Union of Concerned Scientists

EXECUTIVE SUMMARY

"Advanced" Isn't Always Better

Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Nuclear Reactors

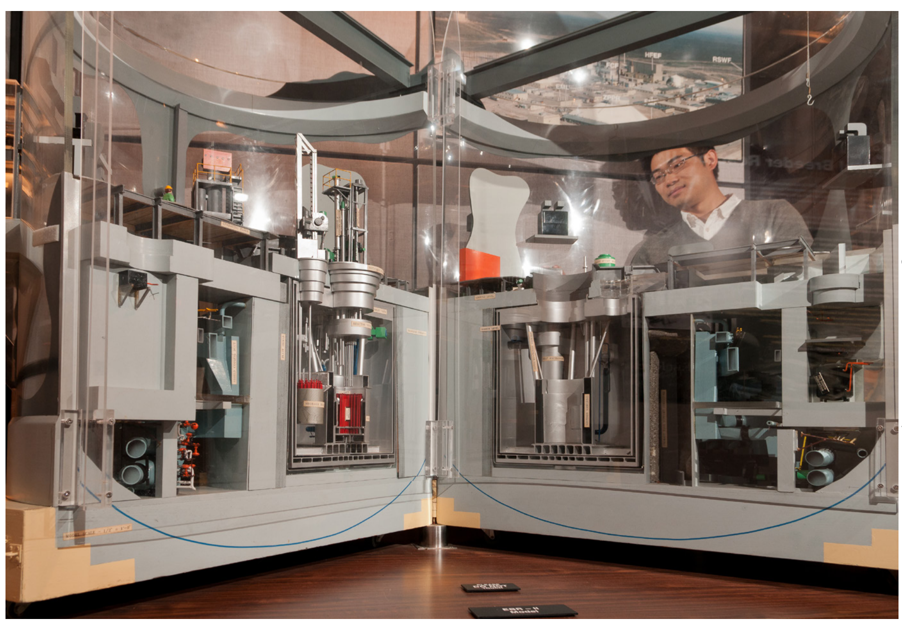
HIGHLIGHTS

If nuclear power is to play an expanded role in helping to mitigate climate change, newly built reactors must be demonstrably safer, more secure, and more economical than current-generation reactors. One approach to improving nuclear power has been to pursue the development of non-light-water nuclear reactors, which differ fundamentally from today's light-water reactors. But is different actually better? The answer is "no" for most designs considered in this assessment comparing non-light-water reactors to light-water reactors with regard to safety and security, sustainability, and the risks of nuclear proliferation and nuclear terrorism. The study from the Union of Concerned Scientists (UCS) recommends that policymakers, private investors, and regulators fully vet the risks and benefits of these technologies before committing the vast time and resources needed to commercialize them.

The future of nuclear power is uncertain. Because nuclear power is a low-carbon way to generate electricity, there is considerable interest in expanding its role to help mitigate the threat of climate change. However, the technology has fundamental safety and security disadvantages compared with other low-carbon sources. Nuclear reactors and their associated facilities for fuel production and waste handling are vulnerable to catastrophic accidents and sabotage, and they can be misused to produce materials for nuclear weapons. The nuclear industry, policymakers, and regulators must address these shortcomings fully if the global use of nuclear power is to increase without posing unacceptable risks to public health, the environment, and international peace and security.

Despite renewed enthusiasm for nuclear power in many quarters, its recent growth has been far slower than anticipated 10 years ago. No doubt, the March 2011 Fukushima Daiichi accident in Japan, which resulted in three reactor meltdowns and widespread radiological contamination of the environment, has contributed to nuclear power's stagnation. Even more significant has been the high cost of building new reactors relative to other sources of electricity—primarily natural gas but also, increasingly, renewable energy sources such as wind and solar. The current rate of construction of new nuclear plants around the world barely outpaces the retirements of operating plants that reach the ends of their lifetimes or are no longer economic.

In the United States, new nuclear plants have proven prohibitively expensive and slow to build, discouraging private investment and contributing to public



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The sodium-cooled fast reactor is one type of "alternate coolant" nuclear reactor that has seen a recent resurgence of interest. However, such reactors—as well as gas-cooled and molten salt–cooled reactors—are less technologically mature than the US operating fleet of light-water-cooled reactors and pose additional safety and security risks.

skepticism. In the 2000s, amid industry hopes of a nuclear renaissance, the Nuclear Regulatory Commission (NRC) received applications to build more than two dozen new reactors. All were evolutionary versions of the light-water reactor (LWR), the type that comprises almost all operating reactors in the United States and most other countries with nuclear power. Companies such as Westinghouse, which developed the AP1000, promised these LWR variants could be built more quickly and cheaply while enhancing safety. But prospective purchasers cancelled nearly all of those proposals even before ground was broken, and the utilities that started building two AP1000 reactors at the V.C. Summer plant in South Carolina abandoned the project after it experienced significant cost overruns and delays. Only one project remains—two AP1000 units at the Alvin W. Vogtle plant in Georgia—but its cost has doubled, and construction is taking more than twice as long as originally estimated.

Almost all nuclear power reactors operating and under construction today are LWRs, so called because they use ordinary water (H_2O) to cool their hot, highly radioactive cores. Some observers believe that the LWR, the industry workhorse, has inherent flaws that are inhibiting nuclear power's growth. In addition to its high cost and long construction time, critics point to—among other things—the LWR's susceptibility to severe accidents (such as the meltdowns at Fukushima), their inefficient use of uranium, and the long-lived nuclear wastes they generate.

