BREAKTHROUGH INSTITUTE

HOW TO MAKE NUCLEAR CHEAP

SAFETY, READINESS, MODULARITY, and EFFICIENCY

TED NORDHAUS, JESSICA LOVERING, AND MICHAEL SHELLENBERGER

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EXECUTIVE SUMMARY

Nuclear energy is at a crossroads. It supplies a substantial share of electricity in many developed economies — 19 percent in the United States, 35 percent in South Korea, 40 percent in Sweden, 78 percent in France — but these figures may decline as reactors built in the 1960s, 1970s, and 1980s retire. Meanwhile, developing countries are increasingly turning to nuclear to meet rapidly growing energy demand and to reduce pollution. China is currently building 28 reactors and has plans for dozens more; 11 are under construction in Russia, seven in India. Nevertheless, fossil fuels remain dominant worldwide, with coal the reigning king and natural gas production booming. The central challenge for nuclear energy, if it is to become a greater portion of the global electricity mix, is to become much cheaper.

A number of new advanced reactor designs bring substantial benefits over the existing light-water fleet, such as inherent safety mechanisms and the ability to reuse spent fuel. Yet not all features will result in lower costs. So what are the key characteristics that will make advanced nuclear energy cheaper?

The answer lies in part in discerning what has contributed to rising costs. While existing nuclear plants produce affordable energy — they have the second lowest production costs in the United States — new builds have become expensive largely because of strict building standards, environmental and safety regulations, and labor costs. Safety features necessary for current generation reactors — especially massive containment domes and multiply redundant cooling and backup systems — make up a significant portion of such costs.

It is just as important to identify which factors will not decisively influence cost. Fuel availability, waste disposal, and proliferation risk are largely political and institutional concerns, rather than technological challenges, and will continue to require attention regardless of what new designs are pursued. Innovations in fuel cycle and waste reprocessing are unlikely to reduce costs until nuclear energy is much more widely deployed.

Our assessment of nine advanced designs, from high-temperature gas reactors to fusion, finds four factors that will most likely prove determinative in achieving any significant cost declines. We conclude that policymakers, investors, and entrepreneurs should pursue reactors models that are:

1. **Safe.** Inherent safety characteristics eliminate the need for expensive and redundant safety systems.
2. **Ready.** Ready designs will utilize existing supply chains and will not require the development or commercialization of new or unproven materials and fuels.
3. **Modular.** Modularity allows whole reactors or their components to be mass-produced and assembled uniformly.
4. **Efficient.** High thermal efficiency enables reactors to generate more electricity from a smaller physical plant.

Reactors with advantages in these areas show an emerging technological path to safer and cheaper nuclear energy. A good place to begin is with the Generation III+ reactors currently being deployed, which exploit existing supply chains and incorporate new materials and techniques that will prove important to Generation IV designs. Gas-cooled and salt-cooled thermal reactors, which can also rely on much of the light-water supply chain and fuel cycle, are the most ready candidates for commercialization among Generation IV designs. Over time, fast reactors may become attractive for disposing of nuclear warheads and reusing spent fuel, though their widespread commercialization and deployment will most likely depend on the successful commercialization of advanced thermal reactors.

While it is crucial for policymakers to identify the technologies most amenable to commercialization and deployment, it is also important to not lock in energy systems to a single design, as in the case of light-water reactors. The choice is not, for example, between fast reactors and thermal reactors. Policymakers should instead support a broad commitment to nuclear innovation aimed at expanding, rather than restricting, technological options. To advance these priorities, policymakers should support three key areas of reform:

- **Invest in nuclear innovation.** Expand support for public research, development, and demonstration; certification of new materials; supply-chain development; and test facilities.
- **Innovate across advanced designs.** Prioritize technological challenges that have the greatest cross-platform relevance to multiple reactor designs.
- **Licensing reform.** Increase government cost-sharing; integrate licensing with the innovation process, so developers can demonstrate and license reactor components; and lower the costs, regulatory barriers, and time to market for new designs.

Summary Evaluation of Advanced Nuclear Technologies

	GEN III+ LIGHT-WATER REACTORS	HIGH-TEMPERATURE GAS REACTORS	SALT-COOLED THERMAL REACTORS	SUPER-CRITICAL WATER REACTORS	SODIUM-COOLED FAST REACTORS	LEAD-COOLED FAST REACTORS	GAS-COOLED FAST REACTORS	MOLTEN SALT FAST REACTORS	FUSION REACTORS
INHERENT SAFETY									
AMBIENT PRESSURE	NO	NO	YES	NO	YES	YES	NO	YES	YES
MELTDOWN RESISTANT FUELS	NO	YES	YES	YES	YES	YES	YES	YES	N/A
SAFE COOLANT*	YES	YES	YES	NO	NO	NO	YES	YES	N/A
PASSIVE CONVECTIVE OR CONDUCTIVE COOLING	YES	YES	YES	NO	YES	YES	NO	YES	N/A
MODULARITY									
COMPONENTS	YES	YES	YES	NO	DEPENDS	YES	NO	YES	NO
ENTIRE REACTOR	NO	NO	NO	NO	DEPENDS	YES	NO	DEPENDS	NO
SMALL	NO	DEPENDS	YES	NO	DEPENDS	YES	NO	DEPENDS	NO
THERMAL EFFICIENCY	35-37%	40%	46%	45%	40%	45%	48%	45-55%	DEPENDS
READINESS									
PROTOTYPE	YES	YES	YES	NO	YES	YES	NO	YES	NO
COMMERCIAL SCALE DEMONS-TRATION	UNDER CONSTRUC-TION	YES	NO	NO	YES	NO	NO	NO	NO
OFF-THE-SHELF TECHNOLOGY	YES	YES	YES	YES	NO	NO	NO	NO	NO
NO SIGNIF-ICANT MATERIALS R&D	YES	NO	YES	NO	NO	YES	NO	NO	NO

* Whether a coolant is "safe" depends on its chemical reactivity, corrosiveness, ability to transport fission gases, lifetime of induced radioactivity, and any carcinogenic components or byproducts. These risks can be mitigated through containment vessels, double-walled piping, purification systems, and other measures, all of which add complexity and cost. The coolant's ability to transport heat is contained in other evaluative metrics: passive convection and ambient pressure.

INTRODUCTION: THE NEED FOR ADVANCED NUCLEAR ENERGY

The promise of nuclear technologies capable of producing cheap, clean, and abundant energy once inspired widespread hopes in modern progress and captured the imaginations of policymakers eager to deliver on popular aspirations. That promise has not been altogether unfulfilled. Nuclear energy now represents 12 percent of total global electricity production and comprises 19 percent of total electrical generation in the United States, 35 percent in South Korea, 40 percent in Sweden, and 78 percent in France.[1] Existing nuclear plants are one of the cheapest sources of electrical power production in the United States,[2] while France boasts the lowest electricity prices in Western Europe.[3]

Yet construction of new nuclear plants in the developed world has slowed dramatically in recent decades due to rising public concerns about the risk of nuclear accidents, increased construction costs, and slowing growth in electricity demand. As an older generation of nuclear plants retires in the coming decades, nuclear power may decline as a percentage of the electricity mix in many developed economies. The rising cost of nuclear power was not predestined — it was the result of increasingly complex plants with limited technological innovation, combined with higher costs for material inputs and financing that affected all power plants.[4]

Developing countries, by contrast, are now increasing the share of electricity they generate from nuclear energy. This can be attributed to rapid economic growth, rising energy demand, and fewer negative associations with nuclear power, which are tempered by the hardship of living without electricity at all. Large, fast-growing nations, including China and India, are pursuing nuclear in order to diversify their energy mix, rapidly grow their energy supply, and reduce pollution.[5] Their efforts include the continued use of postwar light-water designs as well as a push into more-advanced, safer, and potentially cheaper Generation IV designs.

Even in the developing world, however, the imperative to deploy low-cost energy as fast as possible has limited the scale at which nuclear technologies have been deployed. Coal is still king in developing countries because it is the cheapest source of reliable energy for building the basic infrastructure of a modern society.

The challenge for nuclear is the same as it has been over the last several decades. In order to provide a significantly greater percentage of the global electricity mix than it does now, nuclear energy will need to become much cheaper. This will require advanced nuclear designs that can be built for less and operated safely for many decades without costly retrofitting and repairs.

While there are many promising nuclear designs with beneficial attributes, not all of them translate into lower costs. The purpose of this assessment is to identify key characteristics and likely technological pathways that promise to make advanced nuclear energy significantly cheaper.

Our analysis finds four factors that will likely determine whether advanced nuclear technologies decrease significantly in price. First, designs must incorporate **inherent safety characteristics** that obviate the need for expensive and redundant engineered safety systems. Second, designs must in whole or in part be **built modularly** so that components of plants can be mass-produced and assembled, rather than fabricated, at the construction site. Third, designs will need to be more **efficient thermally** such that they are able to generate more electricity from a smaller physical plant. Fourth, designs must have a **high degree of readiness** in utilizing existing nuclear or industrial supply chains that do not require development or commercialization of new or unproven materials and fuels.

Our analysis further concludes that fuel availability, waste disposal, and proliferation risk are not significant obstacles to nuclear deployment and lower costs. While these concerns continue to occupy a prominent place in the public discussion of nuclear energy, they do not in fact represent the primary obstacles to accelerated nuclear deployment in the foreseeable future.

I. ANALYTICAL FRAMEWORK

Each advanced nuclear reactor technology offers different attributes and improvements over older designs. These attributes include inherent safety, use of more-abundant fuels, waste recycling, modularity, and protection against weapons proliferation.[6] Making sense of the importance of these attributes depends on an understanding of how nuclear technologies were developed, how they work, and why they have failed to scale up as rapidly or as widely as many proponents believed they should have.

In the 1950s, many combinations of fuels and coolants were tested for nuclear reactors, but commercial nuclear energy production quickly settled on light-water reactor (LWR) technologies. Light-water reactors were developed for use by the US Navy submarine fleet, which made sense because the reactors were small, operated in a constrained, pressurized vessel, and were surrounded by water so that rejecting large amounts of waste heat, due to relatively low efficiency, was acceptable.[7] The first generation of commercial reactors developed in the United States and deployed around the world were essentially scaled-up versions of the light-water reactors developed for submarines. As the industry grew, these designs were routinely improved on and built at a much larger scale. Early commercial reactors were comparatively small, typically generating between 600 and 800 megawatts (MW) of electrical power. Starting in the 1970s and 1980s, electric utilities began building much larger versions, typically producing over 1000 MW.[8]

With the exception of France, virtually all light-water reactors built in the United States and around the world during this period were produced with little design standardization. General Electric, Westinghouse, and others designed light-water reactors that were quite different in their technical details, while the design of the civil structures and non-nuclear systems was performed separately by a number of different architect-engineering firms, resulting in further design variability. Designs were further customized to meet additional requirements imposed by different utilities, so that in the US essentially every nuclear plant- built was different.[9]

With the benefit of hindsight, the choice of light-water reactors as the primary design for commercial reactors was less than optimal. Light-water reactors are both water-cooled and water-moderated, meaning that water is used to slow down and control the chain reaction in the nuclear fuel. Because reactors operate at such high temperatures, water must be kept at high pressure in order to maintain control over moderation. The need to keep water pressurized necessitates costly systems to keep both the cooling system and the reactor vessel pressurized. It also requires costly and complicated backup systems to inject additional coolant in the event that the primary cooling system fails.

In the event of a loss of pressure, light-water reactors face a further critical safety challenge. If the reactor suffers a loss of power, it has limited ability to cool itself. Even after a nuclear reactor is shut down and the chain reaction has ceased in the reactor core, the fission products will continue to decay and release heat, resulting in potentially large temperature increases. Without sufficient cooling, temperatures can rise high enough to melt the metallic cladding of the uranium oxide fuel, at which point the fission product gases in the fuel can escape into the coolant or containment vessel. More importantly, if the fuel melts, dangerous fission product gases can be released into the core or containment vessel. This risk requires the construction of extremely durable and temperature-resistant reactor pressure vessels and large, steel or reinforced concrete containment domes to contain the radioactive material in the event of a meltdown.

