March 2021 ~UCS – Report Summary. 2021. UCS. “Advanced” Isn’t Always Better (Lyman, Mar 2021). (100) (summary updated Sep 15, 2024)

“Advanced” Isn’t Always Better

{S S $} {UCS REPORT} {SMRs. No nuclear reactor is ‘inherently safe’. SMR designs have safety tradeoffs. Several proposed cost-saving features and regulatory exemptions may add to public risk. Proprietary information protection disallows independent expert review.} {NOTE: A graphic of the Holtec SMR is featured on the uppermost left corner of the UCS report’s cover illustration}

‘{!!! Full summary ~UCS – Report. 2021. UCS. Advanced Isn’t Always Better.}

Lyman E, Advanced Isn’t Always Better: Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Nuclear Reactors, Union of Concerned Scientists report, Mar 2021. https://www.ucsusa.org/sites/default/files/2021-05/ucs-rpt-AR-3.21-web_Mayrev.pdf. https://www.ucsusa.org/resources/advanced-isnt-always-better. (Headings and emphasis added.)

ACRONYMS
CAS: Central alarm station
DBT: Design Basis Threat
DOE: Department of Energy
EPZ: Emergency Planning Zone
IAEA: International Atomic Energy Agency
iPWRS: Integral pressurized water reactors
MWth: Thermal megawatts
NEI: Nuclear Energy Institute
NRC: Nuclear Regulatory Commission
PRA: Probabilistic Risk Assessment
SAS: Secondary alarm station
SBO: Station blackout
SMRs: Small modular reactors
UCS: Union of Concerned Scientists

HEADINGS
Background
Conclusion
Cost
Complications of Multiple SMRs at a Site
Distributed Location SMRs
Emergency Planning
Public Health
Regulatory Requirements & Rollbacks
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Security
Transparency

[In the Union of Concerned Scientists (UCS) report “‘Advanced’ Isn’t Always Better”, authored by the physicist and nuclear safety expert Edwin Lyman, PhD, the scientific group undertook a comprehensive analysis of the most prominent and well-funded non-light-water reactor (NLWR) designs being proposed by the nuclear industry, including both large NLWRs and small modular reactors (SMRs) which do not use water as a moderator.

UCS posited the questions: What are the benefits and risks of NLWRs and their fuel cycles? Do the likely overall benefits of NLWRs outweigh the risks and justify the investments needed to commercialize them? Can NLWRs be safely and securely commercialized in time to contribute to averting the climate crisis?

“Two fundamental questions need to be addressed. First, to what extent would any NLWR and its associated fuel cycle be significantly more sustainable in practice than the LWR once-through cycle? And second**, would those benefits be significant enough to justify the substantial investment required to develop and deploy such a reactor at a large scale? These highly complex questions depend on many variables and are very sensitive to model assumptions**.” (p 32)

BACKGROUND

Almost all nuclear energy plants operating or being built today are large ~1,100 megawatt (MW) – 3,400 MW of thermal energy (MWth) – light water reactors (LWRs) which use ordinary water as a coolant. (p 13)

As per the laws of thermodynamics, most of the heat energy is discharged to the environment as waste heat. A LWR that produces 3,300 MWth generates about 1000 MW of electricity. (p 24)

{COMMENT: For conventional nuclear plants, less than 33% of the energy generated by goes onto the grid as electricity. Then some more is lost during delivery. Hence keeping old reactors online is not particularly efficient.}

Compared with other low-carbon sources, nuclear power has “fundamental safety and security disadvantages”. (p 13)

Fukushima and the poor image projected by troubled recent LWR construction projects (e.g., Vogtle, Olkiluoto, with their AP1000 and EPR designs) has contributed to a credibility problem for an industry that promotes nuclear power for mitigating climate change based on assertions that it is affordable and can be quickly deployed on a large scale.

{COMMENT: trouble-riddled AP1000 and EPR reactors}

Reactor concepts that differ from conventional LWRs are often referred to as “advanced” reactors, although characterization differs from one government agency to another and even from one piece of federal legislation to another.

In the Energy and Water Development and Related Agencies Appropriations Act of 2020, Congress put forth the definition of an advanced reactor as “*any light water or non-light-water fission reactor with significant improvements compared to the current generation of operational reactors*” (p 16, reverencing Energy and Water Development and Related Agencies Appropriations Act of 2020, Pub. L. No. 116-94, 133 Stat. 2535 (2019).)

In the FY 2020 Energy and Water Development Appropriations Act, Congress defined an advanced reactor as "*any light water or non-light-water fission reactor with significant improvements compared to the current generation of operational reactors. Significant improvements may include inherent safety features, lower waste yields, greater fuel utilization, superior reliability, resistance to proliferation, increased thermal efficiency, and the ability to integrate into electric and nonelectric applications*." (p 18, citing Energy and Water Development and Related Agencies Appropriations Act of 2020, Pub. L. No. 116-94, 133 Stat. 2535 (2019).)

However, the relatively low state of maturity of NLWR technologies does not support the conclusion that they will be able to achieve their advertised performance levels any time soon.

The term 'advanced' is also a "misnomer" for most designs being pursued today. (p 16).

