CLEAN AIR TASK FORCE

April 2018

Advanced Nuclear Energy

Need, Characteristics, Projected Costs, and Opportunities

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and Opportunities

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COVER PHOTO
Artist's depiction of small modular nuclear units and solar panels powering a data center with consistent zero carbon energy.
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DISCLAIMER

Company profiles in Appendix A were compiled from publicly available information. The state of the industry is evolving rapidly, so the information may become obsolete or out of date as time goes on. Please verify information from contemporary sources.

Contents

CHAPTER 1

Executive Summary

For nuclear energy to play a meaningful role in a high-energy, low-carbon future, we must fundamentally transform the way nuclear reactors work, how they are built, and what they cost. To serve rapidly escalating climate change mitigation and energy needs in the next few decades, nuclear plants must be competitive on price with coal and gas; deployable as fast as coal plants or faster; and suitable for operation in developing countries that lack significant pre-existing nuclear capabilities.

Characteristics of Advanced Nuclear Energy

Advanced nuclear energy includes technologies using a reactor or fuel cycle that offer many of these features:

- Substantially lower capital and/or operational costs than existing plants
- Reduced material inputs
- Manufacturability or rapid deployment capability
- Passive safety systems and inherent safety strategies
- Ease of operation and maintenance
- Reduced emergency planning zones
- Reduced offsite impact during an accident and increased flexibility/scalability of siting
- Increased proliferation resistant, decreased waste production and/or actinide management capacity, and more efficient use of fuel resources
- Hybrid generation adaptability (e.g. hydrogen production, desalination, etc.) and/or load following

While new water-cooled technologies can have some of these features, non-water based technologies ultimately offer the greatest chance of achieving more of these objectives.

"Advanced" does not necessarily mean "small." Advanced reactor designs range in size from 1 MWe to 1,000 MWe or more. More often manufacturability, rather than size, radically lowers costs and reduces construction times.

How do advanced reactors achieve these desired attributes?

- **Safety.** Cooling water was a common denominator of the Three Mile Island, Chernobyl, and Fukushima accidents. By using non-water coolants, the likelihood of an unsafe temperature or pressure event is substantially reduced. Some designs, such as certain molten salt reactors, incorporate such fail-safe features as plugs that dissolve should temperatures in the fuel core rise, draining the fuel into an isolated underground chamber.
- **Waste Management.** Light-water reactors use less than 5% of the energy value of their fuel, leaving 95% as waste. Many advanced reactors, operating on the fast neutron spectrum, can use up to 95% of the energy value of the fuel, leaving a much lower waste volume. Moreover, the remaining wastes are far less persistent, with toxicity half lives of hundreds, rather than tens of thousands, of years. These waste forms, rather than requiring geological isolation for millennia, would need only to be contained for several hundred years and could thus be housed and monitored in man-made containers.

Artist's depiction of a large advanced nuclear power plant paired with desalination to provide power, water, and economic growth in an arid part of the developing world.

- **Weapons Proliferation and Physical Protection.** As with current reactors, there is always some risk of diversion of nuclear material for illicit purposes. A potential benefit of advanced reactors is that many designs use fuels and produce waste streams that are less desirable for diversion—first, because many advanced fuels are not readily accessed (e.g. the fuels are contained in sealed cores that are designed so as *not* to be opened in the host country) and second, because waste streams are often much smaller due to high burnup of fissile material during operation. Ongoing efforts in this area by the Gen IV Forum Working Group on Proliferation Resistance and Physical Protection to quantify and assess "safeguardability" must continue apace and must be factored into any regulatory and licensing effort. Safeguards compatibility should be a priority in the design of advanced reactors.
- **Multiple applications.** Today's nuclear power plants are best at producing electricity in base-load operation. But many advanced reactors are more versatile and can more easily cycle to match fluctuating load, which may become more important as increasing amounts of wind and solar energy are added to global grids. And because many advanced reactors produce much higher temperature heat, they can substitute for process heat in the chemical, refining, food processing, and steel industries—whose heat use from fossil fuels accounts for more than 10% of global energy CO_2 emissions—as well as displace boilers in existing coal plants. (Higher temperature output also enables much more efficient power conversion processes such as the Brayton Cycle.)
- **Capital Cost.** Less than 20% of the costs of a conventional light water nuclear plant are connected to the cost of the nuclear reactor itself and power production equipment. Most of the cost comes from the construction of large containment structures, cooling equipment, site infrastructure, and financing costs for lengthy construction periods that typically last four to five years or more (as compared with months to two years for a gas or coal plant). Advanced reactors address the cost issues in two ways. First, by using coolants with different characteristics and using inherent safety

strategies, the need for large pressurized containment and redundant cooling equipment is eliminated or reduced, decreasing total plant mass of concrete and steel by as much as two thirds. Second, by reducing the complexity and size of the on-site structures needed, most of the advanced plants can be built in a factory or shipyard and delivered to a site. This can reduce construction times by half or better, avoiding two years or more of plant financing costs, which can in turn result in substantial savings. A recent survey of a dozen advanced reactor developers suggests advanced reactor capital costs of roughly a 33% to 80% of current large light water reactor (LWR) levels in the U.S., and "nth of a kind" construction times of slightly more than two years.

- **Deployment rates.** Many estimates suggest that to power a rapidly modernizing and urbanizing planet and while managing climate change would require a minimum of 1,600 GWe of installed nuclear capacity by mid-century. With likely retirements of the existing fleet of 386 GWe, this goal would demand an annual reactor build rate roughly ten times the current rate—the equivalent of 100 large reactors. In a factory- or shipyard-build model, this goal can be achieved. Manufacturers such as Boeing produce 600 to 700 airplanes per year, and the world's shipbuilders annually turn out dozens of large ocean-going vessels. Also, because of the enhanced safety and waste characteristics, advanced reactors would likely need less site development and approval lead time.

The Policy Agenda

Several policy initiatives could facilitate development and global diffusion of advanced reactors:

- **Develop international safety, construction, and quality-assurance standards for advanced reactors.** A core set of standards reviewed and accepted internationally would enable more rapid deployment, since each nation would not need to reassess designs based on unique national standards or try to harmonize a number of differing standards.

The full report is available online at *http://www.catf.us/publications/Advanced_Nuclear_Energy.pdf.*

- **Improve regulatory process and regulator experience.** In addition to common standards, regulatory processes must be developed and expertise and experience built within regulatory agencies. Standards should be risk informed and nonprescriptive, allowing for phased licensing of new reactor designs rather than "all or nothing" commitments that may deter investment. Programs will be needed to eventuate depth and expertise for an expansion of advanced reactor regulatory oversight and encourage an international effort to build training pipelines that cover unique aspects of advanced reactor development and operation.
- **Provide test and development infrastructure.** In many cases, advanced nuclear designs require use of new materials and fuels. Better testing facilities, especially a flexible fast neutron source, will be needed to enable efficient certification of these new materials. Additionally, once a design is well developed, a demonstration plant must be built, which requires significant effort for site development and licensing. Either a sustained national effort or a coordinated international effort would accelerate development. Investment in other tools such as modeling and simulation should continue to support innovation, and research in complementary technologies such as advanced manufacturing, modular construction, advanced power cycles, and 3-D printing should be scaled up and coordinated with nuclear innovation to increase the utilization of these new technologies in the nuclear field.
- **Streamline export control procedures and requirements.** In the U.S., some innovators have found the time, complexity, cost, and stringency of the export control process to be overly burden-some, delaying or deterring international cooperation and international business agreements. Efforts can and should be made to reduce the burden of the export control process without endangering the national security interests of the U.S. The market for advanced nuclear energy is global: it is important both to utilize international resources in development and to compete in international markets in deployment.

CHAPTER 2

Why Advanced Nuclear Energy?

The need for expanded nuclear energy is urgent. Global energy demand is predicted to grow by at least 30% by 2035, with electric demand in the developing world expected to triple.[1] Presently, more than one billion people lack electricity access and billions more consume one tenth or less of the electricity per capita consumed in the OECD. Much of that supply is intermittent.[2] Abundant, on-demand, 24/7 power is essential to economic growth and social development.

At the same time, approximately 81% of the world's energy, and two thirds of the world's electricity, come from fossil fuels,[3] while emissions from fossil fuel combustion are a major factor driving global climate change. In the December 2015 Paris climate agreement, 195 nations adopted a goal of containing global warming to a 1.5–2 degree (Celsius) increase in global average temperatures compared to pre-industrial levels. Analysis by the Intergovernmental Panel on Climate Change (IPCC) has determined that achieving this goal will require a global energy system that, by soon after mid-century, emits almost no CO_2.[4]

Recent reports suggest the world will need up to 1,600 GWe of nuclear capacity by 2035–2050 to meet climate targets.

Nearly every analysis of the energy technologies required over the next several decades to create a near-zero carbon energy system has concluded that there will likely be a need for large amounts of nuclear energy. Recent reports from the IPCC, the International Energy Agency, the UN Sustainable Solutions Network, the Joint Global Change Research Institute, and the Pacific Northwest National Laboratory suggest the world will need up to 1,600 GWe of nuclear capacity or more by 2035–2050 to meet the targets.[5] With present global installed operating capacity at 386 GWe (slightly less than 100 GWe of it in the US), today's global nuclear capacity would have to nearly quadruple in the next several decades to meet the world's climate goals—an increase in the annual rate of deployment from the 2015 rate of 9.4 GWe to 90 GWe or more per year. (See Figures 1 and 2.)

1 BP Energy Outlook to 2035 accessed 21 Aug 2016 at *http://www.bp.com/en/global/corporate/energy-economics/energy-outlook-2035/drivers-of-energy-demand.html.*

2 World population data at: *https://esa.un.org/unpd/wpp/Download/Standard/Population/*; Electricity access data at *http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS.*

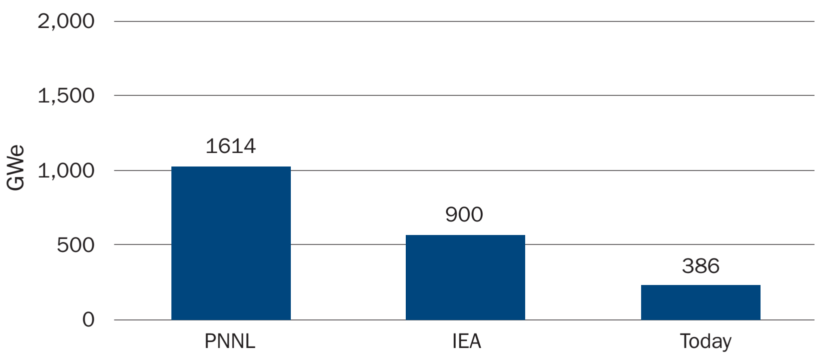
3 Fossil fuel energy consumption at *http://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS; http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators#.*

4 Fawcett, Allen A., et al. "Can Paris pledges avert severe climate change?" *Science* 350.6265 (2015): 1168-1169.

5 See, e.g., Intergovernmental Panel on Climate Change, Working Group III – Mitigation of Climate Change, *http://www.ipcc.ch/report/ar5/wg3*, Presentation, *http://www.slideshare.net/IPCCGeneva/fifth-assessment-report-working-group-iii* slides 32–33; International Energy Agency, World Energy Outlook 2014, p. 396; UN Sustainable Solutions Network, "Pathways to Deep Decarbonization" (July 2014), at page 33; Global Commission on the Economy and Climate, "Better Growth, Better Climate: The New Climate Economy Report" (September 2014), Figure 5 at page 26; Joint Global Change Research Institute, Pacific Northwest National Laboratory, presentation to Implications of Paris, First Workshop, College Park, MD, 4 May 2016 (JGCRI, College Park, MD, 2016); *http://www.globalchange.umd.edu/wp-content/uploads/2016/03/Summary-ImplicationsOfParisWorkshop-CollegePark2016-08-24.pdf.*

FIGURE 1

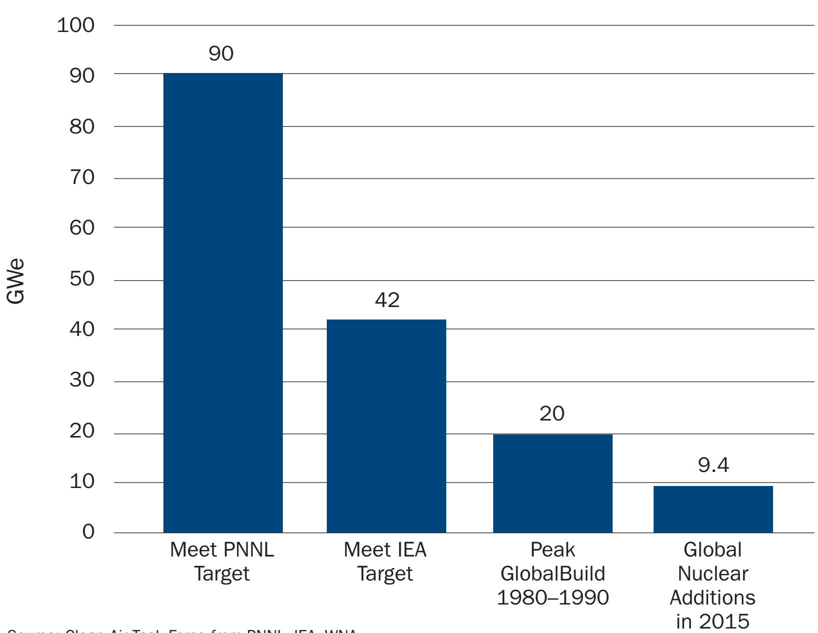
Nuclear capacity needed to meet climate targets by various estimates



Source: Clean Air Task Force from PNNL, IEA, WNA

FIGURE 2

Annual nuclear build rate required to meet various nuclear energy targets, assuming half of all current reactors will need to be replaced by 2040



Source: Clean Air Task Force from PNNL, IEA, WNA

Meeting these substantial climate change mitigation and economic growth targets simultaneously will require a different kind of nuclear reactor that is less expensive, faster to realize, and more likely to achieve public acceptance.