The inherent safety challenges faced by light-water reactors were further exacerbated as utilities began building much larger reactors. As plants were scaled up, new safety systems had to be engineered to contain potentially larger accidents. Larger reactors generated more electricity but also required larger and stronger containment domes that used costly concrete and steel. The failure to standardize designs provided further challenges. Utilities increasingly found themselves committed to building large, complex, first-of-kind plants whose costs greatly exceeded initial estimates.[10]

While the downsides of the light-water reactor design became readily apparent to observers in the wake of the Three Mile Island accident and a subsequent wave of high profile cost overruns and bankruptcies in the 1980s and 1990s, it has been difficult to get off the light-water reactor path. The advent of passive safety system designs for light-water reactors that can provide cooling without using electrical power represent a significant improvement. But nuclear reactors are complex technologies with similarly complex and costly supply chains. Regulators at the Nuclear Regulatory Commission and other bodies around the world were familiar with the design and operation of light-water reactors and had almost no familiarity with alternative technologies. Many new designs required fuels and materials that had never been fabricated at commercial scales, if at all. These novel materials also need to be tested and certified for reactor conditions. Together with the costs of navigating an extremely complicated and expensive licensing process, the challenges of developing and procuring new materials and fuels proved too great for most nuclear developers.

As we look to new nuclear technologies that might ultimately prove superior to today's light-water reactors, the problems that have bedeviled present designs and have created substantial obstacles for alternatives offer a useful road map for the challenges that nuclear innovation must address in order to shift the basic economics of nuclear deployment.

Innovations likely to increase the pace and scale of nuclear energy diffusion include:

1. Inherent safety features. Recently developed light-water reactor designs implement passive systems to remove decay heat without the use of electrical power. Reactors that are more reliable because of inherent passive safety systems do not need expensive redundant safety mechanisms or complex equipment and power supplies, and will cut substantial costs in both areas.

2. Modular design, in whole or in part. Modularity enables reactors to benefit from economies of scale that come with manufacturing and simplifies site construction work.

3. High thermal efficiency. Reactors that produce more electricity per amount of heat created can be cheaper and use less fuel and cooling water.

4. High level of readiness. Designs that can use more off-the-shelf materials and components should be easier to commercialize at lower cost.

A. Factors *Unlikely* to Significantly Affect the Economics of Advanced Nuclear

Readers familiar with nuclear technology and policy will note this framework does not address waste generation, the nuclear fuel cycle, or nuclear proliferation. These omissions are intentional. Despite continuing public concern regarding these issues, their solutions are largely political and institutional, not technological. Many advanced reactor designs, to varying degrees, mitigate waste and proliferation concerns. But they do not eliminate them. As such, even with designs that produce less waste and are less prone to proliferation, appropriate policies and institutions will be necessary in order to manage high level radioactive waste and discourage states from developing nuclear weapons capabilities. Here we explain why.

1. FUEL CYCLE

Several advanced reactor designs have the capacity to use nuclear fuels much more efficiently than previous generation reactors. They can burn existing waste as fuel, reprocess and reuse spent fuel several times over, and burn a broader range of fuels including thorium. This feature is an advance over light-water reactors — which use only a tiny portion (less than one percent) of the potential energy stored in the enriched uranium fuel — and allows for greater utilization of the energy potential in nuclear fuels and reduced demand for mined and enriched uranium.

Should nuclear energy ever become the primary energy source for human societies, the capabilities of these advanced fast reactors to use nuclear fuels more efficiently would be a great asset. But in the short- to medium-term, this capability is of little direct value.[11] There is no shortage of uranium suitable to power all manner of nuclear designs in the foreseeable future. Until nuclear energy is able to overcome the economic obstacles to its accelerated deployment, the availability and cost of mined and enriched uranium is unlikely to substantially factor into the cost of building or operating nuclear power plants.[12]

In fact, the cost of reprocessing or recycling nuclear fuels today is substantially greater than the cost of using new fuel. Even if this were not the case, the high energy density of nuclear fuel and the high capital costs of building nuclear plants mean that fuel represents a small fraction of the cost of building and operating a nuclear plant. As such, the capability to burn a wide variety of fuels is unlikely to have much impact on the scalability or economics of nuclear technology in the short- or medium-term.

2. WASTE

The ability to recycle fuel, thereby greatly eliminating remaining waste, is also unlikely to improve the economics of advanced nuclear or have much effect on whether nuclear energy can scale.

Should nuclear energy production expand dramatically over the coming century, nations may want or need to recover stored waste for reprocessing at some point. At such time, reactors capable of reusing that waste will become much more important. But for the time being, the capability to burn waste is unlikely to prove particularly important technologically or economically.

Moreover, advanced designs that create less nuclear waste still create high-level radioactive waste that must be disposed of. They may create waste that releases more energy and needs to be handled more carefully, which may draw strong public opposition.[13]

While concern over nuclear waste is one of the most common reasons for public opposition to nuclear power,[14] most nuclear nations are moving forward with spent fuel storage, either after reprocessing or a once-through fuel cycle. A broad scientific consensus exists that deep geologic disposal, in stable geologic formations, can provide effective and safe long-term isolation of nuclear waste. The United States and its long-running dispute over the proposed Yucca Mountain waste repository is an exceptional case.[15] To the degree to which there have been challenges in developing long-term waste storage around the world, those challenges have been mostly political, not technical.[16]

3. PROLIFERATION

Due to the fuels they use and/or the waste they create, certain technologies offer greater resistance to nuclear proliferation than others.[17] Proliferation concerns, however, have never been particularly well founded in relation to specific nuclear energy technologies.[18] Developing a legitimate civilian nuclear energy program is a costly and inefficient way to covertly acquire weapons-grade nuclear material. While states surreptitiously seeking nuclear weapons have, on occasion, veiled their efforts as civilian nuclear energy programs, the act of doing so has usually been transparently false.[19]

Some states may continue to claim they are embarking upon legitimate nuclear energy programs when they are actually seeking weapons, irrespective of the dominant nuclear energy technology. But international efforts to control proliferation will succeed or fail based on the efficacy of international inspections, diplomacy, and institutions — not how amenable particular nuclear energy technologies are to produce weapons-grade material.[20]

In reality, virtually all nuclear technologies, with enough effort and knowledge, can be modified to produce weapons-grade material. In almost every case, however, the cost and effort is substantially greater than pursuing weapons through traditional means, namely by covertly obtaining centrifuges and enriching uranium or building "research reactors" designed intentionally to produce weapons-grade material easily and discretely.[21] Neither tactic is easily confused with developing a legitimate nuclear energy program.

As such, the expansion of nuclear energy technologies is unlikely to have much bearing on the pace of nuclear weapons proliferation. None of the nuclear designs presently under development are likely to represent an easier, less costly, or less obvious path to weapons capability than the well-established path that most nations have taken in recent decades.[22]

B. Key Factors Affecting the Economics of Nuclear

Stricter building standards, evolving environmental and safety regulations, local opposition, and rising labor costs have driven dramatic cost increases for many kinds of large-scale public works projects in developed countries in recent decades. Nuclear construction represents the convergence of those trends, involving large-scale construction projects of enormous complexity, a highly skilled workforce, technologies that entail significant potential public health and environmental risk, and substantial regulatory oversight.

High costs of nuclear cannot simply be blamed on public irrationality. Some nuclear proponents have suggested that irrational public fears of radiation exposure, in combination with the onerous regulation of nuclear designs, construction, and operation, has had a major impact on the rising costs and slowing expansion of nuclear energy. These dynamics appear overstated.[23] While there is strong evidence that public fears of low-level radiation exposure are exaggerated, major nuclear accidents that result in off-site land contamination, however rare, carry substantial localized social and economic costs. The public and policy makers are justifiably reluctant to expose themselves to such risks. It is difficult to imagine public acceptance of nuclear energy technologies that are not openly and comprehensively regulated. Regulatory reforms to streamline the nuclear licensing process and more-holistically regulate nuclear technologies are, without question, desirable. But absent significant technological innovation, those measures in themselves are unlikely to significantly change the basic economics of nuclear energy.[24]

As such, much of the cost associated with construction of current generation light-water reactor technologies is probably inevitable. Technologies that carry significant risk of meltdown, catastrophic accidents, and widely dispersed environmental and public health risks require substantial and costly technological measures and regulatory oversight to mitigate those risks. The fact that nuclear energy has proven remarkably safe is a testament to the extent to which such measures have been taken. Large, heavy-duty containment domes, multiply redundant cooling and backup systems, and close regulatory oversight of plant design, construction, and operation are why nuclear energy has proven to be both extremely safe and increasingly costly.

If they are to fundamentally change the economics of nuclear energy, new nuclear technologies must offer designs that are less prone to meltdown and catastrophic accidents, achieve simpler and more effective containment and use fewer multiply redundant active safety systems. The path to cheaper nuclear energy will in large part require technologies that are inherently safer and simpler.

Yet making nuclear cheaper cannot be reduced to simply making nuclear safer. Poor oversight, management, and labor relations have also been major factors in rising costs.[25] Standardized designs that can be assembled from prefabricated components reduce the burden on and risk from management. Designs that promise substantially greater standardization and modularization thus offer another path to significant cost reductions.

Reactors that are more efficient — produce more electricity compared to heat — can also reduce costs. They require less fuel, produce less wastewater from cooling, and can be relatively smaller in plant size for a given amount of energy production.

Finally, designs that are able to utilize existing supply chains, operational know-how, and regulatory familiarity are likely to face a faster and cheaper path to commercialization. The history of energy technologies is mostly evolutionary, not revolutionary. Because the evolution is so capital-intensive, the slow progression away from light-water reactor technologies is not surprising. The degree to which any new reactor technology is derived from the incremental evolutions of existing materials, fuel sources, components, supply chains, and manufacturing capabilities, and is developed within the context of existing institutions, legal frameworks, and regulatory structures will likely play a strong role in determining its prospects.

1. SAFETY

A. AMBIENT PRESSURE

Building reactors that can operate at very high pressures is one of the key drivers of the high cost of present-day nuclear technologies. Multiple cooling systems with multiply redundant pressurization mechanisms must be included in such designs to minimize the risk that the reactor will lose pressure and potentially cause meltdown and radiation release. Containment systems must be capable of withstanding both high pressures and high temperatures in the event of the loss of pressurized coolant.

New reactor designs that can operate at ambient pressure — using coolants capable of functioning at normal pressures and higher temperatures — promise substantial cost savings. Such designs require less steel and concrete, which comprise over 95 percent of the material energy inputs for nuclear power plants.[26] And they require fewer costly nonmaterial inputs such as skilled labor to install complex cooling and control systems. Nonpressurized designs can also be configured as a pool-type reactor — where the primary coolant loop sits inside a pool of coolant along with the reactor core — instead of a loop design, which is larger and more complex. Ambient pressure designs, especially pool-type designs, often require fewer pumps, valves, and circulating systems, which reduces complexity of construction and capital costs.

B. NEW FUELS AND COOLANTS

How prone the reactor design is to continued heating after the reactor has shut down is another feature that can enhance inherent safety and thus lower costs. Reactors capable of cooling themselves in the event of an accident or loss of power, with no human or mechanical intervention, dramatically reduce the possibility of temperatures inside the reactor core rising high enough for the fuel to melt and fission product gases to breach the reactor vessel.

New reactor designs are able to cool themselves passively in one of two ways. Either they feature low power density, meaning that they cool themselves through conduction (heat dissipates through the structure to the ground), or they rely upon coolants and cooling systems capable of cooling the reactor through natural convection (coolant continues to circulate due to buoyancy forces and dissipate heat with no assistance from power systems or pumps).

As with low pressures, reactors that can cool themselves without power or mechanical assistance should require substantially less containment and backup safety systems. As such, the risk of meltdown is vastly lower.

2. MODULARITY

Another potential pathway to substantially lower nuclear construction costs involves size and modularity. Modular plant designs can be large, like the AP-1000 or the European Pressurized Reactor (EPR), where major components like the pressure vessel are built in a factory and shipped to the site; or they can be very small, where the entire reactor is built in a factory and then plugged into an electricity generating system, either a traditional Rankine steam engine or a Brayton power system. Building components — and ultimately entire reactors — modularly promises to standardize construction techniques and bring significant cost efficiencies.