In response, the US Department of Energy's national laboratories, universities, and numerous private vendors—from large established companies to small startups—are pursuing the development of reactors that differ fundamentally from LWRs. These non-light-water reactors (NLWRs) are cooled not by water but by other substances, such as liquid sodium, helium gas, or even molten salts.[1]

NLWRs are sometimes referred to as "advanced reactors." However, that is a misnomer for most designs being pursued today, which largely descend from those proposed many decades ago. At least one NLWR concept, the liquid metal–cooled fast reactor, even predates the LWR. Nevertheless, NLWR designers claim such reactors have innovative features that could disrupt the nuclear power industry and solve its problems. They state variously that their designs could lower costs, be built quickly, reduce the accumulation of nuclear waste, use uranium more efficiently, improve safety, and reduce the risk of nuclear proliferation. More specifically, they cite the advantages of features such as passive shutdown and cooling, the ability to consume or recycle nuclear waste, and the provision of high-temperature process heat for industrial applications such as hydrogen production. And some NLWR vendors claim that they can demonstrate, license, and deploy their designs within a decade or two.

Are these claims justified? How can we identify genuine innovations and recognize those that are likely unattainable? As with any technology, an independent reality check is needed. From self-driving cars to cheap flights to Mars, the Silicon Valley–style disruptive technology model of rapid, revolutionary progress is not always readily adaptable to other engineering disciplines. And nuclear energy, which requires painstaking, time-consuming, and resource-intensive research and development (R&D), is proving to be one of the harder technologies to disrupt.

In part, the nuclear industry's push to commercialize NLWRs is driven by its desire to show the public and policymakers that there is a high-tech alternative to the static, LWR-dominated status quo: a new generation of "advanced" reactors. But a fundamental question remains: *Is different actually better?* The short answer is no. Nearly all of the NLWRs currently on the drawing board fail to provide significant enough improvements over LWRs to justify their considerable risks.

Key Questions for Assessing NLWR Technologies

It is critical that policymakers, regulators, and private investors fully vet the claims that the developers of NLWRs are making and accurately assess the prospects for both successful development *and* safe, secure, and cost-effective deployment. Given the urgency of the climate crisis, rigorous evaluation of these technologies will help our nation and others avoid wasting time or resources in the pursuit of high-risk concepts that would be only slightly better—or perhaps worse—than LWRs.

Key questions to consider are the following:

- What are the benefits and risks of NLWRs and their fuel cycles compared with those of LWRs?

[*Given the urgency of the climate crisis, rigorous evaluation is needed to avoid wasting time or resources in the pursuit of high-risk energy concepts.*]

- Do the likely overall benefits of NLWRs outweigh the risks and justify the substantial public and private investments needed to commercialize them?
- Can NLWRs be safely and securely commercialized in time to contribute significantly to averting the climate crisis?

To help inform policy decisions on these questions, the Union of Concerned Scientists (UCS) has evaluated certain claims about the principal types of NLWRs. In particular, this report compares several classes of NLWRs to LWRs with regard to safety and security, the risks of nuclear proliferation and nuclear terrorism, and "sustainability"—a term that in this context includes the often-claimed ability of some NLWRs to "recycle" nuclear waste and use mined uranium more efficiently. The report also considers the potential for certain NLWRs to operate in a once-through, "breed-and-burn" mode that would, in theory, make them more uranium-efficient without the need to recycle nuclear waste—a dangerous process that has significant nuclear proliferation and terrorism risks.

Non-Light-Water Reactor Technologies

UCS considered these principal classes of NLWRs:

Sodium-cooled fast reactors (SFRs): These reactors are known as "fast reactors" because, unlike LWRs or other reactors that use lower-energy (or "thermal") neutrons, the liquid sodium coolant does not moderate (slow down) the high-energy (or "fast") neutrons produced when nuclear fuel undergoes fission. The characteristics and design features of these reactors differ significantly from those of LWRs, stemming from the properties of fast neutrons and the chemical nature of liquid sodium.

High-temperature gas–cooled reactors (HTGRs): These reactors are cooled by a pressurized gas such as helium and operate at temperatures up to 800°C, compared with around 300°C for LWRs. HTGR designers developed a special fuel called TRISO (tristructural isotropic) to withstand this high operating temperature. HTGRs typically contain graphite as a moderator to slow down neutrons. There are two main variants of HTGR. A prismatic-block HTGR uses conventional nuclear fuel elements that are stationary; in a pebble-bed HTGR, moving fuel elements circulate continuously through the reactor core.

Molten salt–fueled reactors (MSRs): In contrast to conventional reactors that use fuel in a solid form, these use liquid fuel dissolved in a molten salt at a temperature of at least 650°C. The fuel, which is pumped through the reactor, also serves as the coolant. MSRs can be either thermal reactors that use a moderator such as graphite or fast reactors without a moderator. All MSRs chemically treat the fuel to varying extents while the reactor operates to remove radioactive isotopes that affect reactor performance. Therefore, unlike other reactors, MSRs generally require on-site chemical plants to process their fuel. MSRs also need elaborate systems to capture and treat large volumes of highly radioactive gaseous byproducts.

THE FUELS FOR NON-LIGHT-WATER REACTORS

Today's LWRs use uranium-based nuclear fuel containing less than 5 percent of the isotope uranium-235. This fuel is produced from natural (mined) uranium, which has a uranium-235 content of less than 1 percent, in a complex industrial process called uranium enrichment. Fuel enriched to less than 20 percent U-235 is called "low-enriched uranium" (LEU). Experts consider it a far less attractive material for nuclear weapons development than "highly enriched uranium" (HEU), with a U-235 content of at least 20 percent.

The fuel for most NLWRs differs from that of LWRs. Some proposed NLWRs would use LEU enriched to between 10 and 20 percent uranium-235; this is known as "high-assay low enriched uranium" (HALEU).[2] While HALEU is considered impractical for direct use in a nuclear weapon, it is more attractive for nuclear weapons development than the LEU used in LWRs. Other types of NLWRs would use plutonium separated from spent nuclear fuel through a chemical process called reprocessing. Still others would utilize the isotope uranium-233 obtained by irradiating the element thorium. Both plutonium and uranium-233 are highly attractive for use in nuclear weapons.