Despite the fact that 63 new reactors are under construction in the world today (almost half in China), net global nuclear growth is slow.[6] Existing reactors in Germany, Japan, and the US have been prematurely idled or retired. Further potential early shutdowns loom in several countries, including France, Sweden, and the US. Efforts to avert the premature closure of safe and effective nuclear power plants should be redoubled. The decarbonization challenge is vast, and is made only greater by the unnecessary removal of carbon-free generation.

Obstacles to rapid nuclear expansion differ around the world, but include: technology costs; complexity and long lead times; high cost relative to fossil fuels; lack of supporting deployment and innovation policy (of the type that has existed more recently for renewable energy); public perception of risk; and issues related to waste, nuclear security, and proliferation. Nearly all of the reactors currently under construction are Generation III and Generation III+.[7] These offer enhanced safety over designs of the past, but do not sufficiently solve or mitigate many of the key challenges noted above, especially cost and time to build. The next iteration of reactors must be a radical departure from past designs if the nuclear option is to be scalable, efficient, and economically viable in the fight against climate change.

Fortunately, ttechnology is not standing still. Existing nuclear development leaders and dozens of innovative start-up companies are pioneering new or updated designs that could be commercially viable with appropriate business infrastructure, development, and policy support. These designs

6 International Atomic Energy Agency PRIS database; updated 4/16.

7 Notable exceptions are a high temperature gas reactor in China and sodium-cooled fast reactors in India and Russia.

employ different fuels and reactor technologies that are potentially much safer and more economically viable and faster to build, and that offer reduced waste and proliferation risk. They include smaller, modular reactors that can be manufactured and shipped to sites for installation rather than custom built, thus accelerating construction times and lowering direct and financing costs. The designs include reactors that use coolants such as molten salts and gases; reactors that provide adequate passive cooling during an accident when no external energy supply is involved; reactors that operate at or near atmospheric pressure, eliminating the possibility of rapid loss of coolant and the need for expensive containment vessels; reactors that use nuclear waste or plutonium as fuel, addressing two problems at once; and reactors that use thorium and other fuels. (See Box 1).

Of note: ***Nearly all the advanced nuclear designs referred to in this paper are based on concepts that have already been technically demonstrated.*** The US at one point had a robust, multi-design nuclear Research, Development, and Demonstration (RD&D) program. Decades have passed since that time, but the knowledge remains, to be enhanced by modern materials, simulation, and manufacturing techniques.

BOX 1

What is advanced nuclear energy?

Advanced nuclear energy is not a specific technology. Rather, it encompasses many new reactor designs that provide solutions to one or more key challenges faced by existing nuclear energy in meeting the enormous need for affordable clean power in the developed and developing world. Advanced nuclear is not limited to the six so-called "Generation IV" concepts identified by multilateral government cooperation; it also includes novel reactor concepts that have emerged from the private sector and academia. To be classified as "advanced nuclear energy," a reactor or fuel cycle must offer some of the following attributes:

- **lower capital and/or operational costs**
- **manufacturability or rapid deployment capability**
- **passive safety systems and inherent safety strategies**
- **ease of operation and maintenance**
- **reduced emergency planning zones, reduced offsite impact during an accident, and increased flexibility/scalability of siting**
- **increased proliferation resistance**
- **decreased water use**
- **decreased waste production and/or an actinide management capacity**
- **more efficient use of fuel resources**
- **hybrid generation adaptability (e.g. hydrogen production, desalination, etc.) and/or load following**
- **reduced material inputs**

A single technology may or may not offer all these improvements. But a wide range of technologies, including both fission and fusion technologies, offer some. A selection of such designs and companies/organizations are profiled in Appendix A and a representative listing of organizations from the US, Canada, UK, South Korea, and China is contained in Appendix B. More detail on the six most commonly referenced Generation IV designs can be found in Appendix B of the July 2016 Advanced Demonstration and Test Reactor Options Study issued by the Idaho National Laboratory.

CHAPTER 3

Characteristics of Advanced Reactors

The history of nuclear energy development is directly tied to the early days of fission development for military purposes, specifically use for electricity and propulsion on submarines (and, later, on US Navy aircraft carriers). This association resulted in an emphasis on light-water reactor design as the system best suited for use aboard naval vessels.[8] Leveraging the enormous sums being spent to support US naval development, the electricity industry moved ahead with light-water technology for grid-scale power plant developments, despite some expert calls for advanced non light-water designs (such as molten salt-cooled reactors) that were far better suited for large-scale electricity generation.[9] As a result, though there have been a number of non-light water designs developed and fielded (including the first-ever electricity generating plant, the Experimental Breeder Reactor), today's world fleet is comprised predominantly of pressurized water or boiling water reactors. With this type of fleet come significant design and operational characteristics that have driven the performance, economic viability, and safety and risk perception for the nuclear industry over the last 40 years and more. As noted in Box 1, advanced reactors have characteristics that may address some of the limitations of the existing fleet. Some of these are examined in greater detail below and the related significant issue of affordability is addressed in Chapter 4.

Safety

One of the critical aspects of nuclear energy development has been public risk perception related to the safety of the technology. Though nuclear energy has repeatedly been demonstrated to be one of the safest forms of electricity generation when considering health and environmental effects,[10] new nuclear development has frequently faced an uphill battle for public acceptance, driven often by fears of exposure to radiation and environmental contamination from a worst-case scenario accident. As a result, significant effort and funding has been expended on improving the safety of the operating fleet. But ultimately the existing technology—light-water reactors—cannot achieve the type of **inherent safety** that may come with advanced designs.

The key factors that determine safety are accident risk, which is composed of accident probability (the likelihood of an accident) and accident consequence (the severity of an accident, often measured in terms of contamination and exposure risk). In the case of nuclear fission, this risk is driven by the probability of excessive heat generation leading to failure of the fuel elements and subsequent atmospheric release of **fission products** outside containment boundaries.

To address accident risk, the light-water fleet of today relies on a "defense in depth" strategy that involves both **active safety** systems and

8 "Light water" refers to the use of normal water (H_2O) as a coolant and as a neutron moderator, as opposed to "heavy water" (^2H_2O) which has a higher proportion of deuterium isotopes than normal water. This also differentiates the existing fleet from many advanced reactors, which use materials such as helium or molten salts for cooling and graphite as a neutron moderator.

9 See history and background of Dr. Alvin Weinberg at Oak Ridge National Laboratory accessed at *http://atomicinsights.com/alvin-weinbergs-liquid-fuel-reactors-part-1*.

10 Markandya, A., Wilkinson, P.; "Electricity generation and health." *The Lancet* 370.9591 (2007): 979-990.

some passive capabilities to ensure there is no loss of cooling, that a backup source of cooling flow is immediately available, or that natural circulation of the coolant will provide adequate **grace time**[11] to restore power and cooling flow. Many advanced reactor system designs take a somewhat different approach: while they will still rely on defense in depth, they will remove the need for most active systems and backup power sources to ensure cooling is maintained. This is known as a **passive safety** approach, where safety system components are designed to fail in a way that will leave the reactor in a safe condition. A passively safe component is, by definition, one "whose functioning does not depend on an external input such as actuation, mechanical movement, or supply of power."[12,13] Some of the newest Gen III+ designs incorporate these newer components and systems, and most Gen IV systems are being designed with this as a standard criterion.

Of note, the term "passive safety" is often used in two ways when discussing accident risk. The first use relates to any devices or safety systems as described above. The second is related to plant physics parameters. As described by an Argonne National Laboratory expert, the goal for modern reactor design is to provide protection by relying on the laws of nature, rather than on engineered systems that require power to operate, equipment to function properly, and operators to take corrective actions in stressful emergency situations.

A reactor vessel is lowered into place at the HTR-PM nuclear plant in China. The HTR-PM is a passively safe nuclear reactor.

In the case of advanced reactors, the choice of design features that ensure these safety performance parameters are met is also known as making the reactor **inherently safe** and relates to the ability to eliminate an inherent hazard through a fundamental design choice. While greater detail would be beyond the scope of this discussion, it is helpful to note that these innovations focus on thermodynamics and heat transfer characteristics of the coolant and **moderator** used in the reactor system. Ultimately, the design of advanced reactors (such as a molten salt or high-temperature,

Ultimately, the design of advanced reactors reduces the probability of an accident because there is lower likelihood of a temperature or pressure event that would lead to fuel damage. Consequences are also reduced because the systems are operated with coolants and fuels that lead to lower potential release and contamination.

11 Words in bold typeface are defined in Appendix C.

12 IAEA Safety Glossary; Terminology used in Safety and Radiation Protection; 2007 Edition; p140.

13 Passive safety discussion found at *http://www.ne.anl.gov/About/hn/logos-winter02-psr.shtml.*

gas-cooled reactor) is such that the probability of accident is reduced, since there is much lower likelihood of a temperature or pressure event that would lead to fuel damage. There also exists a lower consequence since the systems are designed to operate with coolants and fuels that would lead to lower potential fission product release, reducing the scope of possible contamination.

A critical aspect for broadening the use of nuclear energy to help decarbonize the energy sector is the availability of suitable sites for new plants.

Siting/Deployment

A critical aspect for broadening the use of nuclear energy to help decarbonize the energy sector is the availability of suitable sites for new plants. Essential factors for the use of existing light-water designs include the need for adequate water supply and a reasonable distance from population centers to mitigate accident risk. With advanced reactors, as discussed in the safety section above, the need for large supplies of water is minimized since most do not use water as a coolant or moderator, thus opening more sites to use worldwide. New dry-cooling technologies also expand the possibilities for siting. Additionally, with a much lower risk of accidental release, the emergency planning boundaries (known as emergency planning zones or EPZs) for a plant could be significantly reduced. This is especially true for newer small-modular reactor (SMR) designs (both light-water and non-light water) which have a lower fuel loading and lower potential core damage frequency. These designs in turn may allow siting closer to population centers—perhaps as replacements for existing coal and gas generating plants.

Waste and waste management

Along with accident risk and cost, another major challenge for nuclear energy is the issue of long-lived, high-level radioactive **waste**. Though the actual volume of high-level waste is quite small in relative terms (the average 1,000 MW plant generates ~27 tons of used fuel per year or ~20 m^3 which leads to a disposal volume of ~75 m^3. This compares to more than 400,000 tons of coal ash from a coal-fired plant of the same capacity[14]), the issue of waste handling and storage creates a significant concern as reflected in the ongoing political dispute over the certification and use of the proposed Yucca Mountain waste storage site in the US.

An issue with the continued use of light-water technologies is that they generate far more high-level waste than necessary, due to a relatively low-fuel utilization/burn up during power operations and production of many long-lived **actinides** as byproducts. Though fuel burnup has improved greatly in the last 30 years (generally due to the use of higher enrichment fuels) there are still significant improvements that could be made through use of newer fuel designs and through leveraging advanced reactor designs, especially those which operate with fast spectrum neutrons. At the end of core life for a typical LWR, only 4–6% of the actual fuel "fissionable material" (e.g. uranium, plutonium) has been expended. This leaves used nuclear fuel (UNF) behind with the remaining ~95% of fissionable material, some other long-lived actinides, and a large quantity of shorter-lived fission products. Though the amount of fissionable material left behind is quite large, the combination of poisoning effect from these fission byproducts and the somewhat lower fissibility of the remaining actinides means the reactor can no longer sustain a chain reaction without some remediating action, such as fuel refresh in a large core.

Advanced reactors that operate with a **fast neutron** spectrum can address this problem, allowing UNF and waste to become a more manageable issue. Reactors of this type have a higher fuel utilization rate and, with a fast neutron spectrum, UNF from LWRs can be used as a fuel source, after some processing. The higher energy of the fast neutrons,

14 Source: *http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx.*

when absorbed by the nucleus of the actinides in the UNF fuel, can offset the somewhat lower fissibility of these actinides. These advanced designs, if deployed at scale, could allow for a very high utilization/burnup rate for fuels across the fleet and minimize the total footprint of high-level waste worldwide. If UNF actinides were effectively "burned" using a fast spectrum reactor design, then the remaining **spent fuel** would be primarily composed of fission products with half-lives in the hundreds of years rather than actinides with half-lives in the tens of thousands of years. This significant difference drives the required capabilities and certification requirements for any high -level waste storage facility.

Proliferation Risk and Physical Protection

Tightly coupled with the issue of waste management is the issue of proliferation risk. Key to this area is a discussion of **safeguards**, which relates to the material control and accounting program for control of the enriched nuclear material. For the International Atomic Energy Agency (IAEA), safeguards also involve verifying that the peaceful use commitments made in binding nonproliferation agreements, both bilateral and multilateral, are honored.

Safeguards have traditionally been focused on the "…timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices…"[15] To the extent that plants are designed to be proliferation resistant, they are addressing the risk of host nation diversion or misuse. Addressing the risk of diversion from a non-state actor through theft or sabotage would fall in the category of physical protection of a design.

