Nuclear Power Sustainability

The operating light-water reactor (LWR) fleet uses mined uranium for fuel and generates highly radioactive nuclear wastes. Both the front and the back ends of this fuel cycle have the potential for significant health and environmental impacts if not rigorously managed.

Two Primary Goals for Increasing Sustainability

One of the primary goals cited by NLWR developers is to reduce these impacts by increasing the "sustainability" of nuclear power—or, as the Department of Energy (DOE) puts it, to "extend natural resource utilization" and "reduce the burden of nuclear waste for future generations" (Petti et al. 2017). In other words, for a nuclear reactor to be more sustainable than an LWR, it should (1) use natural uranium more efficiently than LWRs, and (2) generate less nuclear waste requiring long-term disposal—or even use fuel obtained by reprocessing and "recycling" the mountain of highly radioactive nuclear waste that LWRs have already produced, more than 80,000 metric tons and counting in the United States today.

However, although these goals certainly sound worthwhile, it is not clear whether achieving them is practical or even necessary for the future of nuclear power. Two fundamental questions need to be addressed. First, to what extent would any NLWR and its associated fuel cycle be significantly more sustainable in practice than the LWR once-through cycle? And second, would those benefits be significant enough to justify the substantial investment required to develop and deploy such a reactor at a large scale? These highly complex questions depend on many variables and are very sensitive to model assumptions. While it is beyond the scope of this report to fully answer these questions, this chapter discusses key issues that must be considered.

REDUCED LEVELS OF LONG-LIVED RADIOACTIVE WASTE

Spent fuel from LWRs contains highly radioactive, long-lived isotopes that must be isolated from the environment for hundreds of thousands of years to protect public health and the environment. The only way this can plausibly be achieved it to dispose of the waste in a robust underground facility known as a geologic repository. However, most countries with nuclear plants, including the United States, have failed to open geologic repositories for spent nuclear fuel. Only Finland, with a much smaller amount of nuclear waste than the United States, is making steady progress.

Highly radioactive wastes requiring disposal in a deep geologic repository are generated by all reactors and fuel cycles. However, some advocates of reprocessing argue that, given the political difficulties and technical challenges of establishing repositories, geologic disposal space will be scarce and valuable in the future and must be conserved by reducing nuclear waste volume (Bailly 2014). A new reactor design could reduce the future waste burden if it produced less long-lived waste than an LWR while generating the same amount of electricity. Furthermore, if the reactor could efficiently use actinides extracted from existing LWR waste as new fuel—often misleadingly referred to as "burning" nuclear waste—this approach could reduce the repository space needed for the current waste stockpile.

EFFICIENT USE OF URANIUM

While reducing the amount of uranium used by nuclear reactors to generate a given amount of energy could conserve uranium resources, uranium is currently not in short supply; therefore, there is no economic driver at present for such a change. Early in the nuclear era, estimates of worldwide uranium ore were low, and the nuclear power community feared that there would not be enough uranium to fuel reactors in the future. But these estimates have risen over time, and there is little risk that the world will run out of uranium for the foreseeable future.

The latest assessment of resources by the Nuclear Energy Agency and the International Atomic Energy Agency in 2020 found that identified recoverable uranium resources would be sufficient to fuel the global nuclear reactor fleet for more than 135 years at the 2019 rate of consumption (just under 400 gigawatts of electricity) (NEA 2020). Better recovery methods could make available up an additional 40 years' worth of consumption. Thus, even if nuclear energy generation worldwide were to double over the next few decades—more than the projected 80 increase in the International Atomic Energy Agency's current "high case" scenario for growth by 2050—identified resources would likely be adequate until the end of the century. In addition, sources of uranium that are believed to exist but remain undiscovered are estimated to be nearly as great the currently identified resources (NEA 2020). And ultimately, the world's oceans, which contain a vast quantity of uranium at a low concentration, serve as a backstop to any supply shortage. Although the cost of uranium will increase as more readily exploitable resources are depleted, that should be compared to the additional costs and risks associated with developing and operating new reactor types that are more uranium-efficient.

However, resource depletion is not the only concern associated with uranium consumption. Uranium mining is dangerous for workers and pollutes soil, air, and groundwater. Uranium mining is less widespread in the United States today than in the past, but over time it has left thousands of abandoned mines and dozens of uranium processing sites that require cleanup, many of which are located within the Navajo Nation and continue to have a disproportionate impact on the Navajo people. Moreover, uranium waste dumps and mines emit carcinogenic radon gas decay products that pose health risks to both miners and individuals living downwind. More modern mining and processing methods, although less damaging than historical practices, can also harm public health and the environment if not implemented with the most rigorous standards and oversight.

Reactors that use uranium more efficiently could have health and environmental benefits by reducing the need for mining. However, the benefits from reducing uranium mining activities would have to be balanced against the increased environmental risks of more uranium-efficient reactors and their fuel cycles. Increasing uranium efficiency usually entails reprocessing spent fuel, which generates a number of different radioactive waste streams and emits radioactive gases into the atmosphere—many with wide-reaching health and environmental impacts themselves.

To maximize the utilization of natural uranium, NLWRs would have to be capable of effectively using depleted uranium—the leftover material produced during enrichment—as fuel. Depleted uranium has a U-235 content of 0.3 percent or below. Only a small fraction of mined natural uranium ends up in the enriched uranium fuel used in LWRs; the depleted uranium "tails" of the process are stored as waste requiring disposal. The production of one year's supply of enriched uranium for a typical LWR—20 metric tons—generates about 180 metric tons of depleted uranium. This material has accumulated as waste in the United States and most other countries because it is not economical today to re-enrich it for use as LWR fuel. The DOE now holds more than 500,000 metric tons of uranium tails in the form of uranium hexafluoride gas, requiring hundreds of football fields' worth of storage space. Although this material poses a relatively low radiological hazard in storage, it will likely require disposal in a deep geologic repository in the long term, but there is no clear disposition path at present.

