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ISSUE BRIEF

US nuclear energy leadership:

The United States' role in managing the nuclear fuel cycle

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Introduction

Nuclear energy is indispensable in an energy-secure world with growing energy demand and, in the next few decades, considerable growth is expected in nuclear energy usage globally.

Many recent papers and reports by various energy agencies have explored the role of nuclear energy in an energy-secure world.[1] Not surprisingly, there is no consensus among the various assessments about the exact magnitude of nuclear generation needed to meet the growing clean energy demand.

Announcements at the COP28 conference in late 2023 focused on tripling global nuclear energy capacity by mid-century to about 1000 gigawatts electrical (GWe).[2] Other studies argue that much larger nuclear energy capacity [up to 6000 gigawatts (GW) by mid-century] is needed if the role of renewables in the electricity grid is constrained and nuclear power is used for delivering heat to industrial processes.[3] In addition to addressing climate change, demand for nuclear power is driven by energy security concerns in various parts of the world.

While how much nuclear energy is needed and how quickly this amount can be achieved is up for debate, what is clear is that global nuclear energy use will increase significantly in the next few decades. Such a major expansion will require considerable growth in the nuclear energy ecosystem and enabling technologies, with or without meaningful participation by the United States.

The Atlantic Council Global Energy Center develops and promotes pragmatic and nonpartisan policy solutions designed to advance global energy security, enhance economic opportunity, and accelerate pathways to net-zero emissions.

1 International Atomic Energy Agency, *Nuclear Energy in Mitigation Pathways to Net Zero* (Vienna: IAEA, 2023), https://doi.org/10.61092/iaea.pf2q-c1y0; International Energy Agency, *Nuclear Power and Secure Energy Transitions* (Paris: IEA, 2022), https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions; Nuclear Energy Agency, *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables* (Paris: OECD Publishing, 2019), https://www.oecd-nea.org/jcms/pl_15000/the-costs-of-decarbonisation-system-costs-with-high-shares-of-nuclear-and-renewables; World Nuclear Association, *Nuclear Power Economics and Structuring - 2024 Edition* (WNA, 2024), https://world-nuclear.org/images/articles/economics-report-2024-April.pdf.

2 "At COP28, Countries Launch Declaration to Triple Nuclear Energy Capacity by 2050, Recognizing the Key Role of Nuclear Energy in Reaching Net Zero," US Department of Energy, December 1, 2023, https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key.

3 For example, see: Jef Callens, "The Renaissance of Nuclear Power to Accommodate Net-Zero by 2050: New Energy Outlook 2021," Bloomberg NEF, November 4, 2021, https://about.bnef.com/blog/the-renaissance-of-nuclear-power-to-accommodate-net-zero-by-2050-new-energy-outlook-2021/.

Announcements at the COP28 conference in late 2023 focused on tripling global nuclear energy capacity by mid-century. REUTERS/Amr Alfiky

Regional choices about energy technologies have global consequences, and isolationist approaches to combatting climate change will not be sufficient. Therefore, enabling the deployment of clean and reliable energy sources in the developing world is also in the best interest of the United States. The fact that nuclear energy partnerships with other nations help establish strong diplomatic ties (the so-called "hundred-year relationship") is an added national security benefit. A major US leadership role in shaping the global nuclear energy landscape (including the associated fuel cycles) in an energy-secure world is critically important to uphold the highest standards of safety, security, and nonproliferation.

The Atlantic Council has published a previous report that examined the role of the United States in fostering a robust nuclear innovation ecosystem.[4] This issue brief primarily focuses on the need for US global leadership in the nuclear fuel cycle, under the assumption that there will be a multifold increase in the amount of uranium mining, enrichment, and spent fuel globally, which will be commensurate with the increase in nuclear generation.

Energy economics

Properly addressing energy production and associated fuel cycle economics is essential for nuclear energy deployment scenarios.

With the world's population now past eight billion people, many analysts acknowledge that nuclear energy has the potential to meet a large portion of global energy demand. However, carefully planned and executed short-, mid-, and long-term strategies and substantial upfront investments are needed to effectively lead the global energy transition.

The cost of nuclear reactors and associated fuel cycles within the context of energy economics needs to be properly integrated into global energy strategies. When the costs of different energy-production options are compared, the focus is often on the technology cost. Because of the high upfront cost for nuclear power plants compared to the capital cost of alternative energy sources, investors often view nuclear technologies as expensive. However, while the return on investment is relatively slow, the total lifecycle cost for nuclear energy is comparable to that of all other clean energy sources.[5] This is especially true when one considers the actual cost of energy, including system costs and social costs associated with energy production, distribution, and consumption. To reverse high reliance on fossil fuels without carbon capture, especially in developing nations, a more comprehensive energy-economics model must be developed and executed. This model must include the system cost and societal cost of the nuclear fuel cycle, including uranium mining and management of spent fuel.

In addition to properly accounting for societal costs, this model must include adequate incentives with innovative financing options for deploying clean energy technologies. Understandably, nuclear generation and associated fuel cycles are highly regulated, and new ideas require extensive and expensive testing before commercial use. Thus, innovation in nuclear technologies is relatively slow.

4 Jackie Toth and Khalil Ryan, "The imperative of the Versatile Test Reactor for nuclear innovation," Atlantic Council, April 24, 2023, https://www.atlanticcouncil.org/in-depth-research-reports/report/the-imperative-of-the-versatile-test-reactor-for-nuclear-innovation/.

5 Nuclear Energy Agency, *Projected Costs of Generating Electricity - 2020 Edition* (Paris: OECD Publishing, 2020), https://www.oecd-nea.org/jcms/pl_51110/projected-costs-of-generating-electricity-2020-edition.

The slow pace of innovation in nuclear energy technologies is a major impediment to private investment. Investments in nuclear energy must rely on managing the economics for many decades with slower returns on investment compared to other energy sources. Being able to accelerate the innovation cycle, so that advances in supporting technologies can be quickly adopted into nuclear energy production, is also an important element of the economic equation—and also requires upfront investments.

Countries with major ongoing investments in nuclear energy, such as Russia and China, rely heavily on state-owned enterprises and government-led planning and execution. Russia and China are investing heavily in their nuclear innovation ecosystems, increasing their domestic nuclear energy use, and developing and shaping export markets. In these emerging markets, US companies are competing with largely government-subsidized efforts, primarily by Russia and China. Finding innovative means of enabling the US private sector to compete in this environment is not a trivial problem. Conventional public-private partnership models do not seem adequate for nuclear economics.