Typically, the chemical forms of NLWR fuels also differ from those of conventional LWR fuel, which is a ceramic material composed of uranium oxide. Fast reactors can use oxides, but they can also use fuels made of metal alloys or chemical compounds such as nitrides. The TRISO fuel in HTGRs consists of tiny kernels of uranium oxide (or other uranium compounds) surrounded by several layers of carbon-based materials. MSR fuels are complex mixtures of fluoride or chloride salt compounds.

The deployment of NLWRs also would require new industrial facilities and other infrastructure to produce and transport their different types of fuel, as well as to manage spent fuel and other nuclear wastes. These facilities may use new technologies that themselves would require significant R&D. They also may present different risks related to safety, security, and nuclear proliferation than do LWR fuel cycle facilities—important considerations for evaluating the whole system.

NON-LIGHT-WATER REACTORS: PAST AND PRESENT

In the mid-20th century, the Atomic Energy Commission (AEC)—the predecessor of today's Department of Energy (DOE) and the NRC—devoted considerable time and resources to developing a variety of NLWR technologies, supporting demonstration plants at various scales at sites around the United States. Owners of several of these reactors abandoned them after the reactors experienced operational problems (for example, the Fort St. Vrain HTGR in Colorado) or even serious accidents (the Fermi-1 SFR in Michigan).

Despite these negative experiences, the DOE continued R&D on various types of NLWR and their fuel cycles. In the 1990s, the DOE initiated the Generation IV program, with the goal of "developing and demonstrating advanced nuclear energy systems that meet future needs for safe, sustainable, environmentally responsible, economical, proliferation-resistant, and physically secure energy." Although Generation IV identified six families of advanced reactor technology, the DOE has given most of its subsequent support to SFRs and HTGRs.

Today, a number of NLWR projects at various stages of development are under way, funded by both public and private sources (Table 1). With support from Congress, the DOE is pursuing several new NLWR test and demonstration reactors. It is proceeding with the design and construction of the Versatile Test Reactor (VTR), an SFR that it hopes to begin operating in the 2026–2031 timeframe. The VTR would not generate electricity but would be used to test fuels and materials for developing other reactors. In October 2020, the DOE selected two NLWR designs for demonstrating commercial power generation by 2027: the Xe-100, a small pebble-bed HTGR that would generate about 76 megawatts of electricity (MWe), and the 345 MWe Natrium, an SFR that is essentially a larger version of the VTR with a power production unit. The DOE is also providing funding for two smaller-scale projects to demonstrate molten salt technologies. In addition, the DOE, the Department of Defense (DOD), and a private company, Oklo, Inc., are pursuing demonstrations of so-called micro-reactors—very small NLWRs with capaci-ties from 1 MWe to 20 MWe—and project that these will begin operating in the next few years. A number of univer-sities also have expressed interest in building small NLWRs for research.

Congress would need to provide sufficient and sustained funding for any of these projects to come to fruition. This is far from assured—for example, funding for the VTR to date has fallen far short of what the DOE has requested, all but guaranteeing the project will be delayed.

TABLE 1. Current Status of US NLWR Projects

Reactor Type	Power Level	Developer	Funding	NRC Licensing Status	Planned Startup Date
Sodium-Cooled Fast Reactors					
Versatile Test Reactor	300 MWth[a]	DOE	DOE	Not NRC licensed	2026–2031
Natrium	840 MWth/345 MWe	TerraPower-GE Hitachi	50–50 cost share with /ARDP[b]	Preapplication	2025–2027
Aurora Powerhouse[c]	4 MWth/1.5 MWe	Oklo, Inc.	Mostly private; some DOE subsidy	Combined operating license accepted for technical review June 2020	Early 2020s
High-Temperature Gas–Cooled Reactors					
Xe-100	4 x 200 MWth (76–80 MWe)	X-Energy	50-50 cost share with ARDP	Preapplication	2025–2027
Molten Salt–Fueled Reactors					
IMSR	440 MWth/ up to 195 MWe	Terrestrial Energy	Private	Preapplication	—
Hermes reduced-scale test reactor[d]	Full-scale Kairos reactor 320 MWth/ 140 MWe; reduced scale > 50 MWth	Kairos Power	80 percent ARDP; 20 percent private	Preapplication	2027

a MWth: megawatts of thermal energy. MWe: megawatts of electricity.
b ARDP: DOE Advanced Reactor Demonstration Program
c The Aurora is potassium-cooled, with liquid sodium bonding contained in the fuel rods.
d The Hermes is not molten salt–fueled but uses TRISO fuel and a molten-salt coolant.

THE GOALS OF NEW NUCLEAR REACTOR DEVELOPMENT

If nuclear power is to play an expanded global role to help mitigate climate change, new reactor designs should be demonstrably safer and more secure—and more economical—than the existing reactor fleet. Today's LWRs remain far too vulnerable to Fukushima-like accidents, and the uranium enrichment plants that provide their LEU fuel can be misused to produce HEU for nuclear weapons. However, developing new designs that are clearly superior to LWRs overall is a formidable challenge, as improvements in one respect can create or exacerbate problems in others. For example, increasing the physical size of a reactor core while keeping its power generation rate constant could make the reactor easier to cool in an accident, but it could also increase cost.

Moreover, the problems of nuclear power cannot be fixed through better reactor design alone. Also critical is the regulatory framework governing the licensing, construction, and operation of nuclear plants and their associated fuel cycle infrastructure. Inadequate licensing standards and oversight activities can compromise the safety of improved designs. A key consideration is the extent to which regulators require extra levels of safety—known as "defense-in-depth"—to compensate for uncertainties in new reactor designs for which there is little or no operating experience.