The Challenging and Conflicting Goals of Sustainability

Many NLWR developers argue that their systems will achieve breakthroughs in improving nuclear power sustainability. A good example is the Argonne National Laboratory, a DOE facility, which has been developing sodium-cooled fast reactor technology (see chapter 1) and an associated fuel reprocessing system (known as pyroprocessing) for decades. In a 2012 brochure, ANL claimed that its pyroprocessing technology, used in conjunction with fast reactors, would turn nuclear waste into a "wonderfuel" (ANL 2018).

Specifically, Argonne National Laboratory asserts that its fast reactor and pyroprocessing system would:

- "allow 100 times more of the energy in uranium ore to be used to produce electricity compared to current commercial reactors"
- "ensure almost inexhaustible supplies of low-cost uranium resources"

- “markedly reduce the amount of waste and the time it must be isolated—from approximately 300,000 to approximately 300 years—by recycling all actinides” (ANL 2018)

The first two bullets refer to increasing uranium efficiency and the third to reducing the waste disposal burden.

While this reactor system certainly sounds promising, this study finds that these claims are highly misleading. First, it is important to note that these two aspects of sustainability—significantly reducing the quantity of TRU elements (primarily neptunium, plutonium, americium, and curium) contained in nuclear waste and significantly increasing uranium utilization efficiency—cannot be *simultaneously* achieved with the same reactor and fuel cycle system. The two goals are technically incompatible. This is because a nuclear reactor can only extract energy from a fixed amount of fissionable material per year, which depends on its power level. If the energy is produced by the fission of a TRU element that comes from nuclear waste, it cannot be produced by the fission of new fissionable materials generated from depleted uranium.

To significantly reduce the high-level waste disposal burden, the reactor system would be designed to prioritize the fission of long-lived TRU isotopes extracted from nuclear waste—thus, most of the energy it produces would result from TRU fission. That is, the TRU contained in the LWR spent fuel stockpile would be the primary makeup source of fissionable material for fresh fuel. On the other hand, to significantly increase the efficiency of uranium utilization, as discussed above, a reactor system must produce most of its energy by converting the U-238 in the depleted uranium to plutonium and then fissioning the plutonium. In this case, the depleted uranium stockpile would be the primary source of fresh fuel. But because the amount of energy produced per year in a reactor is constant, it cannot effectively use the existing stockpile of TRU in nuclear waste and the existing stockpile of depleted uranium at the same time.

Moreover, while attaining either sustainability goal individually may be achievable on paper, neither can be attained in practice over a reasonable time scale, as both would require a level of system performance far beyond what nuclear facilities are capable of today or are likely to achieve in the foreseeable future. In order to make good decisions regarding the development of reactors systems with greater sustainability, it is critical that expectations for their real-world performance be distinguished from their theoretical performance in an ideal world.

High-Level Waste Reduction

The United States has a nuclear waste problem—as do almost all other nations with nuclear power plants. Today, no country has a geologic repository ready to accept spent fuel or high-level waste, and only Finland is constructing one for a nuclear power sector much smaller than that of the United States or other larger countries. While the United States does operate an underground repository—the Waste Isolation Pilot Plant in New Mexico—the facility accepts only TRU-containing wastes from military activities. It is legally prohibited from accepting spent fuel or high-level radioactive waste.

Decades ago, the United States decided as a matter of policy to dispose of its spent fuel and high-level waste in a deep underground mined repository. However, for political, technical, and legal reasons, it has not yet been able to successfully build such a repository. It officially chose Yucca Mountain in Nevada as the repository site in 2002, and the DOE applied to the Nuclear Regulatory Commission for a construction license in 2008. Two years later, the DOE withdrew its application, stating that Yucca Mountain was not workable. Although early in former President Donald Trump’s tenure the DOE attempted to provide funds to restart Yucca Mountain project licensing at the Nuclear Regulatory Commission, the requests were rebuffed by Congress. In its budget request for fiscal year 2021, the DOE did not seek funding to move Yucca Mountain forward.

Nevertheless, the site remains the only one in the United States designated by law for geologic disposal of spent nuclear fuel. In order to prevent the disposal burden from being imposed on only one state, the law currently limits the capacity of Yucca Mountain to 70,000 metric tons heavy metal (MTHM) of waste. The US stockpile of waste has already exceeded this limit—as of mid-2017, US commercial reactor sites stored nearly 80,000 MTHM of spent fuel (GAO 2019). Subsequently, the reactor fleet has added about 2,000 MTHM of waste per year to this stockpile.

However, the physical capacity of Yucca Mountain is four to nine times greater than maximum amount of waste it is legally allowed to store (Maden 2009). If the statutory limit were relaxed or eliminated, the United States might not need a second repository for centuries. A bill passed by the House of Representatives in May 2018 would increase the capacity to 110,000 MTHM, and the bill was introduced in both houses of Congress in the 2019-2020 session, but no votes were taken by either house.

CONSUMING NUCLEAR WASTE: THE HOPES AND CLAIMS

Given the lack of progress on spent fuel disposal, the notion that "advanced" nuclear reactors could consume existing nuclear waste is a very compelling idea to the public and to many policymakers. For example, Senator Sheldon Whitehouse (D-RI), in a floor speech in February 2016, referred to "advanced reactors that could actually consume spent fuel from conventional reactors and help us draw down our nuclear waste stockpile" as "the Holy Grail" (Whitehouse 2016).