Traditional market-based and private-sector energy economics are not readily adaptable to large-scale nuclear energy and fuel cycle deployment scenarios. Current levels of US government investment and traditional financing options fall short of addressing the unique challenges associated with nuclear energy and fuel cycle leadership.

The United States' role and the great-power competition

The role of the United States is unclear in a world with rapidly expanding nuclear energy use.

As indicated above, this issue brief is predicated on the assumption that a multifold increase in global nuclear energy deployment will occur in the next several decades. Studies looking at potential multitrillion-dollar nuclear energy markets identify more than fifty countries as potential markets for advanced nuclear energy by 2050.[6] A considerable fraction of the extended capacity is expected to be deployed in countries that are new to nuclear energy and with their first set of imported reactors. Russia is operating nuclear reactors in eleven countries, and more reactors are under construction or being planned. Additionally, Russia has also signed either memoranda of understanding or intergovernmental agreements with at least thirty countries, mostly in Africa.[7] Along with supplying reactors, Russia is offering fuel cycle management support, including takeback of spent fuel from the Russian-supplied reactors. Meanwhile, China is playing the long game and investing in the nuclear energy infrastructure in potential future markets in Africa.

In addition to deploying GW-scale light-water reactors (LWRs), Russia is aggressively developing and marketing liquid-metal-cooled fast reactors. China is building more than twenty GW-scale LWRs domestically, while also investing in innovative advanced reactors of many different kinds, including fast reactors. China projects that fast reactors will make up a large portion of its nuclear fleet in the second half of the century, allowing it to implement a closed fuel cycle with continuous recycling of fertile and fissile materials. The United States is aiming to deploy an additional 200 GWe domestically by 2050.[8] In addition to investment models, major policy adjustments and careful considerations for fuel cycle management, domestically and in support of export markets, appear to be necessary for the United States to be a serious player on the global landscape.

Unfortunately, at the current pace, the United States is quickly falling behind Russia and China in influencing deployment models outside its own borders. Soon, the United States may lose influence over how the new global nuclear energy landscape is taking shape.

Desire for US Leadership

US leadership in nuclear energy is strongly desired by national policymakers and even by some likeminded allied nations, but what that leadership entails is not well defined.

Most US policymakers and decision-makers in various government agencies articulate the need for US leadership in the new nuclear energy landscape, like the leadership it provided in the deployment and operations of LWRs until the end of the twentieth century. However, there are multiple schools of thought among US decision-makers regarding the definition of this global nuclear leadership. A unified plan of action to quickly re-establish and maintain leadership is not readily available for all stakeholders.

If the United States is to reclaim leadership in nuclear energy, it must comprehensively define what global leadership entails and the necessary steps to achieve it. The most prominent differences emerge between the US nonproliferation community and the advanced-reactor community—and their respective views about how to uphold safety, security, and nonproliferation standards—because of their respective roles in the nuclear energy ecosystem. This is particularly true on the topic of spent-fuel recycling.

Meaningful and influential penetration of a multitrillion-dollar market, and the associated economic benefits, only repre-

6 For example, see: "2022 Map of the Global Market for Advanced Nuclear," Third Way, October 24, 2022, https://www.thirdway.org/memo/2022-map-of-the-global-market-for-advanced-nuclear-emerging-international-demand.

7 Kristyna Foltynova, "Russia's Stranglehold on the World's Nuclear Power Cycle," Radio Free Europe/Radio Liberty, September 1, 2022, https://www.rferl.org/a/russia-nuclear-power-industry-graphics/32014247.html.

8 "Pathways to Commercial Liftoff," US Department of Energy, April 2023, https://liftoff.energy.gov.

sent part of the leadership needed in nuclear energy, and perhaps not the most important element. US leadership must offer fuel cycle solutions while maintaining and improving safety, security, and nonproliferation standards. The leadership vision should especially address spent-fuel management and related concerns in emerging markets. The potential diplomatic benefits of leadership in nuclear energy should not be overlooked.

Clearly, a strong commercial sector, resilient supply chains, tight collaboration with friends and allies, and the highest regulatory standards, supported by a state-of-the-art innovation ecosystem, are necessary to reclaim leadership. Having the capability to more effectively deal with spent fuel, as well as initial enrichment for the front of the fuel cycle for various reactors, must be included in the domestic innovation ecosystem. Such an ecosystem will enable the United States to adopt, on a timely basis, to the realities of global needs as they develop, as opposed to assuming that the rest of the world will adopt to choices and capabilities offered by the United States.

Future nuclear energy technologies

It is unlikely that the nuclear energy technologies (including reactors and associated fuel cycles) of the future will be the same as those used today.

Light-water reactors of 1-GWe scale have been optimized through multiple decades and make up most of the global nuclear fleet. All ninety-four reactors operating in the United States today are GW-class LWRs. Smaller versions of the light-water cooled reactors (so-called water-cooled small-modular reactors, or SMRs) are being designed. However, it is not yet proven if the economies of scale optimized for GW-class reactors can be replaced by economies of modularity without additional changes in the technologies. Except for their size, water-cooled SMRs are very similar to LWRs in terms of their fuel cycle. Uranium-oxide fuel with up to 5 percent enrichment (referred to as low enriched uranium, or LEU) is used in all the light-water-cooled reactors.[9] In some countries, such as France, plutonium recovered from spent fuel is recycled once in LWRs (instead of 5 percent uranium enrichment in the fresh fuel). Reprocessing and fresh fuel fabrication in France also make uranium-plutonium mixed oxide (MOX) fuel available to other interested nations in Europe (e.g., Belgium and Switzerland). France views this limited recycling as an initial step for future continuous recycling of spent fuel.

Some companies are designing advanced reactors that are not water cooled. In the United States, two demonstration projects are aimed for completion in early 2030s: TerraPower's sodium-cooled fast reactor and X-energy's gas-cooled high-temperature pebble-bed reactor. Other advanced reactor concepts at the research-and-development stage in the United States include lead or lead-bismuth eutectic-cooled fast reactors, gas-cooled fast reactors, prismatic-core high-temperature gas reactors, and molten salt reactors (with solid or liquid fuel).

