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A Summary of the Department of Energy's Advanced Demonstration and Test Reactor Options Study

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ABSTRACT

An assessment of advanced reactor technology options was conducted to provide a sound comparative technical context for future decisions by the Department of Energy (DOE) concerning these technologies. Strategic objectives were established that span a wide variety of important missions and advanced reactor technology needs were identified based on recent Department of Energy and international studies. A broad team of stakeholders from industry, academia and government was assembled to develop a comprehensive set of goals, criteria and metrics to evaluate advanced irradiation test and demonstration reactor concepts. Point designs of a select number of concepts were commissioned to provide a deeper technical basis for evaluation. The technology options were compared on the bases of technical readiness and the ability to meet the different strategic objectives. Using the study's evaluation criteria and metrics, an independent group of exerts from industry, universities and national labs scored each of the point designs. Pathways to deployment for concepts of varying technical maturity were estimated for the different demonstration systems with regard to cost, schedule and possible licensing approaches. This study also presents the tradeoffs that exist among the different irradiation test reactor options in terms of the ability to conduct irradiations in support of advanced reactor research and development (R&D) and to serve potential secondary missions.

1. Introduction

Nuclear power provides 20% of electricity production in the United States (U.S.) and is increasing in countries undergoing rapid growth around the world. Because reliable, grid-stabilizing, low-emission electricity generation, energy security, and energy resource diversity will be increasingly valued, nuclear power's share of electricity production has a potential to grow. In addition, there are non-electricity applications (e.g., process heat, desalination, hydrogen production) that could be served by nuclear power.

Between 2030 and 2040, almost 75% of the existing U.S. light water reactor (LWR) capacity may be retired. Almost all of the existing reactors will be retired by 2050, unless their operating licenses are renewed. Some of this capacity will almost certainly be retained by extension of the licenses of existing LWRs (perhaps to 80 years) or with the addition of new LWRs (whether advanced large or new small modular options under development). However, the timely development, demonstration, and commercialization of advanced non-LWR nuclear reactors in the 2030 to 2040 timeframe are needed to diversify the nuclear technologies available and offer attractive technology options to expand the impact of nuclear energy for electricity generation and non-electricity missions.

The purpose of this study was to provide transparent and defensible technology options for a irradiation test and/or demonstration reactor(s) to be built to support public policy, innovation and long-term commercialization within the context of the Department of Energy's (DOE's) broader commitment to pursuing an "all of the above" clean energy strategy and associated time lines. This planning study includes identification of the key features and timing needed for advanced irradiation test or demonstration reactors to support research, development, and technology demonstration leading to the commercialization of power plants built upon these advanced reactor platforms. This study is consistent with the Congressional language contained within the fiscal year 2015 appropriation that directed the DOE to conduct a planning study to evaluate "advanced reactor technology options, capabilities, and requirements within the context of national needs and public policy to support innovation in nuclear energy".

Today, there are numerous diverse advanced reactor concepts under development, both nationally and internationally. [1,2] Many concepts can be classified as small and/or modular while others generate baseload electricity at magnitudes comparable to modern LWRs. The missions of some of these concepts go beyond fundamental electricity production to address important issues in the U.S. as noted in the recent Vision and Strategy document [3] including:

- Process heat applications, including cogeneration, to reduce the carbon footprint of U.S. industry
- Actinide management to extend fuel resource utilization and reduce the nuclear waste burden for future generations
- Integration of nuclear systems with non-baseload (intermittent) energy sources to form reliable alternative energy systems.

Advanced reactors are defined in this study as reactors that use coolants other than water. Advanced reactor technologies have the potential to expand the energy applications, enhance the competitiveness, and improve the sustainability of nuclear energy. These advanced reactor concepts offer a range of technology innovations including:

- Higher outlet temperatures than LWRs, which provide both higher efficiency electricity generation and process heat for a variety of industrial applications
- Enhanced inherent safety, including passive decay heat removal systems
- Advanced fuels (liquid, particle, metallic, ceramic) and cladding enabling high burnup, extensive actinide destruction, and enhanced accident tolerance
- Advanced power conversion systems (helium and supercritical CO_2Brayton cycles) to improve overall energy conversion efficiency and reduce water usage
- Modular design to shorten construction times and to support phased deployment to allow flexibility in meeting demand
- Greater degrees of autonomous control to minimize operating cost.

2. Approach

The approach used in the study is illustrated in Figure 1. For the fundamental mission of efficient and reliable electricity production, advanced reactor technologies feature higher thermal efficiency and inherent safety that, in principle, can lower capital costs and increase revenue. Furthermore, advanced reactors have other attributes that make them better suited than LWRs for certain missions such as actinide management and process heat generation. As no one reactor concept will excel in *all* of these missions for the foreseeable future, any comparison must be necessarily be conducted with respect to a particular mission or objective. For this study, four strategic objectives that span the range of key advanced reactor nuclear energy missions and needs were established with three focused on potential demonstration reactor options and a fourth on irradiation test reactors options. These four strategic objectives are:

1. Deploy a high-temperature process heat application (e.g., synfuels production) for industrial use and electricity demonstration using an advanced reactor system to illustrate the potential that nuclear energy has in reducing the carbon footprint in the U.S. industrial sector
2. Demonstrate actinide management to extend natural resource utilization and reduce the burden of nuclear waste for future generations
3. Deploy an engineering demonstration reactor for a less-mature reactor technology with the goal of increasing the technology readiness level (TRL) of the overall system for the longer term
4. Provide an irradiation test reactor to support development and qualification of fuels, materials, and other important components/items (e.g., control rods, instrumentation) of both thermal and fast neutron-based Generation-IV (Gen-IV) advanced reactor systems.

For this study, the goals were a subset of the desired attributes of either an irradiation test or demonstration reactor. Some attributes are presumed of all designs (e.g., safety and security) and are not used to differentiate the concepts. Other key performance attributes will differ between concepts and between the overall irradiation test and demonstration missions. Thus, the goals are the set of desirable attributes that are used to differentiate among designs. A separate set of goals was established for the irradiation test reactors and the demonstration reactors.

For each goal, specific *criteria* were identified. Criteria comprise the key features and/or performance parameters needed to meet each goal (e.g., capital cost for an economic goal, or flux level for an irradiation testing goal). For evaluation in this study, it is not the intent that the identified criteria be an exhaustive list for each goal; rather, criteria were selected to discriminate among the concepts considered in this study.