Senator Whitehouse should not be faulted for his enthusiasm—many credible nuclear experts make assertions that NLWRs could essentially eliminate nuclear waste. For instance, the American Nuclear Society's statement "Fast Reactor Technology: A Path to Long-Term Energy Sustainability" states that for a fuel cycle with fast reactors and reprocessing, "virtually all long-lived heavy elements are eliminated during fast reactor operation, leaving a small amount of fission product waste that requires assured isolation from the environment for less than 500 years" (ANS 2005). This statement is echoed by a number of NLWR developers who say that their designs could "consume," "burn," or "recycle" spent fuel from LWRs. These include not only liquid metal–cooled fast reactors, but also gas-cooled reactors and molten salt reactors. One example—Argonne National Laboratory—has been cited above. Other examples follow.

OKLO, INC.'S FAST MICROREACTOR

Jacob DeWitte, co-founder of Oklo, Inc, testified before Congress that the company's 4 megawatt-thermal fast microreactor, now called the Aurora and under licensing review by the NRC, "can consume the used fuel from today's reactors" (DeWitte 2016).

GENERAL ATOMICS' ENERGY MULTIPLIER MODULE

General Atomics has been developing a high-temperature gas–cooled fast reactor—the Energy Multiplier Module (EM^2), with a power output of 265 megawatts-electric (MWe). According to General Atomics, "deployed in sufficient numbers, EM2 is capable of substantially reducing pressures for long-term storage and turning our waste stockpile into an important energy resource" (GA 2019).

SEABORG TECHNOLOGIES' COMPACT MSR

Seaborg Technologies, a Denmark-based company is developing a thorium MSR that it has also referred to as a "waste-burner" (Seaborg Technologies 2015). The company says that "realizing the waste burning potential is part of Seaborg's mission to make nuclear truly sustainable" (Seaborg Technologies n.d.).

TRANSATOMIC POWER'S WASTE-ANNIHILATING MSR

Another MSR startup, Transatomic Power had claimed that its reactor could consume nuclear waste as fuel. However, after errors were discovered in its analyses, it had to backtrack on the claim and lost credibility before shutting down in September 2018 (see chapter 7).

CONSUMING NUCLEAR WASTE: THE REALITY

The story of Transatomic Power is a cautionary tale for other NLWR developers who overstate the nuclear waste burning capabilities of their reactor systems. Unfortunately, as discussed below, it is virtually impossible to completely eliminate or even significantly reduce nuclear waste by using it as fuel in any real reactor system. Therefore, the United States will need a deep geologic repository for nuclear waste regardless of the types of reactors it uses in the future.

What most NLWR developers actually mean by "consuming" nuclear waste is using some of the components of spent fuel—namely, plutonium and other fissionable TRU isotopes—as fresh fuel in their reactors. These isotopes have half-lives from hundreds to millions of years. When they undergo fission, they primarily yield shorter-lived fission products such as cesium-137, with a half-life of 30 years. A process that could completely fission these long-lived TRU isotopes would greatly reduce the time the remaining waste would need to be isolated from the environment—but not enough to obviate the need for a geologic repository. For example, although cesium-137 would remain dangerous for only 300 years, instead of the 240,000 years needed for plutonium-239, geologic disposal would still be necessary, since one cannot assume that current institutions will remain viable and able to safely manage an interim surface storage facility for even that period of time.

But the long-lived TRU is only part of the problem. LWR spent fuel also contains long-lived fission products, such as iodine-129 (half-life: 15.7 million years), and technetium-99 (half-life: 211,000 years) that cannot be fissioned. For decades, elaborate schemes have been devised to attempt to separate such fission products and transmute them to stable isotopes, but none has been implemented. Even if ultimately successful, the cost and difficulty would be formidable (Chiba et al. 2017). These fission products would also need to be geologically isolated in a deep underground repository for as long as some TRU isotopes.

And in any event, it would not be practical for any real-world system to effectively reduce the entire inventory of TRU to the extent necessary to eliminate or even greatly diminish the need for long-term deep geologic repositories, contrary to the American Nuclear Society and Argonne

National Laboratory claims cited above. Notably, it is impossible to eliminate all the TRU in spent fuel—some fraction will inevitably end up in the waste stream and will require hundreds of thousands of years of geologic isolation. Nevertheless, if a system could reduce the quantity of TRU by a significant fraction—say, by 99 percent or more—this might enable a repository to meet less stringent safety criteria, reducing the cost and increasing the number of technically suitable sites. The process would also reduce the decay heat of the remaining waste in the long term. Depending on repository characteristics, this long-term heat reduction could potentially allow waste to be packed more densely in a repository, reducing the disposal space required per unit of electricity generated. (For the Yucca Mountain repository, in order to realize this benefit, the shorter-half-life elements cesium-137 and strontium-90 would also have to extracted from the waste and stored above ground for 300 years—a questionable assumption, as discussed above.)

But if the amount of TRU that is ultimately left over is too large, then the benefits for repository disposal would not be great enough to justify the cost and security risks of reprocessing and recycling TRU. As discussed below, although the amount of TRU lost to waste streams is a critical factor, one also must consider the total TRU amount remaining in the system—including the reactor cores, fuel cycle facilities, and storage sites. If the system shuts down in the future, all of the remaining material would also need to be disposed of in a repository. But as shown below, the system would need to operate for hundreds or even thousands of years to reduce the total TRU inventory significantly. The present generation cannot guarantee that future generations will continue to operate, repair, and replace these systems for the length of time needed to achieve the necessary TRU reduction goal. If a reactor technology cannot significantly reduce the total TRU inventory in the system within a generation or two, future generations would still be stuck with a large stockpile of TRU—a situation only slightly better than the one that exists now.

INTERGENERATIONAL EQUITY

In addition to being impractical, a nuclear waste management strategy obligating future generations to maintain and operate a TRU burning system is inconsistent with the "intergenerational equity" principle. According to this principle, "those who generate the wastes should take responsibility, and provide the resources, for the management of these materials in a way which will not impose undue burdens on future generations," and "a waste management strategy should not be based on a presumption of a stable societal structure for the indefinite future, nor of technological advance; rather it should aim at bequeathing a passively safe situation which places no reliance on active institutional controls" (NEA 1995).