Most of these concepts already have operating and planned prototypes in Russia and China. It may not be feasible for the United States to develop every reactor concept to the point of deployment. However, some designs that meet specific regional needs, while benefiting from advantages listed below, should be developed rapidly to offer an alternative solution to what Russia and China are offering to new markets. This process can be accelerated through collaboration with like-minded allies.

In the rapid growth of nuclear energy deployment, it is likely that LWRs will continue to dominate ongoing and near-term deployment for another few decades. However, depending on regional needs, advanced reactors of different kinds will likely be deployed at a fast rate soon. Once the initial demonstrations are completed and a few of them are deployed, these reactors are expected to be more attractive in global markets because

- most of them operate at or near atmospheric pressure, eliminating the need for high-pressure systems and components;
- they operate at higher temperatures than LWRs, increasing conversion efficiency and also enabling various process heat applications instead of—or in parallel to—electricity generation;
- most active safety systems used in LWRs are replaced by passive safety systems with inherently safe operations under most of the off-normal conditions; and
- fast reactors and liquid-fueled reactors are particularly efficient for recycling spent fuel, while increasing uranium utilization and reducing the amount of waste destined for a repository.

Most advanced reactors require higher uranium enrichments not to exceed 20 percent enrichment, or high-assay low-enriched uranium (HALEU). With fuel recycling, plutonium can be used to replace the U-235 content in the fuel, and fast reactors can be used to continuously breed the needed plutonium from the fertile uranium isotope U-238. Because of the additional enrichment requirements, HALEU fuel is more expensive than standard low-enriched uranium (LEU) fuel for LWRs. The economics of using HALEU fuel might require cost-effective means of recycling and/or innovation to achieve much higher burnups before the fuel is discharged. Continuous recycling,

9 Enrichment is the fraction of the fissile isotope, U-235, in the uranium. About 0.7 percent of natural uranium is the U-235 isotope, while a heavier fertile isotope, U-238, makes up most of the rest. U-238 cannot be used directly for energy production. With externally supplied high-energy neutrons, U-238 can fission but cannot sustain a chain reaction. Therefore, it is sometimes referred to as "fissionable," as opposed to fissile. However, U-238 is fertile, meaning when exposed to a neutron environment, it produces a fissile isotope of plutonium, Pu-239, which can be used for power generation.

coupled with fast reactors, must be considered as an option for deployment in the next couple of decades to support the potential global expansion of nuclear energy use.

At the same time, it is important to note that pursuing recycling does not eliminate the need to develop HALEU production capabilities. Currently, expanding into advanced-reactor markets is a global race, and demonstrating and deploying the initial set of such reactors should not wait for large-scale recycling technologies to be available. Early commercial non-LWR reactors will require HALEU to operate until recycled fuel with plutonium is available. Also, some reactors are not ready, or may not be suitable, for recycled plutonium, especially if it contains high levels of impurity in the recycled feedstock. For instance, the use of plutonium in tristructural isotropic (TRISO) fuel needed for high-temperature gas reactors requires more development and testing.[10] The need to use HALEU in some research reactors will also continue. Thus, HALEU production capability should proceed as planned, but the longer-term scaling of production should consider a comprehensive strategy, including recycling at the right time.

The United States also has considerable inventory of spent fuel from specific reactors using highly enriched uranium (HEU), such as high-performance test reactors like the Advanced Test Reactor (ATR) and the High-Flux Isotope Reactor (HFIR), as well as naval reactors. Spent fuel from these reactors is limited in quantities but it contains more than 20 percent enriched uranium. Reprocessing that fuel to extract uranium and down-blend the reprocessed uranium to HALEU is also an option that must be evaluated.

Therefore, proceeding on multiple and coordinated paths, it is imperative that the United States develop and demonstrate a high level of competency in advanced reactor technologies and the associated fuel cycles, with the ultimate option of continuous recycling.

Once-through fuel cycle

The once-through fuel cycle used in the United States is very inefficient in terms of utilization of uranium resources.[11]

The once-through LWR fuel cycle is quantified (Fuel Cycle Overview – World Nuclear Association) as a function of different fuel burnups in LWRs.[12] With a once-through fuel cycle, about less than 0.5 percent of natural uranium is used for energy production. The remaining 99.5 percent of natural uranium either takes the form of depleted uranium generated during the enrichment process (more than 90 percent of natural uranium) or is discharged in the spent fuel destined for permanent disposal (waste).

A GW-class LWR discharges roughly 20 metric tons (MT) of spent fuel a year, which contain about 200 kilograms (kg) of plutonium and 19,000 kg of uranium with less than 1 percent enrichment. Less than 1000 kg of uranium is consumed for energy production. More than 50 percent of the plutonium in the spent fuel is fissile and can be used for additional energy generation if recycled. Likewise, the fertile uranium in the spent fuel can be used to generate additional fissile plutonium and generate more energy.

For reactors that use HALEU, uranium utilization with the current achievable burnups would be even lower. Compared to LWR fuels, higher burnups are possible for solid fuels used in advanced reactors using HALEU, but current data would justify only doubling the burnup compared to LWRs (10 percent burnup instead of 5 percent in LWRs). This translates to a uranium utilization of 0.2 percent—in other words, only 0.2 percent of natural uranium is used for energy production, starting with 20 percent enriched uranium. Additional fuel qualification is needed to increase this number.

With recycling, especially using fast reactors, the utilization factor can theoretically be increased all the way up to 100 percent. Discussing various recycling and fissile-material breeding schemes is beyond the scope of this paper, but that discussion can be found in other studies.[13] With continuous recycling in fast reactors, the practical limit of uranium utilization is probably significantly less than 100 percent (somewhere between 25 percent and 50 percent), but is certainly much greater than the current 0.2–0.5 percent. One practical, immediate impact of increased utilization factor is the reduction in additional mining by a factor of one hundred or more, further mitigating the environmental impact of nuclear energy.

If the projected growth in nuclear energy materializes, it is unlikely that the once-through fuel cycle will be the fuel cycle of choice for the global nuclear energy industry, and the United States must be ready for widespread recycling both domestically and internationally. Partial use of once-through fuel cycles, especially for LWRs and reactors utilizing fuels that are difficult or expensive to reprocess, will likely also continue under certain circumstances—especially in countries with a small number of nuclear power plants and the ability to only manage the small amount of spent fuel generated in those plants.