For each criterion, specific *metrics* were identified. The metrics are quantifiable measures of key performance characteristics that are important to a given criterion. As the point designs considered in this study are at varying levels of technical maturity, the values of some metrics reflect relative performance or qualitative assessment. The demonstration reactor goals, criteria and metrics are shown in Figure 2 and those for the irradiation test reactor are shown in Figure 3.

Goals, criteria, and metrics were employed to assess these point design options against the strategic objectives. Goals, criteria, and metrics were elicited from the expert judgment of a large group of scientists and engineers from the nuclear community spanning industry, national laboratories, and universities. Different teams comprised of industry and national laboratory partners developed point designs within a standardized evaluation framework as part of the study.

The evaluation process involved the assignment of “weightings” to the different goals, criteria, and metrics. The intent is that the weightings reflect importance of features within specific strategic objectives. An independent assessment team then evaluated the concepts against the metrics. Finally, sensitivity studies were performed to determine whether the weightings of the metrics and criteria influenced the results. The following sections document important findings of the study. The evaluation informs the decision process by providing information on the relative benefits and challenges for different options toward a variety of strategic objectives. In practice, one would expect subsequent clarification of strategic targets and refinement of a particular design to be an iterative process. This study represents an initial evaluation to identify reactor concepts that have the potential to meet the irradiation test and demonstration reactor goals.

In Section 3, a number of technology neutral findings are documented, followed by Section 4 with an assessment of options against each identified strategic objective. A summary and conclusions are provided in Section 5. Additional details are found in Reference 4.

Figure 1. Overview of approach used in technical evaluation of options.

Demonstration Reactor Goals, Criteria and Metrics		
Goal	**Criteria**	**Metrics**
1. Demonstration Reactor significantly advances the technology toward a potential commercial plant	1.1 Capability to demonstrate safety behavior of commercial system	1.1.1 Does the demonstration system have safety characteristics and systems/components expected in the commercial plant?
	1.2 Detailed instrumentation and data for code validation tests	1.2 1 Does the design have adequate instrumentation and will it gather appropriate data for code validation tests?
	1.3 Scalable technology choices	1.3.1 Does the design implement technology selections that are prototypic or scalable to commercial unit?
	1.4 Scalable maintenance techniques and schedules	1.4.1 Does the design have maintenance approaches that are prototypic or scalable to commercial unit?
	1.5 Scalable fabrication options	1.5.1 Does the design use prototypic of scalable technologies in the fabrication of important systems and components?
2. Demonstration Reactor operations help resolve technical barriers (e.g. predictability) to advanced reactor economics and reliability	2.1 Project costs and Schedule	2.1.1 Project cost
		2.1.2 Project schedule - the time from today to first operation
	2.2 Operational costs	2.2.1 Annual operating costs
	2.3 Reliability of operations	2.3.1 Availability factor
3. Demonstration Reactor has a robust safety design basis for licensing	3.1 Licensed by Nuclear Regulatory Commission	3.1.3 Ability to address key licensing issues for follow-on commercial units
		3.1.2 EPZ size
4. Demonstration reactor supports demonstration of technology and system integration (enhancing immediate, intermediate and long term value of the project)	4.1 Facilitate component demonstration	4.1.1 Does the system facilitate demonstration of components in an integral sense of that expected in follow-on commercial units?
	4.2 Ability to demonstrate alternate core configurations and fuel types	4.2.1 Number of alternative core configurations
		4.2.2 Number of alternative fuel types
	4.3 R&D required before demonstration reactor construction/operation	4.3.1 R&D time
		4.3.2 R&D cost
	4.4 Provide ability to conduct irradiations of materials and fuels	4.4.1 Fast flux conditions at test location
		4.4.2 Thermal flux conditions at test location
		4.4.3 Irradiation volumes and length
5. Demonstrate reactor stage of advanced fuel cycle	5.1 Ability to demonstrate utilization of natural resources	5.1.1 Use of natural fuel resources
	5.2 Prototypic fuel fabrication	5.2.1 Is the fuel fabrication approach prototypic or scalable to commercial unit?
	5.3 Prototypic fuel performance	5.3.1 Is anticipated fuel performance prototypic or scalable to commercial unit?
	5.4 Used fuel handling	5.4.1 Is the spent fuel handling prototypic or scalable to commercial unit?
6. Demonstrate high temperature reactor process heat applications	6.1 Demonstrate integration with various energy conversion systems or process heat for industrial applications	6.1.1 Number of energy conversion systems or industrial applications
	6.2 Ability to demonstrate industrial heat applications	6.2.1 Coolant outlet temperature

Figure 2. Demonstration reactor goals, criteria, and metrics.

Test Reactor Goals, Criteria and Metrics		
Goal	**Criteria**	**Metrics**
1. Test Reactor provides irradiation services for a variety of reactor and fuel technology options	1.1 Irradiation conditions	1.1.1 Fast flux conditions
		1.1.2 Thermal flux conditions
		1.1.3 Irradiation volumes and length for largest test location
		1.1.4 Maximum sustainable time at power, to provide a time-at-power for a single irradiation (i.e. cycle length)
		1.1.5 Provisions for testing prototypic and bounding conditions (temperature, coolant, chemistry)
	1.2 Support diverse irradiation testing configurations concurrently (accommodate various sizes and tailor irradiation parameters to wide group of simultaneous users)	1.2 1 Number of test zones
		1.2.2 Number and type of distinct irradiation test loops each with a different cooling system independent of the primary reactor coolant
		1.2.3 Ability to insert/retrieve of irradiation specimen while staying at power
2. Test Reactor will be built and operated reliably and in a sustainable cost-effective manner. (Need to be able to justify initial and long-term expense)	2.1 Project costs and schedule (including design, licensing, R&D, construction, and contingency that	2.1.1 Project cost
		2.1.2 Project schedule - The time from today to first operation
	2.2 Operational costs and schedule (including contingency that reflects technical maturity of the concept)	2.2.1 Annual operating costs
	2.3 Reliability of operations	2.3.1 Availability factor
3. Capability to accommodate secondary missions (electricity, isotope production, etc.) of modest value (million dollar) without compromising primary mission of testing fuels and materials for advanced reactor technologies	3.1 Identification of secondary missions	3.1.1 Number of secondary missions

Figure 3. Test reactor goals, criteria, and metrics.