Modularity and standardized designs also increase safety, which can yield economic benefits by decreasing downtime for repairs. Standardized designs can also improve plant performance and reduce operating and maintenance costs, as operating procedures and training can also be standardized.[27] But some studies suggest that operations and maintenance costs are higher per unit of energy in smaller nuclear power plants.[28]

Reactors that are small — defined as having a power capacity less than 300 MW — can be constructed entirely modularly from components small enough to be shipped by rail. Fully modular reactors (small modular reactors, or SMRs) promise cost reductions in two ways. First, by manufacturing more reactors of smaller size at centralized facilities, manufacturers are likely to see faster learning curves, which should translate into faster cost reductions. Second, by allowing nuclear plant operators to gradually scale up the number of SMRs in a single location, up-front costs are lower. SMRs provide a way for utilities to have nuclear on the grid without the risks that accompany the up-front investments in large reactor designs.

In theory, virtually all reactor designs, including current light-water reactor designs, can be produced modularly. However, many new nuclear technologies, as noted above, promise substantially simpler designs thanks to greater inherent safety characteristics, which may make them more promising to build modularly at significant cost savings.

3. THERMAL EFFICIENCY

Increasing thermal efficiency, the ratio between electricity and heat produced, is another key lever to improve the overall economics of nuclear power. Fossil-fueled power plants have slowly improved their thermal efficiencies over the last several decades, but light-water reactors haven't changed. LWRs have thermal efficiencies under 33 percent, compared to modern coal plants at approximately 39 percent and combined cycle gas plants at 50 to 60 percent.

A higher thermal efficiency increases the amount of electricity produced for a given reactor size. Higher thermal efficiency also means less waste heat and less water needed for cooling, which lessens the thermal environmental impact and the costs of dealing with that waste heat.

Thermal efficiency is dependent on the temperature of the reactor core and how efficiently the working fluid can be compressed and expanded. Higher temperatures allow for the use of a more efficient power conversion system, usually through the use of a Brayton cycle turbine, the same system used in a combined-cycle natural gas turbine. For this reason, many advanced reactor designs target higher operating temperatures in order to utilize Brayton cycle turbines, while others use alternate means to boost efficiency.

Reactor designs that employ a Brayton cycle engine are also better able to adjust their power output (load-follow). This may be economically attractive to utilities that operate in deregulated electricity markets, as they can more easily match demand.

4. READINESS

The fourth characteristic of reactor designs that may substantially reduce cost is readiness: how similar the design and key components are to the existing nuclear designs. The more components a given design shares with either existing light-water designs or other proven, widely diffused industrial technologies, the greater the opportunity to take advantage of existing supply chains and cost advantages that come with highly scaled technologies, materials, and components. New nuclear designs that rely upon components and materials that are off-the-shelf are likely to be much cheaper. The more new designs require only incremental evolution of existing regulatory frameworks, the more likely and quickly they are to be commercialized.

II. ADVANCED NUCLEAR TECHNOLOGIES

In 2001, the United States Department of Energy (DOE) developed a reactor classification system called "generations" to distinguish between different families of reactor technologies.[29] The early prototypes of commercial reactors are all classified as Generation I. Generation II refers to the standard commercial designs that were constructed and operated through the 1990s in the United States, and almost every reactor in operation around the world today. Generation III reactors incorporate improvements developed during the decades of operating Generation II reactors: improved fuels, advances in thermal efficiency, some passive safety systems, and a standardized design.[30]

Presently, Generation III reactors have only been constructed and operated in Japan, with several under construction in Russia, India, and China.[31] The US Nuclear Regulatory Commission approved several Generation III designs, but quickly switched focus to Generation III+ designs, which require specific passive safety features (no human or mechanical intervention to cool the reactor in an emergency). No Generation III+ reactors have begun operation at this time, but several are under construction around the world, including in the United States. Anything radically different from previous designs falls under the classification of Generation IV.

The Generation IV International Forum (GIF) created a taxonomy of Generation IV designs under development around the world.[32] Gen IV reactors include metal-, salt-, and gas-cooled designs, high-temperature reactors, and breeder reactors. In the sections that follow, we evaluate the designs identified through this taxonomy, as well as leading Gen III+ and proposed fusion designs based upon the framework elaborated above.

A. Generation III+ Reactors

Description

Generation III+ reactors developed from traditional light-water reactors. Generation III+ reactors are designed for a 60-year lifespan, in comparison to the 30- to 40-year lifespan of Generation II light-water reactors, which makes them more attractive for investors and utilities. Gen III+ reactors are also more efficient at burning fuel. For example, the European Pressurized Reactor uses 17 percent less uranium per kilowatt-hour (kWh) than existing LWRs.[33]

Generation III+ reactors are water-cooled and water-moderated thermal designs. The reactors are pressurized to keep the water liquid, or control the phase change as in a boiling-water reactor (BWR, a subset of LWRs). Most designs use a low-enriched uranium-oxide fuel (less than 5 percent U-235 compared to U-238). These designs can also burn mixed-oxide fuel — a combination of plutonium and uranium made from reprocessed spent fuel or decommissioned weapons material. The specific reactors are similar to existing LWR designs, but have important yet incremental improvements in cost reduction, thermal efficiency, safety, and design simplification.[34]

Inherent Safety Features

Gen III+ designs like the Westinghouse AP1000 plants being built in China and the United States and the European Pressurized Reactor (EPR) feature a range of safety improvements. These include stronger containment domes to better withstand earthquakes and airplane crashes. Passive plant designs like the AP1000 have safety systems that can cool and stabilize the reactor core for a minimum of 72 hours after an emergency shutdown with no human intervention or electrical power required.[35] Other Gen III+ designs use increased redundancy for active safety systems and diesel generators to improve reliability. Core Damage Frequencies (CDF) in Gen III+ reactors — the probability of a significant core-damaging event like a meltdown — are hundreds of times lower with these safety features than today's light-water reactors[36].

Several Gen III+ designs — like the EPR, the Economic Simplified Boiling-Water Reactor (ESBWR), and VVER-1000 (the Russian version of a pressurized-water reactor) — have a core catcher: if the core were to meltdown, it would melt into a large structure which spreads out the molten fuel into heat resistant channels to quickly cool and halt reactions.[37] The passive designs also employ a gravity-fed coolant, where a large tank of coolant is stored above the reactor, and is released automatically in the case of a power loss. Other features include stores of high-pressure gas that pump water in the case of a loss-of-power accident and redundant backup–power generation and battery systems.

The main safety and economic problem facing such Gen III+ designs is that they are light-water reactors. While their safety systems are a great improvement, the reactor core is still pressurized, meaning that the loss of coolant is more difficult to cope with, allowing decay heat to raise the fuel temperature. Water at high temperatures is also corrosive, so the reactor must be shut down periodically for component inspection and monitoring. (These inspections are now often coordinated with refueling shutdowns.) In short, high pressure makes the design more complex to construct, and thus more expensive.

Modularity

Generation III+ reactors use standardized designs and some modular components and equipment, such as pressure vessels. Single, standardized designs are meant to streamline licensing, reduce capital costs and construction time through institutional learning, and allow future problems to be addressed uniformly.

Babcock and Wilcox, Westinghouse and Holtec, and NuScale are currently developing small Gen III+ reactor designs that are entirely modular, meaning the whole reactors are built offsite and shipped by railcar or flatbed truck. Small, fully modular versions of Gen III+ designs could bring more safety and simplicity.[38] Thanks to their much smaller size, they can be located "below grade" (underground), which facilitates improved decay-heat removal and cooling through natural circulation, and reduces the risk of accidents due to airplane crashes or malicious attacks. Their simpler and smaller design also significantly reduces the numbers of valves, pumps, and other equipment used, simplifying maintenance and increasing reliability.

Thermal Efficiency

Most Gen III+ reactors have been designed to achieve modestly higher thermal efficiency than existing Gen II LWRs. For example, Areva's EPR has a thermal efficiency of 36 percent. Other designs claim higher efficiencies, but since they have not been licensed yet, these are uncertain. In general, Gen III+ reactors range in thermal efficiencies from 35 to 37 percent. These reactors are limited by their use of existing materials, which means that their outlet temperatures are only 10–20 degrees higher than existing LWRs. Because they are water-cooled and operate at relatively low temperatures, Gen III+ reactors cannot utilize Brayton cycle engines.

Readiness

There are currently six AP1000s under construction globally, four in China and two in the United States. Two more are under contract in the United States and eight more are under contract in China. One of the Chinese plants will begin operation in 2014.[39] Additionally, there are 10 more applications to build AP1000s in the United States.[40] There are also four EPRs under construction in France, Finland, and China.[41]

The US NRC approved the AP1000 and has three other designs under review: the Economic Simplified Boiling-Water Reactor (ESBWR), the European Pressurized Reactor (EPR), and the Advanced Pressurized-Water Reactor (APWR).[42] Small modular Gen III+ designs from Babcock and Wilcox, Westinghouse, Holtec, and NuScale are currently preparing for NRC licensing with initial commercialization slated for 2022.[43]

Gen III+ reactors with very large size have experienced construction delays and cost overruns. Areva began construction on the first 1600 MW EPR in 2005 in Finland. Construction delays and cost overruns have plagued the plant, with an expected start date now 2015 at the earliest. Its estimated total cost today is $10 billion. The EPR in France began construction in 2007, and its costs have also escalated to more than $10 billion. Completion has been pushed back to 2016.

Areva is constructing its third and fourth EPR in China on the schedule and budget originally expected for the first Finnish unit, which is still not complete. These may end up being the first Gen III+ reactor to come online, with expected grid connection in late 2013 and early 2014. They will have taken about four years to construct — less than half the time needed for the French and Finnish plants.[44]

Bottom Line

Generation III+ designs deliver improved safety and better economics, but they remain large, capital-intensive, and dependent on water coolant and engineered safety systems. The numerous and continuing orders for these designs demonstrate they fill a niche, particularly in rapidly growing countries, and even in some Western countries looking to replace aging reactors or coal-fired plants. A forthcoming wave of small, fully modular Gen III+ reactors may offer opportunities for much greater economies of repetition or multiples leading to cost reductions. However, all Gen III+ designs require pressurization and feature cooling systems that need various mechanical interventions in order to cool the reactor in the event of loss of power or pressure.

B. Generation IV Reactors

OVERVIEW

Generation IV nuclear reactors include a broad range of technologies, but their unifying characteristic is they are not light-water reactors. They may burn a different fuel, use a different coolant, have passive cooling systems, use fast neutrons, or have entirely different geometries and structures. Many of these designs were created and tested in the early years of nuclear power, but were abandoned as the United States settled on light-water reactors.

The Generation IV International Forum aims to design Gen IV reactor materials to last for 60 years,[45] but whether the NRC will license reactors for this long remains to be seen. While longer lifespans give utilities more financial confidence in their investment, the NRC requires rigorous testing for such materials and equipment before licensing. Reactor developers need to guarantee that materials can withstand decades of radiation, neutron bombardment, high heats, and pressures, or else be economically monitored and replaced. Many advanced nuclear designs rely on new types of materials that are undergoing this strident strength and durability testing.

It is for this reason that, at today's pace of innovation, the nuclear industry and nuclear regulators do not anticipate commercialization of Gen IV reactors for many years. For commercialization to quicken globally, there would need to be greater and more-focused efforts as well as increased financing for the demonstration of Gen IV reactors around the world.

What follows is a description of the most mature Generation IV reactor designs, followed by an evaluation of each technology based upon the criteria defined above. We also offer a compilation of the most significant technical obstacles each must overcome to be ready for commercialization.

THERMAL VS. FAST REACTORS

Gen IV designs are characterized by two basic types of reactors: thermal reactors and fast reactors. Like all commercial reactors today, thermal reactors require a moderator to slow down neutrons released in the atomic fission reaction. Thermal reactors need enough neutron reactions to maintain a chain reaction, but not so many that the reaction generates transuranics (heavy atoms that don't easily fission and stall the chain reaction) too quickly.[46] Conventional commercial reactors use pressurized water to moderate the neutron reactions. Gen IV thermal reactors depart from earlier generations of thermal reactors because they use either graphite or supercritical water to moderate the reaction instead of conventionally pressurized water.

