangeable with uranium dioxide fuel pellets with negligible or no impact to the cladding, rod, and assembly geometry or function.

The second important criterion that must be satisfied by thorium fuel is compatibility with the water coolants of current commercial reactors. Cladding is designed to shield the fuel from coolant interactions and retain radioactive species produced by fission, but experience has proved that isolated cladding failures do occur and must not dictate that reactors shut down. Fortunately, with uranium dioxide fuel, the result of a cladding failure—whether due to a manufacturing defect or some other cause—is far from catastrophic.

In fact, quite the opposite is true. At the comparatively low temperatures encountered during normal operation, uranium dioxide can be exposed to water without any noticeable impact on performance or safety. Cause for concern comes only in the event of an accident scenario during which temperatures may rapidly reach several times those of steady-state operation. In the event of an accident in which wide-scale cladding breaches are likely and fuel exposure to water or steam at high temperatures will immediately follow, it is unacceptable for a nuclear fuel to rapidly lose integrity or undergo detrimental chemical reactions.

Unfortunately, metallic thorium fuels are fatally flawed in just such a way. Reaction with oxygen, nitrogen, and

water vapor disastrously degrades the material at even moderate temperatures. It would be possible to improve the high-temperature corrosion performance of metallic thorium through an alloying process, but this would entail development of an entirely new nuclear fuel and is infeasible on a reasonable timeline.

Thorium dioxide is, therefore, the only possible candidate for near-term deployment in existing reactors. Thorium dioxide pellets have been successfully fabricated in the cylindrical geometry required and irradiated in several reactors, providing a limited but invaluable level of experience. Second, the experiments performed to date suggest that this form is at a minimum as resilient to oxidation as uranium dioxide under both liquid water and steam environments. More detailed studies may in fact discover gains in this area if thorium dioxide is used.

The technical challenge of using thorium dioxide in existing reactors does not involve the capacity of industry to fabricate the material.⁶ Instead, the dominant technical constraint governing replacement of conventional uranium dioxide with thorium dioxide involves reactor performance.

To remain commercially viable, all reactor cores—either conventional low-enriched-uranium driven or proposed thorium variants—must operate at a prescribed heat output for a requisite time. Reduced heat output equates to less electricity production; a more frequent need to refuel requires reactor shutdowns, generally lasting roughly one month.

The limitation facing reactor engineers seeking to incorporate thorium into fuel-loading schemes for existing reactors is simple: The available fuel

volume is fixed. Introducing thorium atoms as an oxide must replace an approximately equivalent number of uranium atoms. The balancing act can thus be crudely considered in this way: At one end of the spectrum, the core would be loaded with mostly thorium dioxide containing only a small quantity of uranium dioxide. At most, 6 percent of the total available uranium atoms will be fissile uranium-235.⁷ This may be enough to provide brief criticality for start-up, but the available uranium-235 supply will be quickly extinguished, and the core will become subcritical before any uranium-233 can be bred. The opposite extreme would be when the vast majority of the core is conventional uranium dioxide. The small fraction of thorium included would result in a negligible departure from the performance of an existing core, but clearly a very small quantity of thorium would not realize any potential benefits.

The issue at hand thus becomes balancing the uranium and thorium contents at start-up such that the evolved population of uranium-233 and uranium-235 maximizes both performance and fuel use.⁸ Many studies have focused on this problem under a wide range of assumptions. They show there is another factor of equal importance to the fraction of thorium initially included within the core: distribution.

The reality of reactor design depends on neutron management at a millimeter spatial resolution in all three dimensions. The specific location of fissile isotopes within the core will drive this distribution. Fuel pellets could be fabricated of the same composition for the entire core—that is, each fuel pellet would contain a prescribed fraction of thorium and uranium. The second

option would be fabricating pure thorium dioxide separately, such that both uranium and thorium fuel pellets would be used to construct the core.

Either option has a critical impact on reactor performance and the potential benefits of thorium use. Separate uranium dioxide and thorium dioxide pellets allow the important advantage of flexibility in core design. It is possible to place fuel rods loaded entirely with either uranium dioxide pellets or thorium dioxide pellets into different arrangements within fuel assemblies to obtain optimal reactor performance.