3. Reactor Technology, Deployment and Licensing Options

3.1 Advanced Reactor Technology Readiness Assessment

A technology readiness assessment was conducted to determine which reactor technology concepts the study would consider. The starting point for the assessment was the six Gen-IV advanced reactor technology concepts. In some cases, two variants of a particular concept were evaluated. For example, both solid-fueled and liquid-fueled molten salt-cooled reactors were assessed. Technology Readiness Levels defined by the Department of Energy were assigned to a common set of plant subsystems and rolled up to an overall concept maturity level. Of all the concepts evaluated, the ones with both a medium-to-high technological maturity *and* significant interest among U.S. companies were selected for detailed comparison. This filter yielded four options for consideration as demonstration reactors and two options for consideration as irradiation test reactors for this study:

- The modular high temperature gas-cooled reactor (HTGR) and sodium-cooled fast reactor (SFR) have high enough technology readiness levels to support a commercial demonstration in the near future. These technologies are considered mature as a result of several successful demonstrations brought about through billions of dollars of public and private investment in the U.S. over more than fifty years. These systems are also being built internationally, further confirming the high level of maturity of these systems as evaluated in this study.
- The fluoride-cooled high-temperature reactor (FHR) and lead-cooled fast reactor (LFR) are less mature and require additional research and development (R&D) and engineering demonstration in the

near future. International and U.S. technology development activities are underway to mature these technologies, and technology demonstrations are planned.

Other options examined were considered to be of low technological maturity (e.g., gas-cooled fast reactor) or did not have significant U.S. commercial interest (e.g., super-critical water-cooled reactor, molten salt reactor).

An irradiation test reactor must be based upon a mature technology platform if it is to be deployed in a timeframe to support the research needs of Gen-IV reactors. The HTGR and SFR were deemed the only sufficient mature options for this mission.

3.2 Deployment Options, Cost and Schedule

The study identified a step-wise approach to reactor technology deployment that has been used historically in the U.S. and internationally. This historic four-step pattern is shown in Figure 4 and the steps are defined as follows:

- Research and development to prove *scientific feasibility* of key features associated with fuel, coolant, and geometrical configuration. Irradiation test reactor services are particularly important in this phase, although they can be beneficial at each step (e.g., to explore additional fuel/material options).
- Engineering demonstration at reduced scale for *proof of concept* for concepts that have never been built. The goal at this demonstration level is the viability of the integrated system. Historically, these have been small reactors (<50 MWe).
- Performance demonstration(s) to *confirm effective scale-up* of the system and to gain operating experience to validate the integral behavior of the system (including the fuel cycle in some cases) resulting in proof of performance.
- Commercial demonstrations that will be replicated for subsequent commercial offerings if the system works as designed.

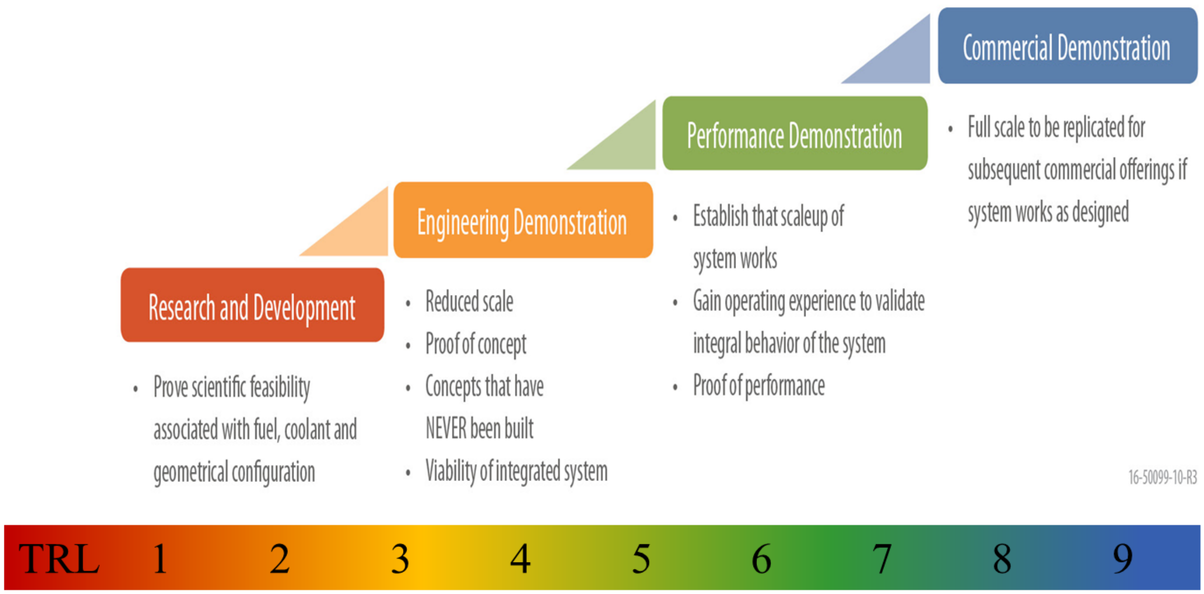

Figure 4. Reactor development and deployment steps based on U.S. and international experience.

The location along the deployment path depends on the maturity of the underlying advanced reactor technologies. As shown in Figure 5, the maturity of HTGRs and SFRs are based on technologies that underwent engineering and performance demonstration steps to the extent that they put electricity on the grid over a period of many years. They are mature enough to enable deployment of their first modules at commercial scale (the commercial demonstration step) in the early 2030s with additional commercial offerings soon thereafter.