Evaluation Criteria

UCS has considered three broad criteria for assessing the relative merits of NLWRs and LWRs: safety and security, sustainability, and risks associated with nuclear proliferation and nuclear terrorism.

One characteristic that UCS did not consider here is the ability of reactors to provide high-temperature process heat for industrial applications—sometimes cited as a major advantage of NLWRs. However, potential industrial users have demonstrated little interest in these applications to date, and will likely continue to be wary of co-locating nuclear power plants at their facilities until outstanding safety, security, and reliability issues are fully addressed. It is also doubtful that industrial users would want to assume the cost and responsibility of managing the reactors' nuclear wastes. Consequently, UCS regards the generation of high-temperature process heat as a secondary objective that would first require significant improvements in nuclear safety and security.[3]

Safety and security risk is the vulnerability of reactors and fuel cycle facilities to severe accidents or terrorist attacks that result in significant releases of radioactivity to the environment. Routine radioactive emissions are also a consideration for some designs. The UCS assessment primarily used qualitative judgments to compare the safety of reactor types, because quantitative safety studies for NLWRs with the same degree of accuracy and rigor as for LWRs are not yet available. Far fewer data are available to validate safety studies of NLWRs than of LWRs, which have accumulated a vast amount of operating data.

Sustainability, in this context, refers to the amount of nuclear waste generated by reactors and fuel facilities that requires secure, long-term disposal, as well as to the efficiency of using natural (mined) uranium and thorium. Sustainability criteria can be quantified but typically have large uncertainties. To account for those uncertainties, this report considers that sustainability parameters, such as the amount of heat-bearing transuranic (TRU) elements requiring long-term geologic disposal, would have to improve by a factor of 10 or more to be significant.

Nuclear proliferation and nuclear terrorism risk is the danger that nations or terrorist groups could illicitly obtain nuclear-weapon-usable materials from reactors or fuel cycle facilities. LWRs operating on a once-through fuel cycle present relatively low proliferation and terrorism risks. However, any nuclear fuel cycle that utilizes reprocessing and recycling of spent fuel poses significantly greater nuclear proliferation and terrorism risks than do LWRs without reprocessing, because it provides far greater opportunities for diversion or theft of plutonium and other nuclear-weapon-usable materials. International safeguards and security measures for reactors and fuel cycles with reprocessing are costly and cumbersome, and they cannot fully compensate for the increased vulnerability resulting from separating weapon-usable materials. Also using HALEU instead of less-enriched forms of LEU would increase proliferation and terrorism risks, although to a far lesser extent than using plutonium or uranium-233.

Nuclear proliferation is not a risk in the United States simply because it already possesses nuclear weapons and is designated as a nuclear-weapon state under the Nuclear Non-Proliferation Treaty. As such, it is not obligated to submit its nuclear facilities and materials for verification by the International Atomic Energy Agency (IAEA), although it can do so voluntarily. However, US reactor development does have implications for proliferation, both because US vendors seek to export new reactors to other countries and because other countries are likely to emulate the US program. The United States has the responsibility to set a good international example by ensuring its own nuclear enterprise meets the highest nonproliferation standards.[4]

Not all these criteria are of equal weight. UCS maintains that increasing safety and reducing the risk of proliferation and terrorism should take priority over increasing sustainability for new reactor development at the present time.

Given that uranium is now cheap and abundant, there is no urgent need to develop reactors that use less. Even so, there would be benefits from reducing the need for uranium mining, which is hazardous to workers and the environment and historically has had a severe impact on disadvantaged communities. Developing more efficient reactors may become more useful if the cost of mined uranium increases significantly, whether due to resource depletion or strengthened protections for occupational health and the environment.

UCS also did not consider the potential for NLWRs to be more economical than LWRs. Although economics is a critical consideration and is interrelated with the criteria listed above, such an evaluation would depend on many open and highly uncertain issues, such as final design details, future regulatory requirements, and supply chain availability.

Assessments of NLWR Types

UCS has reviewed hundreds of documents in the available literature to assess the comparative risks and benefits of the three major categories of NLWR with respect to the three evaluation criteria (Table 2).

SODIUM-COOLED FAST REACTORS

Safety and Security Risk: SFRs have numerous safety problems that are not issues for LWRs. Sodium coolant can burn if exposed to air or water, and an SFR can experience rapid power increases that may be hard to control. It is even possible that an SFR core could explode like a small nuclear bomb under severe accident conditions. Of particular concern is the potential for a runaway power excursion: if the fuel overheats and

TABLE 2. How NLWRs Compare with LWRs on Safety, Sustainability, and Proliferation Risk

NLWR Types	Safety	Sustainability		Nuclear Proliferation/ Terrorism
		Long-Lived Waste Generation	Resource Efficiency	
Sodium-Cooled Fast Reactors				
Conventional burner or breeder (Plutonium/TRU, with reprocessing)	- - -	++	+	- - -
Conventional: Natrium (HALEU, once-through)	- - -	- -	- -	- -
Breed-and-burn mode (HALEU, once-through)	- - -	- -	+ +	+
High-Temperature Gas-Cooled Reactors				
Prismatic-block (HALEU, once-through)	N	-	-	-
Pebble-bed: Xe-100 (HALEU, once-through)	N	-	-	- -
Molten Salt-Fueled Reactors				
Thermal: IMSR/TAP (LEU <5% U-235)	- - -	+	-	-
Thermal: Thorcon (HALEU/Thorium/U-233)	- - -	-	+	- -
Thermal: Molten Salt Breeder (HALEU/Thorium/U-233)	- - -	++	++	- - -
Molten Salt Fast Reactor (TRU/Thorium/U-233)	- - -	+++	++	- - -

Significantly Worse — Moderately Worse — Slightly Worse — Not Enough Information
Slightly Better — Moderately Better — Significantly Better

the sodium coolant boils, an SFR's power will typically increase rapidly rather than decrease, resulting in a positive feedback loop that could cause core damage if not quickly controlled.