There is, however, a significant drawback to such an approach: the near-complete lack of any tangible commercial benefit from the use of thorium. A significant quantity of conventional uranium dioxide would remain in the core and operate according to established experience, both positive and negative. A once-through fuel cycle dictates that no extraction of uranium-233 bred in the thorium dioxide rods following their removal from the core would be possible. From a performance standpoint, therefore, it appears probable that such a core loading could meet the required metrics for use in an existing reactor, but gains—judged from the perspective of electricity put to the grid—would not be possible.

All of the above factors point toward the use of separate thorium dioxide and uranium dioxide pellets in commercial reactors as an experiment without the possibility of any payoff for utilities.

The alternative—modifying the fuel fabrication process to produce a single type of pellet that contains both thorium and uranium—is potentially feasible. Such an approach would create more straightforward fuel management, as all

fresh fuel would be identical. Limited research would be necessary to adapt benchtop fabrication techniques to the industrial scale. But there would be no substantial uncertainties to resolve before the existing fuel-processing infrastructure could be used to fabricate uranium-thorium dioxide pellets. Most critically, this composition would represent an entirely different fuel form compared with conventional uranium dioxide, and it would be capable of providing unique advantages.

Possible performance advantages of thorium

The prospects for deployment of thorium-uranium oxide pellets as fuel for existing nuclear reactors can be summarized by the answers to two critical questions: What are the possible performance gains offered by such a fuel? And does the price paid for these benefits justify the required economic investment and deviation from decades of industrial experience?

Compared with conventional uranium dioxide, thorium-uranium dioxide fuel could, when viewed in the abstract, provide a number of potential benefits. Pure thorium dioxide does generally possess properties superior to those of uranium dioxide. Unfortunately, the focus of including thorium in reactors is to breed uranium in-pile. This process will generate a fuel form that includes not only thorium and uranium, but also protactinium as an intermediate product. While limited studies have investigated the properties of uranium-thorium dioxide, to date no experimental data have included the effects of protactinium included in a

thorium-uranium dioxide composition of interest.

Even if performance is somehow improved through use of thorium-uranium dioxide fuel, a critical question remains: at what cost and risk? Commercial interests need significant motivation to tolerate increased uncertainty in the function of nuclear reactors—and a new fuel will, inevitably, create such uncertainty.

In the case of thorium, enhanced thermophysical properties—increased thermal conductivity or a higher melt point, for example—could provide engineers a greater thermal margin within the fuel. In other words, the reactor fuel might be safely driven to generate more heat while still maintaining an acceptable safety margin, which could appear to be an important advantage for a nuclear plant operator. For one practical reason, however, it is not.

The cost of replacing the fuel in a nuclear reactor is almost nominal, when considering the cost of upgrading the heat exchangers and turbines that turn the heat of a reactor core into electricity. If these components are already operating near their capacity, there is no motivation for increasing heat generation in the core.

The general consensus of the industry is that there is minimal interest in deployment of a new fuel form (such as thorium) designed for the current generation of reactors that is capable of greater heat generation. The nuclear industry has enjoyed remarkable success uprating and extending the operating lifetimes of commercial plants originally designed and largely constructed more than five decades ago. The generation capacity of these plants is thus largely at its upper limit due to a

range of factors having nothing to do with the fuel itself.

Utilities would be interested in another possible benefit of thorium fuel, extended fuel cycles. Unfortunately, thorium-uranium dioxide fuels driven by uranium enriched to less than 6 percent cannot extend the fuel cycle in current nuclear plants, because such a mixed fuel would be challenged even to meet the cycle performance of uranium dioxide.⁹

The only other significant advantage of thorium-uranium dioxide fuels may be found in the venue of accident performance. At high temperatures, zirconium-cladding alloys will readily oxidize in the presence of water and generate hydrogen. Zirconium dioxide formation, in combination with hydriding at even further extremes, results in a rapid loss of mechanical integrity and probable failure of the cladding.

At this point, the response of the fuel itself to the oxygen-rich environment governs further deterioration of the core and release of both accumulated fission products and transmutation products such as plutonium. Thorium-uranium dioxide fuels may contain a number of favorable performance attributes under this scenario, including increased time that the fuel could endure a loss of coolant before melting.¹⁰

Studies executed to date also suggest that thorium-uranium dioxide possesses an enhanced resistance to fracture and cracking, problems associated with uranium dioxide. Reduced crack propagation improves both steady-state fuel operation and performance under potential accident scenarios. Release of highly radioactive fission products during a cladding failure and loss of containment initially occurs at the exposed

pellet surfaces. A highly fractured fuel pellet provides many surfaces that may rapidly release collected fission products in the event of a clad breach. Finally, the chemical characteristics of thorium-uranium dioxide are likely to retard the rate at which the fuel oxidizes during high temperature exposure to water vapor as encountered during a loss-of-coolant accident. Oxidation of a uranium dioxide fuel pellet during an accident is responsible for the ultimate pulverization of the pellet and widespread release of radioactivity during a catastrophic reactor accident and loss of containment.