10 TRISO fuel is a coated particle fuel form originally developed for use in high-temperature gas reactors.

11 In the once-through fuel cycle used in the United States, fresh fuel is irradiated in the reactor, while the discharged fuel is referred to as spent fuel and is considered waste. After sufficient cooling time, the fuel is stored in dry canisters until it can be sent to permanent disposal in a geologic repository. The alternative to the once-through fuel cycle is reprocessing and recycling, in which uranium and plutonium are separated from the spent fuel and recycled back into the reactor for additional energy generation. With continuous recycling, the fuel cycle is referred to as a closed fuel cycle. Fast reactors enable multiple recycles while continuously breeding fissile materials and, thus, are optimal for uranium utilization.

12 https://world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.

13 Roald Wigeland, et al., "Nuclear Fuel Cycle Evaluation and Screening—Final Report," US Department of Energy, October 8, 2014, https://fuelcycleevaluation.inl.gov/Shared%20Documents/ES%20Main%20Report.pdf.

Proliferation risk management

Management of proliferation risk is an inherent component of nuclear energy deployment, especially in non-weapon states.

For the purposes of this discussion, proliferation risk is defined as a nation aiming to develop nuclear weapons under the disguise of civilian nuclear energy production. The pathways for misuse of civilian nuclear energy infrastructure include:

- enrichment capabilities developed to produce HALEU but used to achieve weapons-grade enrichments—that is, 90 percent or higher enrichment of U-235;
- clandestine separation of plutonium from spent fuel discharged from the reactor; and
- diversion of a fraction of plutonium from the recycling facilities.

The nonproliferation community in the United States and globally has viewed LWRs as representing an acceptable risk because, in the current LWR-dominated landscape, enrichment capabilities are limited to a few locations globally with appropriate safeguards. Fresh fuel is supplied to the reactors only from those facilities.

As mentioned previously, LWR spent fuel contains plutonium. However, because of the isotopic blend, the longer the fuel is irradiated, the less attractive the plutonium becomes for weapons use. LWRs are operated on refueling cycles of twelve to twenty-four months. With short-duration irradiations, it is possible to generate weapons-grade plutonium using LWRs (or any reactor operating with the uranium fuel cycle); however, efforts to generate weapons-grade plutonium with frequent refueling are easily detectable.

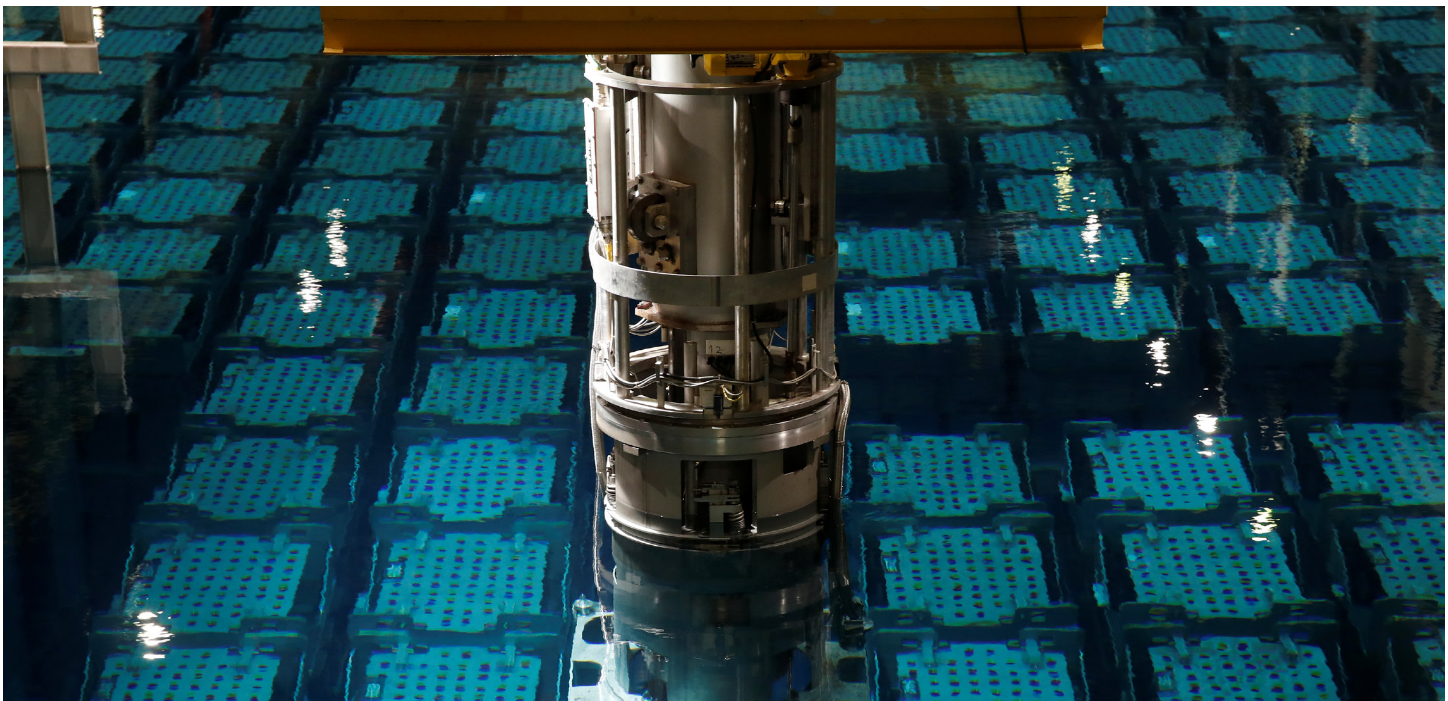
Commercial reprocessing and recycling are limited to a few nations such as France, Japan, Russia, and China, under very strict safeguard regimes (material accounting to assure no plutonium is diverted from the civilian recycling process), which makes the likelihood of diversion from reprocessing extremely low. Some European nations also use plutonium in their LWR fuel in the form of MOX. But the reprocessing and fresh-fuel fabrication for those European reactors is done only in France. Japan is the only non-weapons state where reprocessing and recycling are currently conducted.

It is possible to manage proliferation risk with adequate safeguards and tightly defined operational envelopes (such as long-duration irradiations without frequent refueling and strict materials-accounting protocols during recycling).