Chernobyl Unit 4 in the former Soviet Union, although not a fast reactor, had a similar design flaw—known as a "positive void coefficient." It was a major reason for the reactor's catastrophic explosion in 1986. A positive void coefficient is decidedly not a passive safety feature—and it cannot be fully eliminated by design in commercial-scale SFRs. To mitigate these and other risks, fast reactors should have additional engineered safety systems that LWRs do not need, which increases capital cost.

Sustainability: Because of the properties of fast neutrons, fast reactors do offer, in theory, the potential to be more sustainable than LWRs by either using uranium more efficiently or reducing the quantity of TRU elements present in the reactor and its fuel cycle. This is the only clear advantage of fast reactors compared with LWRs. However once-through fast reactors such as the Natrium being developed by TerraPower, a company founded and supported by Bill Gates, would be less uranium-efficient than LWRs. To significantly increase sustainability, most fast reactors would require spent fuel reprocessing and recycling, and the reactors and associated fuel cycle facilities would need to operate continuously at extremely high levels of performance for many hundreds or even thousands of years. Neither government nor industry can guarantee that future generations will continue to operate and replace these facilities indefinitely. The enormous capital investment needed today to build such a system would only result in minor sustainability benefits over a reasonable timeframe.

Nuclear Proliferation/Terrorism: Historically, fast reactors have required plutonium or HEU-based fuels, both of which could be readily used in nuclear weapons and therefore entail unacceptable risks of nuclear proliferation and nuclear terrorism. Some SFR concepts being developed today utilize HALEU instead of plutonium and could operate on a once-through cycle. These reactors would pose lower proliferation and security risks than would plutonium-fueled fast reactors with reprocessing, but they would have many of the same safety risks as other SFRs. And, as pointed out, most once-through SFRs would actually be less sustainable than LWRs and thus unable to realize the SFR's main benefit. For this reason, these once-through SFRs are likely to be "gateway" reactors that would eventually transition to SFRs with reprocessing and recycling. The only exceptions—if technically feasible—are once-through fast reactors operating in breed-and-burn mode. However, the only breed-and-burn reactor that has undergone significant R&D, TerraPower's "traveling-wave reactor," was recently suspended after more than a decade of work, suggesting that its technical challenges proved too great.

HIGH-TEMPERATURE GAS-COOLED REACTORS

Safety and Security Risk: HTGRs have some attractive safety features but also a number of drawbacks. Their safety is rooted in the integrity of TRISO fuel, which has been designed to function at the high normal operating temperature of an HTGR (up to 800°C) and can retain radioactive fission products up to about 1,600°C if a loss-of-coolant accident occurs. However, if the fuel heats up above that temperature—as it could in the Xe-100—its release of fission products speeds up significantly. So, while TRISO has some safety benefits, the fuel is far from meltdown-proof, as some claim. Indeed, a recent TRISO fuel irradiation test in the Advanced Test Reactor in Idaho had to be terminated prematurely when the fuel began to release fission products at a rate high enough to challenge off-site radiation dose limits.

The performance of TRISO fuel also depends critically on the ability to consistently manufacture fuel to exacting specifications, which has not been demonstrated. HTGRs are also vulnerable to accidents in which air or water leaks into the reactor; this is much less of a concern for LWRs. And the moving fuel in pebble-bed HTGRs introduces novel safety issues.

Despite these unknowns, HTGRs are being designed without the conventional leak-tight containments that LWRs have—potentially cancelling out any inherent safety benefits provided by the design and fuel. Given the uncertainties, much more testing and analysis are necessary to determine conclusively if HTGRs would be significantly safer than LWRs.

Sustainability: HTGRs are less sustainable than LWRs overall. They use uranium no more efficiently due to their use of HALEU, and they generate a much larger volume of highly radioactive waste. Although pebble-bed HTGRs are somewhat more flexible and uranium-efficient than prismatic-block HTGRs, the difference is not enough to overcome the penalty from using HALEU fuel.

Nuclear Proliferation/Terrorism: HTGRs raise additional proliferation issues compared with LWRs. Current HTGR designs use HALEU, which poses a greater security risk than the LEU grade used by LWRs, and TRISO fuel fabrication is more challenging to monitor than LWR fuel fabrication. Also, it is difficult to accurately account for nuclear material at pebble-bed HTGRs because fuel is continually fed into and removed from the reactor as it operates. On the other hand, it may be more difficult for a proliferator to reprocess TRISO spent fuel than LWR spent fuel to extract fissile material because the required chemical processes are less mature.

MOLTEN SALT–FUELED REACTORS

Safety and Security Risk: MSR advocates point to the fact that this type of reactor cannot melt down—the fuel is already molten. However, this simplistic argument belies the fact that MSR fuels pose unique safety issues. Not only is the hot liquid fuel highly corrosive, but it is also difficult to model its complex behavior as it flows through a reactor system. If cooling is interrupted, the fuel can heat up and destroy an MSR in a matter of minutes. Perhaps the most serious safety flaw is that, in contrast to solid-fueled reactors, MSRs routinely release large quantities of gaseous fission products, which must be trapped and stored. Some released gases quickly decay into troublesome radionuclides such as cesium-137—the highly radioactive isotope that caused persistent and extensive environmental contamination following the Chernobyl and Fukushima nuclear accidents.