Advanced reactors pose interesting opportunities and challenges regarding safeguards and proliferation resistance. Key issues related to safeguards for advanced designs include review and updating of accountancy tools for non-conventional fuel types (especially liquid fuels) that are proposed for some new designs. New fuel loading schemes for pebble bed or molten salt reactors may also pose challenges, as would the presence of on-site **reprocessing** or **hot cells** for some designs.

In order to address the complexity in accounting for some new designs, experts are recommending the use of a "safeguards by design" process for designers to ensure that the facilities are built to consider accounting at the conceptual design stage.[16] These same experts indicate that while aspects of proliferation resistance are unique for each design, most reduce the likelihood of accessibility because of "inherent operational conditions such as high temperatures, high radiation levels, inert environments, or presence of toxic materials." They also note that some are designed as sealed systems and others are designed to be sited below ground, again limiting access. These same measures can enhance physical protection.

In order to address the complexity in accounting for some new designs, experts are recommending the use of a "safeguards by design" process for designers to ensure that the facilities are built to consider accounting at the conceptual design stage.

The Generation IV Forum (GIF) and the IAEA International Project on Innovative Reactors and Fuel Cycles (IAEA-INPRO) are closely examining proliferation and physical protection issues that are unique to advanced reactors. GIF has included proliferation resistance and physical protection

15 IAEA INFCIRC/153; The Structure and Content of Agreements between the Agency and States required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons; Paragraph 28. June 1972.

16 Flanagan, G., Bari, R; *Nexus of Safeguards, Security and Safety for Advanced Reactors*; Oak Ridge National Laboratory; 23 Feb 2016.

(PR&PP) as one of four key technology goals and established a separate working group to assess this area. The goal of the effort is:

> ***"Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism."***

Advanced reactors can be designed to have enhanced nonproliferation characteristics and physical protection, but the key will be to begin early and include these as central design criteria.

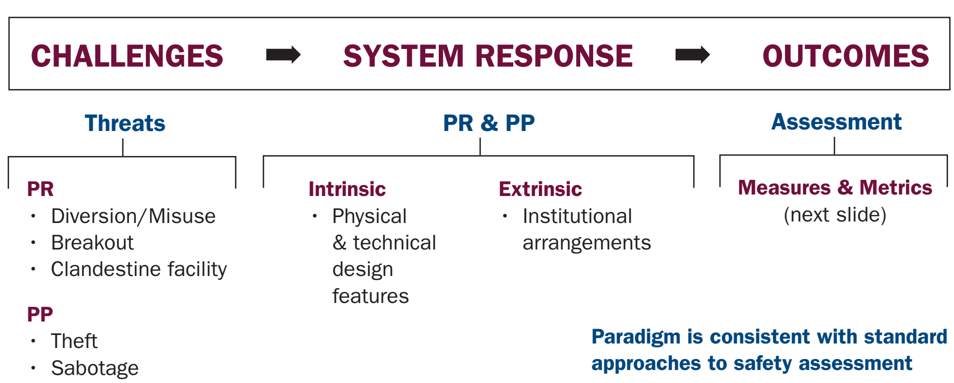
In carrying out its mandate, the working group has followed the methodology shown in Figure 3 below, ensuring that challenges for proliferation and security are identified, intrinsic and extrinsic features are put in place to address these challenges, and a methodology for safety assessment is well established.[17]

The ultimate goal is to develop a set of attributes that can be used to assess facilities to evaluate their level of "safeguardability." This includes looking at areas as diverse as ease of detection for nuclear material within a facility to transparency of facility layout.[18]

Hybrid/Non-electric Applications/ Load Following

Each advanced design can be used in a fashion similar to the existing LWR fleet, primarily for the generation of electricity. But many advanced designs could potentially be employed for other applications by taking advantage of their different performance characteristics. In many cases, plants can be used as "hybrid" energy systems, designed to operate with other generating systems (e.g. renewables). Others have characteristics (especially higher operating temperature) that make them suitable for co-generation or to serve as a process heat source for use in industries such as desalination, hydrogen production, or chemical production. Table 1 is a World Nuclear Association breakdown of the types of processes that can be supported by advanced reactors according to their operating temperatures.

FIGURE 1
Generation IV Forum PR&PP Methodology



Source: *https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/gif_prppem_rev6_final.pdf*

17 Whitlock, J., Status of GIF PR&PP Evaluation Methodology; GIF/INPRO Interface Meeting 1–3 March, 2010 IAEA, Vienna, Austria.

18 Cojazzi, G.G., et.al; Proliferation Resistance Characteristics of Advanced Nuclear Energy Systems: A Safeguardability Point of View; ESARDA BULLETIN, No. 39, October 2008.

These illustrations (above and below) show an artist's depiction of small modular nuclear units providing carbon-free high temperature heat for industrial use.

Table 2 below provides a summary of the potential uses of different designs based on their coolant type. This table reflects a US national lab estimate of capability; however, newer systems may also provide the benefits listed.[20] A significant benefit for the use of advanced reactors in hybrid co-generation systems is the potential for use in an effective **load following** mode, which means dual use in a co-generation application and, for electricity generating purposes, allowing operation at high capacity regardless of electrical demand. This ensures the most economical use of the asset.

TABLE 1

World Nuclear Association breakdown of possible industrial/utility applications for nuclear power plants according to operating temperature.[19]

Process Temperature	up to 700°c	up to 900°c	up to 950°c
Electricity Production	Rankine (steam) system	Brayton (direct) cycle	
Utility Applications	Desalination	H_2 via steam reforming of methane or high-temperature electrolysis	Thermochemical H_2 production
Oil & Chemical Industry	• Tar/oil sands and heavy oil recovery • Syncrude • Refinery and petrochemical	Syngas for ammonia and methanol	Thermochemical H_2 production

TABLE 2

Potential Reactor Applications based on coolant type and neutron spectrum.[20]

Coolant	Neutron Spectrum	Reactor Applications
Pressurized Water	Thermal	1, 2
Helium	Thermal	1, 2, 3
Helium	Fast	1, 2, 4, 6
Sodium	Fast	1, 4, 5, 6
Lead	Fast	1, 4, 5, 6
Salts	Thermal	1, 2, 3, 6
Salts	Fast	1, 3, 4, 6
1. Electricity Production 2. Hybrid Systems 3. Co-generation	4. Transmutation of Waste (actinide burner) 5. Fuel recycle (breeder) 6. Burner (limited to U-235)	

19 Source: *http://www.world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-process-heat-for-industry.aspx.*

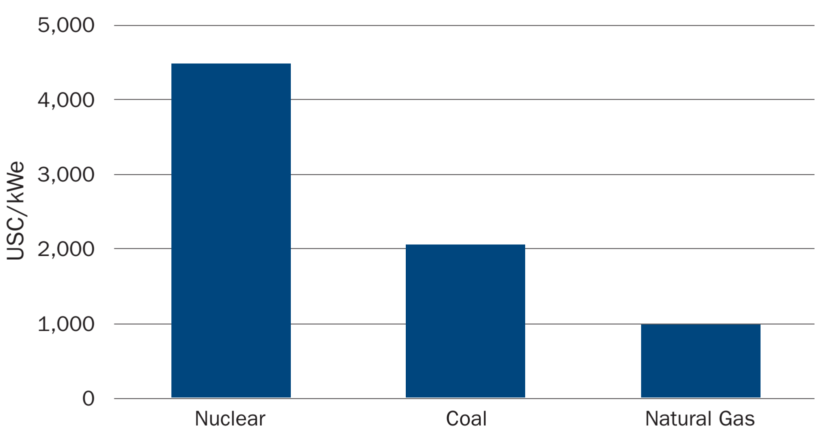
20 Mays, G.T., Status of Advanced Reactor Development and Deployment; Oak Ridge National Laboratory; Feb. 23, 2016.

CHAPTER 4

Costs and Timing of Advanced Nuclear Energy

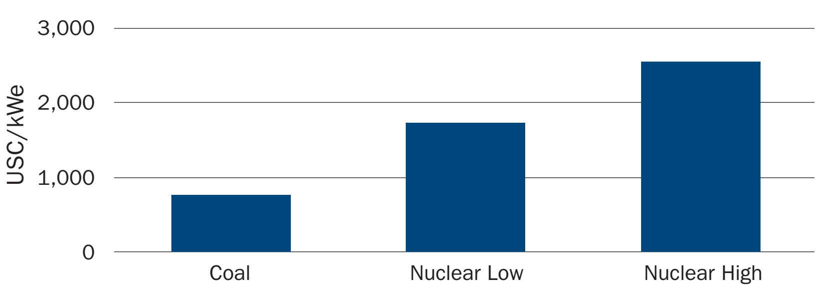
The primary barrier to widespread and rapid scale up of nuclear energy is cost. Especially in the absence of aggressive carbon policies, conventional nuclear power cannot compete in most developing world markets against cheap coal and, in North America, against cheap natural gas.

FIGURE4
Global overnight capital costs of electricity sources



Source: OECD NEA 2015

FIGURE4
China overnight capital costs of electricity sources



Source: OECD NEA 2015

A comparison of overnight capital costs between nuclear and other electricity sources is shown in Figures 4 and 5 below. If anything, the costs shown understate the differentials because they do not include interest costs during construction, which is greater for nuclear than other sources.

Another critical influence on the potential contribution of nuclear power is construction efficiency. As noted in Figure 2, the 2015 nuclear deployment rate of less than 10 GWe per year installed would need to be increased tenfold just to meet the PNNL target for nuclear for 2035. There is little hope, however, of significantly increasing the rate of deployment on present technology, even if cost were not a major constraint. The construction time for the fastest-in-class current generation plants is in the 4.5– to 5.5–year range, as shown in Table 3, a pace that is inconsistent with the required build rate.

TABLE 3
Average Nuclear Project Times (Selected Countries 2005–2015)[21]

	Units	Average Time
Japan	3	4.6 years
South Korea	5	4.9 years
China	18	5.7 years

This rate could be substantially accelerated through the successful application of a manufacturing model, as discussed further below.

21 Schneider, M., et al., The World Nuclear Industry Status Report 2015, Table 2 (p. 34).

Cost Reduction Potential: Overview

Several features of advanced nuclear energy suggest the potential for significantly reduced cost and therefore improved economic viability:

- Use of coolants (e.g. molten salt, liquid metal) that do not boil off rapidly like water. This reduces the need for elaborate emergency back-up systems to deal with rapid water loss.
- Use of alternative coolants to allow some plants to operate at atmospheric pressure, therefore reducing the need for large pressurized containment structures, which consume as much as two thirds of the concrete and steel embedded in current generation nuclear plants.
- Plants that are simpler, smaller, and less complicated to maintain, resulting in reduced hardware and labor costs.
- Simplification of plant design and reduction in plant mass, which enables the industry to move towards a manufacturing model akin to the aircraft- and ship-building industries. Moving to a manufacturing model reduces construction costs and onsite fabrication through factory production of a high percentage of components. The potential result is a radical reduction in construction duration (>50%) and schedule risk. Since 30–50% of conventional nuclear plant costs derive from financing costs during construction, reducing construction time will have a profound impact on overall nuclear costs.
- Much higher temperatures for advanced nuclear power cycles, leading to 30–40% less thermal power required to achieve the same power rating as a typical current generation plant. This can produce a 30–40% reduction in the **levelized cost of electricity**, provided the capital cost does not significantly increase.
- Designs with ultra-long **fuel cycles** that contribute to lower power cost based on higher capacity factor and lower total lifetime fuel cost. However, the main advantages of the long fuel cycle are less waste and better use of energy resources.
- Higher efficiency to reduce costs. The General Atomics Energy Multiplier Module (EM^2) has a net efficiency of 53% and a 30–year fuel cycle, which contribute to a 95% capacity factor compared with 92% for LWRs. Consequently, EM^2 uses only one fifth of the fuel of an LWR for the same electricity output and produces only one fifth of the waste.[22]

In the spring of 2016, the Energy Options Network (EON) completed a review of 12 advanced nuclear energy developers, under non-disclosure agreements. While the assessment covered an array of issues, nearly all companies provided preliminary estimates of plant costs and construction lead times. Construction times ranged from three to four years. Recognizing that the estimates were early stage (and actual costs will be revealed when companies commission their first plants), the costs that companies reported were highly competitive with existing baseload options. Cost reductions were primarily enabled by innovations in manufacturing and delivery strategies, new business models, simpler reactor and plant designs (requiring fewer components and enabling quicker construction/assembly), and less complex (and thus less expensive) safety systems. Anonymized costs are shown in Table 4. The cost figures are updated based on a more detailed 2017 survey by EON, as described in the Energy Innovation Reform Project report “What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development.”[23] These are representative targets for “Nth-of-a-kind” plants, excluding licensing costs. While licensing requires both significant time and expense, Table 4 highlights that advanced nuclear energy could be highly competitive with existing, dispatchable baseload options. Moreover, the prospect of safer and simpler designs as well as modularity and mass manufacturing (like that done for constructing airplanes and large tankers) enables the potential for advanced nuclear plants to achieve rapid scale, which would be necessary

22 Choi, H, Schliecher, R.W., Gupta, P; A Compact Gas Cooled Fast Reactor with Ultra-Long Fuel Cycle; Science and Technology of Nuclear Installations; Volume 2013; Article ID 618707; March 2013.