Changes in proliferation risk

Global expansion of nuclear energy and the deployment of advanced reactors may introduce new proliferation risks.

If many new reactors operate in other parts of the world, proliferation risks may increase unless strict controls that exist today are properly implemented in all new markets. With more rapid accumulation of spent fuel in various parts of the world,



Used nuclear fuel sits in a storage pool at a reprocessing plant in La Hague, near Cherbourg, France, one of the few nations that conducts commercial reprocessing and recycling of nuclear fuel. REUTERS/Benoit Tessier and the additional demand for uranium mining and enrichment, recycling will receive more interest, which could also change the risk profile, especially in countries new to nuclear.

For advanced reactors, the operational constraints need to be carefully developed. Reactors that operate with online refueling (e.g., pebble-bed reactors and CANDU reactors) combined with online separations and purification (e.g., liquid-fueled molten-salt reactors) require particular attention. In these reactors, material diversion is more difficult because reactors are not shut down for refueling. For some in the nonproliferation community, liquid metal-cooled fast reactors are of particular concern because of their ability to produce more fissile materials than they consume during operations. Larger quantities of plutonium can be obtained at a faster rate with fast reactors compared to LWRs. However, operational constraints (such as irradiation duration, fuel burnup, and materials accounting) can be used to control the plutonium isotopic vector.

In a world with many advanced reactors and more widespread enrichment and reprocessing capacity, the proliferation risk could increase, and it is in the US national interest to develop strategies to manage and mitigate those additional risks.

Proliferation risk with domestic use of technologies

Often lost in heated debates is the nuance between nonproliferation considerations for recycling done domestically versus recycling done abroad.

It must be emphasized that the domestic use of any nuclear energy technology in the United States does not pose a direct proliferation risk. Some opponents of US domestic reprocessing have argued that it could set a precedent that could lead to increased proliferation risk globally, but that argument is not backed by historic data and is further discussed in the next section.

On the other hand, it must be acknowledged that proliferation risk might increase with widespread use of recycling globally, especially in non-weapon states. However, this risk is also manageable as long as US standards of security and safeguards are followed, with Japan serving as a positive example.

Policy debates based on explicit distinctions between domestic and international uses will enhance the clarity of the discussions moving forward.

Leading by example

Instead of demonizing fuel recycling using fast reactors and expecting that the rest of the world will limit itself to deploying technologies approved by the United States, it is important to understand the risks of those technologies and develop strategies to mitigate them.

Current US practice of not reprocessing partly relies on the argument that, if technologies that are deemed high risk are not deployed in the United States as part of the civilian nuclear energy infrastructure, the rest of the world will follow that example and not deploy these technologies either. However, history shows that this nonproliferation stance is not realistic. Instead, Russia and China are filling the void left by the United States, offering fuel takeback with reliance on recycling.

Its lack of reprocessing and recycling offer striking examples of the ineffectiveness of the US approach.[14] Besides adversarial nations such as Russia and China, allied nations such as France and Japan are not willing to follow the US example when it comes to reprocessing and recycling. France and Japan separate plutonium and uranium from spent fuel, and recycle them for use in LWRs in the form of MOX fuel. The small amount of waste after the separation of uranium and plutonium (mostly fission products) is converted to glass, which is a durable waste form for ultimate disposal in a repository. Currently, France and Japan only conduct a once-through recycling process in existing LWRs, but they are exploring options for multiple recycling processes. Both France and Japan are looking into deploying fast reactors in the second half of the century for continuous recycling and a more sustainable fuel cycle with less reliance on uranium mining and enrichment. In its economic model, France argues that recycling is more cost-effective than a once-through fuel cycle. France also sells MOX fuel to other European nations to use in their reactors. It is important for the United States to acknowledge the legitimate national interest of allied nations and work with them toward an acceptable solution (as it has done with Japan by implementing strict materials-accounting controls under International Atomic Energy Agency (IAEA) protocols) that reduces the risk of proliferation while optimizing the benefits of nuclear energy.

A more realistic and productive approach might be to demonstrate and deploy some of these technologies domestically, consistent with the US national interest. This will allow the United States to properly understand technological constraints during controlled operations and to develop a safe and secure operational envelope (including implementation of state-of-the-art safeguard technologies). Technology leadership achieved through this process will allow the United States to influence international standards for the deployment of these technologies. A comprehensive overview of all the international fuel cycles is beyond the scope of this paper, but the trend in countries with considerable nuclear energy usage is to recycle spent fuel, contrary to US practices.

Any reactor can be used for producing weapons-grade plutonium if it is operated outside the operations envelope. The

14 In the nonproliferation community, some argue that it is US policy not to recycle. There is a continuous debate about whether this is just an accepted practice or a legal framework that prohibits recycling. However, based on economic considerations, there was no urgent demand by the commercial sector to restart reprocessing and recycling after the 1970s.

Growth in nuclear fuel recycling would reduce the need for permanent disposal in geologic repositories such as the Swiss Haberstal area, a favored location for an underground nuclear waste storage site. REUTERS/Arnd Wiegmann

quantities a country intent on proliferation needs for its first few weapons do not require large reactors or large reprocessing facilities. If short-duration irradiations are enabled, the type of reactor becomes irrelevant. The irradiation duration, composition of the fresh fuel, and the reprocessing technology determine the quality of the plutonium production. Also, large commercial reactors, combined with commercial-scale reprocessing, are arguably the most expensive and difficult way to obtain relatively small quantities of materials needed for weapons.

It is important for the United States to lead by example by deploying innovative nuclear technologies (including recycling) while upholding the highest standards of safety, security, and nonproliferation. Other countries will forge ahead in these technologies with or without the United States. It may be in the best interest of the United States to understand recycling technologies, demonstrate technologies that minimize the proliferation risk, and determine the actual risk based on technical facts.

Benefits of recycling

Recycling, if executed under the correct security and safety protocols, offers considerable benefits for increased nuclear energy utilization, both domestically and globally.