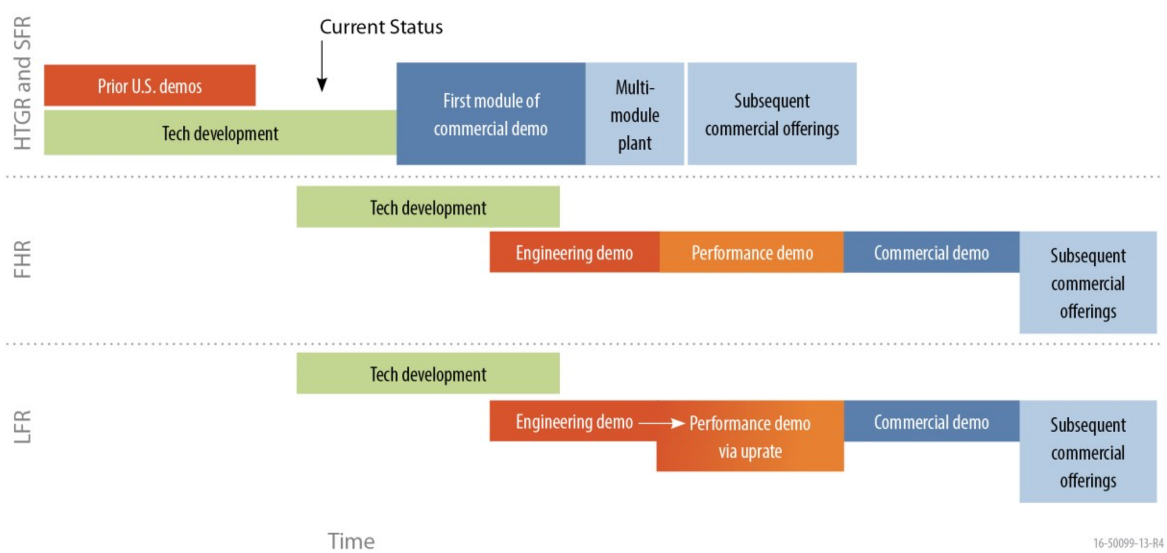

Figure 5. Development and deployment pathway of different advanced reactor technologies.

The relatively more mature technologies (5<TRL<7) estimate similar timelines for deployment of the first module. Both SFRs and HTGRs could be deployed commercially within 13 to 15 years given sufficient capital for design and construction. A notional schedule based on a number of the demonstration vendor schedules is shown in Figure 6. This schedule reflects many parallel efforts such as 7 years for design, and 8–9 years for obtaining an operating licensing for the first unit.

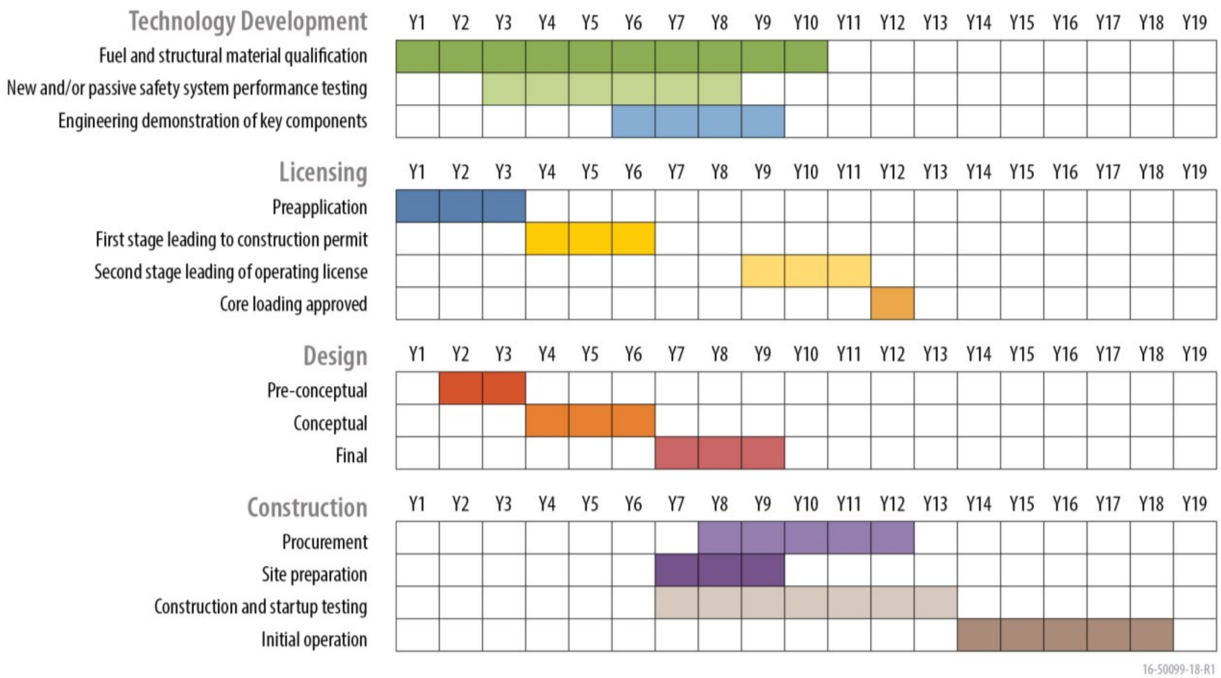

Figure 6. Notional schedule for a high TRL advanced reactor technology.

As shown in Figure 6, fuel and structural material qualification are critical and extensive development tasks; ones which differentiate between low-to-medium technological readiness (2<TRL<5) and medium-to-high technical readiness (5<TRL<7). Both the SFR and HTGR concepts have spent significant resources qualifying their unique fuel forms; metallic fuel rods for the SFR and TRISO-coated particle fuel for the HTGR. The TRISO fuel program is scheduled to complete in the next 6 years and will have established a domestic vendor for its fuel to fabricate first core for an HTGR. For SFR metallic fuel, the fuel was qualified at pilot scale when EBR-II was in operation. Early cores can be fabricated at INL using the same equipment. In parallel, a domestic vendor would be established for future fuel loadings. For either technology, this work can be completed in the 13–15 years prior to operation of the first module and is incorporated in their costs and schedules.

The R&D costs depend extensively on the maturity of the technology and the design. Hundreds of millions of dollars is not unreasonable for these advanced non-LWR reactor concepts because of the use of new coolants, fuels, materials, and configurations not already qualified for LWRs. Based on the most detailed vendor input from AREVA for the SC-HTGR (Table 1), design costs of up to $800 million are expected for these facilities and an additional $200 million for licensing. The design, licensing, and most of the construction costs are independent of the thermal power rating of the plant. Some construction costs scale with the reactor power, particularly those associated with the civil engineering footprint. The point design estimated construction costs for the SC-HTGR point design are ~$1.5 billion. Many important costs, such as field engineering, are indirect but are not trivial. For the SC-HTGR, AREVA estimates this to be $638 million. Thus, the overall cost of their first module is ~$4 billion. The cost estimate for the SFR commercial demonstration estimate is similar.

Table 1. Summary costs for AREVA SC-HTGR.