"As an Oak Ridge National Laboratory scientist put it succinctly in a January 2019 presentation, 'today's 'advanced reactors' closely resemble their 1950s–1970s predecessors in: core configuration; materials in structure, core, and fuel; approach to [fuel] qualification; and control systems'". (p 16, citing Terrani 2019)
In addition, some of the aimed improvements in one or more areas can present significant disadvantages in other, resulting in drawbacks that outweigh benefits. (p 18)

Problematically, in its 2017 assessment of NLWRs, the U.S. Department of Energy (DOE) chose to focus on only two technology development objectives: (1) deployment of a high-temperature process heat application for industrial activities and (2) to extending natural resource (e.g. uranium) utilization and future nuclear waste burden. (p 18, citing Petti et al 2017) **"Notably, the {DOE} report did not stress the importance of other considerations, including safety, security, proliferation resistance, or economics."** (p 18)

With respect to the first DOE objective, while the nuclear industry has been pushing the idea of developing high-coolant-temperature reactors for process heat applications for decades, there is little evidence that non-nuclear industries are interested in using nuclear power. **"And it is unclear why these other industries would want to incur the additional risks of operating nuclear reactors in proximity to chemical plants."** (p 18)

Statements put out by developers exaggerate the actual capabilities of current NLWR designs to reduce the waste burden. It is "critical to understand" that 'burning' spent fuel involves reprocessing to separate out and re-use plutonium and other weapon-usable elements, which makes them more accessible for use in nuclear weapons by states or terrorists. (p 19)

The DOE's failure to consider safety and nuclear proliferation was a "significant shortcoming" of the DOE's 2017 study and skewed the results. Attention to proliferation and terrorism risks is critical to the evaluation of alternative reactors and fuel cycles. (p 19)

CLIMATE MITIGATION, EQUITY & SUSTAINABILITY

If the world must wait several decades for NLWRs to become commercially available, it is difficult to see how they could be deployed quickly enough to avert the worst impacts of climate change.

Resource depletion – the concern of the DOE – is not the only concern associated with uranium consumption. "Uranium mining is dangerous for workers and pollutes soil, air, and groundwater.

Uranium mining is less widespread in the United States today than in the past, but over time it has left **thousands of abandoned mines and dozens of uranium processing sites that require cleanup, many of which are located within the Navajo Nation** and continue to have a disproportionate impact on the Navajo people**. Moreover, uranium waste dumps and mines emit carcinogenic radon gas decay products that pose health risks to both miners and individuals living downwind**.” (p 33)

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

(p 34)

Specifically, many detailed systems analyses demonstrate that a real world **spent fuel reprocessing and recycling system would need to operate for hundreds or even thousands of years to significantly reduce the total TRU inventory**. This **means that the present generation would bequeath future generations** the need to continue to operate, repair, and replace these systems – with all the attendant cost and risk burdens for hundreds or thousands of years or otherwise be stuck with a large stockpile of TRU. (pp 36-38)

“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.” (p 115)

Reprocessing and recycling require chemically treating spent fuel to extract plutonium and other transuranic elements, which must then be refabricated into new fuel – steps which introduce “grave danger”. (p 115) : plutonium and other transuranic elements can be used in nuclear weapons. Reprocessing and recycling renders 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 “oncethrough” cycle with direct disposal of spent fuel in a geologic repository

“Two fundamental questions need to be addressed. First, to what extent would any NLWR and its associated fuel cycle be significantly more sustainable in practice than the LWR once-through cycle? And second**, would those benefits be significant enough to justify the substantial investment required to develop and deploy such a reactor at a large scale? These highly complex questions depend on many variables and are very sensitive to model assumptions**.” (p 32)

CONCLUSION

UCS concluded that, based on the available evidence, these NLWR designs are **not likely** to be significantly safer than today’s nuclear plants and some alternative reactor designs pose even greater environmental, nuclear proliferation, and safety risks than the current fleet.

Most "advanced" nuclear reactors are anything but demonstrably safer and secure than traditional nuclear reactors.

Large scale production and use of HALEU has **significant security implications. The risks of nuclear terrorism and nuclear need to be “thoroughly assessed” before the US goes forward with an NLWR development program that could stimulate global demand for the material.** (p 47)

“In summary, recent studies have confirmed that the adoption of a closed fuel cycle utilizing fast reactors and reprocessing will increase the cost of nuclear power. Given that reprocessing and plutonium recycling make waste management more difficult while simultaneously increasing cost and safety and security risks, it is hard to see the benefits of advanced reactor systems that are lauded for their ability to ‘consume’ nuclear waste.” (p 59)

In conclusion, the deployment of a fast reactor–based closed fuel cycle would likely decrease safety, would likely cost far more than LWRs on a once-through fuel cycle, and would make nuclear weapons materials more accessible to terrorists. And these reactors would neither solve the nuclear waste problem nor significantly reduce uranium use over reasonable time scales.” (p 73)

“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**.” (p 115)

“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.” (p 115)

Reprocessing and recycling means chemically treating spent fuel to extract plutonium and other transuranic elements and then fabricated materials into new fuel. “This introduces a grave danger: plutonium and other transuranic elements can be used in nuclear weapons. Reprocessing and recycling renders 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.” (p 115)

COST

“The various cost and time projections for commercializing NLWRs may differ in the details, but they all illustrate the significant technical challenges encountered in developing a new reactor design and its associated fuel cycle.” (p 22)

Commercializing any NLWR design will likely involve the need for the government to provide "substantial and sustained funding – not only for fundamental research, development, and demonstration, but perhaps even for the deployment of the first commercial units." (p 22)

The need for enhanced security for HALEU – already reflected in domestic and international material security standards – alone would increase security costs for fuel cycle facilities and reactors that use HALEU. (p 47)

"Many studies over the last few decades have confirmed that nuclear fuel cycles including reprocessing and plutonium fuel fabrication will increase cost relative to the once-through cycle with direct disposal of LEU spent fuel that is used by LWRs (Bunn et al. 2003; MIT 2011; NEA 2013)." (p 59) Further, even if a closed fuel cycle did reduce the need for geologic repository capacity, it would not translate into significant cost savings. (p 59)

