LWVNM Nuclear Issues Study
Task 4 Report

Advanced Nuclear Reactor Concepts and Implementation Status

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Task 4. Evaluation of Advanced Nuclear Reactor Concepts with Enhanced Safety features and Efficiency with Related Implementation Status.

Introduction and Summary

According to the IAEA (International Atomic Energy Agency), there are around 440 commercial nuclear reactors in operation in the world in 39 countries; 93 are in the United States. Nuclear reactors produce roughly 20% of electric power in the US, and 10% worldwide. All of the US commercial reactors and most of the commercial reactors worldwide are LWR's (Light Water Reactors), a genre that originated with naval submarine reactors in the early 1950s. One author projects that if no new reactors come online, the US fleet will begin to decline in 2050, and be nearly completely retired by 2070 (See Kim 2022 p. 8). There are some new LWR reactors under construction and a number of non-LWR research, experimental, and special purpose reactors of various types in operation both in the US and worldwide. While the looming losses due to retirement of the existing fleet of LWR reactors could be replaced with new LWR reactors, new technological developments hold promise to eliminate many of the disadvantages of the old LWR technology. Eighteen nations have active programs to develop advanced nuclear reactors based on these new technologies.

The continued growth in the atmosphere of greenhouse gases, largely due to the burning and leakage of fossil fuels, and the consequential changes in the earth's climate, have led to the development of alternate renewable sources of energy to produce electric power. These mostly solar- and wind-powered technologies share the disadvantage that they are intermittent and must be backed up by other generating and storage technologies, including battery, liquid salt, hydro, geothermal, pumped water, and nuclear.

In a 2018 IPCC (International Panel on Climate Change) report reviewing studies of mixes of electric energy sources and sinks ("pathways") that could limit global warming to 1.5 C by 2050, nuclear was included in the global mix in most of the models at levels that ranged from ~ 2% to ~10% (IPCC SR1.5C p 131). The IPCC is not relying heavily on expanding nuclear power to combat climate change; although it acknowledges its potential for carbon free electric power, it cites uncertainties in cost and construction time, lack of public acceptance, lack of permanent waste disposal, and proliferation potential (IPCC 2022-III, pp 438-439, and 639-641). This contrasts with the self-image of the nuclear industry, which presents itself as an essential part of the global warming solution.

Advanced Nuclear Reactors (ANR's, defined in Section 2002 of the Energy Act of 2020) are seen by proponents as solutions to the problem of meeting the demand for backup electric power as well as production of hydrogen, desalination of water, and other heat-intensive industrial processes (process heat). Engineering studies suggest that by replacing the well-developed but dated LWR technology with new technologies, the thermal and fuel efficiencies, production and storage of waste, operational characteristics, proliferation resistance, and safety of an expanded nuclear reactor fleet will be greatly improved. In addition, regulatory reform made possible by simpler designs should reduce construction time and cost overruns. The Energy Act includes fusion reactors in its definition of ANR's, but we restrict our analysis here to fission reactors.

Advanced Nuclear Reactor Program in the US

To facilitate and coordinate the worldwide development of new reactor types, the US DOE-NE (Department of Energy Office of Nuclear Energy, or DOE for short) in 2001 initiated a study of Advanced Nuclear Reactors (designated Generation IV, or GEN IV). The Generation IV International Forum, or GIF committee, representing 13 nations, reviewed nearly 100 proposed designs and agreed to recommend and collaborate in the development of six. Three of these are being pursued in the EU. (See WNA-GENIV). DOE, which already was supporting some new reactor proposals, is now promoting five of the six GEN IV proposals as well. In addition, the US Military is supporting the development of fieldable mobile designs (microreactors) and a number of private efforts have sprung up.

Congress has helped to fund most of these development efforts through a series of appropriations supporting several programs directed at the development of different aspects of nuclear technology. Any given project may be supported by one or more of these programs and/or by private investment, and may provide data on several new ideas for functional aspects of nuclear reactors. (For a nice review of current US ANR efforts, see AIP-9-21-22. For details of congressional funding for ANR, see CRS Holt).

Understanding the ANR Program

To more easily comprehend the mix of projects, the reader may consider that each project combines different sets of elements from lists of possible solutions or attributes for each particular functional aspect of a nuclear reactor.

Appendix Table 1 is a list of advanced nuclear reactor types ("technologies") under development in the US; it includes some of the attributes or functional aspects of each and the names of the corporate entities developing versions of these technologies. Some of these are not in the GIF list of six technologies, but have been selected by the DOE or by private industries for support. Most are in a conceptual or design stage.