Item	Cost
R&D	$321M
Design	$800M
Licensing	$200M
Infrastructure Supply Chain Development	$175M
Fuel	$168M
Construction	$1500M
Owner's Indirect Cost	$638M
Total	~$4000M

Many of these commercial demonstration costs (e.g., design, R&D) are onetime costs; thus, costs for multiple unit and commercial nth-of-a-kind reactors are expected to be much lower. For example, based on detailed Next Generation Nuclear Plant (NGNP) estimates [5], the first-of-a-kind cost for <u>four</u> 600 MWt HTGRs is ~$6.5 billion and the overnight cost is ~$6200/kWe. For the nth-of-a-kind, the corresponding values are ~$4.6 billion and ~$4365/kWe.

In summary, the two most mature demonstration reactor concepts, the HTGR and SFR, have benefited from billions of dollars and decades of research, development, and design trade studies to establish an optimized configuration culminating in the designs described in this report. They have high degrees of passive safety and provide opportunities for nuclear power to expand into missions beyond just baseload electricity. Specific designs of both concepts have been the subject of preliminary safety evaluations by the Nuclear Regulatory Commission (NRC). More recently, the modular HTGR has been the subject of pre-application discussions with the NRC as part of the NGNP program. <u>Deployment of either of these concepts is a ~$4 billion endeavor, taking about 13–15 years from preliminary design to operation of the first module.</u> Commercial demonstration reactors built upon similar technologies are being built around the world today, reaffirming the readiness of these systems.

These costs and the associated financial and deployment schedule uncertainties at this stage are high enough that private industry in the U.S. will most likely not deploy these systems without government assistance, most likely in the form of a public-private partnership. Any cost and risk-sharing model that is developed should exploit the relative strengths of both government (e.g. R&D) and industry (e.g. engineering and construction) as part of a deployment strategy that acknowledges the need to generate revenue while achieving broader energy security goals.

The less-mature technologies, FHR and LFR, are facing a longer technology development path to commercial offerings because, as shown in Figure 5, they still need to progress through a combination of both the engineering demonstration step and the performance demonstration step. Given the historical precedent, engineering demonstration would not be expected before 2040 with commercial demonstration about a decade later. With innovation and flexibility in development, construction, licensing, and financing, however, an expedited deployment path may emerge.

A range of test capabilities will also be needed for these advanced reactors, and will be provided through a combination of both new and existing facilities. From a long-term perspective, many advanced concepts will benefit from an irradiation test reactor that can support fuel and material testing and qualification. Design and construction of an irradiation test reactor are estimated to take about 10 to 13 years. Cost estimates for the SFR and HTGR irradiation test reactors are both around $3 billion and are highly uncertain at this early stage in the design process. The cost is sensitive to such factors as: the number and complexity of loop testing facilities and the ability to perform secondary missions such as energy production that could offset annual operating costs and/or be used in demonstration of integrated or hybrid energy systems.

3.3 Licensing Options

A key component of all reactor technology development activities, and the primary focus of the NRC and its associated licensing processes, is to confirm that proposed reactor facilities do not pose an undue risk to public health and safety. The establishment of this "safety case," and the development of the underlying technical bases and associated justifications that support it, are foundational elements of successful advanced reactor development, licensing, and commercial deployment.

The key to the safety case, for both the previously deployed large LWR fleet and the advanced reactor technologies under development, is to establish a very clear understanding of the following high-level attributes of the proposed reactor technology and the associated facility design being developed for the use of that technology:

- Identify the various plant events that could lead to radionuclide release
- Establish the form and quantity of the radionuclide source in the proposed fuel type and reactor design that could potentially be released when challenged by those plant events
- Establish the capability to analyze and assess the timing, form, and magnitude of the transport and release of that radionuclide source to the environment and members of the public.

The applicant's demonstration of the "safety case" supporting its application requires comprehensive documentation of the research conducted, testing accomplished, and analyses performed necessary to support both the design and the technical basis for the safety analysis. For example, applicants are responsible for conducting R&D to:

- Demonstrate safe performance of the proposed design and applied technology
- Provide the technical basis for the application
- Demonstrate sufficient margins to safety-significant structures, systems, and components (SSC) design and safety limits
- Search for and identify, as well as assess and resolve, safety issues involving large uncertainties
- Develop, verify, and validate the proposed safety analysis evaluation methods

- Provide the technical basis for requirements, criteria, codes, or standards that are proposed for the licensing design basis
- Quantify the failure thresholds for safety-significant SSC
- Support NRC regulatory and licensing decisions.

Advanced reactor development must therefore involve close coordination and integration of the technical aspects of the design being established to meet commercial end-user needs with the technical aspects required to support the safety case and associated regulatory requirements. Although a more detailed assessment of technical knowledge gaps is needed for each advanced reactor technology being considered, technical areas typically requiring consideration and technical justification as a part of the development and licensing processes associated with commercial reactors are reflected in Figure 6.

It is critical that these technical issue analyses and resolution efforts, with identification of necessary R&D, are closely integrated with the confirmation and defense of the respective advanced technology's safety case. This integration is a key to assuring that critical path and long-lead items are not overlooked on the technology development timeline, giving investors and other stakeholders confidence that technical progress and readiness can indeed support a successful NRC licensing and advanced reactor technology deployment effort.

The licensing options vary by concept maturity. For the mature concepts (HTGR and SFR), both reactor vendors providing demonstration reactor point designs have reported they would pursue a commercial power reactor Class 103 Nuclear Regulatory Commission (NRC) license. Considerable data exist from past demonstration projects and R&D activities conducted over the past 50 years to support licensing of these concepts. Both concepts (General Atomics MHTGR and GE PRISM) have received safety evaluation reports from the NRC. The modular HTGR has also been the subject of recent pre-application discussions with NRC as part of the Next Generation Nuclear Plant Project (NGNP). As a part of the point design effort focused on Strategic Objectives #1 and #2, both reactor vendors (AREVA and GEH) proposed licensing the first module using the Part 50 process which allows detailed design to be completed after the start of construction, in advance of issuance of the operating license. The reactor vendor can then use the operational experience (e.g., construction, testing, operations, maintenance, etc.) from this first module to modify or refine the design, before next applying for NRC design certification. This would then allow the refined and certified design to be replicated for follow-on modules using the Part 52 licensing process, without the need for additional NRC reviews of the certified design.