"In summary, recent studies have confirmed that the adoption of a closed fuel cycle utilizing fast reactors and reprocessing will increase the cost of nuclear power. Given that reprocessing and plutonium recycling make waste management more difficult while simultaneously increasing cost and safety and security risks, it is hard to see the benefits of advanced reactor systems that are lauded for their ability to 'consume' nuclear waste." (p 59)

Pyroprocessing

"Proponents of pyroprocessing, a key component of several proposed advanced-reactor fuel cycles, argue that the technology would be cheaper than conventional aqueous reprocessing. They have a long way to go to demonstrate that, however. To date, the actual cost of the only operating pyroprocessing system has averaged more than $50,000 per kilogram of spent fuel—20 times greater than the highest value assumed in the {2013} Nuclear Energy Agency study." (p 59)

TerraPower

"Even TerraPower – likely the best funded reactor startup – was apparently unwilling to spend the many billions of dollars needed to commercialize its concepts on its own, and did not move forward with a demonstration reactor until it had secured government funding through the ARDP {Advanced Reactor Demonstration Program}." (p 22)

Small Modular Reactors

Small modular LWRs would produce more expensive electricity per megawatt unless they could significantly cut capital and operating costs – which introduces potential safety and security

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The high-temperature gas–cooled reactor (HTGR), a thermal-neutron reactor, is another NLWR concept being funded by DOE. In October 2020, it selected X-Energy's Xe-100 pebble-bed HTGR design as a commercial demonstration plants with plans for it to be built by 2027 under DOE's Advanced Reactor Demonstration Program (ARDP). "High temperature" here is defined as an outlet temperature (where the coolant gas exits the reactor core) of up to 800°C.16 In comparison, pressurized water reactors have a coolant temperature below 300°C." (p 74) "The

HTGR uses graphite as a neutron-moderating material and helium gas as a coolant. Another of the HTGR's distinctive characteristics is its fuel, which must be capable of withstanding far higher operating temperatures than LWR fuel. The current standard fuel, called TRISO (tristructural- isotropic), is composed of tiny spheres about one millimeter in diameter, each consisting of a kernel of fissile material (typically uranium oxide or uranium oxycarbide) surrounded by a porous graphite buffer layer, which is encapsulated in two spherical layers of pyrolytic carbon (a graphite-like material) with a silicon carbide layer sandwiched between them." (p 74)

It is difficult to assess how safe HTGRs would be. HTGRs are not invulnerable to loss of coolant accidents and TRISO fuel "must be manufactured to very exacting specifications", which shifts part of the safety burden from the reactor to the fuel fabrication process. (p 75) HTGRs could also be subject to sabotage which could result in core damage and fission product release – risks which have "not been thoroughly analyzed". (p 75)

GROWTH UNCERTAINTY

"The future of nuclear power is uncertain, both in the United States and worldwide." (p 13)

Compared with other low-carbon sources, nuclear power has "fundamental safety and security disadvantages". (p 13)

Almost all nuclear energy plants operating or being built today are large ~1,100 megawatt (MW) – 3,400 MW thermal energy (MWth) – light water reactors (LWRs) which use ordinary water as a coolant. (p 13)

Despite expectations of a so-called 'nuclear renaissance', nuclear has lagged behind other forms of electricity generation. This is largely because of cost. Natural gas and, increasingly, renewable energy sources such as wind and solar are cheaper.

Even the International Atomic Energy Agency (IAEA) has projected nuclear will have stagnant or declining capacity in industrialized nations. (p 14)

Even with aid from a carbon tax, it is not clear that nuclear would thrive because a carbon tax would also benefit other low-carbon electricity options burdened by fewer safety and security problems. (p 14)

One response of the industry to public skepticism about nuclear power is developers' pursuit of different types of reactors, including some radically different design models, that they promise will be cheaper, quicker to build, and safer

A fundamental question about such alternative designs, however, remains: "Is different actually better?" (p 14)

New Large Light Water Reactors

Westinghouse (with its AP1000) and Areva (with its EPR) have pursued new types of large LWRs, but these have run into difficulties

RADIONUCLIDES & URANIUM FUEL ENRICHMENT & USE

Conventional LWRs use only about 0.6% of the uranium mined for fuel to generate energy. The remaining more than 99% becomes depleted uranium (just under 90%) or contained in spent fuel (~10%). (p 39)

Developing advanced reactors and fuel cycles that use uranium more efficiently is not essential for nuclear power's future, and could increase economic, safety, proliferation, and terrorism risks. (p 39)

Natural uranium is roughly ~0.7% uranium-235 (U-235), which is fissionable.

Low-enriched uranium (LEU) is uranium enriched to below 20%. Fresh LWR fuel for conventional reactors is typically composed of U-235 enriched to just 3% to 5%, with the balance being primarily the isotope uranium-238 (U-238).

High-assay LEU (HALEU) is a category of LEU with a U-235 enrichment ≥10% and ≤20%. HALEU poses less proliferation and security risks than HEU, but more than LEU.

Highly enriched uranium (HEU) is enriched to a concentration of 20% U-235 or more. Any level of HEU can be used to make nuclear weapons, but more is material required for weapons made from lower enrichment levels. HEU for nuclear weapons is typically enriched to 90%. (p 27)

Plutonium, like HEU, is a nuclear explosive material. All isotopic combinations of plutonium except for pure super-hot plutonium-238 (Pu-238) can be used to build nuclear weapons.