23 “What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development.” *http://innovationreform.org/wp-content/uploads/2017/07/Advanced-Nuclear-Reactors-Cost-Study.pdf*

TABLE 4

Advanced Reactor Levelized Costs of Energy Compared with Current Technology

Levelized Cost of Energy	CAPEX ($/kw)	Capacity Factor (%)	Capitalization Period (yrs)	Fuel ($/MWh)	O&M ($/MWh)	Cap Charge ($/MWh)	Total Levelized Cost ($/MWh)
Advanced Nuclear (Low)	$2,053	95	25		$14.00*	$22.00	$36.00
Advanced Nuclear (Avg)	$3,782	95	25		$21.00*	$39.00	$60.00
Advanced Nuclear (High)	$5,855	95	25		$30.00*	$60.00	$90.00
Combined Cycle Gas Turbine (CCGT)	$1,000	92	20	$23.20	$5.00	$12.45	$40.65
Combustion Turbine Gas Peaker	$600	25	20	$34.00	$5.00	$39.89	$78.89
Light-Water Reactor (US Current)	$7,000	92	20	$8.00	$10.00	$87.18	$105.18

Source: Energy Options Network 2016 & 2017

* For advanced nuclear, fuel and O&M are combined.

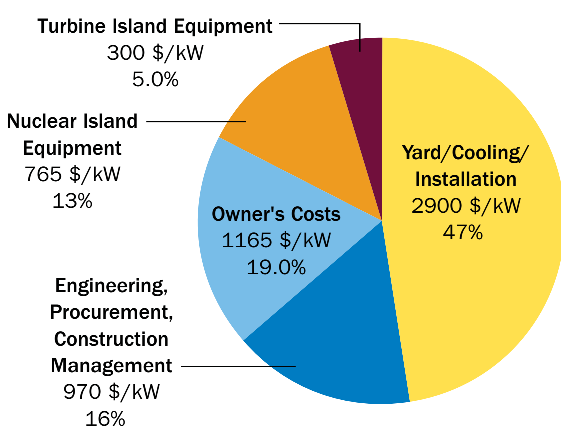
for companies to achieve their intended cost targets. Many companies are aspiring to have their technology licensed and commercially available by the middle of the next decade.[24]

Cost Reduction Opportunities: A Close-up

A central and important fact about nuclear energy today is that ***most of its overnight capital costs lie outside the cost of the power island equipment.***

FIGURE 6

Gen III+ nuclear plant cost components as estimated by Black and Veatch for the National Renewable Energy Laboratory using an AP1000 plant as representative example.[25]



As shown in Figure 6, nuclear island and turbine island equipment constitute only about 17.5% of total plant costs; the rest is balance of plant, containment construction, site preparation, owner's costs, and on-site labor.

Additionally, building nuclear plants as civil engineering construction projects with large material masses results in substantial financing costs. As shown in Figure 7 below, every additional year of construction adds $200–500/kw to final project costs.

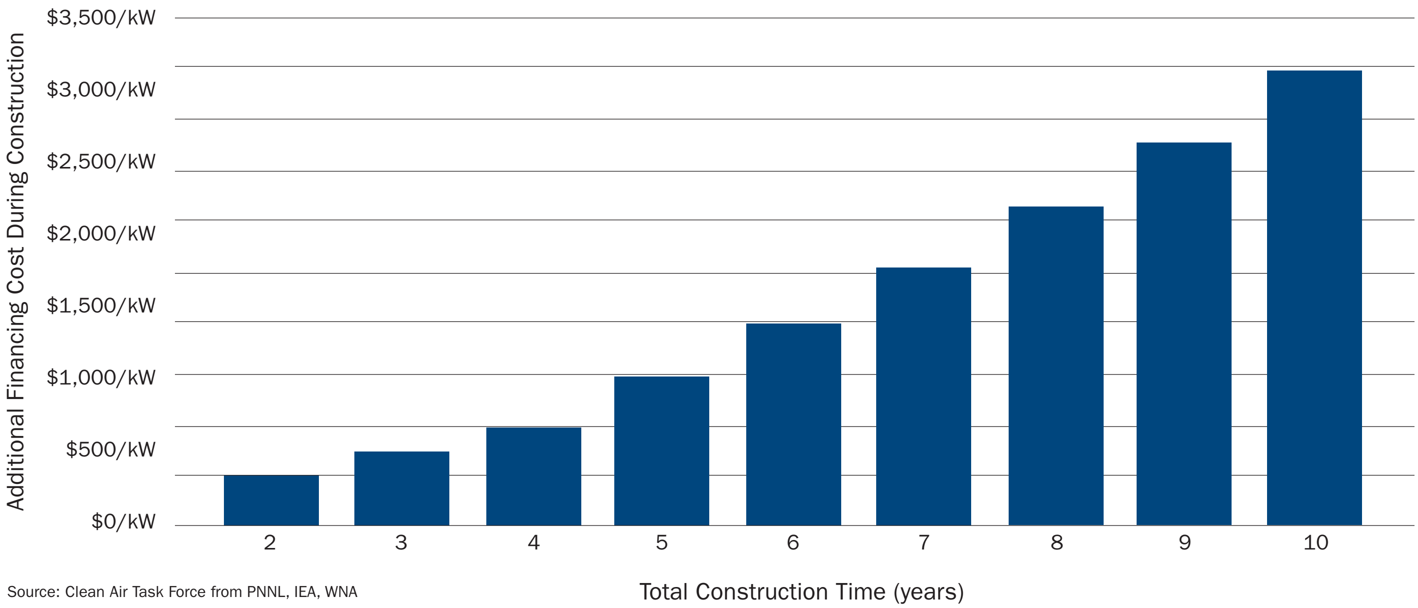
As noted above, one of the keys to future viability of nuclear development is improved economics. A key to reduction in the dominant cost factors is the ability to design plants in a modular fashion so that significant portions of the plants can be built in a factory/shipyard environment. This will allow cost reductions based on:

- Factory production of a high percentage of components
- Standardized, "pre-fab" construction of significant portions of the plant
- Improved workforce management

24 Data represented in Tables 4 and 5 are a composite of various advanced ("Gen IV") designs, such as molten salt reactors, sodium-cooled fast reactors, and high-temperature gas reactors, developed from a survey under non-disclosure agreements by EON in 2016 as well as a more detailed survey in 2017 (see footnote 24). The inputs reflect US installation and are expressed in constant 2016 dollars.

25 Black and Veatch (2012) Cost and Performance Data for power Generation Technologies. Prepared for the National Renewable Energy Laboratory, Black and Veatch, Overland Park, KS, USA.

FIGURE 7
The impact of increases in construction time on cost as measured in $/kW



Source: Clean Air Task Force from PNNL, IEA, WNA

Assumptions: $4,000/kW total overnight cost, 25% of which is spent in each of the first three years, then remaining overnight cost is spent evenly in the remaining years; annual interest rate is 8% (based on costs spent mid-year through each year).

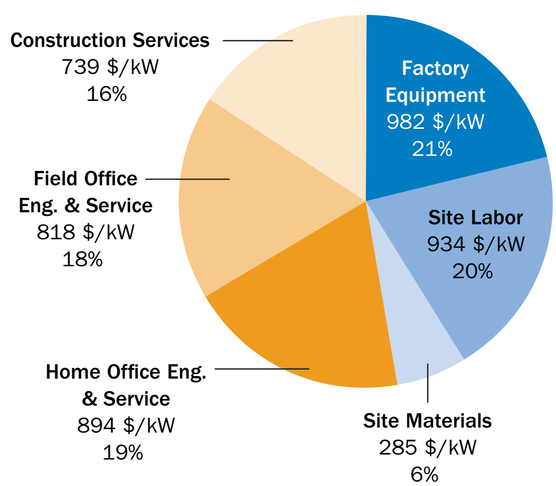
As shown in Figure 8 below, large portions of the development schedule lend themselves to cost savings via a migration from stick-built to modular processes.

Additionally, many advanced designs have lower material intensity due to lower pressure operation and more inherent safety strategies. For example, because a molten salt reactor operates at or near atmospheric pressure, significant reductions in steel are possible. A comparison of existing plant specific steel requirements compared with a Gen IV molten salt design by ThorCon is shown in Table 5.

While steel reductions are significant, reductions in nuclear-grade concrete are often larger and enable even greater cost savings.

The GIF Working Group for Economic Modeling has evaluated the potential cost reductions from a shift to modular construction, and in its G4Econ cost model guidelines, has estimated the range that may be possible. These are shown in Table 6 below. Most savings are related to improvements in schedule and therefore reduction in financing costs.

FIGURE 8
U.S. Pressurized Water Reactor (PWR) Overnight Cost: Areas of Potential Cost Savings



- **Total Overnight Cost: $4,652/kW**
- **Blue cost components represent direct costs**
- **Orange cost components represent indirect costs**

Source: Adapted from US Department of Energy, Phase VIII Update Report for the Energy Economic Data Base Program, Dec. 1986, Table 5-3 (Median Experience)

While these savings are yet to be proven in actual construction, the scale of savings is significant enough to suggest that NOAK advanced reactor development could be economical against even the lowest price alternative generating technologies.

TABLE 5

Steel Intensity for Existing Reactors vs. ThorCon's Molten Salt Reactor

	GEN II	GEN III (active)		GEN III+ (passive)		GEN IV
Vintage/Make	1970s PWR	ESBWR	ABWR	ESBWR	AP-1000	ThorCon
Capacity	1000 MWe	1600 MWe	1380 MWe	1550 MWe	1090 MWe	1000 MWe
Tonnes of Steel per mW	40	49	51	40	42	15

Source: Adapted from ThorCon Power (2015), pg. 26. Accessed at http://thorconpower.com/slides/hanford_2015.pdf

TABLE 6

Stick-Built and Modular Plant Features vs. Cost Reduction Potential[26]

Consideration	Stick-built Plant	Modularized Plant	% Reduction
Direct construction cost	All field construction	With shop fabrication	0–5
FOAK-NOAK learning effect	Larger plants, less doubling of experience (eight each)	Smaller plants, larger number of plants for same capacity (32 each)	0–10
Direct labor	All field construction	Transfer to shop	30–50
Direct labor hours (productivity)	Direct hours	Reduced field work, lower worker densities, improved access	10–25
Construction/installation schedule	Regular work schedule	Parallel construction, early start fabrication, reduced field work	30–50
Field indirect cost	Regular work schedule	Reduced field work, reduced construction schedule	30–50
Field management costs	All field construction	Reduced field work, reduced construction schedule	15–25
Direct cost contingency	All field construction	Shop safety, security, environment, seasons, support, interference, logistics, controls, etc.	10–20
Owner's costs	Regular work schedule	Early plan and start-up, factory and site	0–10
Supplementary costs	All field construction	Provisions for d&d	0
Capitalized finance cost	Regular work schedule, All field construction	Parallel construction, early start fabrication, early start operations	30–50
Robotics and automation	Minimum utilization	Future potential	30–50
Annualized costs	Regular work schedule	Designed for o&m	0–5

26 The Economic Modeling Working Group of the Generation IV International Forum; COST ESTIMATING GUIDELINES FOR GENERATION IV NUCLEAR ENERGY SYSTEMS; 26 Sep 2007; Table 11.2

CHAPTER 5

Technical Challenges and Opportunities

A key issue with most of the advanced reactor technologies is the need for continued research and/or development. Each technology has unique challenges that must be addressed before it becomes a viable alternative for use in the future energy mix. In assessing each technology, the Department of Energy uses a system of “Technology Readiness Levels (TRL)” that categorizes the technology by maturity levels using a scale from 1–9. At low TRLs (1–3), a technology is at its most basic level, with essential principles observed in the lab and practical applications only at the formulative stage. At higher levels (4–6), technologies are developed and demonstrated, with pilot-scale systems tested. The highest levels of the scale (7–9) reflect technologies that are ready for commissioning and operation. Details of these levels can be found in DOE 413.3-4A.[27]

In a recent study, U.S. National Laboratories evaluated the Generation IV concepts based on their TRLs.[28] In reviewing their efforts, which are summarized in the table (adapted from that report, p. 20), the challenges and opportunities can be determined for each technology. Highlighted in green are TRLs below six. Universities looking for opportunities for new research options or innovative startup companies looking to play a role in the advancement of new nuclear should look to the details provided in this comprehensive work. While the example reactors in Table 7 are representative, specific challenges and opportunities for other companies can be found through contact with these vendors using the details provided in Appendices A and B. GFR = Gas-cooled Fast Reactor; LFR = Lead-cooled Fast Reactor; SFR = Sodium-cooled Fast Reactor; VHTR = Very High-Temperature Reactor; SCWR = Supercritical Water-cooled Reactor; MSR = Molten Salt Reactor.

A key issue with most of the advanced reactor technologies is the need for continued R&D. Each technology has unique challenges that must be addressed before it becomes a viable alternative for use in the future energy mix.

27 Source: *https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a.*

28 Petti et.al; Advanced Demonstration and Test Reactor Options Study; Idaho National Laboratory ART Program; July 2016; Appx B; pp104-105.