In a market-based economy, decisions around commercial reprocessing and recycling should be based on fuel cycle economics, as they are in countries like France and Japan. At present, in the United States, the once-through fuel cycle is believed to be more economical than recycling, with the current market prices for fresh LEU fuel. However, because fresh HALEU fuel will be more expensive, the economic equation will need to be revisited if many reactors requiring HALEU fuel are deployed. Also, the existing economic model depends on the total fuel cycle cost, including storage and disposal. There are large uncertainties associated with the cost of managing the spent fuel. Thus, different stakeholders will reach different conclusions. For instance, the French and Japanese models assume that even limited recycling is more economical, even though the fresh-fuel prices in those countries are equivalent to those in the United States. The lack of indigenous uranium resources also factors into economic uncertainties and energy security concerns. Thus, the jury is still out on the economics of LEU fuel. Because fresh HALEU fuel will be more expensive, and is currently less efficient in terms of uranium utilization, recycling HALEU fuel for certain applications might be the favorable economic solution.

In quantifying fuel cycle costs, one needs to consider the societal cost along with the technology and system costs, while also considering the societal benefits of recycling. These benefits include:

- Increased utilization of natural uranium for energy production: Theoretically, recycling can yield a two-hundred-fold increase in utilization for LEU fuel, with the same amount of natural uranium. That benefit increases to five-hundred-fold for HALEU fuel.
    - The proportional reduction in mining requirements will have considerable environmental benefits that must be reflected in economic models. (For uranium mining,

social equity is also an important issue that must be factored into the social cost).

- Decreased geologic repositories: Although geological repositories are needed with or without reprocessing and recycling, engineering and licensing requirements for the geologic repository are simplified considerably with reprocessing and recycling.
    - The volume of high-level nuclear waste that requires permanent disposal in a geologic repository can be reduced by an order of magnitude through recycling. Consequently, the size of repositories and the number of repositories needed will be reduced proportionally.
    - Depending on the recycling scheme, the long-term radiotoxicity of the waste can be dramatically reduced. Instead of requiring more than one hundred thousand years of isolation from the environment, the isolation requirement can be reduced to a few thousands of years.
    - For the remaining waste, durable and engineered waste forms—such as glass logs—can be developed, reducing the risks of containment failure that could lead to leakages to the environment.

The United States must make informed decisions based on its national interest and the interests of allied nations, and find ways of providing nuclear energy options to nations interested in peaceful uses of the technology.

Accumulation of spent fuel

Spent-fuel accumulation is a serious consideration during a large global expansion in nuclear energy.

A GW-scale LWR produces roughly 20 MT of spent fuel a year. If there is 1000-GWe equivalent of nuclear energy production a year by LWRs or reactors with a similar fuel cycle, roughly 20,000 MT of spent fuel will accumulate every year, containing 200 MT of plutonium. Operating under current refueling cycles, the plutonium will be reactor grade, with 50–60 percent fissile content. This is not a desirable isotopic mixture for weapons production. However, it still requires protection in specialized and safeguarded facilities. If recycled just into a GW-class LWR, this amount of plutonium can fuel an additional one hundred GW-class reactors or more.

Because the spent-fuel characteristics (in terms of the heat load and radiotoxicity) are proportional to the amount of fission products, these characteristics are roughly the same per unit of energy produced for advanced reactors. The volume of waste will vary for different reactors, and additional activated materials (such as graphite in gas-cooled reactors) will also differ for advanced reactors. Another important characteristic of spent HALEU fuel is that the uranium in spent fuel has a higher enrichment (up to 10 percent) compared to the spent LEU fuel (which has less than 1 percent enrichment). The waste generation and characteristic details are beyond the scope of this paper, but are discussed in a Academy of Sciences study from 2023.[15] What is relevant is that there will be a large amount of spent fuel containing plutonium and enriched uranium, assuming that the world reaches the equivalent of 1000 GWe of nuclear power production or more. It is difficult to imagine a nuclear energy landscape of that magnitude without fuel recycling.

For newcomer countries, dealing with spent fuel is a major concern. In new markets, Russia offers a fuel takeback option for exported Russian reactors. How that option will be executed remains to be seen, but it provides Russia with a competitive advantage in new markets. Depending upon the amount of spent-fuel takeback, it is hard to imagine that Russia will not reprocess that fuel to generate fresh fuel for commercial use—certainly domestically, and also potentially internationally.

Until a decision is reached on the US fuel cycle and a much clearer picture emerges for permanent disposal, it is difficult to imagine the United States offering fuel takeback options. However, as once strategized under the Department of Energy's Global Nuclear Energy Partnership (GNEP) program in 2006, the notion of regional recycling centers operated jointly with allied countries may need to be considered as an alternative. This option may level the playing field in emerging market countries in favor of the United States and allies. Preventing spent-fuel accumulation in many different countries (especially in countries where safety and security infrastructures are not fully developed) is an added advantage.

The United States has a choice to either remain on the sidelines or to proactively manage the changing landscape, by offering attractive alternatives to Russia's and China's dominance in this landscape while reducing the risk of proliferation.

Demonstration for closing the fuel cycle

Demonstrating a closed fuel cycle is necessary to prepare for the new global nuclear energy landscape and manage the proliferation risk.

Another important factor to consider is the uncertainty of future projections. Even if the United States decides that recycling is the preferred option, it could take more than a decade before commercial-scale recycling will be feasible. Thus, there is also some sense of urgency on moving forward with demonstration today to enable the option by the time 1000-GWe nuclear capacity is deployed globally by 2050.

15 "Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors," National Academies of Sciences, Engineering, and Medicine, 2023, https://nap.nationalacademies.org/read/26500/chapter/1.

There are multiple technology options for reprocessing spent fuel.[16] Because reprocessing is already being done at commercial scale in other nations, the commercial technology exists. Ongoing commercial-scale reprocessing is being done using the continuous aqueous solvent extraction process, which is derivative of the original PUREX process.[17] There is ongoing research in advanced reprocessing in the United States, by programs in both the US Department of Energy's Office of Nuclear Energy and Advanced Research Projects Agency-Energy (ARPA-E), particularly focusing on dry processes (so called pyro-processing). Pyro-processing or electro-chemical process is done in a batch mode, which allows for modular deployment.

Determining reliable and verifiable control of the product composition (to avoid separation of pure plutonium) is an important topic for assessment. This ongoing research is valuable in terms of improving the efficiency of managing the purity and composition of recycled material, development of durable waste forms for various gaseous and solid fission products, minimizing the secondary waste generated during recycling, and developing and testing safeguards by design approaches during recycling.