Since spent fuel is highly radioactive, reprocessing requires heavily shielded facilities and use of remote-handling equipment. Separated plutonium is not highly radioactive and a weapon's worth of material – less than 10 kilograms (kg) is readily carried by a single person. (p 27)

"In the same way that plutonium-239 is produced when U-238 absorbs a neutron, successive neutron capture will produce elements with higher atomic numbers than that of uranium, which is 92. Such elements are referred to as transuranic elements (TRU). Plutonium, with an atomic number of 94, is a transuranic element. Other transuranic elements, also referred to as minor actinides, are neptunium (Np), americium (Am), and curium (Cm), with atomic numbers of 93, 95, and 96, respectively." (p 27)

"Fast reactors can therefore use TRU isotopes as fuel far more effectively than thermal reactors. Since many of these TRU isotopes are long-lived and generate significant decay heat, they could potentially cause problems for nuclear waste disposal. Thus the ability of fast reactors to more efficiently fission TRU isotopes is often cited as an advantage over thermal reactors. Some observers refer to this as nuclear waste 'burning,' even though the TRU elements are only a small component of the total mass of nuclear waste." (p 29)

As the reactor fuel is irradiated, energy is released by fission of U-235 the amount of U-235 becomes depleted. Conversion of U-238 to Pu-239 compensates as the Pu-239 also fissions and releases energy. Nevertheless, the amount of U-235 and Pu-239 ultimately becomes too low to sustain the nuclear chain reaction and the fuel becomes spent – i.e., 'spent fuel' – requiring discharge from a reactor core and replacement with fresh uranium fuel.

Not just efficiency, but safe operation also limits how long fuel can be used. The fuel matrix and cladding materials degrade as they are subject to chemical interactions, high heat, pressure from fission product gases, and radiation. Fuel degradation eventually creates a risk of rupture. (p 29)

Reactor cores typically will have several batches of fuel that were loaded in the reactor at different times. Irradiating fuel to higher burnup – i.e., increasing 'burnup' – enables the fuel to stay in the reactor longer and allows for less frequent refueling. (p 29)

The term 'fissile material' commonly denotes nuclear materials that can be used to make nuclear weapons. Fissile or fissionable isotopes are those capable of being split when struck by a neutron. Some fissionable isotopes are fissile.

"To compensate for a lower probability of fission, fast reactors must use fuel with a higher concentration of fissile material—historically either HEU or a mixture of uranium and at least 12 to 15 percent plutonium. Such reactors pose security concerns because HEU and plutonium can be used directly to make nuclear weapons." (p 28)

The claims made by Argonne National Laboratory (ANL) that its fast reactor and pyroprocessing system would "*allow 100 times more of the energy in uranium ore to be used to produce electricity compared to current commercial reactors*" and "*ensure almost inexhaustible supplies of low-cost uranium resources*" are "highly misleading", according to UCS. (p 34, referencing ANL 2012)

Correct calculation of uranium utilization efficiency requires account for the entire amount of natural uranium used to produce all the fuel needed by a reactor over its lifetime. "This includes not only fuel that is periodically fed into the reactor when it reaches steady-state operation, but also the fuel for the startup core and for the intermediate cycles during the transition to steady-state operation. The latter contribution is particularly important for some reactor systems that can take many years or even many decades to reach a steady state." (p 40)

"A system can be optimized either for increased uranium utilization (breeding) or for recycling TRU (burning), but cannot do both effectively at the same time." (p 42)

"Moreover, increasing fuel burnup alone does not increase uranium utilization if higher levels of enrichment are needed to enable higher burnup, because then even more depleted uranium would be generated." (p 42)

Many NLWR designs proposed today require high-assay LEU (HALEU) because they need higher fissile enrichments and burnups than LWRs. (p 46)

New uranium enrichment capacity for HALEU would be required, either domestically or internationally.

{COMMENT: US use and export of HALEU and HALEU-using reactors would establish the dangerous normalization of use of HALEU.}

RISK

Diverse and redundant safety and security measures are referred to as 'defense-in-depth'.

With the wide range of variables involved, it is difficult to develop a simple way to compare the overall safety of different reactor types. *To rigorously determine whether any advanced reactor would be safer overall than current generation LWRs, one would need to sum up the risk of a large radiological release over all potential severe accident sequences, including waste storage accidents, and compare it to the risk associated with a current-generation LWR.* ***This would require a comprehensive probabilistic risk assessment, validated with data from operating experience****.*

While probabilistic risk assessments for LWRs have operating experience to draw upon for validation, achieving the same level of validation remains far in the future for any NLWR design. ***And even the best risk assessments have large uncertainties associated with unknowns such as the risks of catastrophic external events, human errors, and sabotage****. Thus, qualitative safety measures such as defense-in-depth, which are needed to compensate for such uncertainties, need to be given great weight in comparative assessments*.

(p 31)

{COMMENT: Validation is not being required. NRC is not requiring operational records to be maintained following shutdowns. Palisades, operated in its final days by Entergy, for example, shut down supposedly permanently. Then soon after, Holtec, which ostensibly acquired the site and its decommissioning trust fund to decommission the site, announced its intention to restart the old reactor, which has been identified by experts as dangerously embrittled. The NRC has said it was 'reconstructing' the records, but there is no way to know the extent or import of the information lost.}

{COMMENT: Operating experience also can no longer be viewed as validating safety or defense-in-depth, as external threat conditions (climate, domestic terrorism, geopolitical instability) are dramatically changing.}

{COMMENT: Probabilistic risk assessment accepted by the NRC – even in the past, before the ADVANCE Act effectively demolished its ability to regulate – was wanting. Examples abound: Davis-Besse (+ 2003 blackout and Slammer worm); Indian Point baffle bolts and transformer fire, Superstorm Sandy affecting Indian Point and Oyster Creek.}

SAFETY

Many NLWR designs proposed today require high-assay LEU (HALEU) because they need higher fissile enrichments and burnups than LWRs. (p 46)

Accidents

Design-basis accidents are those that are taken into account in reactor design to prevent core meltdowns and large releases of radioactivity. **Beyond design basis (or severe) accidents are presumed less probable. However, they can and have occurred**.