TABLE 7

Technology Readiness Levels of Various Advanced Reactor Technologies[29]

Technology Readiness Levels for Each System and Subsystem for Deployment								
Technology	**GFR**	**LFR**	**SFR**		**VHTR**	**SCWR**	**MSR**	
Example plant	**EM^2**	**Gen4**	**AFR-100**	**PRISM**	**SC-HTGR**		**FHR**	**LF-MSR**
Nuclear Heat Supply	2	3	3	5	5	3	3	3
Fuel Element (Fuel, Cladding, Assembly)	2	3	3	5	6	3	6	5
Reactor Internals	3	3	3	6	6	3	6	5
Reactivity Control	4	3	6	6	6	3	4	4
Reactor Enclosure	4	3	3	5	5	3	3	3
Operations, Inspection, Maintenance	4	3	3	5	5	5	3	5
Core Instrumentation	3	3	3	5,3	6,3	3	3	5,3
Heat Transport	3	3	4	4	5,3	5	4	3
Coolant Chemistry Control/Purification	6	3	6	6	6	5	4	3
Primary Heat Transport System	6	3	6	6	6	5	4	4
Intermediate Heat Exchanger	NA/3	3	3	6	NA/3	NA	4	4
Pumps, Valves, Piping	5	3	4	4	5	5	4	4
Auxiliary Cooling	6	3	NA	NA	6	5	4	4
Residual Heat Removal	3	4	5	5	5	5	4	4
Power Conversion	3	7	4	7	6	7	6	6
Turbine	3	7	4	7	7	7	7	7
Compressor/Recuperator (Brayton)	3	NA	4	NA	NA	NA	NA	NA
Reheater/Superheater/Condenser (Rankine)	NA	7	4	7	7	7	7	7
Steam Generator	3	7	4	7	7	7	7	7
Pumps, Valves, Piping	3	7	4	7	6	7	6	7
Process Heat Plant (e.g. H_2)	NA/3	NA	NA	NA	NA/3	NA	NA/3	NA
Balance of Plant	6	6	4	4	6	7	4	4
Fuel Handling and Interim Storage	6	6	4	4	6	7	6	4
Waste Heat Rejection	7	6	6	6	7	7	6	6
Instrumentation and Control	7	6	6	6	6	7	4	6
Radioactive Waste Management	6	6	6	6	6	7	6	6
Safety	2	3	6	6	6	3	3	3
Inherent (Passive) Safety Features	3	3	3	6	6	3	4	5
Active Safety System	2	3	3	6	6	3	3	3
Licensing	1	3	3	3	3	1	2	2
Safety Design Criteria and Regulations	3	3	3	3	3	3	3	3
Licensing Experience	1	1	3	3	3	1	2	2
Safety and Analysis tools	3	3	5	5	4	3	3	3
Fuel Cycle	6	6	6	6	NA	NA	NA	5
Recycled Fuel Fabrication Technology	3	3	6	6				5
Used Fuel Separation Technology	3	3	6	6				5
Safeguards	3	3	3	3	3	7	3	3
Proliferation Resistance—Intrinsic Design Features	3	3	3	3	3	7	3	3
Plant protection—Intrinsic Design Features	3	3	3	3	3	7	3	3

* Key systems and subsystems are shown in bold

29 Ibid.

CHAPTER 6

Institutional Obstacles and Policy Approaches to Licensing, Demonstration, and Diffusion

There are many challenges facing global development and deployment of advanced nuclear energy that go beyond the need for additional research and development. Good policy can confront and tackle these challenges. Possible initiatives include:

- ***Develop internationally harmonized safety construction and quality assurance standards for advanced reactors.*** Though advanced reactors such as high-temperature gas reactors and sodium-cooled fast reactors have been built in the past, the experience in development is limited; a history of technical challenges has led to poor performance and, in many cases, early decommissioning of these plants. As new materials and techniques emerge that may solve some of these issues, the next challenge will be development of standards that can be used for regulatory approval—standards that are largely in place for the light-water fleets of the world. Early development of a core set of standards that are reviewed and accepted internationally would enable much more rapid deployment, since each nation would not need to reassess designs based on unique national standards or try to consolidate a number of differing standards.
- ***Improve regulatory processes and regulator experience.*** In addition to common standards, regulatory processes must be developed and expertise and experience built within regulatory agencies. Standards should be risk informed and nonprescriptive, allowing for phased licensing of new reactor designs rather than all or nothing commitments that may deter investment.[30] Many of the current personnel at national regulatory bodies have the necessary technical background and skill to learn the new designs and standards, but they have been focused on light-water reactor regulation for most of their careers. Programs must be developed to respond accordingly to advanced reactor regulatory oversight. An international effort offers the most promising way to build the training pipelines that could cover the unique aspects of advanced reactor development and operation.

Regulatory processes must be developed and expertise and experience built within regulatory agencies. Standards should be risk-informed and nonprescriptive, allowing for phased licensing of new reactor designs rather than all or nothing commitments that may deter investment.

30 See, e.g., recommendations in Nuclear Innovation Alliance, "Enabling Nuclear Innovation: Strategies for Advanced Reactor Licensing" (April 2016), *http://www.nuclearinnovationalliance.org/advanced-reactor-licensing.*

- ***Provide test and development infrastructure.*** In many cases, advanced nuclear designs require use of new materials and fuels. Better testing facilities, especially one with a flexible, fast neutron source, will be needed to enable efficient certification of these new materials. Additionally, once a design is well developed, a demonstration plant must be built, which will require significant effort for site development and licensing. Either a sustained national effort or a coordinated international effort would accelerate development. Investment in other tools such as modeling and simulation should continue to support innovation, and research in complementary technologies, such as advanced manufacturing, modular construction, advanced power cycles, and 3-D printing should be scaled up and coordinated with nuclear innovation to improve the utilization of these new technologies in the nuclear field.
- ***Streamlining export control procedures and requirements.*** In the US, some innovators have found the time, complexity, cost, and stringency of the export control process to be overly burdensome, delaying or deterring international cooperation and international business agreements. Efforts can and should be made to reduce the burden of the export control process without endangering the national security interest of the US. The market for advanced nuclear energy is global: it is important both to utilize international resources in development and to compete internationally in deployment.
- ***Develop the capability for manufactured, modular, and sound business approaches to building new nuclear plants that are not vulnerable to the types of cost and schedule overruns that have typified recent western nuclear power projects.*** Success in using advanced nuclear energy to address climate change and energy needs is entirely dependent on the ability to deploy nuclear energy economically at scale. Achieving the cost projections discussed in this paper will require new business models and factory-based construction approaches. This is likely to be the most pivotal change needed; it is incumbent upon all stakeholders, but most of all upon the nuclear design and construction industry, to address this challenge. This has been a topic of discussion in the West, but little else; a robust effort in this area is sorely needed.

CHAPTER 7

Conclusion

The next several decades will bring an increasingly urgent need for clean, reliable, affordable energy sources to repower a predominantly fossil-based energy system and to fuel growing energy demand in the developing world. Alongside other clean energy sources, nuclear power can play a valuable role. However, the failure to address limitations of past technology—including cost, scalability, and concerns about safety, waste, and proliferation—will only hamper nuclear power's contribution. To serve rapidly escalating climate change mitigation and energy needs, nuclear plants must be competitive on price with coal and gas; deployable as fast as coal plants or faster; and suitable for operation in developing countries that lack significant pre-existing nuclear capabilities. Advanced nuclear energy technologies that could help us meet these goals are currently under development: with adequate policy and investor support they could be available for use within the next decade. All viable efforts should be made to accelerate their commercialization, but also to ensure that their development reflects societal priorities and consensus, including safety, sustainability, affordability, nonproliferation, and security.

Nuclear plants must be competitive on price with coal and gas; deployable as fast as coal plants or faster; and suitable for operation in developing countries that lack significant pre-existing nuclear capabilities.

Artist's depiction of a remote Alaskan ommunity powered by zero-carbon advanced nuclear and wind energy.

APPENDIX A

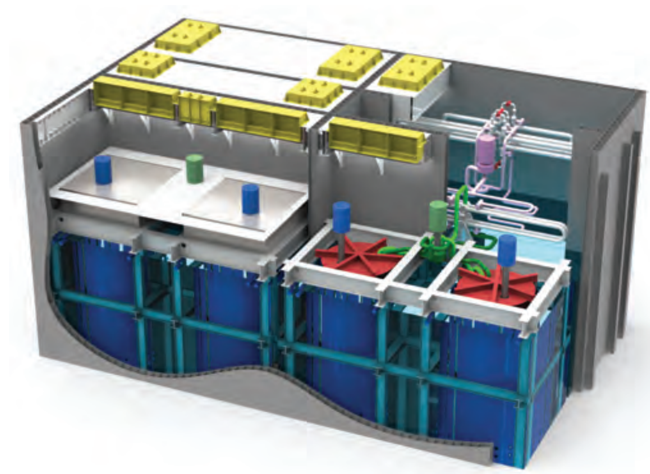
Profiles of Representative Advanced Nuclear Energy Companies

Some examples of advanced nuclear reactor types and companies developing them are highlighted below.[31]

ThorCon Power (Tavernier, FL)

ThorCon is using the molten salt reactor design developed at Oak Ridge National Laboratory and building it entirely in modular blocks on a shipyard-like assembly line. The shipbuilding "grid block" approach can minimize on-site construction, dramatically reduce costs, and enable rapid manufacturing and deployment.

Technology



- ThorCon's molten salt reactor is based on the Molten Salt Reactor Experiment (MSRE) that operated at Oak Ridge National Laboratory from 1965 to 1969. The fuel salt is a mixture of sodium, beryllium, uranium, and thorium fluorides. ThorCon's fuel salt, containing 20% enriched uranium, can be used for eight years before being replaced. About 25% of the power comes from thorium, converted to uranium during operation. The company intends to subject a prototype to a full battery of stress tests to ensure it meets performance requirements under a range of conditions and contingencies.
- ThorCon uses $NaF\text{-}BeF_2$ (NaBe) for both fuel salt and secondary salt. NaBe is available and reasonably inexpensive.
- ThorCon's plant is made up of one to four 250 MWe modules, each containing a pair of "Cans" containing the reactor and highly radioactive parts. Each Can is operated for four years. After four years of initial use in one Can, the fuel salt is reused in a second Can for four more years.
- The reactor is 9 to 25 m underground with three gas-tight barriers between the fuel salt and the atmosphere. Operating at near-ambient pressure, the reactor does not, in the event of a primary loop rupture, experience dispersal energy nor phase change. Any spilled

31 Vendor descriptions are compiled from publicly available information, primarily provided by the vendors. The information has not been independently verified.

fuel salt merely flows to a drain tank where it is passively cooled.

- After four years of reactor operation, its entire Can is left in place for an additional four years to allow its radioactivity to decay. There is no separate, vulnerable radioactive storage facility. The Can is then returned to a recycling facility where it is refurbished for its next cycle of use, similar to the airline industry's periodic replacement of aircraft jet engines.

Business

- The unit will be built in a shipyard and towed to the plant site, providing an opportunity to further prove ThorCon's shipyard-based manufacturing strategy.
- The company believes that assembly lines similar to the best-in-class shipyards in South Korea and Japan could manufacture approximately 100 1GWe reactors in a year.
- The company believes it can have a full-scale prototype operating in four years.
- The base cost is estimated to produce a levelized cost of energy of 3 cents/kWh.
- In October 2015, ThorCon signed an MOU with the Indonesian government to pursue a pathway toward a license to build a ThorCon molten salt reactor. The MOU was specifically signed with INUKI (the state-owned nuclear corporation), which has a license to import nuclear fuel, PLN (the state-owned utility), which will help site and interconnect ThorCon plants, and Pertamina (the state-owned oil and natural gas corporation), which will support project development and government negotiations.
- ThorCon intends to work cooperatively with regulators to establish a "test then license" protocol in which tests are performed on the unit as it gets built. The approach requires that test results be approved before moving to subsequent tests, obviating the need for separate materials testing facilities and providing better visibility into how the unit will behave during typical (and non-typical) operations.

Oklo (Sunnyvale, CA)

Oklo has developed a small (2 MWe), fast spectrum reactor, designed for off-grid applications. The company participated in the Y Combinator accelerator program (the most successful startup incubator in the world).

Technology

- Oklo is building a 2 MWe fast spectrum reactor that fits in a shipping container, designed to serve remote, rural, and native communities, as well as industrial and military sites (e.g., areas too remote and small to be served by larger reactors and often powered by expensive diesel generators).
- The reactor operates purely on natural physical forces, with very few moving parts, and is designed to operate for 12 years before refueling.
- Reactor is up to 300 times more fuel efficient than current reactors, and can consume the used fuel from today's reactors, as well as plutonium and depleted uranium stockpiles.
- The company is currently working with the Gateway for Accelerated Innovation in Nuclear (GAIN) fast reactor group at Argonne National Laboratory.

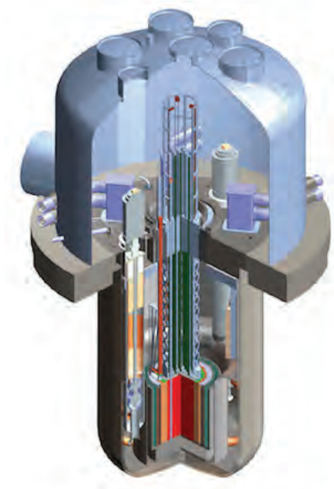
Business

- Oklo is targeting off-grid and weak-grid markets (e.g., mining operations, remote communities, island nations, military microgrids, etc.) with its initial 2 MWe offering.

TerraPower (Bellevue, WA)

TerraPower is backed by Bill Gates and other well-known impact investors and has developed a breed-and-burn sodium-cooled fast reactor called the "traveling wave reactor." It is much more fuel efficient than typical LWRs and uses depleted or natural uranium, requires no chemical reprocessing, and ultimately eliminates the need for fuel enrichment.

Technology



Turns depleted uranium into electricity, using a simple fuel cycle without requiring separations.