Any fuel form that offers delayed chemical or mechanical response to high-temperature water vapor will be of interest in the ongoing critique of current reactors' responses to accident scenarios. It appears probable that thorium-uranium dioxide will offer advantages over conventional uranium dioxide in this area. But it is important to consider that the response of the fuel is, in reality, of engineering importance only if the cladding fails. If enhanced accident tolerance is the primary goal, it makes sense to first address the cladding material itself. A new cladding or modification process found to successfully protect the fuel under all envisioned scenarios would largely eliminate interest in improved fuel response.

The near-term potential of thorium fuels in existing reactors: Low

Within the confines of the thorium scenario most likely to be seen in the next decade, deployment in an open nuclear cycle driven by uranium capped at 6

percent enrichment of uranium-235, a number of the commonly promoted advantages of thorium are significantly crippled. The claim that thorium fuels are “meltdown proof” has no basis in reality, barring the design, development, and construction of completely new reactor types.

The advantages in terms of waste disposal would be minimal, at best. Use of thorium-uranium dioxide would provide a small but legitimate reduction in the inventory of transuranic elements such as neptunium, plutonium, and americium in spent fuel. These gains, however, would not meaningfully impact the radioactivity, handling procedures, or storage requirements of spent fuel. If the United States chose to change its waste disposal policies and impose a charge on utilities for their nuclear waste output based on quantity, the reduced waste production facilitated by the use of thorium in existing reactors could serve to make it more attractive as a fuel. But there is no reason to suspect that the federal government will change long-standing policy.

Spent fuel from a thorium-uranium oxide-powered nuclear plant would not have a nonproliferation advantage over currently used fuel. Thorium would not eliminate plutonium production in current reactors and would provide a second weapons-usable isotope, uranium-233, to spent fuel.¹¹

More important than arguing for or against the particular merits of the proliferation outcomes of thorium is to recognize a practical reality: Commercial entities and fuel vendors will assign minimal value to any minor differences in theoretical proliferation risks. Certainly this is an area that the government must

fully understand before deployment of thorium in existing reactors is undertaken. But from the utilities' point of view, the only legitimate driver capable of motivating pursuit of thorium is economics.

One of the historically cited benefits of a thorium cycle is the availability of fuel, given thorium's abundance relative to uranium. But this benefit is often hypothesized from a situation many decades past, when a significant expansion of nuclear energy was anticipated. The reality of the current and forecast marketplace, however, is one of stable uranium prices. Additionally, the need for a uranium-235 driver to initiate all once-through cycles will never completely free current reactors from the need for uranium.

The only other possible significant economic impact of thorium would come from extended fuel cycles. A capability to operate the reactor for longer periods of time without stopping to refuel would be viewed as a significant triumph. Studies executed to date, however, suggest that it will be exceedingly difficult for thorium introduced into existing reactors in the form of thorium-uranium dioxide pellets to meet the currently required performance metrics in cycles longer than currently used.

Thorium-uranium dioxide fuels may well contain a range of properties that make them superior to uranium dioxide. To justify further consideration for use in the current reactor fleet, however, basic property studies are needed to characterize parameters of fundamental importance to both normal operating conditions and severe accident scenarios. It may be possible to trade the current uranium dioxide fuel for

an alternative that shows improved in-reactor behavior and achieves identical reactor output at a negligible cost difference. Unfortunately, the capacity of thorium-uranium fuels to match existing reactor performance benchmarks remains uncertain, and fabricating thorium-uranium oxide fuel would require up-front development costs and qualification efforts. It seems extremely unlikely that utilities would make such an investment for the minimal payoffs discussed above.

Looking forward, policy makers and nuclear operators should not discount the possibility of translating America's nuclear infrastructure toward a full thorium fuel cycle as the existing fleet of reactors approaches the end of service. A true closed thorium cycle that incorporates full recycling of uranium-233 would provide clear benefits in the area of reduced waste generation, whether deployed in reactors using traditional solid fuels and coolants or perhaps in advanced designs that have yet to be fully developed or tested. Unfortunately, within current policy restraints, adaptation of thorium fuel for use in existing water-cooled reactors would require too great an investment and provide no clear payoff.