Fast reactors, by contrast, don't moderate neutrons but provide different fuels that fission more readily when bombarded with neutrons. Fast reactors can burn more of their fuel before fission products build up and the fuel must be replaced. They are also able to burn a greater variety of fuels, including depleted uranium, spent fuel waste, and thorium. These fuels make them an attractive option for long-term spent fuel management and waste disposal. However, fast reactors, as the name implies, have many more neutrons reacting with core materials at higher energies. This high neutron flux causes the fuel rods to swell and deform and makes the core materials prone to void swelling, irradiation creep, and structural changes,[47] which requires special fuels and steels that are still in the experimental stage.

1. THERMAL DESIGNS

A. HIGH-TEMPERATURE GAS-COOLED REACTORS

Description

The high-temperature gas-cooled reactor (HTGR) is a thermal reactor that uses ceramic uranium fuel. The designs can be cooled with helium or carbon dioxide, and are moderated with graphite. HTGRs are designed to create electricity along with process heat for use by industries and manufacturing processes like oil refining, chemical and fertilizer production, and desalination.[48] Government goals of reducing carbon emissions from heavy industry are currently hampered by a lack of low-carbon process heat.[49] Some designs are known as very high–temperature reactors (VHTR).

The United Kingdom and France built dozens of gas-cooled thermal reactors for commercial electricity productions in the 1960s and 1970s; they were also used to produce plutonium for weapons. Although not high-temperature reactors, these reactors were graphite-moderated and cooled with supercritical carbon dioxide.

Inherent Safety Features

The many passive safety features of the HTGR make it an extremely safe design that should substantially reduce the possibility of significant accidents or meltdowns. A test of the passive safety features of an HTGR was performed in China in front of a panel from the International Atomic Energy Agency in 2004; the reactor successfully withstood a loss of coolant and dissipated heat without any human or mechanical intervention.[50]

Unlike most reactor designs characterized by high power density, HTGRs are designed to have a very low power density, which makes them difficult to overheat.[51] Because HTGRs are large in relationship to power output, they take a long time to ramp up in temperature not only under normal operation, but also when there is a loss of coolant. Thus, operators have a longer period of time to inject coolant or repair the reactor before the decay heat raises the temperature enough to melt the fuel.

While HTGRs require pressurization, the consequences of losing pressure and the coolant are much less significant than with light-water reactors. Low power density, combined with the fact that HTGRs are designed to operate underground, means that in any emergency where there is a loss of coolant, the reactor reaches a temperature equilibrium with the surrounding earth long before any components become hot enough to be damaged.[52]

The HTGR uses pressurized helium as a coolant, which poses no threat to human health. Helium is inert and does not react with other elements or become radioactive when bombarded with neutrons. Helium is also noncorrosive — a critical feature for helping materials last for 80 years or longer — and single-phase, meaning that it will always remain a gas in the range of temperatures required for operation.

If an accident occurred that punctured the cooling system and released all the helium from the reactor, there would be no radioactive material released or ill health effects. The inherent safety features of the HTGR, namely the low power density and stable coolant, also make modeling the reactor's safety systems much simpler.

The HTGR, like a number of the other Gen IV designs, utilizes ceramic fuel particles called TRISO (Tristructural-isotropic), which bring a number of important safety advantages. These fuel particles have a core of uranium dioxide, surrounded by several buffer layers, and a final outer coating of silicon carbide, which contains the fission product gases. The particles are able to withstand temperatures up to 2000^{o}C before they begin to fail and release fission product gases — well above the temperatures expected in even the most serious reactor accidents.[53] These properties effectively mean that the fuel is extremely difficult to meltdown.

HTGR spent fuel can be moved straight to dry storage on site and does not require years of water cooling like LWR spent fuel. Due to its ability to withstand pressure and temperature, the ceramic cladding on the fuel particles ensures it can be safely stored for long periods of time without degradation.

There are a number of potential challenges, primarily economic, associated with the cooling system of the HTGR. While the loss of coolant in an accident would not have significant health or safety consequences, the cost of replacing the helium and repairing damaged equipment could be significant. Additionally, if pressurization is lost in an incident, water leakage could create a positive void coefficient around the core, which would increase the rate of fission reactions as the fuel came into contact with the water. This could lead to minor accidents and unplanned outages, but not dangerous meltdowns with radioactive releases as in the cases of Chernobyl and Fukushima. While loss of pressure may be a rare occurrence, developers will need to prove that this problem is mitigated in all accident scenarios before licensing.

A more serious problem is air leakage; oxygen reacts with the carbon in graphite to produce CO and CO_2, which can be corrosive to graphite components. Nevertheless, this problem would mainly be an economic issue. Potential owners and operators of HTGRs will need to know how common air leakage is, how much it costs to repair, and how much life a reactor core loses with each incident.[54]

Modularity

The simplicity of the design and safety systems of HTGR may lead to lower costs. Many HTGR developers are designing very low–power reactors that could be constructed modularly. These designs will have output powers of around 300MW, in comparison with the 1200MW of today's LWRs. Building HTGRs modularly may mean construction cost savings in exchange for much lower power output.[55] However, the HTGR will most likely be built with modular components and construction techniques, similar to large Gen III+ LWRs.

Where many Gen IV designs promise significant cost saving from generating large amounts of energy from relatively smaller physical plants, the HTGR achieves its admirable safety characteristics in exactly the opposite manner, generating similar levels of energy from a larger physical plant. The pressure vessel, which holds the reactor, is unique in its large size and thickness. Novel welding and fabrication techniques will need to be developed for commercial development of these reactors.

Thermal Efficiency

One of the main benefits of high temperature reactors is their high thermal efficiency. The GIF roadmap sets a target for VHTR designs to achieve high enough temperatures to employ a Brayton power cycle and reach thermal efficiencies of 50 percent. However, the challenge of finding materials able to withstand such high temperatures along with irradiation has caused most VHTR developers to design reactors with lower temperatures and efficiencies. The US Next Generation Nuclear Plant VHTR only has a 40 percent thermal efficiency because it uses a Rankine steam power system with a target outlet temperature of 750°C.

Readiness

HTGRs can be constructed entirely with existing materials that are already certified. The Nuclear Regulatory Commission and other regulators are familiar with the HTGR due to its similarities with light-water reactors. In a 2012 solicitation of nuclear experts, the HTGR was chosen as the most mature Generation IV thermal design.[56] Because the fuel pebbles are ceramic based, they are not currently compatible with the existing fuel supply chain. Developers are in the early stages of optimizing components and beginning licensing work in the United States, but this work has stalled as funding has slowed.

Europe has significant experience with gas-cooled reactors, and both China and Japan have operating test reactors. China is currently building two commercial scale pebble-bed HTGR demonstration reactors, which should be completed in 2014.

The HTGR's unique ability to dissipate heat without its primary coolant creates licensing challenges. The NRC has no rules for evaluating reactors that can rapidly dissipate heat with only air as a coolant or fuel incapable of melting. NRC regulations focus entirely on preventing loss of primary coolant. Commercial licensing of the HTGR is thus expected to be a long and expensive process, as developers will have to fund the NRC's research and rulemaking. For these reasons, the first HTGR prototype capable of receiving NRC licensing is expected to cost a total of $3.5 billion and will not be finalized until 2025.[57]

Bottom Line

The HTGR seems an unlikely candidate for broad commercialization due to its low power-density, though it may serve a niche market for low-carbon process heat. The inherent safety of the HTGR means that the plant can be colocated with industrial plants, which could prove very economic for cogeneration and process heat. Large industrial corporations like the Dow Chemical Company and ConocoPhillips have joined the Next Generation Nuclear Plant Industry Alliance (NGNP) to support commercialization of HTGRs.[58] A partnership between one of these large companies and an HTGR developer that secured a cost-sharing grant from the DOE for licensing and demonstration could accelerate commercialization.

B. SALT-COOLED THERMAL REACTORS

Description

Fluoride Salt–Cooled High-Temperature Reactors (FHR) utilize a molten salt coolant, slow neutrons, and either solid or liquid fuel. Due to its high boiling point, fluoride salt coolant remains liquid at low pressures and high temperatures. This allows the reactor vessel to be unpressurized and employ a pool-type reactor configuration, as opposed to the traditional loop configuration used in LWRs. A pool-type reactor has the benefit of natural convective cooling in the case of pump failure. As a result, FHRs can naturally remove heat without human or mechanical intervention.

There are currently two closely related salt-cooled thermal reactors under development. The pebble bed advanced high-temperature reactor (PB-AHTR) utilizes the same ceramic fuel particles as the HTGR. A second design, the liquid fluoride thorium reactor (LFTR), uses a thorium molten salt fuel dispersed in a pool of molten fluoride salt coolant.

Inherent Safety Features

The PB-AHTR offers many of the same inherent safety features as the HTGR discussed above. Fuel pebbles are cycled through the reactor several times and can be inspected in situ between each pass through the reactor core for integrity, damage, and how much fissile material is left. The LFTR requires no fuel cladding whatsoever. There is no risk of the fuel melting because the reactor vessel is designed to operate and contain the fuel in liquid form.

Both the PB-AHTR and the LFTR utilize fluoride salt compounds as coolant. There are several different fluoride salt compounds that can be used, each presenting trade-offs among performance, safety, and cost. The most promising coolant is a mixture of lithium fluoride and beryllium fluoride, aka "flibe," which has a negative void coefficient[59] — meaning that the rate of nuclear reactions will slow if coolant is removed. Beryllium, however, requires careful handling because it is toxic and can lead to lung problems if inhaled.

Other fluoride salt coolants without beryllium are cheaper, but generally have positive void coefficients, which means the rate of nuclear reactions increases and more heat is produced if the coolant is removed. Beryllium alternatives also have higher neutron absorption, reducing the amount of fuel that is burned (mainly an economic and waste storage problem). It is unclear whether the NRC would license a reactor with a positive void coefficient, though the larger negative temperature coefficient may offset this issue.[60]

Salt coolant can also be corrosive to metals, weakening the core structures and depositing corrosion products in cold regions, leading to potential plugging. Corrosion can be significantly minimized if salt that is devoid of all impurities is used, but manufacturing pure salt can be expensive. When flibe was used in the late 1960's to transfer heat through the secondary loop of the Molten Salt Reactor Experiment, no corrosion was detected in the loop and negligible contamination of the salt was found after four years of operation.[61] This same coolant test will need to be run through an FHR. Both the PB-AHTR and the LFTR designs rely on continuous coolant monitoring for contamination and an integrated coolant purifying system, which removes contaminates like fission product gases and transuranics in situ. This system adds complexity to the overall plant; performance and reliability need to be fully demonstrated at scale.

Ceramic fuel particles (TRISO) used in the PB-AHTR were originally created in the United Kingdom in 1959 for a high-temperature test reactor, and were later used in two German gas-cooled reactors. They are currently employed in just two test reactors, one in China and one in Japan.[62] High quality TRISO particles must be produced with extreme uniformity, and although this has been achieved, commercial scale production may place new demands on manufacturing facilities. Strict quality control of TRISO fabrication would have to be maintained in order to prevent declines in pebble lifetime and performance. TRISO particles still require irradiation testing to confirm their stability in the conditions specific to the PB-AHTR.

Liquid fuel, dissolved in the fluoride salt coolant of the LFTR, avoids many of the manufacturing challenges associated with utilizing TRISO particles. However, liquid fuel requires careful monitoring and removal of noble-gas fission products and other waste that will otherwise poison the nuclear reactions, a process that has yet to be demonstrated commercially.

Modularity

Both the PB-AHTR and the LFTR are well suited to modularity. Because of the pool-type design and integrated containment structure, the overall footprint of the plant can be up to a third of the volume and area of a Gen III+ plant, and about one-fifth the size of a sodium-cooled fast reactor.[63] Prominent LFTR designs are even smaller, expected to range from capacities of 25 to 100 MW.

PB-AHTR developers also plan to employ a modular construction technique currently used in China and South Korea for large LWRs that uses steel plate reinforced concrete, an innovation that has reduced construction time by 10 months in Korea. This technique makes the concrete structure stronger, more flexible, and able to withstand even airplane crashes and earthquakes. It also doubles as the containment structure for the reactor. While any new nuclear builds could use steel-reinforced concrete, the PB-AHTR incorporates this modular technology into its plant design.