For the engineering demonstration and irradiation test reactors, a Class 104(c) non-power reactor license is an option that may allow for greater regulatory framework flexibility given the state of the technology. However, it is noted that for any reactor above 10-20 MWt, the NRC could be expected to apply the same level of technical review to an engineering demonstration or irradiation test reactor as to a similar sized power reactor, due to the potential public risk from the larger source term.

An additional restriction regarding this class of reactor license is that the facility must be used so that no more than 50% of the annual cost of owning and operating the facility is from the production of materials, products, or energy for sale or commercial distribution. This license type has been used in the past for small university reactors and the National Institute of Standards and Technology research reactor. It is noted that the last large-scale demonstration reactors were built and operated in the U.S. (e.g., Peach Bottom, Fermi-1) before the NRC existed.

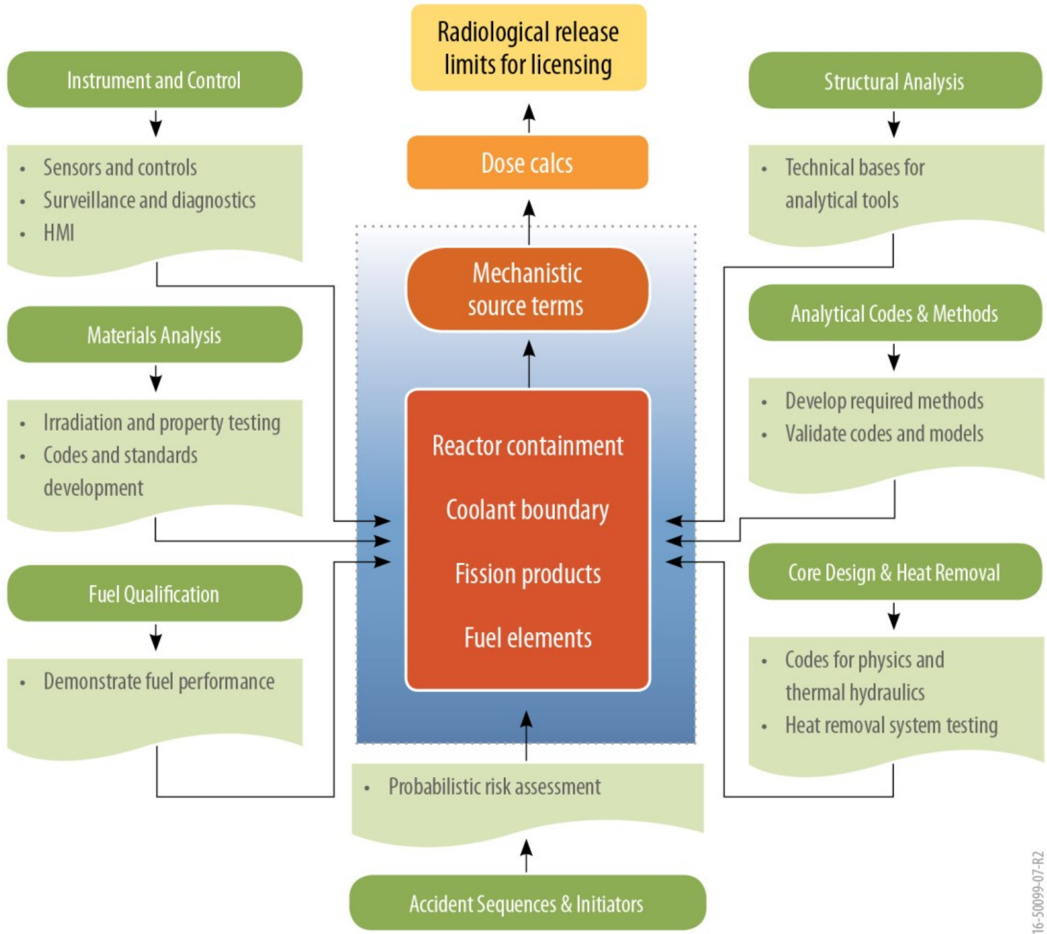

Figure 6. Technology development typically required for licensing.

4. Promising Options for Each Strategic Objective

Four demonstration reactor point designs were developed: a modular high temperature gas-cooled reactor by AREVA, a sodium fast reactor by GE, a lead fast reactor by Westinghouse and a fluoride cooled high temperature reactor by Oak Ridge National Laboratory. Key design parameters of the demonstration reactors are summarized in Table 2. In addition, two irradiation test reactor designs were developed: a modular high temperature gas-cooled reactor by the Idaho National Laboratory and a sodium fast reactor by Argonne National Laboratory. Key design parameters for the irradiation test reactors are found in Table 3. The most promising option for each key strategic objective is described in this section.

4.1 Assessment Methodology and Scores

Participants from DOE and the national laboratories developed the goals, metrics, and criteria. This material, as well as the point design reports for the two test and four demonstration reactor designs, were distributed to the evaluation team before a 3-day workshop was held. The 11 "voting" participants at the assessment workshop were requested to evaluate the designs using a three-tiered scoring system, ranging from a top score of 9, a mid-score of 5, and a low score of 1 (the performance ranges and scoring bins for the metrics can be found in reference [4]). The evaluation team members each had to assign one score per metric. The 11 votes all had equal weights.

Table 2. Key design parameters of the demonstration reactors.

Parameters	SC-HTGR	PRISM SFR	FHR DR	DLFR
Rated power	625 MWth 272 MWe	471 MWth 165 MWe	100 MWth 42 MWe	500 MWth 210 MWe
Thermal efficiency	43.5%	35%	42%	42%
Power conversion system	Conventional Rankine steam cycle	Superheated Rankine steam cycle	Open-air Brayton cycle	Superheated Rankine steam cycle
Core inlet/outlet temperature	325°C/750°C	352°C/500°C	660°C/700°C	390°C/510°C
Primary pressure	6 MPa	~0.1 MPa	~0.1 MPa	~0.1 MPa
Cycle length	18 months	18 months	18 months	18 months
Reactor vessel	SA-508/533	SS-316	Alloy 800H lined with alloy N	SS-316
Primary coolant	Helium	Sodium	FLiBe (99.995% ^{7}Li)	Lead
Moderator	Graphite	N/A	Graphite	N/A
Fuel type	TRISO-coated UCO particles	U-Zr in HT-9 cladding	TRISO- coated UCO particles	UO_2 in alumina coated D-9 cladding
Fuel enrichment	15.5%	<20%	15.5%	17.5% (inner) 19.9% (outer)
Fuel form	Hexagonal graphite blocks with cylindrical fuel compacts	Fuel rods in a hexagonal assembly	Hexagonal graphite blocks with cylindrical fuel compacts	Fuel rods in a hexagonal assembly
Fueled core configuration	102 columns, 10 blocks/column	99 assemblies	18 assemblies, 3 blocks/column	82 assemblies

Table 3. Key design parameters of the test reactors.