Sustainability: A main argument for MSRs is that they are more flexible and can operate more sustainably than reactors using solid fuel. In theory, some MSRs would be able to use natural resources more efficiently than LWRs and generate lower amounts of long-lived nuclear waste. However, the actual sustainability improvements for a range of thermal and fast MSR designs are too small, even with optimistic performance assumptions, to justify their high safety and security risks.

Nuclear Proliferation/Terrorism: MSRs present unique challenges for nuclear security because it would be very difficult to account for nuclear material accurately as the liquid fuel flows through the reactor. In addition, some designs require on-site, continuously operating fuel reprocessing plants that could provide additional pathways for diverting or stealing nuclear-weapon-usable materials.

MSRs could also endanger global nuclear security by interfering with the worldwide network of radionuclide monitors put into place to verify compliance with the Comprehensive Nuclear Test Ban Treaty after it enters into force.[5] MSRs release vast quantities of the same radioactive xenon isotopes that are signatures of clandestine nuclear explosions—an issue that MSR developers do not appear to have addressed. It is unclear whether it would be feasible or affordable to trap and store these isotopes at MSRs to the degree necessary to avoid degrading the effectiveness of the monitoring system to detect treaty violations.

Safely Commercializing NLWRs: Timelines and Costs

Can NLWRs be deployed quickly enough to play a significant role in reducing carbon emissions and avoiding the worst effects of climate change? The 2018 special report of the UN's Intergovernmental Panel on Climate Change identified 85 energy supply pathways to 2050 capable of achieving the Paris Agreement target of limiting global mean temperature rise to 1.5°C. The median capacity of nuclear power in 2050 across those pathways is about 150 percent over the 2020 level. Taking into account planned retirements, this corresponds to the equivalent of at least two dozen 1,000 MWe reactors coming online globally each year between now and 2050—five times the recent global rate of new LWR construction. If the world must wait decades for NLWRs to be commercially available, they would have to be built even faster to fill the gap by 2050.

> ***Commercial deployment in the 2020s would require bypassing prototype stages that are critical for assuring safety and reliability.***

Some developers of NLWRs say that they will be able to meet this challenge by deploying their reactors commercially as soon as the late 2020s. However, such aggressive timelines are inconsistent with the recent experience of new reactors such as the Westinghouse AP1000, an evolutionary LWR. Although the AP1000 has some novel features, its designers leveraged many decades of LWR operating data. Even so, it took more than 30 years of research, development, and construction before the first AP1000—the Sanmen Unit 1 reactor in China—began to produce power in 2018.

How, then, could less-mature NLWR reactors be commercialized so much faster than the AP1000? At a minimum, commercial deployment in the 2020s would require bypassing two developmental stages that are critical for assuring safety and reliability: the demonstration of prototype reactors at reduced scale and at full scale. Prototype reactors are typically needed for demonstrating performance and conducting safety and fuel testing to address knowledge gaps in new reactor designs. Prototypes also may have additional safety features and instrumentation not included in the basic design, as well as limits on operation that would not apply to commercial units.

By a 2017 report, the DOE asserted that SFRs and HTGRs were mature enough for commercial demonstrations without the need for additional prototype testing. For either of these types, the DOE estimated it would cost approximately $4 billion and take 13 to 15 years to complete a first commercial demonstration unit, assuming that reactor construction and startup testing take seven years. After five years of operating the demonstration unit, additional commercial units could follow in the mid-2030s.

In contrast, for MSRs and other lower-maturity designs, the DOE report judged that both reduced-scale and full-scale prototypes (which the report referred to as "engineering" and "performance" demonstrations, respectively) would be needed before a commercial demonstration reactor could be built. These additional stages could add $2 billion to $4 billion to the cost and 20 years to the development timeline. The sub-sequent commercial demonstration would not begin until 2040; reactors would not be available for sale until the mid-2040s or even the 2050s.

In May 2020, after receiving $160 million in initial congressional funding for the new Advanced Reactor Demonstration Program (ARDP), the DOE issued a solicitation for two "advanced" commercial demonstration reactors. In October 2020, the DOE chose SFR and HTGR designs—as one might expect given its 2017 technology assessment. The DOE estimates that these projects will cost up to $3.2 billion each (with the vendors contributing 50 percent) for the reactors and their supporting fuel facilities. The department is requiring that the reactors be operational within seven years, a timeline—including NRC licensing, construction, fuel production, and startup testing—that it acknowledges is very aggressive.

However, even if this deadline can be met and the reactors work reliably, subsequent commercial units likely would not be ordered before the early 2030s. Moreover, it is far from certain that the two designs the DOE selected for the ARDP are mature enough for commercial demonstration. Past demonstrations of both SFRs and HTGRs have encountered safety and reliability problems. Additionally, for both reactor types, the DOE has chosen designs that differ significantly from past demonstration reactors.

In the 1990s, the NRC concluded that it would require information from representative prototype testing prior to licensing either of these reactor types—but no prototypes were ever built. More recently, in a letter to the NRC, the agency's independent Advisory Committee on Reactor Safeguards reaffirmed the importance of prototypes in new reactor development. Nevertheless, the NRC—a far weaker regulator today—has apparently changed its position and may proceed with licensing the ARDP demonstration reactors without requiring prototype testing first. But by skipping prototype testing and proceeding directly to commercial units, these projects may run not only the risk of experincing unanticipated reliability problems, but also the risk of suffering serious accidents that could endanger public health and safety.

An additional challenge for NLWR demonstrations and subsequent commercial deployment is the availability of fuels for those reactors, which would differ significantly from the fuel that today's LWRs use. Even a single small reactor could require a few tons of HALEU per year—far more than the 900 kilograms per year projected to be available over the next several years from a DOE-funded pilot enrichment plant that Centrus Energy Corporation is building in Piketon, Ohio. It is far from clear whether that pilot will succeed and can be scaled up in time to support the two NLWR demonstrations by 2027, not to mention the numerous other HALEU-fueled reactor projects that have been proposed.