SIZE	600 MWe (Prototype Plant) 1150 MWe (Commercial Plant)
TEMPERATURE	510°C
PRESSURE	Low (Atmospheric)
PRIMARY FUEL	Depleted Uranium
COOLANT	Sodium
ENERGY CONVERSION	Steam (Rankine Cycle)
WASTE REPROCESSING	Not Required

The traveling wave reactor (TWR) resulted from the need for a scalable solution to grid decarbonization without nuclear safety, cost, spent fuel, and proliferation issues. The reactor was inspired from decades of operating experience for sodium-cooled fast reactors as well as research and validation for molten salt reactors. TerraPower is currently developing the conceptual core design of the TWR, a liquid sodium-cooled breed-and-burn reactor using a uranium-zirconium metallic fuel.

- The reactor uses fuel from depleted uranium (a waste byproduct of the fuel enrichment process) and gradually converts the material through a nuclear reaction inside the reactor core. This prevents the need to remove fuel at any time during operation and, most importantly, the reactor can sustain this process indefinitely (i.e., operate indefinitely).
- TerraPower's reactor offers a 50x gain in fuel efficiency (which means less waste at the end of life), eliminates the need for reprocessing (effectively eliminating the need for reprocessing plants over time and reducing proliferation concerns), and makes fuel from a current liability (depleted uranium).
- TerraPower's R&D program includes partnerships with a number of US and other national laboratories. In 2016, the company opened a 10,000-square foot R&D facility in Bellevue, WA for testing components, fuels, materials, and other technologies included in the development process.
- TerraPower anticipates building a 600 MWe prototype reactor by the early 2020s. Its full-scale commercial design is 1150 MWe, which company officials hope to deploy to global markets within the next 15 years.
- The reduction in waste production results in a lower repository capacity requirement and reduced waste transportation costs.
- Because of its high breeding ratio, the TWR core produces enough extra fuel to start other TWRs without requiring any additional fuel enrichment. Subsequent generations of TWRs are started with discharged fuel from previous generations.
- Passive decay heat removal is available even without offsite or onsite emergency power.
- In addition to the TWR, TerraPower has longer-term plans to develop a molten-chloride fast reactor (MCFR). Company officials believe the MCFR could excel in safety, waste, non-proliferation, and economics. This may possibly become a more cost-competitive option than the TWR.

Business

- In September 2016, TerraPower signed an MOU with China National Nuclear corporation (CNNC) to collaborate on the TWR design and commercialization. As part of preparing for the MOU, TerraPower secured permission from the US government to collaborate with China on the nuclear technology.
- In 2015, Babcock & Wilcox, which manufactures US Navy nuclear reactors, agreed to support TerraPower by providing design and fabrication of components and fuel, engineering, and materials testing and operations support, among other services.
- TerraPower is backed by a number of high-profile investors including Bill Gates, Nathan Myrvold, Mukesh Ambani, and Vinod Khosla.
- TerraPower recently won a DOE grant to work with Southern Company and Oak Ridge National Laboratory to develop and test molten chloride salt.
- The company has 300 person-years of experience on fast reactors and more than 80 contracts with national labs, universities, companies, government agencies, and expert consultants since 2007.

Transatomic Power (Cambridge, MA)

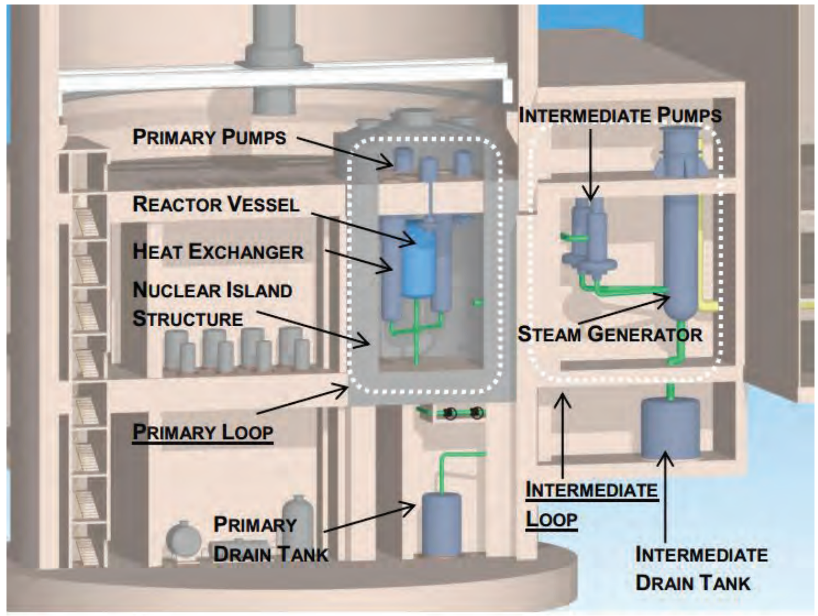
Transatomic Power is a Cambridge-based company developing a passively safe and proliferation-resistant molten salt reactor that can consume low-enriched (5%) fresh uranium, with twice the fuel utilization and half the waste production of a typical LWR.

Technology

- Transatomic Power is developing an advanced molten salt reactor that can consume low-enriched (5%) uranium fuel. It achieves twice the actinide burnup of a conventional LWR and can reduce annual long-lived waste production by more than 50%.
- The reactor design includes several improvements over the molten salt reactors developed at Oak Ridge National Laboratory in the 1950s, 1960s, and 1970s. Transatomic's primary technical innovations include the use of a lithium-fluoride fuel salt and a clad zirconium hydride moderator.
- The company worked with Burns & Roe, a nuclear engineering, procurement, and construction firm, on a system-wide, pre-conceptual 520 MWe plant. The overnight cost is estimated at $2B with a three-year construction schedule. The higher outlet temperatures of the reactor (650°C as opposed to 290-330°C for current LWRs) enables significant savings in the turbine and balance of plant costs.
- Their commercial-scale reactor design is 520 MWe, which can be used for both base load and load following.

Business

- Since its founding in 2011, the company has raised $5.8M from investors.
- The company is currently running laboratory-scale tests of key reactor materials under a three-year sponsored research agreement with the Dept. of Nuclear Science and Engineering at MIT. The company was also awarded a GAIN (Gateway for Accelerated Innovation in Nuclear) award from the Department of Energy to conduct additional design optimization work with the Oak Ridge National Laboratory.



Transatomic Power's Molten Salt Reactor

Early Architectural Rendering of Power Plant

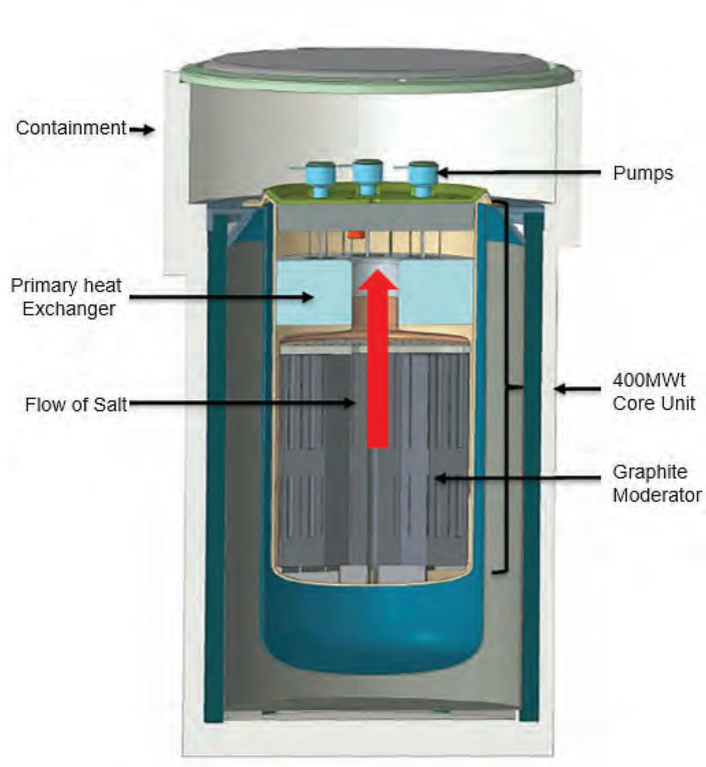
- The next steps in the company's development plan include creating site-independent reactor blueprints for a demonstration-scale facility, and refining those specifications for a specific site location. The company is currently assessing locations for building this demonstration-scale facility.
- Transatomic is also optimizing the commercial-scale reactor design and conducting a thorough cost assessment to demonstrate commercial attractiveness.
- The company aims to have a 10 MWth demonstration-scale reactor operating by the mid-2020s.

Terrestrial Energy (Ontario, Canada)

Terrestrial Energy's designs reflect modifications to the Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Labs by integrating all components into a permanently sealed core unit and replacing it every seven years.

Technology

- Terrestrial Energy has designed an "integral molten salt reactor" (IMSR). The name derives from the integration of the reactor core, primary heat exchanger, and pumps in a sealed reactor vessel within a replaceable unit (with a seven-year operational life). The reactor design is based on the MSRE at ORNL in the 1960s (i.e., uranium-fueled, graphite-moderated, fluoride chemistry, thermal spectrum molten salt reactor system) but also follows in the footsteps of ORNL's more recent SmAHTR reactor design. The IMSR will be constructed in a variety of power outputs, from 30 to 300 MWe (with larger designs possible in later product versions). Its first commercial offering will be 190 MWe.
- The IMSR uses proven materials, readily available salt constituents, and commercially available low-enriched uranium.
- The company completed its pre-conceptual design in October 2014.
- The IMSR can use spent nuclear fuel and most fission products are removed continuously in situ. The company is now developing a recycling process by which the reactor produces virtually zero waste.
- At the end of its seven-year life, the operational reactor core is shut down and coolant lines are connected to the new core. The spent core unit remains in place for seven years to cool. Once cooled, fuel salt can be removed for reuse or recycling.



Business

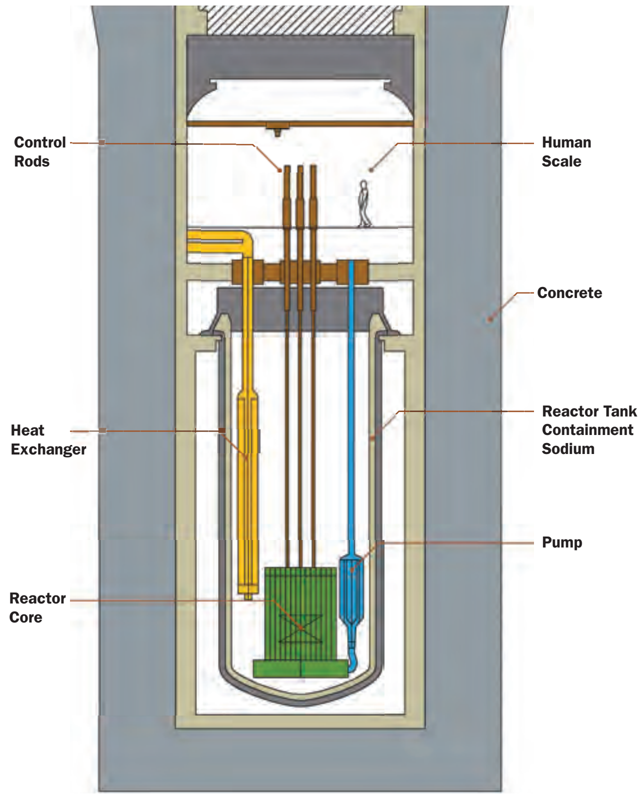
- In February 2016, Terrestrial submitted its IMSR design to the Canadian Nuclear Safety Commission (CNSC) for Phase I of its pre-licensing Vendor Design Review. Given Terrestrial's proposed schedule for submissions, the review is expected to take 18 months. This is the first step towards an eventual license application to build the first commercial demonstration IMSR plant.
- The company plans to submit construction and operation license applications in 2018–19, with a view toward the company's objective of commissioning the first commercial plant in the 2020s.
- In addition to significant progress in Canada, the company is engaging regulators and potential customers in various international markets (both OECD and developing countries).
- The company estimates that it can provide energy at a cost of $40-50/MWh, based on a 300MWe reactor.

Advanced Reactor Concepts (Chevy Chase, MD)

ARC is commercializing the ARC-100, a 100We Sodium-cooled Fast Reactor (SFR) employing metallic uranium fuel and a 20-year refueling cycle.

Technology

- ARC's reactor is a sodium-cooled fast reactor, based on the EBR-II, a prototype that operated successfully for 30 years and produced electricity for the grid at Argonne National Laboratory (ANL) in Idaho. It also builds upon lessons learned from operation of the world's 400 reactor-years of SFR experience (17 test and power-producing reactors in total). The company's approach is to scale up ANL's 20 MWe prototype by a factor of five (making a 100 MWe reactor), update it based on modern licensing requirements, and create a design attractive for rapid, wide-scale deployment. The US government invested approximately $7–8B (in current dollars) on fuels and materials testing, safety evaluation, and prototyping for the SFR at ANL. ARC intends to leverage the technology readiness of the SFR and "stay inside the box" of the original ANL design as much as possible.
- Reactor will be factory-produced and include "walk away" passive safety systems, capability to be fueled with nuclear waste, and a 20-year refueling cycle (as opposed to the one to two years for typical LWRs), which dramatically improves proliferation resistance.
- ARC's team includes many of the country's top experts on sodium-cooled reactors, including members of the EBR-II team. The team is engaged in developing plans, analyses, and designs needed for licensing the ARC-100 and will be working with ANL and the Idaho National Lab to assist in this work.
- Substantial testing and data collection occurred during the 30-year operation of the EBR-II, including fuels testing and qualification and analysis of reactor performance during accident scenarios. Consequently, the company does not anticipate that significant additional R&D, testing, or demonstrations will be required for licensing the ARC-100.