Most initiating events that can trigger nuclear plant core meltdowns and beyond design basis accidents can be classified in three types: "(1) a rapid increase in the rate of nuclear fission (that is, an increase in reactivity) and an uncontrollable increase in power; (2) a loss of coolant due to leakage or inadequate coolant flow, causing the

reactor fuel to overheat; and (3) a loss of the ability to remove heat from the reactor system (such as the total loss of electric power— i.e., a station blackout), which could also lead to core melt.” (p 30)

The Chernobyl Unit 4 explosion in 1986 in the USSR initiated by a rapid increase in reactivity was an example of the first type. The Three Mile Island Unit 1 meltdown in 1979 in the US (in Pennsylvania) was a loss-of-coolant accident caused by a stuck-open valve, illustrating the second type. The Fukushima Daiichi disaster in 2011 in Japan, which caused the meltdown of 3 reactors, was caused by a loss of heat removal resulting from the loss of the electrical power needed to operate coolant pumps and other safety systems.

“The Chernobyl and Three Mile Island accidents were caused by internal events (including operator errors), whereas the total loss of electrical power at Fukushima had an external cause—a severe earthquake that took down power lines and site flooding from subsequent tsunamis that damaged electrical generating and distribution equipment. Intentional acts—known as acts of ‘radiological sabotage’ – can also be accident triggers, by initiating conditions similar to internal and/or external events. Indeed, knowledgeable saboteurs could quickly induce conditions resulting in core damage and radiological releases that would be highly unlikely to occur solely by chance.” (p 30)

Both accidents and acts of sabotage can be severe enough to disable multiple safety systems and cause the temperature of the nuclear fuel to heat up to a point where the fuel begins to degrade and eventually melt and release radioactive fission products into the coolant system. The excess heat also causes a pressure increase within the reactor and containment structure. **“The increases in temperature and pressure, as well as explosions of combustible gases such as hydrogen, can cause the containment to fail, releasing radioactivity into the environment.”** (p 30)

The ‘source term’ – meaning the chemical forms, types, and qualities of radioisotopes – and other factors relating to how the radioactive materials are released and dispersed are key factors in the impacts of a nuclear accident on the environment and public health. Prevailing weather conditions and the population distribution in the vicinity of the reactor are other important factors.

{COMMENT: Also how rapidly the accident evolves, how successful mitigation is, and numerous factors relating to the vulnerability of population affected and the economic, environmental and sociological value of the land and waters affected.}

Fast Reactors

Operating and maintenance costs for fast reactors would be greater than for LWRs. Liquid sodium is a difficult material to work with. For example, safety inspections are more difficult for reactor structures immersed in sodium because of its opacity. (p 58) Needed additional security and material accountancy measures will also increase the cost of liquid sodium reactors relative to LWRs. Beyond the greater capital, operating, and security costs of fast reactors, there is also the heightened cost of the fuel cycle. (p 58)

“The properties of the different chemical forms of fast reactor fuels, such as metals, oxides, or nitrides, can affect reactors’ safety and performance.” (p 60),

Sodium-cooled fast reactors have "inherent safety disadvantages" which reactor designers have worked for decades to address but have largely "failed to resolve". (p 59)

One serious concern is that sodium-cooled fast reactors commonly have a fundamental and significant instability known as a positive void coefficient. If the temperature of the sodium coolant increases and the sodium boils, the power of the reactor typically increases. The positive feedback effect could lead to rapid increase in pressure temperature, more coolant boiling, and core damage. In addition to the positive void reactivity problem, other safety challenges include the "use of chemically reactive liquid sodium coolant; the potential for rapid, hard-to-control power increases; and even the possibility of a small nuclear explosion, or as has often been referred to euphemistically, an 'energetic core disassembly.'" (p 60)

Sodium's high boiling point of nearly 900°C mean it doesn't need to be kept under high pressure during reactor operation. However sodium is "a highly reactive material that combusts upon contact with air and reacts violently with water." (p 60)

{COMMENT 900°C = 1652°F. Steel often melts at 1370°C (2500°F)}

Leaks of liquid sodium coolant have played a significant role in the dismal performance of fast reactor demonstration projects globally. The Monju facility in Japan, for example, was shut down for more than two decades after experiencing a sodium fire in 1995. (p 60)

Among the litany of sodium fires and other performance problems: The **Monju facility** in Japan was shut down for more than two decades after a sodium fire in 1995. The **Fermi-1** reactor in the US also suffered a major accident. France's Phénix experienced operational anomalies that remain unexplained and the Superphénix never achieved full power. (p 67)

{COMMENT: See SMRs – 10. SMRs. Japan}

SECURITY

The term 'fissile material' commonly denotes nuclear materials that can be used to make nuclear weapons. Fissile or fissionable isotopes are those capable of being split when struck by a neutron. Some fissionable isotopes are fissile.