The Future of the LWR

Those who argue that nuclear power's progress depends on developing NLWRs have not made a persuasive case that the LWR has no future. LWR technology can realize nearly all the technological innovations attributed to NLWR designs, including passive safety features, the potential for modular construction, the use of advanced fuels, non-electric applications, greater plant autonomy to minimize labor costs, and underground siting. Although the LWR has its issues, NLWR designs clearly confront a different but no less formidable set of safety, security, and proliferation challenges.

A further consideration is how long it will take for new reactor types to achieve reliable performance once deployed. It took three decades for plant operators and researchers to increase the average capacity factor of the US fleet of LWRs from 50 to 90 percent. The relatively low state of maturity of NLWR technologies does not support the notion that these reactors will be able to achieve a similar level of performance in significantly less time.

Conclusions of the Assessment

The non-light-water nuclear reactor landscape is vast and complex, and it is beyond the scope of this report to survey the entire field in depth. Nevertheless, enough is clear even at this stage to draw some general conclusions regarding the safety and security of NLWRs and their prospects for rapid deployment.

Based on the available evidence, the NLWR designs currently under consideration (except possibly once-through, breed-and-burn reactors) do not offer obvious improvements over LWRs significant enough to justify their many risks. Regulators and other policymakers would be wise to look more closely at the nuclear power programs under way to make sure they prioritize safety and security. Future appropriations for NLWR technology research, development, and deployment should be guided by realistic assessments of the likely societal benefits that would result from the investment of billions of taxpayer dollars.

Little evidence supports claims that NLWRs will be significantly safer than today's LWRs. While some NLWR designs offer some safety advantages, all have novel characteristics that could render them less safe.

All NLWR designs introduce new safety issues that will require substantial analysis and testing to fully understand and address—and it may not be possible to resolve them fully. To determine whether any NLWR concept will be significantly safer than LWRs, the reactor must achieve an advanced stage of technical maturity, undergo complete comprehensive safety testing and analysis, and acquire significant operating experience under realistic conditions.

> ***Most NLWR designs under consideration do not offer obvious improvements over LWRs significant enough to justify their many risks.***

The claim that any nuclear reactor system can "burn" or "consume" nuclear waste is a misleading oversimplification. Reactors can actually use only a fraction of spent nuclear fuel as new fuel, and separating that fraction increases the risks of nuclear proliferation and terrorism.

No nuclear reactor can use spent nuclear fuel directly as fresh fuel. Instead, spent fuel has to be "reprocessed"—chemically treated to extract plutonium and other TRU elements, which must then be refabricated into new fuel. This introduces a grave danger: plutonium and other TRU elements can be used in nuclear weapons. Reprocessing and recycling render these materials vulnerable to diversion or theft and increases the risks of nuclear proliferation and terrorism—risks that are costly to address and that technical and institutional measures cannot fully mitigate. Any fuel cycle that requires reprocessing poses inherently greater proliferation and terrorism risks than the "once-through" cycle with direct disposal of spent fuel in a geologic repository.

Some NLWRs have the potential for greater sustainability than LWRs, but the improvements appear to be too small to justify their proliferation and safety risks.

Although some NLWR systems could use uranium more efficiently and generate smaller quantities of long-lived TRU isotopes in nuclear waste, for most designs these benefits could be achieved only by repeatedly reprocessing spent fuel to separate out these isotopes and recycle them in new fuel—and that presents unacceptable proliferation and security risks. In addition, reprocessing plants and other associated fuel cycle facilities are costly to build and operate, and they increase the environmental and safety impacts compared with the LWR once-through cycle. Moreover, the sustainability increases in practice would not be significant in a reasonably foreseeable time frame.

Once-through, breed-and-burn reactors have the potential to use uranium more efficiently without reprocessing, but many technical challenges remain.

One type of NLWR system that could in principle be more sustainable than the LWR without increasing proliferation and terrorism risks is the once-through, breed-and-burn reactor. Concepts such as TerraPower's traveling-wave reactor could enable the use of depleted uranium waste stockpiles as fuel, which would increase the efficiency of uranium use. Although there is no economic motivation to develop more uranium-efficient reactors at a time when uranium is cheap and abundant, reducing uranium mining may be beneficial for other reasons, and such reactors may be useful for the future. However, many technical challenges would have to be overcome to achieve breed-and-burn operation, including the development of very-high-burnup fuels. The fact that TerraPower suspended its project after more than a decade of development to pursue a more conventional and far less uranium-efficient SFR, the Natrium, suggests that these challenges have proven too great.

High-assay low enriched uranium (HALEU) fuel, which is needed for many NLWR designs, poses higher nuclear proliferation and nuclear terrorism risks than the lower-assay LEU used by the operating LWR fleet.

Many NLWR designs require uranium enriched to higher levels than the 5 percent U-235 typical of LWR fuel. Although uranium enriched to between 10 and 20 percent U-235 (defined here as HALEU) is considered impractical for direct use in nuclear weapons, it is more attractive for weapons use—and requires more stringent security—than the lower-assay enriched uranium in current LWRs.

The significant time and resources needed to safely commercialize any NLWR design should not be underestimated.

It will likely take decades and many billions of dollars to develop and commercially deploy any NLWR design, together with its associated fuel cycle facilities and other support activities. Such development programs would come with a significant risk of delay or failure and require long-term stewardship and funding commitments. And even if a commercially workable design were demonstrated, it would take many more years after that to deploy a large number of units and operate them safely and reliably.