Thermal Efficiency

Due to the thermal properties of salt, salt-cooled reactors can reach higher thermal efficiencies at lower temperatures than VHTRs (700°C compared to 800°C), and many employ Brayton power systems. For example, the PB-AHTR has a thermal efficiency of 46 percent by employing a multiple reheat Brayton engine, similar to those used in combined cycle gas turbines.

Readiness

The PB-AHTR was engineered to use off-the-shelf components and the established US nuclear supply chain. The fuel pebbles were created for the gas-cooled, high-temperature reactors described above. The molten salt coolant was designed and tested in fast reactors. The pool configuration is based on the sodium-cooled fast reactor, and its Brayton engines can be purchased off-the-shelf and are widely used in today's highly efficient natural gas turbines.

While fluoride salt has a large operating range of temperatures, it also has a high freezing temperature (300-500°C). The risk is not meltdown but rather lost capital investment should the salt coolant freeze and seriously damage the reactor. While experience from some initial models suggest that a solidified coolant could have certain benefits, such as sealing in melted fuel or preventing leaks, further testing at different scales and under extreme conditions will be necessary before the design is ready for approval.

The PB-AHTR was engineered to use metals such as 316 stainless steel that have been certified by the American Society for Mechanical Engineers (ASME) — an NRC requirement — for the primary system pressure boundary and structures. Other materials such as Alloy N and molybdenum may be better suited in terms of long-term performance, but it is uncertain how much more testing and characterization these materials need before they can be approved by the ASME and the NRC.

The LFTR brings the advantage of utilizing a liquid fuel, which obviates the need for costly fuel fabrication and cladding, but requires careful monitoring and filtering of dissolved fuel. Technologies capable of monitoring and filtering liquid fuels have not been developed or proven, suggesting that the commercial scale development of the LFTR will likely evolve from the PB-AHTR design if and when the PB-AHTR is commercialized.

The Chinese Academy of Science announced in early 2011 that they would massively scale up their research and development of a molten salt-cooled design and complete a research reactor by 2017.

Bottom Line

Among new nuclear technologies, the PB-AHTR alone meets all of the key criteria identified in this assessment as critical to achieving substantial cost reductions relatively quickly. It operates at ambient pressure and utilizes a fuel and coolant that are not prone to runaway heating or meltdown. It is well suited to be fully modularized. It is largely based on components and materials that have been proven technologically at commercial scale. The PB-AHTR still faces a number of uncertainties, technical hurdles, and supply chain challenges but could be ready for commercialization by the mid-2020s. The LFTR is likely to follow the PB-AHTR into development and commercialization — the LFTR represents both an advancement over the PB-AHTR and a potential evolutionary bridge to the commercialization of fast reactors, as its dissolved fuel, pool type, design, and molten salt coolant are features of molten-salt fast reactor designs.

C. SUPERCRITICAL WATER REACTORS

Description

The supercritical water reactor (SCWR) is a high-temperature pressurized reactor that uses water as both a coolant and neutron moderator. Water becomes supercritical when kept at a high enough temperature and pressure such that steam and liquid have the same density and are thus indistinguishable. The benefit of supercritical water as a coolant and moderator lies in its simplicity. There is no need for extensive equipment to separate or dry the steam. There is no risk of chaotic bubbles forming when the water makes a phase transition. The SCWR can be designed as either a thermal or a fast reactor. It uses traditional uranium-oxide fuels, but could be designed to burn transuranics from spent fuel, fuel pebbles, or thorium, depending on whether it uses fast or slow neutrons.

Inherent Safety

While it shares many features with existing light-water reactors, the SCWR offers a number of design elements that promise greater simplicity and inherent safety. The SCWR employs a once-through cooling system, where the water from the reactor core runs directly through the steam turbine. However, unlike a boiling water reactor, which also uses a once-through cooling system, the supercritical water coolant never changes phase between liquid and gas. Thus, many complicated systems — steam separators, steam dryers, recirculation pumps, and secondary cooling systems — are eliminated from the design. Both the efficiency and simplicity imply a much smaller reactor for the rated power, which could lead to improved economics over LWRs.

Nevertheless, the SCWR shares many design elements that have hobbled deployment of LWRs: a corrosive water coolant, a pressurized reactor core, and engineered safety systems requiring redundancy and backup power. SCWRs operate at very high temperatures and pressures in order to keep the water in a supercritical state. The pressure vessel for the SCWR must have about 1.5 times the pressure of a LWR, and about 250 times more pressure than most Gen IV designs. Passive safety features are more difficult to implement in a pressurized design and are less robust, requiring human or mechanical intervention much more quickly. Fast neutron SCWRs also have a positive void coefficient, which can lead to uncontrolled heating if bubbles form. Finally, supercritical water is more corrosive than steam at these temperatures, and SCWRs may require advanced metals for the core that are still in the experimental phase.[64]

Modularity

SCWR developers are focused on large power outputs, and, due to the complexity of the safety systems in these reactors, this implies very large plants as well. With a target set by Generation IV International Forum at 1700MW, the SCWR does not look promising for modularization.[65] Indeed, no developers describe modularization as a goal. They are more focused on economies of scale through large reactor sizes.

Thermal Efficiency

The high temperatures achieved in SCWRs improve the thermal efficiency: the target SCWR is 45 percent compared to 33 percent for the best LWRs today.[66] Even though it only has an outlet temperature of 625^{o}C, the Canadian CANDU-SCWR will have a thermal efficiency of 48 percent. However, the materials and structural challenges associated with such high temperatures and the highly corrosive supercritical water may prevent the SCWR from ultimately fulfilling such promises.

Readiness

Because it shares many elements with light-water reactors, the SCWR has the advantage of familiarity for NRC licensing. It can make use of many elements of the existing nuclear supply chain and a large knowledge base with regard to construction, operation, and maintenance. One significant drawback is the materials challenge for core materials such as fuel cladding, which need to withstand high temperatures, irradiation, and corrosion.[67]

Bottom Line

The SCWR is one of the least promising Gen IV designs due to its higher core temperatures, its greater neutron flux, and its use of novel materials. While water coolant may be very familiar to LWR operators and regulators, the materials required for the core are not. Supercritical water is highly corrosive. Current research and development programs for SCWR are still identifying potential materials, which are thus several years away from selection and testing and another decade or two from prototyping and approval. Even with significant research funding, the time these materials must be exposed to different temperatures, neutron fluxes, and coolants will require several years at minimum for testing and optimization before a prototype can be constructed. For these reasons, few national nuclear programs have chosen to focus on the SCWR, and its experiments will slowly proceed in the background of other nuclear R&D efforts.

2. FAST REACTORS

A. SODIUM-COOLED FAST REACTORS

Description

The sodium-cooled fast reactor (SFR) is a fast neutron reactor that uses liquid sodium metal as coolant. The SFR is capable of burning either metal alloy or uranium/plutonium oxide fuels. Because sodium is liquid at the reactor's operating temperature, the reactor vessel does not need to be pressurized, allowing the SFR to utilize a pool-type design, where the primary coolant and heat exchanger can sit in the reactor vessel.[68]

A slightly different SFR design is the traveling wave reactor (TWR), most prominently under development by the private company TerraPower. The TWR is a sodium-cooled pool design that uses depleted uranium for fuel. Rather than breed fuel in one reactor and burn it in another, the TWR breeds fuel in one part of the core and burns it in another part following a wave of fission. Another unique aspect of the travelling wave reactor is that the fuel rods allow for fission gases to escape in a controlled process, which prevents void swelling and allows the fuel to stay in the reactor for up to 40 years. This means the reactor is extremely efficient at burning fissionable material.[69] This method was originally developed for the US Integral Fast Reactor (IFR) program, but was never tested because the program was cancelled.[70]

Inherent Safety

The pool configuration and nonpressurized vessel have many safety and economic benefits, as noted above. Sodium has a high heat capacity, meaning that it can absorb a lot of heat before its temperature rises.[71] Sodium also has very high thermal conductivity (the ability to transfer heat) — about 100 times greater than water. In an emergency situation, sodium can cool the core convectively without human intervention. These features allow for a much smaller and more economical design.

Most SFR designs use metal fuels. The earliest experimental nuclear reactors in the 1950s used metal fuels because they were simplest to fabricate. Researchers quickly discovered void swelling, which continues to be a major problem.[72] The fuel rods would deform quickly under irradiation and risked getting stuck in the reactor core — or bursting if left in the reactor core for a few months — thus requiring regular removal. Longer fuel irradiation times were going to be a primary focus of the cancelled IFR project of the early 1990s.[73]

Void swelling requires that fuel in fast reactors be replaced frequently. A standard once-through fuel cycle is expensive, requiring much more uranium fuel than in other reactors. Most SFR designs envision both on-site fuel reprocessing (what is called integral reprocessing)[74] and the use of new materials and fuel rod designs more resistant to void swelling, thus allowing the fuels to spend more time in the reactor before they must be reprocessed. On-site reprocessing adds substantial cost and infrastructure to SFR designs. While new fuel cladding materials show great promise, they are still in the experimentation phase and far from certification.[75] Alternately, the problem of void swelling may be solved with fuel rods designed to vent fission gases, as developed for the US IFR program. This process needs to be demonstrated in a prototype, and the challenges of embrittlement and creep still require innovative materials.

The liquid sodium coolant utilized by the SFR offers a further safety challenge. Sodium burns when exposed to air or water and becomes radioactive when exposed to neutrons. This means that the cooling system must be extremely well sealed. A serious release of sodium — such as in a malicious attack or airplane crash — could release radioactive material. However, the short decay time of radioactive sodium — about 15 hours[76] — means a potential release would lose potency quickly. These issues add cost and complexity to SFR designs, requiring double-walled pipes filled with argon and a range of additional features to assure safe operation. The sodium coolant gives the reactor core a strong positive void coefficient,[77] but this is only a concern if air or gas were to accidentally enter the reactor core.

Modularity

Most SFR developers are aiming for large-scale, nonmodular designs to take advantage of economies of scale and on-site fuel reprocessing facilities. Their cost models show that this will be more economic than producing smaller modular units.[78] General Electric's PRISM design, a small modular reactor, is an exception. GE plans to install several reactors at each location to utilize one central fuel reprocessing facility.[79]

Thermal Efficiency

Sodium-cooled fast reactors have high thermal efficiency for their temperature — around 40 percent for 550^{O}C. However, fast reactors combine the materials challenges of high temperatures and high irradiation, so temperatures may be kept lower to reduce the materials challenges.

Readiness

SFRs share a range of technical, institutional, and materials challenges with other fast reactor designs. Neutron bombardment, due to the high flux of neutrons in the fast reactor core, causes embrittlement and could result in structural failure over time. While there may be new materials better able to resist irradiation, they are still in the R&D phase, requiring at least another decade of testing under different conditions, optimization for different reactor designs, and finally certification and approval.[80]

In order to reprocess metal fuels, a high-heat treatment and electrical separation process called pyroprocessing is required. This type of reprocessing is potentially much simpler and cheaper than reprocessing spent oxide fuels. While this process was demonstrated several times in the United States in the 1960s, it has never been performed at commercial scale. Nor has it been proven to separate significant percentages of actinides (uranium, plutonium, and everything else fissile or fertile) from the waste, which are mostly fission products and other transmuted materials that cannot be used for fuel. South Korea has a project to demonstrate pyroprocessing at commercial scale and to improve its efficiency at separating actinides.[81]

TerraPower aims to finish the prototype of its TWR by 2022, with the first commercial plant beginning construction in the late 2020s.[82] The main challenges for the TWR are to demonstrate fuel strength and stability over long periods of time. Two

SFR designs are currently under preliminary pre-application discussions with the US NRC: GE-Hitachi's Power Reactor Innovative Small Module (PRISM) and Toshiba's Super-Safe Small & Simple (4S) design. The NRC does not list dates for expected application for either design.[83]

In July 2012, GE-Hitachi submitted a feasibility report to the UK Nuclear Decommissioning Authority (NDA) and the Department of Energy and Climate Change, arguing that their S-PRISM design could be used to dispose of the country's plutonium stockpiles. The NDA is still reviewing this proposal. GE-Hitachi commissioned a third-party technical evaluation, which concluded that there were no technical obstacles to licensing the S-PRISM reactor in the UK.[84] The chief engineer from GE estimated that licensing would take five years, and that construction of the first plant would take another five years.[85]

Bottom Line

While significant technical hurdles remain, the safety benefits and reprocessing capabilities of sodium-cooled fast reactors have led several dominant nuclear power countries — France, Japan, and South Korea — to select the SFR as their primary reactor design for long-term research, development, and commercialization programs. Japan plans to complete a prototype of its model, JSFR, in 2025, and expects commercial adoption by 2050. Japan is focusing its R&D program on developing high-performance materials. South Korea is researching commercialization of a technique for on-site reprocessing of metal fuels, and expects a prototype in 2028 and wide deployment by 2040.