NRC (Nuclear Regulatory Commission) regulations require operational data to develop standards for any reactor design being considered for certification for commercial use. Few of the new concepts being developed have been tested extensively enough to provide the data necessary to set NRC standards. Every aspect of nuclear reactor design and certification is done with elaborate computer models that collectively require accurate and precise values of thousands of physical parameters. As an example, see NRC-NDA, a 4-phase study done at Oak Ridge National Laboratory to determine the parameters of various proposed ANR fuels that need to be determined experimentally to validate the computer models that will calculate the operating characteristics of ANR technologies.

As we cannot at this time say which, if any, of these new designs will eventually show suitability for commercial use, it is necessary to operate each project at a research or experimental level to collect this necessary data (NASEM-Found p. 29). In addition, DOE funds so-called Test Bed Reactors, generic reactors that provide an environment in which data on some aspects of new reactor concepts may be collected without building a whole new reactor.

The water-cooled technologies in Table 1 (LWR, BWR) recently evolved from the venerable water-cooled reactor fleet and potentially may come online much more quickly than the others because of 70 plus years of operational data and experience with water-cooled reactors. There is some operational data on the sodium- and lead-cooled reactors, but little on the other technologies.

Criteria For ANR Development (Energy Act Of 2020, Sec 2002)

"Inherent Safety" - in accident scenarios, the reactor passively stops generating heat and radiation – sometimes called "walk-away safe."

"Lower waste yields" – burns more of the fuel and recycles unburned fuel.

"Tolerance to loss of fuel cooling."

"Enhanced reliability or improved resilience."

"Increased proliferation resistance" – achieved by improved security or by manipulating the fuel cycle.

"Increased thermal efficiency" – the reason for the high operating temperatures of the proposed designs. Using water as the coolant places severe limits on the operating temperature, except for one design that uses "supercritical" water.

"Reduced consumption of cooling water and other environmental impacts."

"The ability to integrate into electric and non-electric applications" – high operating and outlet temperature makes "process heat" usable for industrial applications, including production of hydrogen and desalination of water.

"Modular sizes to allow for deployment that corresponds with the demand for electricity or process heat" – many ANR designs will be demonstrated at a size that meets the definition of a small modular reactor [300 MWe (megawatt electrical) or less]. Even smaller Microreactors are small enough to be transported whole by truck or rail.

"Operational flexibility to respond to changes in demand for electricity or process heat and to complement integration with intermittent renewable energy or energy storage" – also known as "load following."

Evaluating The Program

The scope of the set of projects being pursued in the US is broad and includes most of the technologies that have been promoted for decades by advocates of nuclear power to replace the extant water-cooled technologies. The National Academies of Science, Engineering, and Medicine (NASEM) has just this year (2023) published two studies, one analyzing the merits and viability of the different fuel cycles under study (See NASEM Merits) and the other the necessary foundation or infrastructure for the development of the new Nuclear Reactor universe (See NASEM Found). These thorough and well-documented studies by experts in the field have made our evaluation easier. We don't have the resources to repeat their analyses or challenge their detailed findings and recommendations. We draw several broad conclusions.

1) The US has fallen behind the world in several necessary areas of nuclear infrastructure that will support all the projects. For example, we are heavily dependent on Russia for our supplies of enriched uranium because we have only one operational enrichment facility, which at this time only produces LEU (Low Enriched Uranium). Almost all the ANR designs anticipate using HALEU (High Assay Low Enriched Uranium) fuel and the fast neutron spectrum to achieve their goals of efficiency and high burnup. The DOE is developing a new facility to produce HALEU by downblending limited surplus stocks of weapons grade HEU, but this will only support some of the development effort and a production facility or facilities must be built to produce HALEU from domestic sources of natural uranium to supply fuel for a new fleet of commercial reactors and reduce our dependence on hostile nations for a critical resource.

2) The perennial problem of a permanent underground storage facility for nuclear waste is beyond the crisis stage. It is a political problem rooted in residual public resistance to nuclear power - that may be dissipating, but as mentioned above the IPCC seems to consider it to disqualify nuclear power as a solution to climate change. We believe it makes no sense for Congress to support the development of these ANR projects while failing to muster the political will to resolve the biggest obstacle to nuclear power. The new technologies hold promise of reducing the quantity and radiotoxicity of waste, and even burning some of the existing waste to produce useful power and further reduce the volume of waste, but even so there will be huge amounts of waste that we have the technology to dispose of safely – if we will only do it.