Vendors that claim their NLWRs could be commercialized much more quickly typically assume that their designs will not require full-scale performance demonstrations and extensive safety testing, which could add well over a decade to the development timeline. However, current designs for sodium-cooled fast reactors and high-temperature gas-cooled reactors differ enough from past reactor demonstrations that they cannot afford to bypass additional full-scale prototype testing before licensing and commercial deployment. Molten salt–fueled reactors have only had small-scale demonstrations and thus are even less mature. NLWRs deployed commercially at premature stages of development run a high risk of poor performance and unexpected safety problems.

Recommendations

The DOE should suspend the advanced reactor demonstration program pending a finding by the NRC whether it will require full-scale prototype testing before licensing the two chosen designs as commercial power reactors.

The DOE has selected two NLWR designs, the Natrium SFR and the Xe-100 pebble-bed HTGR, for demonstration of full-scale commercial operation by 2027. However, the NRC has yet to evaluate whether these designs are mature enough that it can license them without first obtaining data from full-scale prototype plants to demonstrate novel safety features, validate computer codes, and qualify new types of fuel in representative environments. Without such an evaluation, the NRC will likely lack the information necessary to ensure safe, secure operation of these reactors. The DOE should suspend the Advanced Reactor Demonstration Program until the NRC—in consultation with the agency's Advisory Committee on Reactor Safeguards and external experts—has determined whether prototypes will be needed first.

Congress should require that an independent, transparent, peer-review panel direct all DOE R&D on new nuclear concepts, including the construction of additional test or demonstration reactors.

Given the long time and high cost required to commercialize NLWR designs, the DOE should provide funding for NLWR R&D judiciously and only for reactor concepts that offer a strong possibility of significantly increasing safety and security—and do not increase proliferation risks. Moreover, unlike the process for selecting the two reactor designs for the Advanced Reactor Demonstration Program, decision-making should be transparent.[6] Congress should require that the DOE convene an independent, public commission to thoroughly review the technical merits of all NLWR designs proposed for development and demonstration, including those already selected for the ARDP. The commission, whose members should represent a broad range of expertise and perspectives, would recommend funding only for designs that are highly likely to be commercialized successfully while achieving clearly greater safety and security than current-generation LWRs.

The DOE and other agencies should thoroughly assess the implications for proliferation and nuclear terrorism of the greatly expanded production, processing, and transport of the high-assay low-enriched uranium (HALEU) required to support the widespread deployment of NLWRs.

Large-scale deployment of NLWRs that use HALEU fuel will require establishing a new industrial infrastructure for producing and transporting the material. The DOE is actively promoting the development of HALEU-fueled reactor designs for export. Given that HALEU is a material of higher security concern than lower-assay LEU, Congress should require that the DOE immediately assess the proliferation and nuclear terrorism implications of transitioning to the widespread use of HALEU worldwide. This assessment should also address the resource requirements for the security and safeguards measures needed to ensure that such a transition can occur without an unacceptable increase in risk.

The United States should make all new reactors and associated fuel facilities eligible for IAEA safeguards and provide that agency with the necessary resources for carrying out verification activities.

The IAEA, which is responsible for verifying that civilian nuclear facilities around the world are not being misused to produce materials for nuclear weapons, has limited or no experience in safeguarding many types of NLWRs and their associated fuel cycle facilities. NLWR projects being considered for deployment in the United States, such as the Natrium SFR and the Xe-100 pebble-bed HTGR, would provide ideal test beds for the IAEA to develop safeguards approaches. However, as a nuclear-weapon state, the United States is not obligated to give the IAEA access to its nuclear facilities. To set a good example and advance the cause of nonproliferation, the United States should immediately provide the IAEA with permission and funding to apply safeguards on all new US nuclear facilities, beginning at the design phase. This would help to identify safeguard challenges early and give the IAEA experience in verifying similar facilities if they are deployed in other countries.

The DOE and Congress should consider focusing nuclear energy R&D on improving the safety and security of LWRs, rather than on commercializing immature NLWR designs.

LWR technology benefits from a vast trove of information resulting from many decades of acquiring experimental data, analysis, and operating experience—far more than that available for any NLWR. This gives the LWR a significant advantage over other nuclear technologies. The DOE and Congress should do a more thorough evaluation of the benefits of focusing R&D funding on addressing the outstanding safety, security, and cost issues of LWRs rather than attempting to commercialize less mature reactor concepts. If the objective is to expand nuclear power to help deal with the climate crisis over the next few decades, improving LWRs could be a less risky bet.

ENDNOTES

1 *This report focuses on NLWRs rather than LWR designs that differ from the operating fleet, such as the NuScale small modular reactor design now under review by the NRC. UCS previously evaluated issues related to small modular LWRs in its 2013 report* Small Isn't Always Beautiful. *This report also does not discuss nuclear fusion reactors; despite some recent progress, these likely remain even further away from commercialization than the early-stage fission reactor concepts.*

2 *Some sources define HALEU as LEU enriched from 5 percent to less than 20 percent uranium-235. However, this range does not align with the nuclear security risk of different grades of LEU. This report adopts the definition of HALEU used by the uranium enrichment consortium URENCO.*

3 *In any event, NLWRs do not have a monopoly on non-electric applications. Current-generation LWRs as well as small modular LWRs are being piloted for non-electricity applications such as producing hydrogen. At least one type of novel LWR, the super-critical LWR, would be capable of producing high-temperature steam, but it is not currently under development.*

4 *One way to do that would be for the United States to designate all new reactors and fuel cycle facilities as eligible for IAEA safeguards. This would give the agency an opportunity to develop verification approaches for new facility types—if such approaches are feasible.*

5 *The treaty names 44 countries that must sign and ratify it before it enters into force. To date, eight of these countries have not ratified and/or signed the treaty—including the United States, which has signed but not ratified it.*

6 *Although the DOE has said that an external review of its selections took place, it has not publicly released the reviewers' names and affiliations—nor has it publicly documented their findings.*

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