A robust geologic repository capable of containing waste for tens of thousands of years without the need for active controls and monitoring (beyond a reasonable period of retrievability) is arguably consistent with intergenerational equity. But a system requiring hundreds or thousands of years of costly and complex human activities to achieve its goals is clearly not. Our generation would bequeath to the future the obligation of maintaining and operating the system, without regard to cost and risk burdens. A TRU-burning system could only be consistent with intergenerational equity if it achieved its waste reduction goals within a few generations. The analyses discussed below show that even 120 years would not be sufficient.

SPENT FUEL "BURNING" REQUIRES REPROCESSING

It is also critical to realize that the term "waste burning" is an oversimplification that fails to convey the difficulty, cost, and risks of the industrial processes needed to extract re-usable materials from spent fuel and fabricate them into fresh fuel (see Box 3, p. 37).

BURNING THE TRANSURANIC ELEMENTS (TRU) IN NUCLEAR WASTE

Although complete destruction of radioactive waste is not possible, a key question is whether the TRU in nuclear waste can be reduced deeply and rapidly enough to significantly reduce the need for deep underground repositories. Typically, one of the limiting factors in a geologic repository is the heat load of high-level waste, and the precise limits for a given repository will depend on its geochemical characteristics and design. The TRU is the primary heat source in the waste after several hundred years, so a reduction in the TRU content of high-level waste is a necessary (but not sufficient) condition to pack more waste in a given repository volume. Another limiting factor is the long-term environmental contamination that will occur when a repository starts leaking radioactive material far in the future (because any repository will eventually leak over time). If more waste is packed into the same repository space, dose rates would increase and potentially exceed regulatory limits for public exposure, depending on the nature of the repository and many other factors.

To address this question, one must define what constitutes a "significant" reduction in TRU by a waste-burning system relative to LWRs operating on a once-through cycle. Analysts have used different standards over the decades, ranging from a reduction in total TRU mass by a factor of more than 1000 to as low as a factor of 10 (see Box 4, p. 38).

Unfortunately, even using the least stringent reduction factor of 10, which was adopted by the DOE in a 2009 study, it would take a very long time for TRU-burning systems in practice to have a meaningful impact on repository requirements (see Box 4, p. 38). This general result has been confirmed by many studies of fuel cycle systems, including a seminal National Academy of Sciences study (NAS 1996). In the appendix to this report, simple models are provided to illustrate this important finding.

WHAT LEVEL OF WASTE REDUCTION IS POSSIBLE?

In any real-world spent fuel reprocessing and recycling system, there are two primary sources of TRU-containing radioactive waste. First, there are process losses. Every time spent fuel from a reactor is reprocessed and refabricated into new fuel, a certain quantity of plutonium and other TRU end up in the waste streams. One can reduce that amount to very low levels, but that increases cost. Over time the mass of TRU that end up in unrecoverable waste streams can become significant, even if the waste from any one cycle is very small.

The second source is TRU within the system that remains unfissioned for practical reasons. Many analyses of the waste reduction benefits of reprocessing and recycling only account for the material entering and leaving the system; they ignore the nuclear material within the system. This is a huge oversight. There will always be TRU within a nuclear power system at any one time—in reactor cores, fuel fabrication plants, reprocessing plants, and interim storage facilities. However, unless one assumes that future generations will continue to operate the system (and replace old facilities) forever, eventually it will have to shut down, rendering unused fuel materials as radioactive wastes requiring geologic disposal. These materials need to be counted when estimating the overall reduction in TRU that the system can achieve. This observation was a key insight of the National Academy of Sciences study on separations and transmutation of nuclear wastes (NAS 1996).

The National Academy of Sciences evaluated the TRU reduction performance of a number of burner reactors and associated closed fuel cycles. The study found that if all the TRU in both wastes and operating facilities are considered, these systems will have to operate for an impractically long time—centuries or even millennia—to achieve a 100-fold reduction in the total mass of TRU.

These results have been confirmed by many other detailed systems analyses. A 2009 study by the Electric Power Research Institute and Electricité de France assessed the impact of phasing in a fast reactor system operating together with LWRs (35 percent fast reactors and 65 percent LWRs), while keeping the total US nuclear generating capacity

continued on p. 38

BOX 3.

Reprocessing and Recycling: Turning Spent Fuel into Fresh Fuel

By definition, spent fuel is discharged from a nuclear reactor when it can no longer be used as fuel in its current form. There are several reasons a nuclear fuel rod has a limited lifetime when irradiated in a reactor. The concentration of fissile material in the fuel decreases while the quantity of neutron-absorbing fission products increases—to the point when the fuel rod is unable to sustain a nuclear chain reaction. Irradiation increases the pressure inside the fuel rods (due to the generation of gaseous fission products) and decreases the strength of the metallic cladding surrounding the fuel rods until the rods are at high risk of rupture. A point is reached when it is no longer safe or productive to continue to irradiate the fuel rod.

What would it entail to use the spent fuel from LWRs as fuel for a new reactor? No reactor concept today can safely use spent fuel directly as new fuel. Instead, the spent fuel would have to undergo some type of processing—referred to as reprocessing—before it can be turned into fresh fuel.

First, mechanical and chemical processing would be needed to separate to some degree the fissile components of the fuel, such as plutonium and other actinides, from other spent fuel constituents. This can be an aqueous process, in which the spent fuel is dissolved in an acidic solution, or a non-aqueous process, such as conversion to metal (reduction) and electrometallurgical treatment (pyroprocessing). As discussed in chapter 4, reprocessing is costly, requiring the use of shielded facilities and remote handling equipment. It is environmentally hazardous. And most importantly, it increases the risk of nuclear proliferation and makes bomb-usable material easier for terrorists to steal.