For thorium to hold an important role within the nuclear future of the United States, advocates must include these qualifiers. Presenting thorium as a silver bullet capable of instantly converting the nuclear industry to a melt-down-proof, waste-free power source, free from proliferation concern is not only inaccurate, but also does a significant disservice in communicating the many intricate political and economic drivers that converge to shape the

future of nuclear power generation around the globe.

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Notes

1. Proposed solutions range from the evolutionary—such as coating fuel cladding with a material resistant to high-temperature oxidation—to the truly revolutionary: particulate fuel encapsulated in silicon carbide, a change that could fundamentally alter the way in which a loss of cooling impacts nuclear reactors. The great challenge for any suggested accident-tolerant concept is to achieve high transparency from the perspective of the utility responsible for reactor operation.
2. Two overarching options exist for constructing a nuclear fuel cycle. In the first, known as an open fuel cycle, fuel is fabricated and used only once before it is removed from the reactor and stored indefinitely in a repository. The alternative is reprocessing spent fuel to reclaim usable fissile material or separate radioactive waste for more efficient storage or return to dedicated reactors for destruction. In the 1970s, partly because of India's use of plutonium from reprocessing in its first nuclear weapon test in 1974, the United States decided to pursue the first option. Not only has the United States decided to avoid reprocessing its spent fuel, it has actively discouraged the practice by other countries, for example, in South Korea. Feiveson et al. (2011) provide an extensive review of current international policies on reprocessing and plausible evolutions during the coming decade.
3. Plutonium-239 has been considered in the role of a driver for a thorium cycle as well. The typical motivation for such work, however, is consumption of weapons-grade material from stockpiles rather than electricity generation. Use of plutonium also

- engenders a range of operational concerns and technical challenges.
4. Cracking of the ceramic uranium-dioxide fuel used in existing reactors commonly occurs on a broad scale, affecting normal operation and amplifying the possibility of radioactivity release during a severe accident.
 5. Other metal alloys or ceramics containing thorium as their principal component exist and may contain favorable properties. For near-term deployment, however, it is not feasible to seek development and qualification of a completely new fuel form—a process that can take many decades.
 6. Adaptation of uranium dioxide lines for fabrication of thorium dioxide is possible. Furthermore, uncertainties regarding the performance of thorium dioxide during irradiation are also relatively small. Test irradiations executed to date provide general confidence that no unexpected material evolutions will occur during service.
 7. It is important to distinguish the rationalization for citing a 6 percent enrichment limit rather than the commonly encountered 20 percent. While it is true that reactor design studies considering an enrichment of 19.5 percent uranium-235 are consistent with meeting the “low-enriched” designation, no commercial fuel fabrication facilities are licensed to this limit. Relicensing commercial facilities to fabricate fuel containing up to 20 percent uranium-235, significantly beyond the current limits of 5 or 6 percent, would not occur without additional expense.
 8. The latter is a particularly important consideration under the constraints of a once-through fuel cycle. Uranium-233 bred from thorium in spent fuel following its removal from the reactor may be extractable and valuable under reprocessing scenarios, but in the current environment acts only to pose a possible proliferation risk.
 9. Fuel fabrication facilities would require revisions to their current licenses to allow enrichment to greater than 6 percent. It may be feasible to relicense facilities incrementally, but only following significant operator expense, thus requiring a clear and decisive payoff.
 10. This advantage is tempered by the fact that a number of other excessively damaging and dangerous processes would be encountered within the core before fuel melting occurs.
 - ii. The generation of uranium-232 from the inclusion of thorium would provide an additional radiological deterrent to strengthen the natural barriers of spent fuel to theft and proliferation. Uranium-232 is produced in small amounts in-pile from protactinium-233 neutron capture followed by the decay of two neutrons and subsequent beta decay. The proliferation enhancement attributed to uranium-232 comes from the fact that the isotope in turn decays into a long series of energetic gamma emitters. But this chain terminates at a stable isotope relatively quickly from the perspective of geologic storage of spent fuel. One of the larger concerns to stewardship of spent fuel is the barriers remaining following several hundred years’ storage. At this point, the highly radioactive fission products present initially in spent fuel and providing an appreciable radiological deterrent to proliferation have substantially decayed away. Uranium-232 and its daughter isotopes will not assuage this concern.

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