Parameter	SFR-TR	HTGR-TR
Rated power	300 MWth	200 MWth
	120 MWe	80 MWe
Cycle length	100 days	110 days
Primary pressure	~0.1 MPa	7 MPa
Primary coolant	Sodium	Helium
Moderator	N/A	Graphite
Fuel type	U-Pu-Zr in HT-9 cladding	TRISO-coated UCO particles
Fuel fissile content	19.40%	15.50%
Fuel form	Fuel rods in a hexagonal assembly	Hexagonal graphite blocks with cylindrical fuel compacts
Fueled core configuration	55 assemblies	12 columns, 8 blocks/column
Power conversion system	Superheated Rankine steam cycle	Conventional Rankine steam cycle
Core inlet/outlet temperature	355°C/510°C	325°C/650°C
Irradiation conditions		
Number of irradiation locations	39	36
Peak fast flux level	5.0×10^{15} n/cm^2-s	1.6×10^{14} n/cm^2-s
Peak thermal flux level	>5.8×10^{14} n/cm^2-s	3.9×10^{14} n/cm^2-s
Irradiation length	100–200 cm	634 cm
Irradiation volume	21 L/location	30 L/location
Total irradiation volume	820 L	1100 L

During the workshop, representatives of the reactor design teams presented summaries of their designs and clarified remaining issues. It should be noted that the weights assigned to the metric bins were not provided to the evaluation team to ensure a round of blind scoring and allow equal discussion of all aspects. The scores obtained in this way are referred to in this report as “raw” scores. The weighted scores for each of the three strategic objectives were then processed for the 25 metrics shown in Table 4, using the following simple multiplicative formula (shown here for Metric D1.1.1, for example):

*Weighted_score D1.1.1 = weights (goal D1 * criterion D1.1 * metric D1.1.1) * raw_score (metric D1.1.1)*

The total mean score for a particular design was determined by the sum of these 25 fractional scores. Statistical analyses of the 11 scores sets were then performed to calculate the mean and one standard deviation values for each of the metrics.

The mean raw scores for each metric obtained for all four demonstration reactor designs (Table 4) were weighted to establish the scores by goal and then summed to obtain an overall score for each strategic objective, as summarized in Table 5. The SC-HTGR and PRISM SFR designs were not assessed against Strategic Objective 3.

Table 4. Mean raw scores.

Metric	Description	Mean Values			
		HTGR	SFR	FHR	LFR
D1.1.1	Safety characteristics and systems/components	9.0	9.0	4.3	5.4
D1.2.1	Adequate instrumentation for code validation tests	9.0	9.0	9.0	9.0
D1.3.1	Prototypic technology selections	9.0	9.0	5.4	5.0
D1.4.1	Prototypic maintenance approaches	9.0	9.0	5.0	7.2
D1.5.1	Prototypic fabrication technologies	9.0	9.0	4.6	7.2
D2.1.1	Project cost	7.9	7.9	9.0	6.1
D2.1.2	Project schedule	5.0	4.6	5.7	3.5
D2.2.1	Annual operating costs	7.9	7.2	1.0	6.1
D2.3.1	Availability factor	8.6	8.6	6.1	6.8
D3.1.1	Ability to address key licensing issues	8.6	9.0	6.8	7.2
D3.1.2	EPZ size	8.3	7.5	7.9	7.2
D4.1.1	Prototypic or scalable integral component performance	9.0	9.0	5.4	6.1
D4.2.1	Number of alternative core configurations	9.0	9.0	9.0	9.0
D4.2.2	Number of alternative fuel types	9.0	9.0	9.0	9.0
D4.3.1	R&D time	5.0	7.2	4.3	4.3
D4.3.2	R&D cost	5.4	6.8	5.4	4.3
D4.4.1	Fast flux conditions at test location	1.0	5.0	1.0	5.0
D4.4.2	Thermal flux conditions at test location	5.0	2.1	5.0	1.0
D4.4.3	Irradiation volumes and length	9.0	6.8	9.0	6.1
D5.1.1	Use of natural fuel resources	1.4	9.0	1.4	9.0
D5.2.1	Prototypic fuel fabrication	8.6	8.6	5.0	6.1
D5.3.1	Prototypic fuel performance	8.6	9.0	6.8	5.4
D5.4.1	Prototypic spent fuel handling	8.6	9.0	5.4	8.3
D6.1.1	Number of energy conversion systems	9.0	5.0	9.0	5.0
D6.2.1	Coolant outlet temperature	9.0	5.0	9.0	5.0

Table 5. Summary of demonstration reactor weighted scores (%) by goal.

Goals	Strategic Objective 1				Strategic Objective 2				Strategic Objective 3			
	HTGR	SFR	FHR	LFR	HTGR	SFR	FHR	LFR	HTGR	SFR	FHR	LFR
1	25.0	25.0	14.9	17.7	20.0	20.0	11.9	14.2	*Not scored against this strategic objective*		20.9	24.8
2	16.2	15.7	12.8	12.4	16.2	15.7	12.8	12.4			12.8	12.4
3	14.2	14.2	12.0	12.0	14.2	14.2	12.0	12.0			12.0	12.0
4	16.9	17.7	13.9	14.1	16.9	17.7	13.9	14.1			13.9	14.1
5	0.0	0.0	0.0	0.0	14.9	24.8	10.5	21.1			2.1	4.2

Goals	Strategic Objective 1				Strategic Objective 2				Strategic Objective 3			
	HTGR	SFR	FHR	LFR	HTGR	SFR	FHR	LFR	HTGR	SFR	FHR	LFR
6	20.0	11.1	20.0	11.1	0.0	0.0	0.0	0.0			5.0	2.8
Total	**92.3**	**83.7**	**73.6**	**67.3**	**82.2**	**92.4**	**61.2**	**73.7**			**66.7**	**70.3**
1σ	**4.1**	**3.6**	**7.4**	**11.4**	**6.3**	**3.7**	**8.0**	**13.7**			**8.5**	**13.3**

Sensitivity studies were performed to determine whether changes in weighting functions would alter the outcomes. Three sets of sensitivity studies were performed. In the first set, the weight of one of the goals was set to 100%, while all other goal weights were set to 0%. The relative weights of the criteria and metrics within the goals were unchanged. In the second set, the raw scores of the two participants that on average scored the lowest and highest were removed. In the third set, only the five highest-weighted metrics for each strategic objective were preserved and re-normalized to 100%. The weights for all other metrics were set to zero. In all cases, the results were the same as the base case results discussed here.