After the spent fuel has been reprocessed to remove all the unusable or problematic isotopes, fresh fuel will have to be fabricated, with the new fuel form determined by the requirements of the type of reactor that will use it. Whether this process entails the fabrication of solid fuel or liquid fuel, it provides opportunities for diversion or theft of weapon-usable nuclear materials and therefore must be subject to stringent safeguards and security.

BOX 4.

What Level of Transuranic Reduction in Radioactive Waste Would Make a Real Difference?

A comprehensive 1996 report by the National Academy of Sciences concluded that in order to "have a significant effect" on the total mass of TRU that would require geologic disposal, "an entire system of many facilities would be needed in which all the components operate with high reliability in a synchronized fashion for many decades or centuries.... The magnitude of the concerted effort and the institutional complexity ... are comparable to large military initiatives that endure for much shorter periods than would be required" (NAS 1996). This report estimated in 1996 that the cost of such a system would be at least $500 billion (or more than $800 billion in 2020 dollars).

How great a reduction in the TRU inventory could justify the substantial expense of building and operating such a system over the decades or centuries that would be required? The National Academy of Sciences study pointed out that performance standards "changed markedly in recent years and have not been clearly defined," but that the expectation of the DOE Advanced Liquid Metal Reactor Program in the early 1990s was a "thousand-fold reduction in the quantity of actinide waste going to a geologic repository" (NAS 1996). The study itself did not adopt a specific performance standard but implied that the authoring committee considered a 100-fold reduction as "significant" (NAS 1996).

In 2005, the DOE adopted the objective of achieving a 100-fold reduction in the quantity of TRU requiring disposal as one of the programmatic goals for its Advanced Fuel Cycle Initiative, which sought to develop a spent fuel reprocessing and recycling infrastructure in the United States (Piet et al. 2011). The DOE observed that such a reduction would delay the need for a second geologic repository until the end of the 21st century while allowing for significant nuclear power growth.

In a more recent evaluation of fuel cycle options, DOE scientists used a less stringent criterion—an order of magnitude (factor of 10) or more—to define "significant improvements" in nuclear waste management and other nuclear power metrics relative to the LWR once-through cycle, including repository decay heat load (Wigeland et al. 2009). Their logic was that "significant benefits" should be those "resulting in an improvement that is clearly larger than the uncertainties . . . typically an order of magnitude or greater" (Wigeland et al. 2010).

While it is difficult to define an objective standard because these assessments are so complex and uncertain, the present report will reference the DOE factor of 10 as the standard for a significant reduction in TRU. However, this standard is questionable, given that the analyses used to calculate the actual TRU reduction in a given system have large uncertainties and are highly sensitive to various assumptions. For example, one study finds that the estimated increase in Yucca Mountain repository capacity gained from reprocessing and TRU recycling (which is a function of the TRU reduction factor) would decrease by a factor of 50 as the assumed separation efficiency of TRU and fission products from waste decreases from 99.99 percent to a more realistic 99.0 percent (Wigeland et al. 2006). Thus, it is not apparent that a calculated improvement of a factor of 10 would be "clearly larger than the uncertainties."

Moreover, it is not clear that a TRU reduction factor of 100 or even 1000 would be sufficient to meet waste disposal objectives. The original goal of the DOE's Advanced Liquid Metal Reactor Program was to reduce the quantity of TRU elements in a repository to below the release limits stipulated by 40 CFR 191, the Environmental Protection Agency rule for geologic repositories (other than Yucca Mountain), which would require a reduction in plutonium-239 by a factor of more than 3000 (NAS 1996). In the realm of hazardous waste disposal, the standard for effective destruction of toxics is even higher. For example, a factor of one million (a 99.9999 percent reduction) is used by the Environmental Protection Agency as a standard for the destruction of dioxin, a long-lived and highly hazardous substance. No TRU reduction scheme is capable of achieving such a dramatic goal, no matter how long the system is operated.

Lastly, transmutation is not the only means of achieving an increase in the capacity of a repository. For example, it has been estimated that the long-term decay heat reduction from a 1000-fold reduction in the TRU mass in high-level waste would allow only a five-fold increase in Yucca Mountain capacity unless cesium-137 and strontium-90 are removed for above-ground storage (Wigeland et al. 2006). Given that the physical capacity of Yucca Mountain may be as great as nine times the current legal capacity (and assuming that the project is still viable), changing the law would be far cheaper than developing a TRU-burning system but would have an immediate impact on the quantity of waste that could be buried there.

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constant (Machiels, Massara, and Garzenne 2009). The study found that the system would have to operate for 70 years to reduce the total TRU mass in the system by just a factor of two relative to the once-through cycle used by LWRs. To reduce the TRU mass by a factor of 10 would require continuous operation for 632 years.

It is clear from these estimates why a 2009 DOE study concluded that (assuming a factor-of-10 standard for significance) “continuous recycle appears to be the only practical fuel cycle strategy that can significantly affect waste management issues for [used nuclear fuel] and [high-level waste], but only if all of the TRU is recycled, leaving only fission products and residual amounts of TRU in the [high-level waste]” (Wigeland et al. 2009). Any leftover spent fuel would count against the system’s overall capability for TRU reduction. Or, as an Idaho National Laboratory article in 2011 simply put it, “significant material accumulates throughout the system during recycling; thus achievement of high waste management benefits depends on continuation of recycling. Do not stop!” (Piet et al. 2011). Therefore, the system would have to operate forever. Such an exhortation is clearly inconsistent with the intergenerational equity principle.