"To compensate for a lower probability of fission, fast reactors must use fuel with a higher concentration of fissile material—historically either HEU or a mixture of uranium and at least 12 to 15 percent plutonium. Such reactors pose security concerns because HEU and plutonium can be used directly to make nuclear weapons." (p 28)

{COMMENT: Balance of the Cold War nuclear deterrence era over. During the Cold War, neither nation was run by fools or religious fanatics. Domestic and foreign terrorism (including suicide terrorists) did not pose a significant threat. Asymmetrical power provided by new and developing instrumentalities such as AI, cyber, drones, and directed energy weapons adds a world of complicated threat-multiplying factors.}

The landmark Nuclear Non-Proliferation Treaty (NPT) allows possession of dual-use nuclear facilities for peaceful purposes, but prohibits non-nuclear weapons states from acquiring nuclear weapons. The International Atomic Energy Agency (IAEA) is responsible for implementing a safeguards system trying to ensure countries are not diverting nuclear materials from declared nuclear facilities for use in production of atomic weapons. The 5 acknowledged nuclear weapon states (US, Russia, China, France, and the UK) are not mandated to accept IAEA safeguards. (p 43)

“The IAEA applies safeguards to ‘special fissionable materials,’ which consist of enriched uranium, plutonium, and uranium-233 (U-233), as well as source materials such as natural uranium that can be used to produce special fissionable materials. Of these, it defines highly enriched uranium (HEU) and plutonium (containing less than 80 percent plutonium-238) and U-233 as ‘direct use materials.’” (p 43)

International concern over the potential for Iran to use its uranium enrichment facilities to develop nuclear weapons was a major impetus for the 2015 Joint Comprehensive Plan of Action (JCPA) also known as the Iran Deal. While Iran claimed an intention to only produce LEU, its enrichment facilities could be redirected to produce HEU. After the US withdrew from the agreement in 2018 and launched an airstrike that killed Iranian general Qassem Soleimani in January 2020, Iran announced that it would no longer abide by JCPA’s operational restrictions on its nuclear program that had increased its breakout time. (p 44)

Reprocessing facilities present a greater security risk than do enrichment plants which only produce LEU. It is also feasible to covertly divert enough plutonium to build a nuclear weapon from a commercial-scale reprocessing or plutonium fuel fabrication plant. (p 44) Moreover, reprocessing spent nuclear fuel makes it easier for terrorists to steal weapon-usable plutonium. (p 44 & 51-52)

A key IAEA missive is “timely detection” of the diversion of a “significant quantity” (SQ) of weapons material, roughly the amount needed to make a first-generation nuclear weapon. The SQ value for plutonium is 8 kg. The SQ value for HEU is a quantity of uranium containing 25 kg of U-235.(p 45)

The foundation of IAEA proliferation safeguards is material accountancy: the measurement of a facility’s material inputs, outputs, and in-process inventory, to ascertain whether there is “material unaccounted for” (MUF) and how much. (p 45) Detection of diversion at large reprocessing facilities is difficult however.

Over the last 25 years, several examples of large plutonium MUFs that went undetected for months or even years have come to light at plutonium-processing facilities around the world. These include the Tokai Reprocessing Plant in Japan in 2003 (206 kg of plutonium), the Thermal Oxide Reprocessing Plant (THORP) in the United Kingdom in 2005 (190 kg), and the Cadarache plutonium fuel production plant in France in 2002 (39 kg) (Kuperman, Socolow, and Lyman 2014). These examples underscore the inherent difficulty of achieving safeguards goals at such bulk-handling facilities.

(p 45)

IAEA safeguards and the Nuclear Non-Proliferation Treaty (NPT) do not include prevention of nuclear terrorism within their scope. Protection of nuclear facilities from sub-national terrorist attacks, thefts of weapon-usable materials and radiological sabotage is deemed a nation state responsibility. (p 45)

“Nuclear plant security is also increasingly being challenged by emerging threats such as cyberattacks and malevolent use of aircraft such as drones.” (p 45)

The Nuclear Regulatory Commission (NRC), which has oversight over US commercial nuclear facilities, classifies the most sensitive nuclear materials containing plutonium, enriched uranium, and U-233 as Category I, II, and III, and has developed security standards for each category. These categories depend on the type of nuclear material, the quantity, and whether the material is irradiated to the self-protection standard defined above (but not on other factors such as whether the material is pure or diluted with another substance). The highest level of physical protection, Category I, is applied to certain quantities of materials that can be directly used in the manufacture of nuclear weapons. For example, 2 kg or more of unirradiated plutonium, and 5 kg or more of U-235 contained in HEU, fall under Category I. In contrast, the highest security category for low-enriched uranium with a U-235 content below 10 percent—which includes LWR fuel—is Category III. And 10 kg or more of uranium with a U-235 content from 10 percent to below 20 percent—defined in this report as high-assay LEU (HALEU)—is considered a Category II quantity, with an intermediate security risk.

(p 45)

Many NLWR designs proposed today require high-assay LEU (HALEU) with higher fissile enrichments and burnups than LWRs. (p 46)

The Nuclear Energy Institute (NEI) has projected that the US nuclear industry could need more than 200 metric tons of HALEU per year by 2031 (Redmond 2020). (p 46)

Proliferation and terrorism risks of HALEU – where U-235 enrichment is ≥10% to <20% – are greater than those of lower-assay LEU because it HALEU can be used directly in nuclear weapons and the material it easier to enrich it to HEU.

Compared to the once-through LWR fuel cycle with direct disposal of spent fuel, all reprocessing technologies make weapon-usable materials such as plutonium much more vulnerable to diversion by countries or theft by terrorist groups seeking to obtain nuclear weapons. Fuel cycles with reprocessing require significantly greater resources than once-through cycles to pay for more intensive nuclear material accountancy, physical security, and (in non-nuclear weapon states) international safeguards activities. These additional activities are costly because they require highly trained personnel and more specialized equipment.