3) There is a lack of reprocessing in the US. To achieve the high burnup that supports the efficient use of fuel and reduction of waste, we must have the capability to reprocess spent fuel to recover unused fissile materials and produce new fuel on a scale greater than ever. While LEU fuel is cheap and plentiful today worldwide, if this program evolves as

hoped, demand will likely soon outstrip supply and the efficient use of uranium and thorium resources will demand breeding from U238 and Th232 and subsequent reprocessing.

4) Like the NASEM committees, we do not select any winners from the field of ANR technologies because the set of projects in development will determine the winners. We are confident that there is sufficient cause to believe that one or more commercially viable technologies will eventually emerge from this field and begin to fill the gap left by retiring reactors. The current demonstration projects (Terra Power's Natrium, X-Energy's X-100 HTGR, and NuScale's SMR) are expected by DOE-NE to come online in 2028 – 2030, followed by two more demonstration projects around 2035. (See DOE–Strat. P. 12). Another DOE-NE document (DOE-NE Path) assesses the "pathway" for the US to meet the goal of zero greenhouse gas emissions by 2050: nuclear must supply 200 GigaWatts-electric (GWe) of new generating capacity. The document concludes this is possible, but only if several high barriers are overcome – including those identified above, and in addition learning from a succession of failures that occurred during the construction of the VOGTLE 3 and 4 reactors in Georgia, causing spectacular cost and schedule overruns. The DOE-NE document concludes that construction on a large scale (13 GWe per year, or 7 - 15 units per year) of a new fleet of ANR commercial reactors must begin by 2030. If it is delayed until 2035, 20+ GWe/yr would be required or the 2050 goal would not be met. Without a significantly larger commitment to nuclear power by the US government and US industry, ANR generating power is not likely to be available to have a widespread impact on the electricity supply before 2050 – and not even then, if the US fails to address the issues 1- 3 described above and to overcome the public antipathy to nuclear power.

Appendix Table 1

Reactor Type/ Technology	**Core Outlet Temperature and Pressure**	**Thermal Efficiency**	**Fuel Burnup**	**Neutron Spectrum**	**Nuclear Fuel**	**Coolant**	**Example Reactor Designs**
Small modular light water reactor (LWR)	~560–590 K ~70–140 bar	~31–33%	5–6 atom% using shorter length LWR fuel rods	Thermal	UO2	Water	NuScale, Holtec, GEH–BWRX,Westinghouse
Liquid metal Fast Reactor	~750–850 K	~35–40%	7–10 atom% using	Fast	Uranium-metal	Sodium	GE–Prism,

(SFR)	~ Few bars		metallic fuel with recycle; >40% oncethrough with fuel shuffling				TerraPower-GEH– Natrium Westinghouse W-LFR Gen4Energy-G4M
High-temperature gas reactor (HTGR)	~1000–1100 K ~ 70–100 bar	~43–50%	10–20 atom% using TRISO fuel	Thermal	TRISO UCO	Helium	X-Energy–Xe-100
Gas fast reactor (GFR)	~1000–1100 K ~ 70–100 bar	~43–50%	14 atom% using UC or UO2 fuel in SiC clad	Fast	UO2, UC	Helium	GA–EM2, FMR
Fluoride-salt-cooled Reactor (MSR)	~900–950 K ~Few bars	~42%	Similar to HTGR using TRISO fuel with similar burnup	Thermal	TRISO UCO	Flibe	Kairos–Hermes
Molten-salt-fuel-cooled Reactor (MSR)	~900–950 K ~Few bars	~40–42%	High fissile burnup with dissolved fuel in coolant; burnup limits by reactivity issues	Thermal or Fast	UF or UCl salt	Same as Fuel	Terrestrial Energy– IMSR, Moltex, TerraPower
Heat-pipe-cooled reactor	~750–800 K Low pressures	~30%	5–20 atom% using TRISO fuel	Thermal or Fast	TRISO or UO2	Heat Pipe	Westinghouse– eVinci, Oklo– Aurora,*c* BWXT– BANR

Liquid Fluoride Thorium Reactor (LFTR)				Fast	Th in molten salt	fuel	Flibe Energy
Liquid Metal Fast Reactor (LFR)	650C, ~1 Bar;			Fast	UO2 or MOX,	Lead, Lead-Bismuth	Westinghouse W-LFR Gen4Energy-G4M
Steam cycle High Temperature Gas Reactor (SC-HTGR)				Thermal	HALEU (14.5%) UC/TRISO/cylindrical compacts / prismatic block	water	Fromatome

This table combines Tables 2.1 and 2.2 in NASEM-Found, pp 24 – 25, data from Table 3.1 in NASEM-Merits, pp 60-61, and IAEA-ARIS.