The basis for these conclusions can be illustrated through relatively simple models. In the appendix to this report, examples are provided that demonstrate why it takes so long for a fast reactor system to burn up a significant fraction of its TRU fuel. Using optimistic performance assumptions, a fast neutron reactor operating as a TRU burner for 120 years would only reduce the total amount of TRU in the system by a factor of around eight—below the DOE’s factor-of-10 standard for a significant reduction.

In summary, while the idea of burning nuclear waste sounds appealing on the surface, such burning cannot be done quickly or efficiently enough to be an effective waste management strategy. The marginal benefits of developing and deploying systems for TRU burning do not justify taking on the proliferation, security, and safety risks of reprocessing and recycling spent fuel.

Uranium Utilization Efficiency

LWRs that are operated on a once-through cycle use only about 0.6 percent of the uranium mined for their fuel for energy. The remainder—more than 99 percent—is contained in the reactor’s spent fuel (around 10 percent) and the depleted uranium produced by enriching natural uranium for reactor fuel (just under 90 percent).

Some argue that the LWR once-through cycle is inefficient and wasteful, and should be replaced by fast breeder reactors and a closed fuel cycle with reprocessing (Lynas 2011). They claim that this unsustainable use of uranium will eventually deplete the resource.

This argument has been cited by the International Atomic Energy Agency. In June 2018, then-director general of the agency, the late Yukiya Amano, said that although “identified uranium resources are sufficient for well over 100 years of supply . . . the current over-supply may not last forever. It is therefore important that this vital resource is mined, produced, and managed sustainably.” He pointed to “promising work . . . underway on new generations of nuclear power reactors that require less uranium” (Amano 2018). Along the same lines, in a 2014 study, DOE researchers adopted the following objective for improved natural resource utilization in nuclear fuel cycles: “on a per unit energy basis, [a] reduction in the amount of fuel resources needed by a factor of 100 or more” compared to the once-through LWR fuel cycle (Wigeland et al. 2014).

But is it really critical for the future of nuclear power to develop fuel cycles that use less uranium? The cost of uranium is only a small component of the cost of electricity to begin with (WNA 2020). And the world is not in danger of running out of uranium any time soon, even if nuclear power expands according to the most recent IAEA “high case” projections, and uranium remains so cheap that there is no economic incentive to use it more efficiently. The up-front capital investment needed to build a fast breeder reactor system and associated fuel cycle facilities would be substantial, but significant benefits to a nuclear utility’s bottom line would not be realized until the price of uranium is far higher than it is today, which is likely to be a long time from now (see chapter 5).

Nevertheless, as discussed above, conserving natural resources could be a worthwhile goal even if not warranted by current market conditions. And there are other benefits to using uranium more efficiently. Doing so would reduce the need for uranium mining, which is dangerous for workers and pollutes the environment, and would perhaps even reduce the demand for enrichment, a proliferation-sensitive part of the nuclear fuel cycle. However, the safety and proliferation risks of uranium mining and enrichment could also be reduced by more stringent regulatory controls and nuclear material safeguards—which would likely be less costly than developing and deploying more uranium-efficient reactors.

Thus, developing advanced reactors and fuel cycles that use uranium more efficiently is not essential for nuclear power’s future, but could be beneficial, provided they do not increase proliferation, terrorism, and safety risks and are cost-effective compared to alternatives for reducing the impacts of uranium mining.

IMPROVING URANIUM UTILIZATION

The uranium utilization efficiency of a reactor is generally defined as the ratio of the amount of heavy metal (e.g., uranium or plutonium) that undergoes fission (and hence releases energy) over the reactor's lifetime to the mass of natural uranium that was used to produce all the reactor's fuel. The amount of heavy metal fissioned includes both the direct fission of uranium isotopes (primarily U-235) and the fission of plutonium and other TRU produced through neutron absorption by U-238 and heavier nuclei. Since there is a very low probability that U-238, the major component of natural uranium, will undergo fission, to use natural uranium most efficiently, a reactor and fuel cycle system must convert as much U-238 to plutonium as possible and then fission as much of that plutonium as possible to release energy.

To calculate uranium utilization efficiency correctly, it is necessary to account for the entire amount of natural uranium used to produce all the fuel a reactor will need over its lifetime. This includes not only fuel that is periodically fed into the reactor when it reaches steady-state operation, but also the fuel for the startup core and for the intermediate cycles during the transition to steady-state operation. The latter contribution is particularly important for some reactor systems that can take many years or even many decades to reach a steady state. The uranium utilization efficiency is then defined as the total amount of heavy metal fissioned over the lifetime of the reactor divided by the total amount of natural uranium required (Yu et al. 2019). Also if a reactor uses thorium fuel, as do some NLWRs discussed in the present report, then the amount of natural thorium required should also be included. In that case, the parameter of interest is the "natural resource" utilization.

There are two reasons why the uranium utilization efficiency of current LWRs is so low. First, as discussed in chapter 2, the amount of heat energy that can be extracted from a given mass of fuel (the burnup) is limited. Second, the enrichment process results in the generation of a large stockpile of depleted uranium that is not usable as LWR fuel (and is thus a waste product) unless it is enriched, which is not economical as long as the uranium price remains low.

One reason why the burnup of fuel in LWRs is limited is that the proportion of fissile isotopes decreases as the fuel is irradiated. An insufficient quantity of new fissile isotopes, such as plutonium-239, are generated to compensate for the reduction in the quantity of U-235 in the fresh fuel that is fissioned.