(p 49)

Large scale production and use of HALEU has **significant security implications. The risks of nuclear terrorism and nuclear need to be “thoroughly assessed” before the US goes forward with an NLWR development program that could stimulate global demand for the material.** (p 47)

The IAEA should also take a hard look at the proliferation implications of HALEU. “Unfortunately, such radical changes are nearly impossible at the IAEA, given the reluctance of its international Board of Governors to approve more restrictive or intrusive safeguards obligations.” (p 48)

The need for enhanced security for HALEU – already reflected in domestic and international material security standards – alone would increase security costs for fuel cycle facilities and reactors that use HALEU. Under current US protocols, Category II security measures would be required for HALEU fuel production facilities. Such measures are more stringent than those at Category III LWR fuel facilities. (p 48)

If, as some estimates indicate, the amount of 19.75% enriched HALEU needed for a bomb could be around 300 kilograms, a single Oklo micro-reactor core would contain about 10 nuclear weapons' worth of material for a bomb with a massive core. (p 47)

{**COMMENT**: The size of the core for such a bomb may present a challenge today, but nuclear weapons technology – which is not subject to commercial restraints – will surely advance, especially with wide availability of AI tools. Cyber and AI can also be used in innumerable ways to help malicious actors divert nuclear material and thwart national and IAEA safeguards.}

{**COMMENT**: The supposition held for many decades that highly radioactive spent fuel is 'self-protecting' because concern over personal safety would deter diversion or attack should have been questioned at the onset. In any event, it was thoroughly debunked by Sept 11 and many other terrorist attacks and conflicts worldwide in the years since.}

Some analysts have argued that HEU produced from HALEU feed would require a relatively cheap and small enrichment plant that would be easier to conceal. The amount of separative work needed to produce enough HEU for a weapon in modern compact and scalable gas centrifuge plants is less than the amount needed in older gaseous diffusion plants. (p 47)

For countries with large commercial enrichment facilities producing LEU, availability of HALEU may not make a big difference in the timeline for producing HEU if they decide to overtly violate nonproliferation commitments. HALEU may thus be most advantageous for nations embarking on covert proliferation pathways. For example, HALEU from a declared facility may be diverted to a small clandestine facility to produce HEU. The advantages of access to HALEU would be greatest for a country like Iran that has a relatively small enrichment capacity. (p 47)

{**COMMENT**: The US is a major funder of the IAEA and holds strong sway over its actions and priorities. The US has spent a king's ransom many times over is trying to police the world and restrict the construction of fissile material production infrastructure spread of fissile materials. How much the US has spent on trying to contain Iran over the more than 45 years is not publicly available information. However, it is surely a staggering amount. It must be remembered that the US was the entity that promoted 'peaceful' nuclear facilities under the "US Atoms for Peace" program in what was the ally nation of Iran before the 1979 Islamic Revolution and the overthrow of the Shaw. What should also be recalled is that the Iranian revolution promised three goals: Freedom and democracy, social justice, and independence from great power tutelage. (See e.g., CRS: Iran and Nuclear Weapons Production, Congressional Research Service webpage, updated Mar 20, 2024. https://crsreports.congress.gov/product/pdf/IF/IF12106; Fathollah-Nejad, Ali, Four decades later, did the Iranian revolution fulfill its promises? Brookings commentary, Jul 11, 2019. https://www.brookings.edu/articles/four-decades-later-did-the-iranian-revolution-fulfill-its-promises/. }

{**COMMENT**: For nearly 50 years, the US has had a policy of no federal support for reprocessing in recognition of global security implications and with the goal of discouraging other nations from engaging in reprocessing. This has included trying to restrict export of equipment or technology that would permit uranium enrichment and chemical reprocessing. The current sharp turn in federal policy is shortsighted and puts untold future generations in peril.}

Shipments of fresh fuel containing plutonium are of particular security concern because transport is arguably the hardest activity to protect and most vulnerable segment of the nuclear fuel cycle.

Co-locating reprocessing and fuel fabrication plants at reactors would have the security benefit of reducing the amount of transport. "However, this benefit likely would be outweighed by the far greater risks presented by the large number of sensitive reprocessing and fuel fabrication facilities dispersed at multiple reactor sites." (p 49) In addition to the need for more security, there would be the need for enhanced regulations and more inspectors to cover distributed facilities.

"[M]olten salt reactors, which may require co-located pyroprocessing plants to periodically treat the reactor fuel (or even continuously, depending on the design), would be particularly difficult to safeguard." (p 50)

Should such reactor designs and their associated fuel cycle facilities be built in the US, the risk of nuclear terrorism would likewise increase. If these facilities were built in other nations that do not have nuclear weapons, risks of both nuclear proliferation and nuclear terrorism would increase. (p 50)

{COMMENT: Adoption of this technology in other nations would heighten proliferation and terrorism risk globally, regardless of whether they are atomic weapons states. And security risks go way beyond just nuclear terrorism or even terrorism to the whole panoply of security risks, including blackmail, extortion, black market activities, kidnapping, hostage situations. Indeed, this has (as has happened with nuclear workers already. (See e.g.,.
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Fast reactors using plutonium fuels are generally Category I facilities. Sodium fast reactors would require additional security and material accountancy measures.