B. LEAD-COOLED FAST REACTORS

Description

Like the SFR, the Lead-Cooled Fast Reactor is a metal-cooled fast reactor with a pool configuration, operated at ambient pressure using ceramic fuels. LFRs are cooled with liquid lead instead of liquid sodium, which is much easier to handle since it does not burn when exposed to air and water. The simplicity, stability, and long fuel lifetimes of LFRs make them attractive designs for modularity. LFRs run at higher temperatures compared to SFRs but have lower core irradiations. This means that advanced metals are not necessary for core materials.

The Soviet Union first developed LFRs and remains the only country to have significant experience building and operating these reactors. Most notably, they built seven LFR-powered submarines that operated from 1967–1990.[86] Two of these submarines experienced reactor failure: in one submarine the coolant froze and in another the coolant leaked and solidified.[87] Today there is the European Lead System (ELSY), a design developed by a joint program of 17 European state nuclear programs that plans to have a prototype by 2020 and wide adoption by 2040. The US LFR design was called the Small Sealed Transportable Autonomous Reactor (SSTAR), but has not moved forward since the United States focused its Generation IV research on HTGR designs.[88]

Inherent Safety Features

As a coolant, lead offers certain advantages over sodium, such as a higher boiling point and the fact that it is inert and does not interact with air or water. Nevertheless, lead remains hot — giving off high levels of radioactivity — for very long periods of time, unlike sodium or fluoride salt, and must be disposed of as low-level radioactive waste after use. While the radioactivity of used lead coolant alone may not constitute a substantial health risk, lead itself is a dangerous water contaminant and disposal strategies will need to account for it.

There are two different types of lead coolant, pure lead and a lead-bismuth mix. Each presents a mix of safety benefits and challenges. Both lead coolants have high freezing temperatures, so if the reactor shuts down unexpectedly the coolant could freeze. If the coolant solidifies, the reactor is inoperable until external heat can be applied to melt the coolant, but equipment could be damaged in the process. The lead-bismuth mixture has the benefit of a relatively low freezing temperature, 125^{o}C, which reduces the risks and uncertainties of the coolant freezing during the starting and stopping of the reactor.[89]

Another significant challenge is the density of lead, which has led to serious concern about how LFRs might perform in the event of an earthquake. The weight of the coolant also causes strain on pumps and fuel handling equipment. The solution to this problem is to keep reactors small (less than 100MW) to limit the weight of lead required.[90] Both lead and lead-bismuth produce polonium under irradiation.

Polonium is very toxic and must be continually filtered out of the coolant.[91] Pure lead coolant results in less polonium than lead bismuth.

Uranium-nitride (UN) fuel provides safety benefits including improved strength and stability over uranium oxide fuels used in most LWRs today.[92] UN has a higher melting point than uranium-oxide fuels, and has demonstrated a lower release of fission product gases in emergency situations and less chemical reactivity with most fuel cladding materials.[93] Most interestingly, UN has superior mechanical stability, or reduced swelling and embrittlement, which results in the fuel being able to stay in the reactor core for significantly longer.

Modularity

Because of the weight of lead, most LFR designs are small in order to keep the total volume and weight of lead coolant to a minimum. The desire for a small reactor, combined with the simplicity and nonreactivity of lead, makes the LFR one of the most feasible designs for modular mass production.

Typical LFR designs require refueling every seven to eight years compared to every two years for LWRs. Smaller LFR designs can go upwards of 10 to 20 years between refueling.[94] Small LFRs could be sold as nuclear batteries, shipped on-site completely self-contained, and run for 10 years with little maintenance.

One of the most prominent LFRs is a private design developed by Gen4 Energy (formerly Hyperion Power). Their design, called the Gen4 Module, is a small 25MW modular LFR with a 10-year lifetime.[95] Gen4 Energy is currently determining whether to pursue licensing in the United States, the United Kingdom, or Canada, but they plan to export their reactor primarily to developing markets. They give no timeline for an experimental prototype or a commercial scale demonstration project.

Thermal Efficiency

The Generation IV International Forum target for LFRs includes a thermal efficiency of 45 percent with an outlet temperature of 800^{o}C using a Brayton engine. The two prominent prototypes, ELSY and SSTAR, have slightly lower efficiencies, but with much lower outlet temperatures — only about 500^{o}C.

Readiness

While Russia has operated LFRs in their submarines for decades, technical challenges to commercialization remain. The SVBR design was used on Russian submarines and has 80 reactor-years of experience. In 2010, Russia announced a joint public-private venture to commercialize a 100MW SVBR. They plan to have the demonstration plant come on-line in 2017.[96]

The US NRC has conducted preliminary pre-application discussions with Gen4 Energy for their LFR design, but they do not list an expected application date.[97]

Uranium-nitride fuels are less mature than uranium-oxide fuels, and have received less irradiation and performance testing.[98] The supply chain — from fabrication to reprocessing — will need to be developed before LFRs can be widely adopted. The reprocessing of spent UN fuel has similarities with aqueous reprocessing used in France to make mixed oxide fuel, and a successful reprocessing system may look similar to those used for uranium oxide. However, fabrication of nitride fuels is more challenging than for oxide fuels. Furthermore, an isotope of nitrogen (N-14) decays into C-14, a biological hazard that needs to be properly addressed.[99]

Lead coolants are corrosive at higher temperatures. This can be mitigated with careful introduction of oxygen into the coolant to create an oxidized layer over the steel components.[100] But this requires precise control and monitoring, which needs to be proven economically viable.

Since the coolant cannot be allowed to cool to ambient temperatures, refueling is performed while the reactor is still warm.[101] A remotely operated refueling system will need to be developed for commercial applications and proven safe during full-scale commercial demonstration.

Bottom Line

The passive safety, high heat, small size, modularity, and long refueling time of the LFR make it an attractive Gen IV option in terms of safety and economics. However, significant technical challenges will need to be overcome before these benefits can be realized.

C. GAS-COOLED FAST REACTORS

Description

Gas-cooled fast neutron reactors (GFRs) are designed to combine the benefits of high fuel efficiency and fuel breeding capabilities of fast reactors with an inert, or nonreactive, gas coolant (helium or supercritical CO_2).[102] Unlike liquid-salt and liquid-metal coolants used in other fast reactor designs, gas would not react with oxygen or water should the cooling system be compromised.[103]

Inherent Safety Features

Some GFR cooling systems use supercritical carbon dioxide, but helium is the most common coolant. Helium does not react with other elements, does not become radioactive when bombarded with neutrons, and does not capture fission product gases like cesium and xenon. Leaked helium poses no threat to humans or the environment. It is noncorrosive and single-phase, meaning that it will always remain a gas, which is more stable than having a coolant that changes phase at different temperatures and pressures. Helium also will not capture neutrons like liquid sodium or salts. As a result, the reactor core can have a higher flux of neutrons to breed fuel, something harder to achieve with other fast reactors.[104]

While helium has many advantages, its low heat capacity (which brings quick reactivity to changes in temperature) creates a range of safety challenges. Since helium is transparent, monitoring and maintaining pressurization is more complicated and requires innovative equipment that is still in development.[105] Helium works well in HTGRs because of their very low power density, meaning that the core cools rapidly in the event of an accident. GFRs, by contrast, will have very high power density to take advantage of fast neutrons. Thus, there is a high risk for meltdown if the reactor loses coolant since the reactor cannot cool passively through natural convection or through conduction with the surrounding earth.[106] In addition, GFR cores have positive void coefficients, though they are not as large as in SFRs.

While most Generation IV reactor developers focus on passive safety features, such as cooling via natural convection in the event of a loss of power, the GFR has limited options in this regard. Since the GFR core is pressurized, any rupture in the system will mean a loss of coolant —perhaps even a complete loss. In a power loss, helium will not circulate naturally because of its low heat capacity, so the reactor must rely on backup pumps that either run on diesel generators or batteries to cycle the coolant.[107]

To handle a loss-of-coolant event, the GFR core is cooled by four independent loops, so if one is punctured three will remain. This is a redundant and engineered safety system but it is not a passive one; mechanical intervention is required to trigger it. GFRs can be designed to cool passively if supercritical carbon dioxide is the coolant instead of helium,[108] but most studies have shown the complexity of such a plant is too great to be practical and would bring much higher costs for handling supercritical carbon dioxide.

Modularity

Because of the complex and redundant safety systems required, the GFR does not lend itself to modularity. Specifically, most GFR developers are aiming at very large power outputs to take advantage of economies of scale.[109]

Thermal Efficiency

GFR designs are aiming for very high thermal efficiencies (48 percent) but also very high outlet temperatures (about 850^{O}C). Creating core materials that can withstand these high temperatures and high neutron fluxes is a significant challenge, and one that is more serious for GFRs than for other fast reactors because gas does not absorb or reflect neutrons in the same way that liquid metal or salt coolants do.

Readiness

Creating a suitable fuel has also been a significant problem for GFRs. While many fast reactors use metal fuels, GFRs cannot because of their high temperatures. And where most high-temperature reactors use TRISO fuel particles, GFRs cannot because they need a higher fissile material content and less neutron moderation (graphite coating).[110] GFRs would need to use a unique fuel still under development — most likely a uranium mixed carbide or nitride in novel orientation that will require extensive testing. While there are no significant technical obstacles to the development of nitride fuels, they don't have the industrial maturity of uranium oxide or even metal fuels. They will require significant optimization, testing, and demonstration, as well as supply chain development for manufacturing, reprocessing, and/or disposal.

Since helium is transparent to neutrons, GFRs are great for breeding fuel, but the downside is that the materials in the core experience much higher neutron bombardment. While other fast reactors can engineer partial mitigation of neutron bombardment, GFR core components will require novel materials such as advanced nickel alloys and feritic-martensitic steels.[111] These materials are still in the experimental phase, and their economics are uncertain.

Bottom Line

GFRs were originally developed in the 1970s when concern over the uranium supply reached its peak. High irradiation in the core made building such a reactor with existing materials impossible. Unfortunately, the materials needed are still unavailable for commercial applications. No gas-cooled fast reactor has ever been built or reached criticality. While there remains strong appeal for a fast breeder reactor with an inert coolant, the challenges for core materials and monitoring appear significant. In addition, the reliance on engineered safety systems rather than inherent safety features undermines its potential as a meltdown-proof design.

D. MOLTEN SALT FAST REACTORS

Description

The molten salt fast reactor (MSFR) is a fast neutron reactor that uses molten salt or solid fuels with a salt coolant. When using a molten salt fuel, the fuel is dispersed in the salt coolant. Using either molten salt or oxide fuels, the reactor can operate at ambient pressure, radically simplifying the design while keeping the reactor power dense.

Inherent Safety Features

The liquid salt coolant, generally a fluoride salt, has several advantages over liquid metal coolants like sodium or lead. It remains a liquid at atmospheric pressure, as do sodium and lead, but liquid salt also has high thermal inertia, making it more difficult to overheat and easier to cool with natural convection, an important passive safety feature. Unlike sodium, fluoride salts do not react with air or water, which makes the overall design much simpler.[112]

Liquid fuels offer many benefits: there is less fissile material, higher fuel efficiency, and easier monitoring and inspection. Liquid fuel is much easier to remove from a reactor core, even in an emergency situation. For example, some MSFR designs employ a frozen plug at the bottom of the reactor vessel. The plug is kept frozen via electricity; if there is a loss of power, or the reactor gets too hot, the plug melts, allowing all the fuel and coolant to fall into an underground chamber full of neutron moderators, quickly killing all fission reactions.[113] Finally, the pool design and ambient pressure mean the reactor can cool itself convectively during a loss of power.