As discussed above, spent fuel discharged from an LWR at a typical burnup of around 50,000 megawatt-days of thermal energy per ton of heavy metal has a U-235 content of less than 1 percent by weight and a total plutonium content of just over 1 percent by weight. The spent fuel also contains about 0.1 percent of other TRU, such as americium-241. The balance, around 93 percent, is almost entirely U-238. This means that 95 percent of the remaining heavy metal in the fuel (primarily U-238, U-235, and plutonium) was not used to produce energy and is contained in the waste. In addition, the leftover U-238 in spent fuel is only a fraction of the unused U-238 in the LWR fuel cycle. When natural uranium is enriched in the U-235 isotope for producing LWR fuel, a large stockpile of depleted uranium (containing greater than 99.7 percent U-238) is created, which is typically discarded as waste. A typical 1000 MWe LWR operating at 90 percent capacity and an 18-month refueling cycle requires around 20 metric tons of LEU fuel each year (at 4.5 percent U-235). About 180 metric tons of natural uranium would be enriched to produce this fuel annually. This reactor would fission a little more than one metric ton of heavy metal per year. The uranium utilization is therefore about 1 metric ton/180 metric tons = 0.6 percent.

However, this refueling strategy, which is typical for US LWRs today, is not optimized for efficient uranium use, but instead for maximizing the capacity factor by increasing burnup. Higher burnup fuel can be used for a longer time, increasing the cycle length and decreasing the average outage time for refueling between cycles. The same LWR in the previous example could operate on a yearly refueling cycle with a smaller required uranium enrichment (3.3 percent U-235) and fuel burnup. This refueling strategy would use only about 160 metric tons of natural uranium feed to generate the same amount of energy, increasing the uranium utilization by about 10 percent.

This example illustrates an important fact: uranium utilization is not necessarily improved if burnup is increased only through using higher enrichment fuels, because more depleted uranium will also be generated. This is why high-temperature gas–cooled reactors do not use uranium more efficiently than LWRs even though their fuel can achieve higher burnups than LWR fuel (see chapter 6). This is also true for conventional sodium-cooled fast reactors such as the TerraPower Natrium (see chapter 5).

How then can a fast reactor extract 100 times the amount of energy from a given quantity of uranium ore as an LWR does, as Argonne National Laboratory claims? This is only possible for a fast reactor operating in a breeding mode in a closed fuel cycle with reprocessing. Recall that the quantity of uranium and plutonium in LWR spent fuel comprises only about 10 percent of the mass of uranium mined to produce the fuel, while the remaining 90 percent is primarily bound up in depleted uranium tails. To achieve a 100-fold increase in efficiency—that is, a uranium utilization of 60 percent—the reactors not only would have to fission all of the uranium and plutonium in LWR spent fuel, but also would have to convert 50 percent of the depleted uranium generated to produce the LWR fuel into plutonium and fission it completely. As shown below, this is a formidable task in practice.

THE FAST BREEDER FUEL CYCLE

The goal of the breeder reactor fuel cycle is to maximize natural uranium utilization by converting as much U-238 to plutonium as possible. However, to fully utilize the U-238 in LWR spent fuel in a fast reactor, it must be separated from the spent fuel through reprocessing, fashioned into targets (known as blankets), loaded into the reactor, and bombarded with neutrons. The depleted uranium tails also must be processed and fabricated into blanket fuel, but do not require reprocessing because the material is not irradiated.

Since the blanket material alone cannot sustain a chain reaction, the fast reactor must also be loaded with driver fuel. The preferred fissile fuel for a fast breeder reactor is plutonium, which can be obtained from reprocessing LWR spent fuel. Plutonium fission produces more extra neutrons in a fast spectrum that can be used to convert U-238 to additional plutonium. It is theoretically possible to breed more plutonium (and other TRU) in a fast reactor cycle than are consumed through fission (hence the name "breeder reactor"). The excess TRU generated by a breeder could be used as startup fuel for a new reactor.

The plutonium and other TRU bred in the blankets, as well as leftover uranium, would then be separated by reprocessing and used to fabricate fresh fuel. More blankets would then be loaded into the core and the process repeated. However, the process would not become self-sustaining until the system had reached a steady state, which could take several operating cycles.

Before a fast breeder reactor system becomes self-sustaining, it would need an external supply of plutonium obtained by reprocessing LWR spent fuel. But the process of enriching the fresh fuel needed for the LWRs generates a huge stockpile of depleted uranium. This stockpile must be accounted for in assessing the true uranium utilization efficiency of the system.

URANIUM UTILIZATION EFFICIENCY OF THE FAST BREEDER SYSTEM

In theory, the fast breeder system could achieve 100 percent uranium utilization efficiency, but only if the spent driver and blanket fuel from the fast reactor were repeatedly reprocessed; all of the recovered uranium, plutonium, and other TRU was recycled; and all of the U-238 contained in the original ore were converted to fissionable material that is fissioned to produce energy. (In practice, as with burner reactor cycles, the unavoidable process losses—TRU that is discharged to the waste stream without being converted to energy—provide an upper bound to the utilization efficiency.)

However, using the model given in the appendix, one can show that it would take a very long time for a breeder reactor to convert a large fraction of the initial stockpile of depleted uranium to plutonium and utilize it to generate energy. Since the reactor would require only a small amount of the depleted uranium stockpile each year, the system of reactors and fuel cycle facilities could only utilize the entire quantity if they were rebuilt periodically and operated continuously for thousands of years.

According to the model (see appendix), 14,750 metric tons of natural uranium would have to be mined and enriched to fuel the LWRs needed to produce the plutonium for the initial cores of a 1000 MWe fast breeder reactor. At steady-state, the system would only require an input of 1.1 metric tons of depleted uranium each year. At this rate, the depleted uranium stockpile could fuel this fast reactor for nearly 12,000 years. At first glance, this seems like an amazing resource. And since the 1000 MWe reactor (operating at an 85 percent capacity factor) would fission about 0.8 metric ton of heavy metal per year, it would appear that the reactor's uranium utilization efficiency is about 80 percent (0.8 metric tons of fission/1.1 metric tons of uranium).