Reprocessing and recycling of plutonium and other TRU “greatly increases the likelihood that nations or terrorists seeking nuclear weapon-usable material will succeed.” (p 66) Safeguards measures needed to mitigate security risks are costly, cumbersome, and of limited effectiveness. (p 66)

WASTE

When natural uranium is enriched in the U-235 isotope to produce LWR fuel, a large stockpile of depleted uranium (containing >99.7% U-238) is created and typically discarded as waste. (p 40)

A typical 1,000 MW LWR operating at 90% capacity and an 18-month refueling cycle requires around 20 metric tons of LEU fuel each year.

The DOE aspiration for advanced reactors as reactors which may “extend natural resource utilization” or “reduce the burden of nuclear waste for future generations” (Petti et al. 2017) is not clearly achieved by new designs and requirements being proposed.

“Two fundamental questions need to be addressed. First, to what extent would any NLWR and its associated fuel cycle be significantly more sustainable in practice than the LWR once-through cycle? And second**, would those benefits be significant enough to justify the substantial investment required to develop and deploy such a reactor at a large scale? These highly complex questions depend on many variables and are very sensitive to model assumptions**.” (p 32)

Spent fuel contains highly radioactive, long-lived isotopes that must be isolated from the environment for hundreds of thousands of years to protect public health and the environment. (p 32)

Today, no country has a geologic repository ready to accept spent fuel or high-level nuclear waste. Only Finland, which holds a far smaller amount of nuclear waste than the US, is making progress in constructing a deep geologic repository.

The Waste Isolation Pilot Plant (WIPP) in New Mexico accepts only TRU-containing wastes from military activities and is prohibited by law from accepting spent fuel or high level radioactive waste.

The US officially chose Yucca Mountain in Nevada as its sole repository site in 2002 and the DOE applied to the NRC for a construction license in 2008, then withdrew its application in 2010, stating that Yucca Mountain was not workable. (p 34) Yucca Mountain remains the only site designated by law for geologic disposal of spent nuclear fuel and law currently limits its capacity to 70,000 metric tons heavy metal of waste. The US stockpile already exceeds this limit. (p 34)

{COMMENT: The US already holds 90,000 metric tons of spent fuel and is expected to add an additional 2,000 metric tons a year.}

Claims promoted by nuclear developers and others that NLWR designs such as liquid metal–cooled fast reactors, gas-cooled reactors and molten salt reactors could variously “burn” “consume,” or “recycle” spent fuel are misleading.

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

(p 34)

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

(p 34)

One also must consider the total TRU amount remaining in the system, which includes fuel cycle facilities, reactor cores, and storage sites. And the system would have to essentially operate forever.

Specifically, many detailed systems analyses demonstrate that a real world **spent fuel reprocessing and recycling system would need to operate for hundreds or even thousands of years to significantly reduce the total TRU inventory**. This **means that the present generation would bequeath future generations** the need to continue to operate, repair, and replace these systems – with all the attendant cost and risk burdens for hundreds or thousands of years or otherwise be stuck with a large stockpile of TRU. (pp 36 – 38 & 41)

A 2011 Idaho National Laboratory article sums up the situation succinctly: "*significant material accumulates throughout the system during recycling; thus achievement of high waste management benefits depends on continuation of recycling. Do not stop!*" (p 39, citing Piet et al. 2011).

"It is also critical to realize that the term **'waste burning' is an oversimplification** that fails to convey the difficulty, cost, and risks of the industrial processes needed to extract re-usable materials from spent fuel and fabricate them into fresh fuel." (p 36) Reprocessing involves chemical processing to separate fissile components of the fuel such as plutonium and other actinides, dissolution in an acidic solution or other process such as pyroprocessing, requiring use of costly shielded facilities and remote handling equipment. Then fresh fuel has to be fabricated. The proposal to rely on reprocessing is environmentally hazardous and increases the risk of nuclear proliferation by making bomb-usable material easier for terrorists to steal. (p 37)

Spent fuel discharged from a conventional LWR at a typical burnup of around 50,000 megawatt-days per metric ton (MWd/MTU) of thermal energy per ton of heavy metal has a U-235 content of less than

{COMMENT: Burnup is a measure of the amount of energy released while fuel is being used ('burned') in the reactor. Typically the metric used is gigawatt-days per metric ton of uranium (GWd/MTU). Average burnup for decades ago was around 35 GWd/MTU. Operators then steadily began using higher levels of burnup, with a transition to use of high burnup uranium (HBU) fuel >45 GWd/MTU. As reported by the NRC in June 2024: "Industry is currently looking to receive NRC approval to increase fuel burnup limits from 62 GWd/MTU to 75 or 80 GWd/MTU." (NRC: Higher Burnup, U.S. Nuclear Regulatory Commission webpage updated Jun 13, 2024. https://www.nrc.gov/reactors/power/atf/technologies/burnup.html. }

Pyroprocessing is a key component of several proposed advanced-reactor fuel cycles. Its proponents claim the technology would be cheaper than conventional aqueous reprocessing. However they "have a long way to go to demonstrate" that claim – the actual cost of the only operating pyroprocessing system has averaged more than $50,000 per kilogram of spent fuel. (p 59)

HALEU-fueled once-through fast reactors generate more long-lived radioactive waste than LWRs. As illustrated by one study, the quantity of TRU discharged in the spent fuel per GWe-year would be over 500 kg per year: more than twice the comparable value for an LWR. (p 67, citing Hoffman and Fei 2019) Cost is another hurdle for HALEU. Uranium enrichment plants would have to be built or modified to supply HALEU fuel. Downstream conversion and fuel fabrication plants would have to be modified to handle the criticality risks. Security would have to be upgraded to a Category II level. Moreover, supply is likely to be scarce for the foreseeable future. (pp 70 & 72)

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