Glossary

Fissile – U235, Pu239, U233 – isotopes of actinides that can be split by absorbing a neutron, releasing more neutrons and usable energy. The number represents the sum of the protons and neutrons in the nucleus.

Fertile - U238, Th232 – can be converted to fissile isotopes (Pu239 & U233, respectively) by neutron irradiation (breeding).

Actinides – Elements with atomic numbers 89 – 103, representing the number of protons in the nucleus. In reactors, 90(Th), 91(Pa), 92(U), 93(Np), 94(Pu), 95(Am), 96(Cm) are of interest

Minor actinides – Am, Cm, Np – present in reactor waste and can be burned if recycled

Isotope – U235 and U238 are two isotopes of uranium: the nuclei have the same number of protons but different numbers of neutrons

Reactor Design Characteristics

- fuel cycle – open (once through), closed (reprocessed, reformed), partially closed)
    - fuel – U233, U235, Pu239, waste containing any of these, MOX (mixed oxides of U235 and Pu239 usually from military surplus).
    - fuel form (cylindrical pellets in tubing, TRISO, dissolved in coolant, prismatic matrix, metal, ceramic (C, N, O), TRISO, pellets)
    - enrichment – increases the fissile content of fuel (U235/U238) (LEU, HALEU)

    - waste – fission products, radioactive actinides, irradiated non-nuclear materials
    - reprocessing strategy
    - fuel manufacture
    - fuel source – mining, surplus military
    - burnup – the percentage of fissile fuel consumed
  - Output power – both the thermal power and the electric power ratings are usually specified. MWt means MegaWatts thermal, GWe means GigaWatts electric. Mega = one million, Giga = one billion, etc.
  - Safety considerations – passive or inherently safe, accident scenarios
  - Proliferation resistance – prevention of the diversion of nuclear materials for weapons use
  - Core outlet temperature and pressure
  - coolant – water, molten salt (fluoride, FLIBE, liquid metal (lead, sodium, lead bismuth eutectic, Helium, CO2)
  - moderator - water, graphite, heavy water,
  - neutron spectrum (thermal or fast)
  - reactor technology (Gas, Fast, Molten Salt, LWR, HWR, PWR,BWR, liquid metal, etc.)
  - Decommissioning – disposing of reactors and clearing their sites at the end of their lives.

Radiotoxicity: A measure of the danger to humans from exposure to a radioactive isotope.

Acronyms

HALEU High Assay Low Enriched Uranium (5% < enrichment < 20%)
LEU Low Enriched Uranium (< 5 % U235)
TRISO Tristructural Isotopic Coated Particle Fuel – the ultimate inherently safe fuel form
LWR Light Water Reactor
PWR Pressurized Water Reactor
HWR Heavy Water Reactor
BWR Boiling Water Reactor
NRC Nuclear Regulatory Commission
DOE-NE Department of Energy Office of Nuclear Energy
FLiBe mixed fluorides of Beryllium and Lithium - a molten salt coolant

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[IAEA Advanced Reactor Information Systems (ARIS) http://aris.iaea.org . Thorough database with technical data. There are 9 major players (2 or more reactors) and 8 "other" nations with reactor systems in stages from conceptual design to operational to on hold or shut down. Only 6 are operational, all LWR or HWR. Many frequently updated publications.]

[PRIS: Power Reactor Information Systems https://pris.iaea.org/ . Free registration and institutional affiliation required for access.] [410 NPR's in operation 368.6 GWe 27 suspended 57 under construction. 31 countries have NPR's in operation, 3 more are constructing their first.]

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[• Phase 1: Identify key nuclear data impacting reactivity in non-LWRs, • Phase 2: Assess key nuclear data impacting reactivity in non-LWRs, • Phase 3: Assess relevant benchmarks applicable to the nuclear data identified in Phases 1 and 2, and • Phase 4: Assess the impact of nuclear data uncertainty through propagation to key figures of merit associated with reactor safety.]

Highly technical, this series of four studies illustrates the complexity of just one aspect of developing the technologies for the ANR effort. Not bedtime reading.

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