Modularity

The compact size of the MSFR and the simplicity of overall design provide a good opportunity for modularization. However, the need for on-site coolant purification and fuel reprocessing would mean additional equipment and facilities, which are difficult to include in a small, modular design. The Generation IV International Forum sets the target for a generic MSFR at around 1400MW — not a small design.[114]

There is a private company, Transatomic Power, developing a very simple molten salt reactor designed to burn spent nuclear fuel on site in a low-cost reactor. This design is small (500MW) and will be fully modular.[115]

Thermal Efficiency

Molten salt fast reactors have higher thermal efficiencies compared to salt-cooled thermal reactors but also much higher outlet temperatures. The GIF target MSFR has a thermal efficiency of 45 to 55 percent (the highest of any Gen IV reactor) and an outlet temperature of 700°C. The MSFR also uses the multiple reheat Brayton cycle engine, similar to the PB-AHTR. However, as with other fast reactor designs, the combined materials challenge of withstanding these high temperatures and fast neutrons will prove a significant obstacle to MSFR development.

Readiness

The MSFR's liquid fuel greatly simplifies the fuel cycle since the fuel does not need to be machined and fabricated into precise compacts and geometries. Once the reactor is running, new fuel can be added continuously without shutdown. This avoids repetitive reprocessing, as the fuel can be run through the reactor several times until it is entirely consumed. Transuranics and fission gases can be continually filtered out of the fuel/coolant mixture.[116] As a result, the MSFR requires very little fuel supply infrastructure that would need to be developed, thereby reducing first-of-kind costs and potentially shortening time to commercial development. However, the ability to continuously filter and add fuel has not been demonstrated on any significant scale, and still faces many engineering challenges.

Molten salt coolants have their problems, such as corrosion and toxicity, which are discussed above with PB-AHTRs.

The French-designed MSFR is expected to have a prototype by 2020 and wide adoption by 2040, but many note slow progress and think this timeline is overly optimistic. China is scaling up its MSFR research, alongside PB-AHTR work, but few design details have been released.

Bottom Line

The molten salt fast reactor is a popular choice among private nuclear entrepreneurs because of its inherent safety, simplicity (which makes it easier to model and demonstrate), and lack of fuel fabrication (which greatly shortens the supply chain). Countries with significant domestic thorium reserves are particularly interested in this design as the most mature thorium reactor. China's rapid scale-up of its MSFR research and development program is promising but the challenges of dealing with a corrosive liquid salt need to be overcome.

C. Fusion Reactors

Description

Where fission splits atoms to release energy and neutrons in a chain reaction, fusion fuses together two light elements, usually hydrogen, to release energy.[117] Scientists have repeatedly demonstrated fusion reactions with particle accelerators, but no one has been able to achieve a sustained fusion chain reaction, which releases a greater amount of energy than was used in the process.

Fusion power has long been the "holy grail" of energy research, as it promises clean energy with no nuclear waste, no weapons materials, abundant fuel, and on-demand baseload power. The feasibility of fusion technology has long been elusive,[118] but there are a few large-scale international research projects working on this effort.

For any fusion reaction, the fuel must be sufficiently condensed and heated. There are two main types of reactors under development. Magnetic confinement reactors use powerful magnetic fields to confine and heat a plasma — an ionized gas — in a large doughnut shape until the fuel ignites in a fusion reaction. Laser confinement reactors use dozens of laser aimed at the center of a sphere to compress and heat a small fuel pellet until fusion occurs.

Inherent Safety Features

There is no meltdown risk with fusion. Fusion requires intense energy to ignite a reaction, either in the form of powerful electromagnets or lasers to compress the fuel, and so there is absolutely no risk of a runaway heating. The reactions stop immediately under a loss of power. The only products of this reaction are helium, neutrons, and small quantities of tritium. Tritium is an isotope of hydrogen and is radioactive, but has a half-life of 12 years. Tritium is not dangerous to humans externally, only when ingested.[119] Proper containment of tritium will be a requirement for any commercial fusion reactor.

The high-energy neutrons released in a fusion reaction induce radioactivity in the material surrounding the reactor core, but this radioactivity is short-lived. The fusion reaction releases about 100 times more neutrons per unit of energy than a LWR core, so proper shielding of the reactor core is required.[120]

There are several fuel cycles for fusion. Each has different reactants and outputs, but all are difficult because of threshold energy requirements for fusion in general. For the last 50 years scientists have pursued the DT (deuterium tritium) fuel cycle. While the least challenging from a scientific point of view, the DT fuel cycle presents major engineering challenges because of the high-energy neutrons produced in this reaction. Nevertheless, there are some fusion reactions that do not release high-energy neutrons, and might be easier to engineer using significantly less advanced materials, more normal safety precautions, and ultimately producing less if any long-term radioactive material. This type of fusion — called aneutronic because it lacks neutrons — is significantly more difficult to initiate from a scientific point of view.[121]

Modularity

Since fusion reactors will require huge power inputs, they are not likely to be constructed in a small or modular fashion. Most likely, fusion power plants will be very large.

Readiness

A sustained fusion reaction which creates more energy than is consumed has yet to be demonstrated, though it is theoretically possible and technologically feasible. Engineers have worked for decades on focusing and condensing material tightly enough to create fusion in a controllable fashion.

Among magnetic confinement fusion, the largest demonstration project is the International Thermonuclear Experimental Reactor (ITER),[122] under construction in France and funded and operated by an international team. The ITER plans to produce its first plasma in 2020, but will not develop its first electricity producing demonstration project until 2040.

For laser confinement fusion, there are two major projects: the National Ignition Facility (NIF), in California, and Mégajoule, run by the French government. Mégajoule was slated for completion in 2012 but is still under construction. The NIF began experimental operation in 2009 but has yet to achieve ignition, the point where more energy is created that consumed. NIF scientists are confident they can achieve ignition within two years. The principle associate director of NIF claims the first electricity-producing demonstration plant could be completed within 8–12 years of first ignition. The head of NIF's Future Plan Design project says a 925MW fusion plant that his team designed would cost about $4 billion to construct.[123]

Among aneutronic fusion projects, the private company Tri Alpha Energy, founded in 1998, is developing a reactor that will fuse the element boron-11 with a proton (pB11). The scientific barriers to achieving such a reaction are significant — about 20 times more challenging in terms of the required pressures and temperatures. While about a decade away from a working prototype with electricity production, multiple stages of scientific progress with increasingly large machines have been achieved in the last 15 years. These projects have demonstrated both an increasingly long containment lifetime and a power scaling law pointing the way to better than break-even energy output (thus power plant status). Both of these attributes are necessary if any such reactor is possible, DT or pB11. Tri Alpha Energy has gone through two stages of venture capital funding, and is backed by a financial syndicate consisting of Silicon Valley venture groups, private individuals, and significant international financial institutions and research foundations from around the world.

Thermal Efficiency

The thermal efficiency of a fusion power plant will depend on the final design of the power plant and the type of power conversion system, which still needs to be designed.

Bottom Line

If and when fusion energy is demonstrated, the event will be at least as significant as the creation of fission nuclear energy, and perhaps as significant as steam power and electricity. The miniscule amount of fuel required, the near absence of waste, and the elimination of significant accident risk make fusion the most environmentally benign energy conversion technology. Nevertheless, fusion's future is unknowable. On one side are decades of overly optimistic predictions and a history of incremental rather than radical improvements to energy technologies. On the other are the reality of its physical and technological possibility and its continued pursuit by leading technologists, entrepreneurs, and governments. Given its potential, it is understandable that nations have continued to pursue and develop fusion energy, despite repeated setbacks and long-term horizons for realization.

CONCLUSION

If there is one lesson from the 60-year history of nuclear energy development and commercialization, it is that locking in to a single technological path too early can have significant long-term consequences. Light-water reactors represented the path of least resistance in the 1950s and once that path was taken, the obstacles to diverging from it have proven formidable.

Yet, while there is danger in locking in to a new nuclear technology too early, there is also risk in failing to clarify the real obstacles to expanded diffusion of nuclear energy, what general technological attributes promise to effectively address those obstacles, and hence, which technological paths appear most promising.

A broad commitment to accelerate nuclear innovation, to support multiple pathways to new nuclear technologies that are cheaper and safer, and to avoid foreclosing pathways that may ultimately prove fruitful is not inconsistent with the imperative to bring substantial discernment to those efforts. Indeed, clarity as to which technological pathways offer a likely route to the broad commercialization of nuclear technologies that are substantially safer and cheaper will be necessary to ensure that limited public resources are allocated wisely and that new institutional and regulatory arrangements are well suited to support these efforts.

The technology assessment framework elaborated in this document is predicated upon the conviction that it is possible to ascertain the primary obstacles to broader diffusion of nuclear energy technologies. We conclude that these obstacles primarily constitute rising economic costs associated with ensuring the safe operation of nuclear reactors, and constructing large and extremely complicated nuclear facilities.

We further conclude that the primary drivers of such rising costs are reasonably well established: complexity associated with reactor designs that operate at high pressures, utilize fuels and coolants that bring significant risk of runaway heating and meltdown, and are difficult to standardize and construct modularly.

We can also make reasonable inferences about how close various proposed reactor designs are to commercialization based on the degree to which critical materials, fuels, and components have been demonstrated, and how rapidly cost declines associated with scaling and/or mass production might be realized based on the degree to which materials, fuels, and components are already commercially available.

Reviewing the range of reactor designs currently under some form of development, we begin to see the outlines of an emerging technological path toward commercialization of safer and cheaper reactors. This pathway begins with evolutions of the light-water reactor design that are currently being commercialized. Gen III+ reactors incorporate new materials and construction techniques that will prove important for Gen IV reactors — including steel plate reinforced concrete, off-site fabrication of key components and structures, and the fully modular manufacturing methods of small light-water reactors.

The first commercialized Gen IV reactors will likely be thermal reactors that continue to rely upon much of the existing light-water supply chain and fuel cycle. These reactors utilize graphite moderated ceramic fuel particles, rather than uranium-oxide fuel rods, and are cooled with either gas or liquid salt. Thermal Gen IV reactors use materials that are commercially available and have been approved by the ASME (a requirement for NRC licensing). They use uranium-oxide fuels, which already have extensive testing and approval under the NRC. These supply chain and licensing advantages are significant.

Both gas- and salt-cooled thermal reactors promise to be much more stable and predictable in the event of an accident, and hence much safer. Gas-cooled reactors have low power density, allowing the reactor to dissipate decay heat after a shutdown through conduction. Salt-cooled reactors use a coolant that does not need to be pressurized, which allows the reactor to cool in the event of a shutdown and loss of power through natural convection.

Gas-cooled thermal reactors appear somewhat closer to commercialization in the United States and China. They are well suited to provide process heat for heavy industry and appear suitable for electrical generation. However, the path beyond gas-cooled thermal reactors is unclear. Their large size in relation to their power output does not appear well suited to modularity, and they don't readily open the door to more advanced designs or new fuels that might hasten significant cost improvements.

Salt-cooled thermal reactors do not seem far behind. They will be suitable for the generation of both process heat and electricity. Due to their high power density and simple design, they are well suited to modularity. Moreover, they rely almost entirely upon proven materials, components, and fuels.

The development of salt-cooled thermal reactors opens the door to molten salt-fueled reactors, in which the fuel (rather than being fabricated into pebbles or rods) is dissolved in a pool of molten-salt coolant. Molten-salt fuels further simplify the reactor design and expand the use of a variety of fuels in the future. Since this fuel cycle does not require elaborate fuel fabrications and hence development of a costly new supply chain, new fuels can be deployed in reactors more easily. Also, since durable neutron-resistant fuel cladding poses a significant challenge for fast reactor development, liquid fuels may eliminate this obstacle to commercialization.

The pathway described above suggests that salt-cooled thermal reactors offer a promising route to commercialized fast reactors. It also suggests that salt-fueled fast reactors are the most likely candidates for commercialization among fast reactor designs. Notwithstanding this assessment, there are substantial efforts underway to develop alternative fast reactor designs, most prominently sodium-cooled and lead-cooled fast reactors.