However, it should be clear now that this is a misleading picture. According to the definition of uranium utilization efficiency presented above (Yu et al. 2019), the total amount of mined uranium used to produce the plutonium fuel for the fast breeder reactor over its lifetime must also be included. Using this definition, uranium utilization efficiency of the 1000 MWe PRISM fast breeder reactor operated for a 60-year period at 85 percent capacity would be about 50 metric tons of fissioned heavy metal/14,750 metric tons of natural uranium, or 0.34 percent—even less than that of an LWR. The annual uranium utilization would be less than 0.006 percent. For a breeder reactor to achieve a uranium utilization efficiency of 60 percent as claimed by Argonne—a 100-fold increase in efficiency of uranium use over LWRs—future generations would have to continue to operate, maintain, and replace fast breeder reactors and their associated fuel cycle facilities for thousands of years (around 11,000 years in the above example).

This is similar to the example for a TRU burner fuel cycle discussed earlier, which would also require hundreds or thousands of years to achieve its performance goal. But if a future generation were to decide not to continue to building and operating breeder reactors, then the remaining depleted uranium stockpile would not be utilized. Instead of a resource, it once again would be rendered a waste product.

Analyses of more detailed models confirm that the actual uranium utilization rate during a transition to a fast-breeder based reactor system would be far below 100 percent for hundreds of years. Department of Energy researchers have shown that when dynamic considerations are taken into account, such as the time lag required for spent fuel to be cooled, reprocessed, and refabricated into fresh fuel, the rate at which fast reactors can replace LWRs is significantly lower than indicated through static calculations (Piet et al. 2011). Consequently, even for the highest breeding ratio fast reactor considered (BR=1.75), the uranium utilization of the system would be at best no more than twice that of the LWR once-through cycle (1.2 percent) by the year 2100 and only 10 times more (6 percent) by 2200 (Piet et al. 2013). This assumed, optimistically, that all fast-reactor fuel would be reprocessed and recycled on site within a two-year period. For a more realistic 11-year lag period, the analysis found that the uranium utilization efficiency would only be 1.3 and 1.9 times more than the once-through cycle by 2100 and 2200, respectively. When process losses of uranium and other actinides to waste from reprocessing and fuel fabrication are taken into account, the closed fuel cycle becomes even less uranium-efficient.

BURNERS ARE NOT GOOD BREEDERS, AND VICE VERSA: THE DIFFICULTY OF MEETING BOTH SUSTAINABILITY GOALS SIMULTANEOUSLY

As discussed earlier, some fast reactor developers (such as Argonne National Laboratory) claim that their systems can simultaneously achieve two main goals of sustainability: the ability to greatly increase uranium utilization and to recycle the TRU in spent fuel. In the appendix to this report, it is shown why that is not possible. A system can be optimized either for increased uranium utilization (breeding) or for recycling TRU (burning), but cannot do both effectively at the same time.

The reason for this is simple: to use uranium most efficiently, a reactor and fuel cycle system must convert as much U-238 to plutonium as possible and then fission as much of that plutonium as possible to release energy. In contrast, to most efficiently fission TRU extracted from LWR spent fuel, the system must convert as *little* U-238 into new plutonium and other TRU as possible. TRU burners use only slightly (about 25 percent) less uranium than LWRs (Piet, Hoffman, and Bays 2010). The present study was unable to identify a system that could meet the criteria for significant reductions in TRU mass and efficient use of natural uranium simultaneously.

The reactors and fuel cycles described above represent attempts to improve nuclear power sustainability through reprocessing and recycling spent fuel. However, as discussed in chapter 4, those activities raise serious nuclear proliferation and terrorism concerns, by rendering weapon-usable materials susceptible to theft or diversion. In light of that, it is prudent to consider ways to improve the sustainability of the once-through cycle without increasing proliferation and terrorism risks. If the current once-through fuel cycle could be modified to be more sustainable, the most compelling arguments for adopting a closed fuel cycle would no longer apply.

As discussed in chapter 8, it may be possible to develop reactors that can use uranium much more efficiently than current reactors on a once-through basis. Unfortunately, it is not likely that this can be accomplished by improving LWR technology because of the physical limits on burnup for conventional uranium oxide fuel and cladding. But as seen above, even if an LWR could fission 100 percent of its fuel, that would amount to only about 10 percent of the amount of natural uranium mined to produce the fuel. The remainder would be the depleted uranium left over from the enrichment process, which cannot be used in LWRs without re-enriching it or adding other fissile materials obtained from reprocessing, such as plutonium. Moreover, increasing fuel burnup alone does not increase uranium utilization if higher levels of enrichment are needed to enable higher burnup, because then even more depleted uranium would be generated (Kim and Taiwo 2010).

Therefore, to substantially increase uranium utilization in the once-through cycle, reactor systems would have to increase fuel burnup without an increase in the required level of uranium enrichment. Compared to current LWRs, such reactors would need to convert more U-238 to plutonium and fission more of that plutonium for energy. In addition, the reactors would have to be able to use U-238 as a fuel material, in order to utilize the inventory of depleted uranium tails. This approach is referred to as breed-and-burn. To date, the only reactor designs shown in theory to be capable of true breed-and-burn operation are fast reactors because extra neutrons are available for U-238 conversion in a fast spectrum. The TerraPower traveling wave reactor, which is a liquid sodium–cooled fast reactor, is the most prominent example. The TerraPower Natrium reactor, which is a once-through fast reactor with a conventional refueling cycle, is less uranium-efficient than an LWR (see chapter 5).

As discussed further in chapter 8, the uranium utilization efficiency of a successful breed-and-burn system would compare favorably to that of a fast-breeder fuel cycle, but without the need to separate and recycle weapon-usable TRU. In our assessment, the avoidance of reprocessing is a major selling point for breed-and-burn reactors. However, significant technical and safety challenges remain, and it is not clear at this time whether such reactors will be viable.