The ARC-100 Reactor

Business

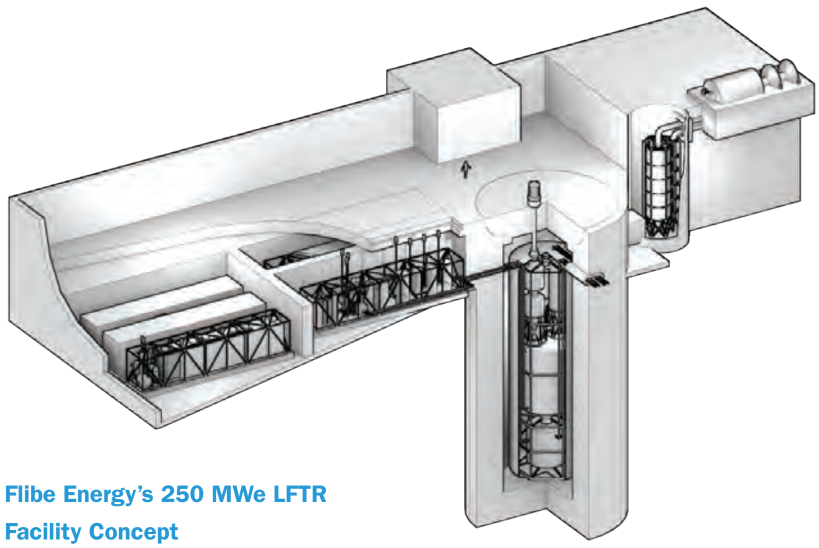
- With the modular 100 MWe reactor, ARC will focus initially on electricity markets in the developed world that have nuclear infrastructure and demand for clean energy to replace coal-fired electricity generation and aging nuclear plants. It will later focus on developing country electricity markets and off-grid electrical production, water desalination, shale oil extraction, and co-generation.
- The ARC-100 is being designed to produce electricity at a target cost (LCOE) not higher than $60/MWh and be delivered for an upfront capital cost (ONC) of not more than $350M.

Flibe Energy (Huntsville, AL)

Flibe Energy is developing a Liquid-Fluoride Thorium Reactor (LFTR). Thorium is the Earth's most abundant energy-dense natural resource, and flibe salt (LiF-BeF2) has the highest volumetric heat capacity of any coolant, is nearly transparent to neutrons, is impervious to radiation damage, and is chemically stable.

Technology

- Flibe Energy is developing a liquid-fluoride thorium reactor (LFTR), a liquid-fueled, graphite-moderated, thermal-spectrum breeder reactor optimized for operation on a thorium-supported uranium-233 (Th-233U) fuel cycle. Current designs range from 250-450 MWe (600–1000 MWt) reactors.
- The reactor technology is based on use of a thorium salt in a liquid fuel—a combination of lithium fluoride (LiF) and beryllium fluoride (BeF2) salts often called "F-Li-Be." FLiBe salts have a liquid range of more than 1,000 degrees (i.e., difference between melting and boiling point) and a very high volumetric heat capacity so they can transfer large amounts of thermal energy at low pressures and pumping rates, offering greater safety and efficiency.
- Thorium is more abundant in nature than uranium, and while not naturally fissile, it can be transformed through neutron absorption into fissile uranium-233, which produces enough neutrons in thermal fission to achieve sustainable consumption of thorium. This nearly eliminates actinide waste from the reactor, generates more energy per ton, and does not produce plutonium.
- Reactor design is based on the 20,000 hours of molten salt reactor operation at Oak Ridge National Laboratory in the 1960s.
- The reactor is designed to be coupled with a supercritical carbon-dioxide closed-cycle gas turbine (as opposed to a conventional steam turbine). Like many molten salt reactor companies, Flibe is looking to ultimately integrate a closed-loop Brayton cycle for its power conversion system.



Flibe Energy's 250 MWe LFTR Facility Concept

Business

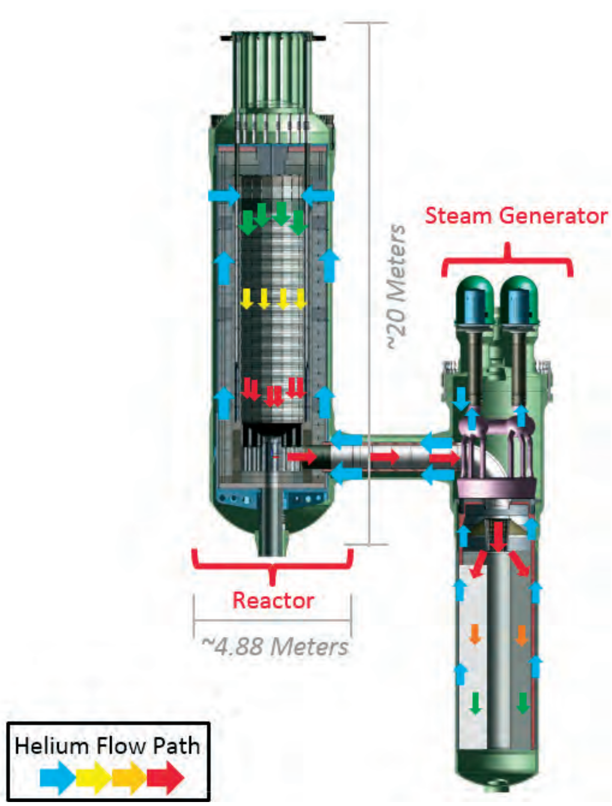
- The company intends to build a 45 MWe (100 MWt) demonstration reactor and then a utility-class reactor in the 250–450 MWe (600–1,000 MWt) size range.
- Flibe Energy completed an EPRI-funded study on its LFTR in 2015.

X-energy (Greenbelt, MD)

X-energy has been working on the Xe-100 Reactor Series—200 MWt High-Temperature Gas-Cooled Pebble Bed Modular Reactor (HTGR) that, due to its unique reactor core and fuel design, cannot physically melt down. The company received a five-year, $53M Advanced Reactor Concept Cooperative Agreement from the DOE in January 2016.

Technology

- The Xe-100 reactor design builds upon decades of research, testing, and demonstration in high-temperature gas-cooled reactor projects worldwide. The Xe-100 can produce zero-emission energy around the clock and ensure reliable electricity and/or process heat for residential, national security, and industrial use.
- This advanced nuclear reactor will expand nuclear power into new markets in increments of approximately 75 MWe and is designed to be small, simple, and affordable. Key attributes of the Xe-100 design are that it requires less time to construct, with factory-produced components, physically cannot melt down, and will be "walk-away" safe without operator intervention during loss of coolant conditions.
- X-energy's principal goal is deployment of its first reactor project within the near term, 10–15 years.
- Unlike today's nuclear power plants, the Xe-100 has a variable output capability that allows for power output to be as low as 25% of nameplate capacity and can replace and supplement other fuel sources (coal, wind, solar) to leverage existing transmission and distribution infrastructure. The Xe-100 has the ability to perform rapid load following in real time within the power range 100-25-100%



Rendering of the Xe-100 Reactor

Business

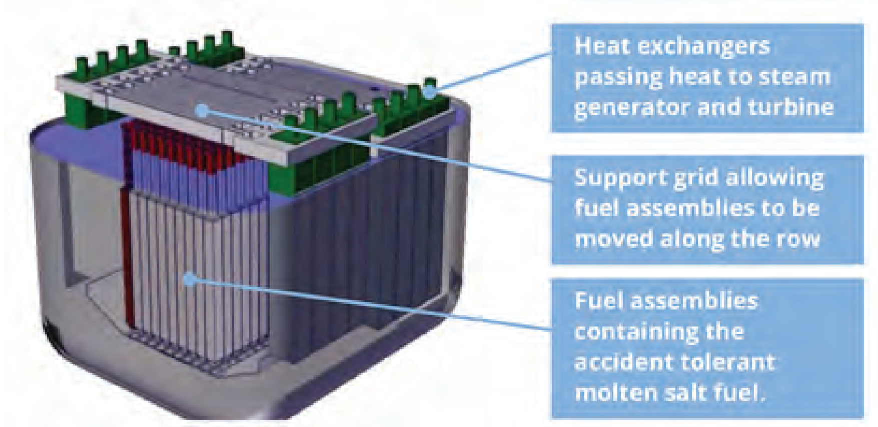
- X-energy officials believe that due to the maturity of the technology (the first HTGR was proposed in 1944 and there have been several reactors built and operated worldwide since then), the Xe-100 licensing process will have an advantage over other advanced reactors.
- X-energy's DOE Advanced Reactor Concept Cooperative Agreement focuses on furtherance of reactor design, fuel development, and initial licensing activities. The X-energy team includes BWXT, Teledyne Brown Engineering, SGL Group, Oregon State University, Idaho National Laboratory, and Oak Ridge National Laboratory.
- In August 2016, the company signed an MOU with Southern Company as potential owner/operator.
- In September 2016, X-energy signed an MOU with Burns & McDonnell as architect/engineer and potential engineering, procurement, and construction partner.

Moltex Energy (London, UK)

Moltex Energy is a privately held British company "set up to solve the world's most pressing challenge: safe and economical, carbon free energy." Moltex has designed a "Stable Salt Reactor" that places molten fuel salt in vented nuclear fuel tubes. This allows for simple online refueling and limits the reactor components experiencing high neutron damage to the consumable fuel assemblies. The reactor uses a combination of radiative heat transfer and air convection to manage reactor decay heat entirely passively, even for a GW-sized reactor.

Technology

- Stable Salt Reactors (SSRs) build on the fundamental safety and simplicity breakthrough of molten salt fuel in essentially standard nuclear fuel tubes.
- The first generation SSR will be a fast reactor able to efficiently burn plutonium and higher actinides from spent conventional oxide fuel.
- The fuel salt is held in vented tubes. Dangerous fission products form stable compounds, not gases making such venting practical and hence avoiding the dangerous high pressures that build up with conventional oxide or metal fuel forms.
- The tubes are bundled into fuel assemblies like those in conventional sodium fast reactors. These are held in the support structure, which forms the reactor modules containing pumps, heat exchangers, controls, and instrumentation.
- The tank is filled with a molten salt coolant. A second, similar coolant salt system takes heat from the primary coolant salt to steam generators kept well away from the reactor.
- Refueling is simple: fuel assemblies are moved sideways out of the core and replaced with fresh fuel assemblies. This results in an on-line refueling process avoiding peaks in core reactivity following a larger refueling campaign.
- The entire construction is simple, with no high-pressure systems in the reactor, few moving parts, and no pressure vessel needing specialist foundries.



Moltex Energy's Stable Salt Reactor

- Natural air flow continuously cools the reactor, giving complete security against overheating in an accident situation.
- The reactors are modular in construction with multiple modules assembled to form a single reactor of power from 300 MWe to 1500 MWe. They therefore gain both the economies of modular construction and the economies of size—instead of trading those economies against each other as happens with other modular reactors where the module is the complete reactor.

Business

- Moltex had the global nuclear engineering consultancy, Atkins, develop early-stage, preliminary estimates for the nuclear island and steam island (representing a clear majority of the overnight capital expenditures). Acknowledging the uncertainty of the estimates, Atkins performed a Monte Carlo analysis that suggested a 90% probability that the nuclear and steam island would cost less than £1,750/kW

(~$2,150/kW). This represents approximately 1/3 the cost of a conventional nuclear power station.

- In addition to the reactor technology, Moltex has invented a very simple and compact two-step process that inputs untreated uranium oxide-spent fuel pellets and outputs ready-to-use fuel for the SSR and an actinide-free fission product waste stream, which will decay to a lower radioactivity than the original uranium ore in just 300 years. This process is a simple adaptation of the established aluminum smelting process and is expected to make closing the fuel cycle for today's fleet of PWR's a highly profitable business.
- Moltex is pioneering the use of molten nitrate salt heat storage (as already commercialized in concentrated solar power) in their GridReserve® technology to allow GW-scale SSRs to operate continuously at full power but vary their electricity output from zero to 200% of full power over the course of a day. This will increase the value of the power output substantially at an additional generation cost of only $5/MWhr and make the reactors highly compatible with electricity grids that have large wind or solar power inputs.
- Moltex has entered the UK government Small Modular Reactor competition but commenced the Canadian Vendor Design Review in 2017 as that represents the fastest route to commercialization.
- The simpler, modular design is not only intended for cheaper manufacturing but also lower operation and maintenance costs. For nth-of-a-kind plants, the capital and operations cost are expected to be lower than new-build coal or gas plants in most (if not all) power markets in the world.

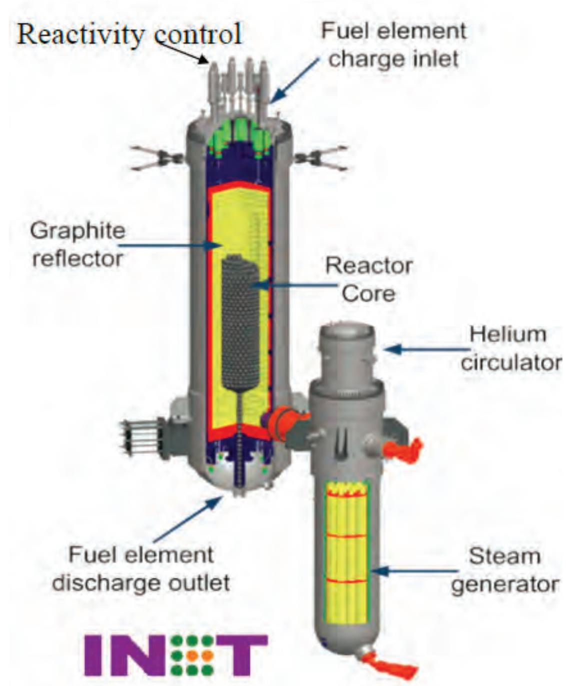
China Nuclear Engineering Corporation and INET (Xicheng, China)

China Nuclear Engineering Group Company provides nuclear project services. The Company contracts with nuclear projects, national defense projects, nuclear power plants, and other industries and civil projects. China Nuclear Engineering Group also offers nuclear energy application and nuclear engineering technology research services.[32] This group is building a demonstration of the High Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM).