Sodium-cooled fast reactors have, in particular, received renewed attention in recent years, with private consortiums pursuing development of several different designs and the governments of Japan, France, and South Korea investing substantial public resources to demonstrate SFR reactors. The benefits of SFRs are indeed great: an unpressurized reactor, natural convective cooling, stable fuel, waste recycling, and the ability to burn multiple fuels.

However it is unclear that SFRs offer benefits that salt-cooled fast reactors do not. In fact, they appear to create substantial new challenges, including the development of new fuel cladding and core materials capable of withstanding high levels of neutron bombardment; a coolant that is highly reactive with both air and water; metal fuels that require a complicated and costly new fuel chain to fabricate; on-site fuel reprocessing capabilities that have not yet been proven feasible at scale or economically viable; and a physical plant that, in most configurations, appears an unlikely candidate for fully modular designs. Moreover, there is not an obvious evolutionary path from current technology to the SFR. The SFR shares no major elements — fuels, coolant, or core materials — with current LWR technology, and there is no intermediate technology (eg, thermal, water-cooled, or uranium-oxide fueled) that might represent a bridge to SFR commercialization.

Perhaps the best path to SFR commercialization may be burning plutonium from weapons and other sources, as currently under consideration in the United Kingdom. This would provide a unique production niche for the SFR that would not require it to compete with other nuclear and non-nuclear technologies. However, it is unclear that the niche is large enough to allow for commercialization at sufficient scale that new supply chains might be developed and replication of production and construction methods might be achieved such that the cost of technology begins to come down substantially.

Lead-cooled fast reactors may be a more promising design for certain applications, but also have significant challenges and disadvantages. Lead-cooled reactors have operated in Russia at very modest scale for many years. Although the fuel and materials have been demonstrated in Russia, this information is not readily available outside its borders. Unlike metal fuels, uranium-nitride fuels do not represent a radical break from present-day uranium-oxide fuels. The coolant is nonreactive. Due to the nature of its cooling system, the LFR is well suited to fully modular design. There are several small LFRs under development, with the potential to find early niche markets that compete with diesel generation in remote, off-grid markets. However, the challenges of dealing with molten lead and handling polonium may prove infeasible.

Fast reactors remain popular among groups and countries like Japan and France concerned about nuclear waste and fuel sustainability. But if the goal is to accelerate nuclear power expansion in an effort to seriously reduce pollution and greenhouse gas emissions, the economic and readiness barriers of fast reactors are significant.

Reprocessing and waste reduction will no doubt remain an important focus of long-term nuclear R&D programs, but in the short term, taking advantage of the existing nuclear supply chain will be a priority. While public concern about nuclear waste remains an obstacle, Sweden and Finland have both demonstrated in recent years that simply moving forward on a permanent waste disposal site has greatly improved the public perception of nuclear power.[124]

However, there may be a niche for fast reactors in countries wishing to dispose of weapons grade nuclear materials. For example, in the UK, the Department of Energy and Climate Change requested a proposal from GE-Hitachi's PRISM design to dispose of their plutonium stockpile. The US was constructing a MOX plant to turn decommissioned nuclear weapons into mixed uranium-oxide fuel rods, but the plant is over budget and behind schedule, and its construction budget may be suspended.[125] This presents an opportunity for a fast reactor proposal to take its place.

While there appear to be multiple paths to non-light-water reactor designs that represent substantial improvements in cost and safety to current reactors, it remains to be seen whether there is any real path to commercialization for these models without substantial and formal state sponsorship. The history of the commercial nuclear power industry is one in which commercialization in virtually all contexts has depended upon heavy state involvement. This is a function of the complexity of the technology; the high costs associated with testing and demonstrating unproven nuclear technologies, materials, and fuels; the development of complicated and costly new supply chains; and the challenges associated with licensing and regulating new nuclear technologies. As such, the prospects for accelerating nuclear technology along any of the pathways elaborated above will likely depend heavily on the evolving policy and regulatory landscape, both in the United States and abroad.

Policy Implications

While operational innovations over recent decades have resulted in today's reactor fleet operating much more efficiently and safely, fundamental innovation in the underlying designs and technologies has proceeded at a glacial pace. The high capital costs associated with developing and demonstrating new nuclear technologies, the difficultly in developing supply chains for new materials and fuels that have little utility beyond nuclear technologies, and the extremely costly and arduous process of licensing have combined to make nuclear energy a sector uncharacterized by rapid technological innovation.

Accelerating the pace of innovation, with the aim of more rapidly commercializing new advanced reactor designs, requires a broad commitment to nuclear innovation that should be reflected in both reform of the present framework for regulating nuclear technology and new institutional arrangements to provide support for nuclear developers.

LICENSING REFORM

While the NRC continues to represent the global gold standard for effective and comprehensive regulation of nuclear energy, today's process of licensing a new nuclear technology is so costly and arduous as to largely foreclose the possibility of licensing for all but the largest and most established nuclear companies. The NRC is legally required to recover its costs through fees charged to applicants.[126] For light-water SMR designs, several companies have estimated the costs for licensing alone to exceed $200 million.

For Gen IV reactors, developers will first have to pay the NRC by the hour to understand these novel designs and develop rules for licensing them, in addition to bearing the later cost of licensing. These costs present a significant disadvantage to the first-movers. To date, no developer of a non-light-water design has pursued licensing through the NRC, and the NRC has no experience or established procedure for how it might do so. The NRC has begun preliminary pre-application discussions for three Gen IV reactors, two SFRs and an LFR, but they have no anticipated date for application submissions.

International collaboration to develop and license new nuclear designs is further hindered by Section 123 Agreement, a subsection of the US Atomic Energy Act that controls how US companies can share nuclear technologies with other countries. While Section 123 encourages technology sharing for peaceful purposes, it is also very restrictive and may constrain innovation and international cooperation. Many nuclear developers have lamented how difficult it can be to demonstrate or deploy a US reactor in another country, even though such a project would significantly accelerate advanced reactor development for US companies.

NRC licensing presently treats nuclear technology like any other highly regulated product. It is incumbent upon nuclear developers to prove the safety of their designs and to bear the cost. The NRC's job is to ensure the public is properly protected from any possible health or safety impact that might result from the operation or failure of a new nuclear technology.

Nuclear developers, of course, have much to gain from the successful commercialization of a new nuclear design. There are substantial risks the commercialization of unsafe designs potentially imposes on the public. At the same time, the development of better, safer, less costly nuclear technologies clearly promises many substantial benefits to the public. Abundant, cheap energy has been the bedrock on which the American and global economies have been built. Providing abundant, cheap energy that produces no pollution or carbon dioxide emissions promises a double economic benefit: positive economic benefits from cheap energy and eliminated negative economic impacts associated with pollution-related health costs in the short term and climate change in the long term.

INVEST IN INNOVATION

Given the public goods nature of nuclear innovation, it seems unwise to force developers to bear all, or even most, of the costs associated with commercial licensing. While the Department of Energy has recently awarded grants to aid development and licensing costs for two developers of new light-water small modular reactors, this initiative does not appear to go nearly far enough in reducing the regulatory costs of entry for all nuclear developers. Developers with significant proof of concept for their designs already face enormous development costs notwithstanding the formal costs associated with commercializing their technologies. Given the huge potential benefits, they ought to be able to avail themselves of substantial public cost sharing of licensing costs.

Moreover, given the complexities associated with developing new nuclear technologies, licensing might be better integrated with the innovation process itself, allowing developers to demonstrate and license elements of their designs iteratively, so as to reduce the need to develop a technology whose technical challenges are fully resolved prior to embarking on the process. A good example of such staged support is the National Aeronautics and Space Administration's Commercial Crew and Cargo Program (C3PO), which funded a multistage competition for private companies to demonstrate various space flight and rocket launching technologies. Prize money was awarded to companies that achieved specific targets, competitive grants were awarded to complete necessary R&D, and ultimately contracts were awarded to three firms to complete payload delivery missions.[127]

Aside from regulatory and licensing hurdles, the costs and technological challenges associated with commercializing any new nuclear design, and more so any design diverging significantly from present light-water technology, are extremely high. It is for this reason that light-water reactors in the United States, as well as alternative designs such as the heavy-water CANDU in Canada and gas-cooled reactors in the United Kingdom, required substantial and sustained state support in order to achieve initial commercialization.

The same dynamics appear to be the case with regard to new non-light-water designs. The two new designs that appear to be on a fast track to commercialization, gas- and salt-cooled thermal reactors, are moving forward with the full force of the Chinese government behind them. This includes enormous resources from Chinese universities, full public funding for the construction of commercial scale demonstration projects, close coordination with state-owned utilities and industrial enterprises, state support for the construction of commercial scale facilities to fabricate ceramic fuel particles, and the commitment of land and infrastructure to support a fully developed industry, including the requisite supply chains.

Similarly, and irrespective of the assessment herein, much of the optimism regarding sodium-cooled fast reactors is a result of a number of national governments — France, Japan, and South Korea — dedicating substantial public support to this particular technology for their long-term R&D programs. The motivation for these countries is focused on waste reduction and actinide management, which explains their choice of the SFR.

Heavy reliance on public development and commercialization support, however, may significantly limit the range of technological options available. Recognizing that the final push to commercialization for any new nuclear technology may inevitably require substantial state support, there may be a number of policy strategies that accelerate the development of both candidate technologies and supply chains in order to facilitate the commercialization of entire classes of new technologies, rather than a single design.

INNOVATE ACROSS ADVANCED DESIGNS

Many emerging nuclear technologies and designs share similar technological challenges. High temperature reactors, whether thermal or fast, require materials in the reactor core that can withstand large temperature variations. Fast reactors need materials that can withstand much higher neutron bombardment, which will also be required for some fusion technologies. Metal fuels suitable for many fast reactor designs require fuel fabrication and cladding able to withstand void swelling and deformation.

As such, public support for research, demonstration, and certification of new materials that might address technological challenges across multiple reactor designs and platforms and make those materials available to all reactor developers seem a high public priority. The DOE Gen IV Materials Project aimed to do exactly this, but many have argued the project has lacked both proper direction and sufficient budget. Relatedly, the United States currently does not have sites available to demonstrate reactor prototypes; both the Savannah River Site and Idaho National Laboratory are not legally allowed to build new reactors on site. Creating flexible test facilities that can prove the viability of new materials and fuels across a range of reactor core conditions in different reactor designs would allow for rapid development of materials that might advance the development of multiple reactor designs.

As with shared materials challenges, different reactor designs can share key supply chains. Gas-cooled and salt-cooled thermal reactors use graphite-clad ceramic uranium fuel pebbles. Several fast reactor designs require metal fuels. All fast reactor designs require core materials and cladding that can withstand high levels of neutron bombardment, as do fusion reactors. High temperature thermal reactors and many fast reactor designs require materials that can also withstand high temperatures. Other new reactor designs are targeting higher temperatures in order to utilize Brayton cycle turbines, which bring much greater thermal efficiency than conventional steam turbines.

As such, publicly supported commercialization efforts would be well served to develop supply chains that are as open source as possible, meaning that they would be developed with an eye to the key components, fuels and materials that could be integrated into alternative designs.

In these ways, the objective of regulatory reform and policy initiatives must be to recognize the essential role that public support and investment have always played, and are likely to continue to play, in the commercialization of nuclear reactor designs. The objective must be to open up the development and licensing process to more developers, to reward rather than obstruct entrepreneurial enterprise. Given the high cost and complexity associated with commercializing new reactor designs and developing supply chains to support them, governments intent on commercialization will likely pick technological winners. But success in private enterprises like C3PO show how entrepreneurship can infiltrate industries considered firmly in the domain of public development, like space travel, public health, and electricity.

Smart technology and regulatory policy, however, can ensure states expand technological possibilities rather than closing them off. Public support for research, development, demonstration, and certification of new materials and fuels should target technological challenges that have the greatest cross-platform relevance to multiple reactor designs. Licensing of new designs should be reformed to lower the costs of licensing, the regulatory barriers to new entrants, and the time to market. Public efforts to commercialize new reactors should target the development of supply chains that can support multiple technological platforms.

Effective public efforts to commercialize advanced nuclear reactors that promise to be safer and cheaper will need to be discerning, investing in technological pathways that have the most promise to change the basic economics of nuclear deployment. But smart policies can ensure that those efforts also grow, rather than close down, our technological options.

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