While the laboratory-scale research is ongoing, it is important to address scale-up challenges of the improved processes for commercial use. Commercial use will require a demonstration, primarily to improve the economics of recycling at the appropriate scale. Therefore, it is important to start planning for the demonstration project in parallel with ongoing research and development. It is desirable that multiple spent-fuel forms are incorporated into the demonstration design to prepare for continuous recycling involving multiple reactor types. The size of the demonstration facilities needs to be smaller than commercial scale for ease and flexibility in operations, but large enough to scale up for pertinent parameters such as economics, safety, and security. The technical community should start performing the scaling studies now, with adequate consideration of economic and flexibility constraints. The scale of the demonstration depends on the extraction and fuel-fabrication processes.

Reprocessing by itself has certain repository benefits in terms of the waste forms destined for permanent disposal. However, accumulating fissile materials that cannot be recycled for long periods of time is not necessarily a desired implementation strategy. Thus, along with demonstrating reprocessing technology, the United States must demonstrate fuel-fabrication and utilization capabilities at appropriate scale using the recycled materials. From safeguards, security, and safety perspectives, it may be desirable to perform the reprocessing and recycled fuel fabrication in the same facility, with the appropriate security measures. A demonstration facility with tightly coupled reprocessing and fuel-fabrication operations also minimizes the diversion pathways and may be the best solution for subsequent commercial-scale applications.

Finally, the fresh fuel fabricated using recycled materials must be qualified and licensed for use in commercial reactors. For continuous recycling with maximum benefits, fast-reactor recycling is known to be the preferred approach in the long term.[18] Thus, a test reactor like the Versatile Test Reactor (VTR) is needed to qualify these fuels before they can be commercially deployed (for more on the VTR, please see "The Imperative of the Versatile Test Reactor for Nuclear Innovation").[19] Some preliminary screening work is already ongoing in test reactors such as the Advanced Test Reactor.

As indicated above, engineering-scale demonstration with the necessary scope may require a decade or more to initiate. The duration mostly depends on whether existing hot-cell and glovebox facilities are adequate for the demonstration or new radiological facilities need to be built. Similarly, the type of reactor that is needed for recycled-fuel qualification must be determined. It is important that these activities start immediately to position the United States for the necessary leadership role by the end of the first half of the century, when many advanced reactors will likely be part of the global nuclear energy landscape.

The cost of the demonstration also heavily depends on the use of existing facilities or the need for new facilities. For instance, if the demonstration entails recycling in fast reactors, the VTR required for fuel qualification is a multibillion-dollar facility that could take between eight and ten years to complete. The cost and schedule also depend on how many process variations are considered for future flexibility, including testing different types of safeguard strategies and accommodating different types of spent fuel.

Therefore, additional financial commitments by the US government are needed, requiring potentially substantial increases in the nuclear energy budget beyond current levels. To maximize the benefits of the demonstration by covering a wide range of alternatives, and to minimize the domestic cost, international collaborations in the form of joint projects with likeminded allies must be seriously considered.

Lessons from the VTR

The VTR project reignited discussions between the nonproliferation and advanced-reactor communities and, if executed, would be highly relevant to the closure of the fuel cycle.

A major divide between nuclear technology developers and leading voices in the nonproliferation community resurfaced

16 Reprocessing refers to separating uranium and plutonium (and minor actinides, if desired) from spent fuel for recycling. In the traditional aqueous process, spent fuel is dissolved in a water-based acid solution before separation. In pyro-processing, spent fuel is dissolved in molten salt.

17 For example, see: K. R. Irish and W. H. Reas, "The PUREX Process: A Solvent Extraction Processing Method for Irradiated Uranium Fuel," General Electric, April 1957, https://www.osti.gov/servlets/purl/4341712#:~:text=The%20Purex%20Process%20is%20another,plutonium%20from%20irradiated%20uranium%20fuel.

18 Wigeland, et al. "Nuclear Fuel Cycle Evaluation and Screening."

19 Jackie Toth and Khalil Ryan, "The Imperative of the Versatile Test Reactor for Nuclear Innovation," Atlantic Council, April 24, 2023, https://www.atlanticcouncil.org/in-depth-research-reports/report/the-imperative-of-the-versatile-test-reactor-for-nuclear-innovation/.

with the start of the VTR project. Some in the nonproliferation community objected to the VTR because it is a fast reactor, and raised concerns that fast reactors are exclusively plutonium-production machines with a disguised objective to produce weapons-grade plutonium.

A more surprising dispute concerned the VTR's use of excess plutonium in the driver fuel. As a test facility, the VTR was designed to achieve high neutron fluxes while minimizing the size (and thermal power) of the reactor. For this purpose, the most attractive solution was to use excess weapons-grade plutonium in the fuel, but no final decision was made on the source for plutonium. In addition to optimizing the VTR design, the nuclear technology community viewed the VTR's ability to burn down and denature the existing plutonium stockpile as an added benefit.

The nonproliferation community's objections to this strategy were not fully anticipated by the nuclear energy community. Plutonium has been used in similar US test reactors before, other nations have done it, and—more importantly—the US government had previously endorsed Russia's use of excess weapons-grade plutonium in fast reactors to manage its stockpile. Later arguments became more nuanced and included concerns about fuel type, such as oxide versus metallic-alloy fuels (proposed for use in VTR), even though the International Atomic Energy Agency and the US Nuclear Regulatory Commission guides do not distinguish between metallic alloys and simple chemical compounds, such as oxides, in terms of material attractiveness for fuels. By the time the VTR project was defunded by the US Congress in Fiscal Year 2022—possibly due to budgetary constraints and funding priorities—the nonproliferation and nuclear energy communities could not reach a consensus, and the planned nonproliferation assessment for the VTR could not be completed.

In the context of recycling, the VTR project does not include recycling of VTR fuel, primarily due to an interest in avoiding scope expansion. The driver fuel was planned to be used in a once-through cycle where the spent fuel still containing plutonium (once the plutonium vector was denatured sufficiently) would be stored in a dry storage container until a repository became available. The multipurpose mission of VTR is discussed in a recent paper, and is not repeated here.[20] Part of the mission includes testing and qualifying fuels from materials obtained from reprocessed spent fuel, thus allowing the closure of the fuel cycle in the future if the United States decides to go in that direction. Simultaneously, other reactor developers openly indicated interest in using metallic-alloy fuels and commercial interest emerged in recycling.[21]

The demise of the VTR points to a lack of a comprehensive long-term strategy for enabling innovation. If closure of the fuel cycle by the second half of the century is to be an option, it is important to reinstate funding for the VTR project and move it forward as part of the fuel cycle closure-demonstration phase.