Technology

Development progress of demonstration plant at Shidao Bay, Rongcheng City, Shandong Province, China:

- First of two pressure vessels installed in March 2016
- Twin reactors will drive a single 210 MWe turbine
- Startup planned 2018
- Nuclear fuel, primary helium circulator, and steam generator were main challenges[33]
- New proposal under consideration for two 600 MWe HTR plants in Jiangxi Province
- MOUs signed with UAE and Saudi Arabia for HTR projects[34]



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The first HTR-PM vessel is lowered into the reactor building.

32 Source: *http://www.bloomberg.com/profiles/companies/601611:CH-china-nuclear-engineering-corp-ltd.*

33 Dong, Yijie; Deputy Director, INET/Tsinghua University; Presentation to IAEA Technical Working Group on Gas Cooled Reactors Feb 2015.

34 Source: World Nuclear News at *http://www.world-nuclear-news.org/NN-First-vessel-installed-in-Chinas-HTR-PM-unit-2103164.html.*

China Institute of Atomic Energy (Beijing, China)

China Institute of Atomic Energy (CIAE), originating from The Institute of Modern Physics of the Chinese Academy of Sciences, was founded in 1950. CIAE is the cradle of nuclear science and technology in China, and a comprehensive R&D base that occupies a leading, fundamental, and forward-looking position in the nuclear field.[35] One CIAE key facility is the China Experimental Fast Reactor (CEFR).[36]

Technology

- CEFR is a 20 MWe sodium fast reactor used for demonstration and testing of sodium fast reactor technology. It began generating power in 2011.
- The fast reactor system has a fast neutron spectrum, with the resulting benefit of enhancing the utilization of uranium resources (utilization ratio up to 60% from 1% of PWR) through breeding and fuel cycle.
- The fast reactor system can transmute the long-lived fission products and consume trans-uranics with a closed fuel cycle, thus reducing the radiotoxicity and heat load, which facilitates waste disposal and geologic isolation.
- The CEFR is one of the key projects of the National High Technology Research and Development Program of China.
- Key phased goals are as follows:
  - December 1995, CEFR project officially approved.
  - May 2000, first tank of concrete poured.
  - March 2001, construction of nuclear island plant started.
  - August 2002, main nuclear island plant completed and erection construction comprehensively launched.
  - August 2005, first batch of Reactor Vessel assembly arrived and site installed.
  - June 2007, installation construction of Reactor Vessel and in-Reactor components completed.
  - March 2008, Rotating Plug successfully installed.
  - May 2008, Nuclear Grade Sodium entered into site.
  - July 2008, installation of nuclear transport chamber completed.
  - July 2010, first criticality achieved.
  - July 2011, connected to grid and generating electricity.

35 CEFR project source: *http://www.ciae.ac.cn/eng/CIAE/index.htm.*

36 Photo source: IAEA at *https://www.iaea.org/NuclearPower/FR.*

Korea Atomic Energy Research Institute (Daejeon, South Korea)

Established in 1959, the Korea Atomic Energy Research Institute (KAERI) is the first science and technology research institute in Korea to be mandated to achieve energy self-reliance through nuclear technology.

Technologies[37]

- KAERI is actively working to develop hydrogen production technology that would be compatible with a Very High Temperature gas-cooled Reactor (VHTR), in conjunction with the Gen IV International Forum.
- KAERI has proposed a pool-type, sodium-cooled fast reactor that will operate in burner (not breeder) mode. A 150 MWe prototype (called the PGSFR) is planned for 2028.
- KAERI has an agreement with Russia's Research Institute of Atomic Reactors (RIAR) to irradiate PGSFR fuel rods in Russia's BOR-60 fast research reactor.

37 Sources: *http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx; http://www.kaeri.re.kr:8080/english/sub/sub04_01.jsp.*

APPENDIX B

Representative Advanced Nuclear Organizations/Technologies

Organization Name	Location (City)	Location (State)	Location (Country)	Reactor Type; Technology	Website/Additional Information
Flibe Energy (LFTR)	Huntsville	AL	US	Liquid Flouride–Thorium (SMR)	*http://flibe-energy.com*
Kairos Power	Berkeley	CA	US	Molten Salt-Cooled (Flouride; High Temp)	*https://kairospower.com*
OKLO	Mountain View	CA	US	Nuclear Battery	*http://oklo.com/ or https://www.facebook.com/okloinc*
University of California, Berkeley (ENHS)	Berkeley	CA	US	Liquid Metal (Pb) cooled Fast	*http://waste.nuc.berkeley.edu/asia/2000/Greenspan.pdf*
General Atomics (EM2/MHR)	San Diego	CA	US	High Temperature Gas Reactor (Fast)	*http://www.ga.com*
Gen4 Energy (G4M)	Denver	CO	US	Liquid Metal-cooled Fast (SMR)	*http://www.gen4energy.com/technology*
ThorCon Power	Stuart	FL	US	Molten Salt (SMR)	*http://thorconpower.com*
Holtec (SMR-160)	Jupiter	FL	US	SMR (PWR)	*http://www.holtecinternational.com/productsandservices/smr*
Argonne National Lab (SUPERSTAR)	Lemont	IL	US	Liquid Metal-cooled Fast	*http://www.ne.anl.gov/research/ardt/hlmr*
Hybrid Power Technologies	Kansas City	KS	US	High Temperature Gas Reactor	*http://hybridpowertechnologies.com*
Massachusetts Institute of Technology (FHR)	Cambridge	MA	US	Molten Salt-cooled	*http://energy.mit.edu/research/fluoride-salt-cooled-high-temperature-reactors*
Transatomic	Cambridge	MA	US	Liquid-fueled Molten Salt	*http://www.transatomicpower.com*
DOE NGNP and SMR Programs	Bethesda	MD	US	High Temperature Gas Reactor and iPWR	*http://energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-technologies*
Areva (SC-HTGR)	Bethesda	MD	US	High Temperature Gas Reactor	*http://us.areva.com/EN/home-3225/areva-inc-areva-htgr.html*
X-Energy	Greenbelt	MD	US	Pebble Bed Modular High Temperature Gas	*http://www.x-energy.com*
GE-Hitachi (PRISM)	Wilmington	NC	US	Liquid Metal-cooled (Na) Fast	*http://gehitachiprism.com*
BAlpha Tech Research Corp	Salt Lake City	UT	US	Thorium Molten Salt	*http://alphatechresearchcorp.com*
NuScale Power	Corvallis	OR	US	SMR (PWR)	http://www.nuscalepower.com
Westinghouse	Cranberry	PA	US	Liquid Metal-cooled (Pb) Fast	*http://www.westinghousenuclear.com/New-Plants/Lead-cooled-Fast-Reactor*

Organization Name	Location (City)	Location (State)	Location (Country)	Reactor Type; Technology	Website/Additional Information
Westinghouse (SMR)	Cranberry	PA	US	SMR (PWR)	*http://www.westinghousenuclear.com/New-Plants/Small-Modular-Reactor*
Oak Ridge National Lab (SmATHR)	Oak Ridge	TN	US	Molten Salt	*https://ornl.gov/msr*
LakeChime (L-ESSTAR)	Williamsburg	VA	US	Liquid Metal-cooled (Pb) Fast	*http://lakechime.com/lakechime-technology/lakechime-technology-advantages*
Lightbridge	Tysons Corner	VA	US	Advanced Nuclear Fuels	*http://ltbridge.com*
ARC Nuclear (ARC-100)	Reston	VA	US	Liquid Metal-cooled (Na) Fast	*http://www.arcnuclear.com*
Terrapower (TWR Travelling wave)	Bellevue	WA	US	Liquid Metal-cooled (Na) Fast	*http://terrapower.com*
Starcore Nuclear	Montreal		Canada	High Temperature Gas Reactor	*http://starcorenuclear.ca/#!/details*
Terrestrial Energy (I-MSR)	Mississauga		Canada	Molten Salt	*http://terrestrialenergy.com*
Dunedin (SMART)	Toronto		Canada	Nuclear Battery	*https://www.dunedinenergy.ca*
Northern Nuclear	Cambridge		Canada	Pebble Bed Modular (Lead cooled)	*http://www.northernnuclear.ca/index.html*
Elysium Industries Limited	Vancouver		Canada	Liquid-fueled Molten Salt	*http://www.elysiumindustries.com/about-us*
China Institute of Atomic Energy	Beijing		China	Liquid Metal-cooled (Na) Fast (CEFR)	*http://www.ciae.ac.cn/eng/cefr/index.htm*
China Nuclear Engineering Corporation/INET	Xicheng		China	High Temperature Gas-cooled Pebble-bed Module (HTR-PM)	*http://www.cnecc.com/en*
Korea Atomic Energy Research Institute	Daejeon		Korea	Liquid Metal-cooled (Na) Fast (Pool Type); VHTGR	*http://www.kaeri.re.kr:8080/english/sub/sub01_01.jsp*
Moltex	London		UK	Molten Salt	*http://www.moltexenergy.com*

APPENDIX C

Definitions[38]

Actinide

The elements in the periodic table from atomic numbers 89-103, characterized as heavy metals. These elements are radioactive and include the well-known elements uranium and plutonium.

Active/Passive safety

"Active" vs. "Passive" safety describes the manner in which engineered safety systems, structures, or components function. They are distinguished from each other by determining whether there exists any reliance on external mechanical or electrical power, signals, or forces. The absence of such reliance in passive safety means that the reliance is instead placed on natural laws, properties of materials, and internally stored energy.

Fast Neutron

A neutron with kinetic energy greater than 0.1 MeV.

Fission Product

The nuclei (fission fragments) formed by the fission of heavy elements, plus nuclides formed by radioactive decay of the fission fragments.

Fuel cycle

The series of steps involved in supplying fuel for nuclear power reactors. In a "once through" or "open" cycle, this includes ore extraction, conversion, enrichment, fuel fabrication, use of fuel in service, interim storage, and final disposition. If **reprocessing** of spent fuel is included, then the fuel cycle is categorized as "closed."

Grace Period

The period of time in which a reactor can remain in a safe condition after an incident or accident without need for human intervention. The term **"walkaway safe"** relates to this period. *As noted by the IAEA—use of the term walkaway safe is discouraged since it may imply that staff would walk away from a plant during a casualty.*

Hot Cell

A shielded nuclear radiation containment used to protect individuals from exposure while conducting work involving radioactive materials.

Inherent Safety

Achievement of safety through the elimination or exclusion of inherent hazards through the fundamental conceptual design choices made for the nuclear plant. Potential inherent hazards include radioactive fission products and their associated decay heat, excess reactivity and its associated potential for power excursions, and energy releases due to high temperatures, high pressures, and energetic chemical reactions.

Levelized Cost of Electricity

The total cost of installing and operating a project expressed in dollars per kilowatt-hour (or dollars per megawatt-hour) of electricity generated by the system over its life. It accounts for installation costs, financing costs, taxes, operation and maintenance costs, salvage value, incentives, revenue requirements (for utility financing options only), and the quantity of electricity the system generates over its life.

38 Definitions are drawn from the Advanced Reactors Information System (ARIS) database glossary accessed at *www.aris.iaea.org/sites/Glossary.html*; IAEA-TECDOC-626—Safety related terms for advanced nuclear plant; IAEA September 1991; U.S. Nuclear Regulatory Commission Glossary found at *www.nrc.gov/reading-rm/basic-ref/glossary.html*.

Load Following
A term that refers to a power plant adjusting its power output as demand for electricity fluctuates through the day.

Moderator
A material that is used to decrease the speed of a fast neutron produced during a fission event.

Passive Safety
See active safety above.

Reprocessing
A process or operation, the purpose of which is to extract radioactive isotopes from spent fuel for further use.

Safeguards
The material control and accounting program which controls enriched nuclear material. For the IAEA, this also means verifying that the peaceful use commitments made in binding nonproliferation agreements, both bilateral and multilateral, are honored.

Spent Fuel
Fuel that can no longer sustain a chain reaction.

Thermal Neutrons
Neutrons that have lost energy by collision and whose energies are near that of surrounding atoms (nominally energies <1 eV)

Waste
The portion of "used" fuel that cannot be reprocessed for future use and must be stored safely.

Advanced Nuclear Energy

Need, Characteristics, Projected Costs, and Opportunities

For nuclear energy to play a meaningful role in a high-energy, low-carbon future, we must fundamentally transform the way nuclear reactors work, how they are built, and what they cost. To serve rapidly escalating climate change mitigation and energy needs in the next few decades, nuclear plants must be competitive on price with coal and gas; deployable as fast as coal plants or faster; and suitable for operation in developing countries that lack significant pre-existing nuclear capabilities. This report makes the case for why advanced nuclear energy is needed, examines the characteristics of advanced nuclear energy technologies, and identifies key challenges and needed policy changes.

CLEANAIR TASK FORCE

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This report is available online at
http://www.catf.us/resources/publications/files/Advanced_Nuclear_Energy.pdf