Policy considerations

Besides financial commitments, achieving closure of the fuel cycle in the United States requires important policy decisions.

The financing model for the demonstration phase must be developed. Even when the demonstration is done under a public-private partnership model, the incentives for private investment must be clearly articulated. For demonstration, the easiest path is likely for the government to finance it, but industrial partnership during this phase is critical to enable subsequent commercialization. For the demonstration phase, this should be a major point of discussion among all stakeholders, including funding agencies. Policy and financial models become more complex if international collaborations with like-minded allies are considered.

For the commercialization phase, even more complex policy considerations are necessary**.** Under US law, spent fuel belongs to the government. Utilities originally paid into the waste funds for the government to take care of the discharged fuel—but because the government failed to fulfil this obligation, utilities no longer pay into the waste fund and are instead paid by the government to store the discharged fuel at their sites. Economically, there is no incentive for utilities to invest in recycling or any alternative means of managing spent fuel. It is the government's responsibility to develop a spent-fuel management strategy and develop and implement policies to support that strategy. If recycling is pursued, especially in parallel with the deployment of the advanced reactors, policymakers will need to address the following types of questions.

- Who owns the discharged fuel from the advanced reactors?
- If recycling is executed, who would own and run the recycling facilities? The options might include full government operations, a fully privatized enterprise, or a hybrid approach similar to the government-owned, contractor-operated model used for national laboratories.
- How would the market economy be structured if the government provides recycled materials for fuel fabrication competing with a fully privatized enrichment service?
- Who pays for the initial investment in the recycling facilities and how will incentives be developed for a cost-shared model for recovery of initial investments?
- If any of the existing spent fuel is used in initial operations,

20 Toth and Ryan, "The Imperative of the Versatile Test Reactor for Nuclear Innovation."

21 "Oklo Selected for U.S. DOE Project to Enable Recycling of Used Nuclear Fuel in Partnership with Argonne National Laboratory, Deep Isolation, and Case Western Reserve University," Oklo, press release, November 2, 2022, https://oklo.com/newsroom/news-details/2022/Oklo-Selected-for-U.S.-DOE-Project-to-Enable-Recycling-of-Used-Nuclear-Fuel-in-Partnership-with-Argonne-National-Laboratory-Deep-Isolation-and-Case-Western-Reserve-University/default.aspx.

how is ownership transferred to private entities operating the recycling facilities and producing fuel with recycled materials?

- How is the secondary waste from recycling managed, and what happens to material that is no longer recycle-worthy after multiple recycles?
- What are the regulatory enhancements needed to enable construction and operation of recycling facilities?
- If the United States can gain a considerable share of the international market for advanced reactors, what are the policy considerations for international spent fuel discharged from US-built reactors vis-à-vis the countries hosting the reactors?

The list above is not meant to be comprehensive and other issues will likely emerge in detailed planning, such as export policies and intellectual-property protection, if international recycling centers are considered. Besides the spent-fuel ownership and public-versus-private commercialization issues, there is a clear need to review other relevant policy issues. Yucca Mountain-centric nuclear waste-management policy will need to be revised or supplemented, especially if the nuclear capacity in the United States will be tripled by 2050. It is important that any revisions or supplements to current nuclear waste-management policy incorporate the option of recycling. The deliberations on nuclear waste-management policies must proceed in parallel with technology development, demonstration, and deployment activities to enable timely implementation, if or when commercial-scale recycling is needed.

If the divide that emerged between the nonproliferation and technology development communities is an indication, closure of the fuel cycle requires additional, and often difficult, conversations that will influence the required policy changes. The recent Academy of Sciences study on the fuel-cycle options for the advanced reactors demonstrates that, other than some arguably obvious observations and recommendations, there is no consensus in the technical community on a long-term fuel cycle strategy. The report is useful in compiling the technical data for advanced reactors waste but is almost silent on a recommended strategy for how to deal with it. A more recent article is also a good demonstration of benefits-versus-risk arguments from different communities but without a contextual basis for an integrated evaluation in a world with rapidly increasing demand for nuclear power.[22]

Therefore, there is clearly a need for additional national dialogue with the aim of developing some concrete steps toward a long-term fuel cycle strategy. The technical community will continue to improve processes for fuel cycle closure. Informed by these developments, but in parallel with technical work, workshops among stakeholders must continue with the aim of better understanding the concerns (especially of the nonproliferation community) and defining a path forward that is in the US national interest and in the interest of enabling large-scale global nuclear energy deployment as part of the clean energy transition.

One important step should be to determine a commonly accepted proliferation risk model and assess different reactor and fuel-cycle technologies against that model. Adopting an existing risk model, if it is sufficient to delineate the technology nuance, might be the preferred approach if all stakeholders agree with the model. The baseline for acceptable risk for the US nonproliferation community appears to be the global deployment of LWRs without any recycling. The incremental risk, if any, of other reactor and fuel cycle options must be assessed, including means of mitigating those risks, whether real or perceived. The risks must be weighed against the benefits of these new technologies, both in terms of their contribution to human development in an energy-secure world and the importance of US leadership in these technologies. This must be a high-priority, concentrated effort, as the United States is falling further behind in global reshaping of nuclear energy. Even for domestic programs, there is clearly a disconnect in the desired outcomes for advanced reactors and the associated fuel cycles.

A policy roadmap consistent with a fuel-recycling demonstration and commercialization roadmap is also needed urgently to enable options in the next couple of decades.

The goal of continued discussions should be to develop a common strategy between the nonproliferation and nuclear-technology communities with participation from other relevant government agencies, such as the US Departments of State and Commerce. The value and benefits of US leadership should serve as the guiding principle of this strategy. Even if consensus on a strategy is not possible, it would still be valuable to present policymakers with pros and cons based on risk-benefit comparisons of different scenarios. It is strongly recommended, in parallel with a technology demonstration and deployment roadmap, that the major stakeholders develop a policy roadmap as soon as possible.

22 David Kramer, "U.S. Takes Another Look at Recycling Nuclear Fuel," Physics Today, February 1, 2024, https://pubs.aip.org/physicstoday/article/77/2/22/3230671/US-takes-another-look-at-recycling-nuclear.

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