4.2 Strategic Objective 1: Process Heat

The assessment for this objective identified two discriminators between point designs: suitability and prototypicality for a variety of high temperature applications and commercially relevant scale of the demonstration. The higher maturity options were favored, with the most promising option being the HTGR because of its high outlet temperature (>700°C), flexibility for energy applications and its state of development.

Of the point designs in the study, the modular SC-HTGR design by AREVA scored highest with respect to this objective. It would generate electricity using a high efficiency Rankine cycle while simultaneously producing process heat for a compatible industrial application (e.g., synfuels). The SC-HTGR is a modular, helium-cooled, graphite-moderated high-temperature energy supply system. With a 750°C reactor outlet temperature, it operates at temperatures much higher than LWRs, but within the range of existing technology demonstrated in previous HTGR projects. Modular HTGRs offer a very high degree of passive safety. The TRISO-coated particle fuel, which retains virtually all fission products at very high temperatures, the tall slender core and low-power density, the inert helium coolant, and the ceramic graphite moderator provide a system that is robust at very high temperatures and does not melt even under postulated beyond design basis events. The modular HTGR does not require off-site emergency power to passively reject decay heat.

4.3 Strategic Objective 2: Extend Natural Resource Utilization and Reduce the Burden of Nuclear Waste

The assessment for the resource utilization and waste reduction objective identified two discriminators between point designs: suitability and the prototypicality for demonstrating high natural resource utilization and commercially relevant scale of the demonstration. The higher maturity options were favored, with the most promising option for resource utilization and waste reduction being the SFR because of its ability to efficiently convert uranium and utilize recycled fuel and its state of development.

Of the point designs in the study, the SFR proposed by GEH best supports the extension of natural resources and reduction of the nuclear waste burden, as well as fulfills the fundamental mission of efficient and reliable electricity production. The Power Reactor Inherently Safe Module (PRISM) module Mod A is a 471 MWth fast reactor cooled by sodium coupled to a superheated Rankine power cycle with a single helical coil steam generator producing 165 MWe (35% efficiency). PRISM's extensive design development, state of knowledge, operational experience, and conservative design approach are based on the use of technologies proven by decades of operation and testing of EBR-II and Fast Flux Test Facility (FFTF). To support fuel cycle closure, U-Zr fuel can be quickly followed by U-Pu-Zr and minor actinide-bearing fuels, although these advanced fuels have yet to be qualified for such use. The PRISM modularity, inherent passive safety and commercial scale allow for a relatively low complexity system that will not be hindered by scaling issues. These features reduce regulatory and financial risks. The inherent safety of metal fueled sodium-cooled fast reactors in beyond design basis events was demonstrated in EBR-II.

4.4 Strategic Objective 3: An Engineering Demonstration Reactor for a Less-Mature Reactor Technology

The ability of engineering demonstration reactors to advance the TRL of a less mature reactor technology was assessed. Both the FHR and LFR are both low maturity technologies that require significant research, development and demonstration before they can be commercialized. Significant discriminators between the FHR and LFR point designs related to readiness for an engineering demonstration were not identified in the assessment. However, the distinct approaches that the two design teams took to advancing the TRL illuminate potential pathways to reactor technology development. The FHR and LFR point designs, as engineering demonstration reactors, scored essentially the same in their ability to increase the technology readiness of these less mature technologies.

The FHR is a class of molten salt reactors (MSRs) that uses solid fuel in low-pressure fluoride salt coolants to produce high-temperature heat with a high degree of inherent safety and significant margins to coolant boiling and fuel damage. The FHR point design proposed by ORNL is a 100 MWth, engineering demonstration designed to test key technologies prior to the next step - a performance demonstration. The current goal of the FHR engineering demonstration is to advance the FHR technologies towards commercial deployment supporting Strategic Objective 1. It is designed using the most mature component technologies currently available but not optimized or configured as a commercial plant. Initially, it would use TRISO fuel compacts in graphite blocks cooled by the molten fluoride-lithium-beryllium (FLiBe) salt with an outlet temperature slightly greater than 700°C. Key features of the FHR demonstration reactor concept are directly relevant and scalable to commercial applications.

By contrast, the LFR point design proposed by Westinghouse is a much larger power system (500 MWth). The LFR engineering demonstration could advance the LFR concept towards commercial deployment supporting Strategic Objective 1 and/or 2. Initially, the uranium oxide fuel would use D9 cladding and will operate with a lower coolant temperature (510°C) than intended for future commercial application. Eventually, the fuel would use D9 cladding with an alumina coating to enable higher temperatures, higher flow rates, and higher power conversion efficiency without the corrosion observed in lead-based systems at those temperatures. Its inherent safety derives from a pool-type integral system design, a bayonet-based passive decay heat removal system, and the favorable thermal properties of lead coolant. This engineering demonstration reactor would then allow for integral testing in a prototypic environment. As confidence is built in its operation and other R&D occurs in parallel, the flow rate, outlet temperature, and power would be increased to values more typical of a commercial LFR (outlet temperature of ~700–750°C and power of 700 MWth).This engineering demonstration would then be modified to support experiments leading to performance demonstration. If successful, the technology maturation could be accelerated, but risks are higher because not all design features/components might not be able to be exchanged or incorporated into the system if the design were to evolve outside of the anticipated envelope.

The assessment determined that the FHR and the LFR point design development strategies will take longer to reach commercialization than those associated with the SFR or HTGR.

4.5 Strategic Objective 4: Irradiation Test Reactor

Water-cooled irradiation test reactors platforms have been the workhorse of nuclear fuels and materials irradiation testing for thermal reactor systems over the past 50 years. These water-cooled materials test reactors (MTRs) produce damage rates (up to 10 dpa/yr) sufficient to support most thermal reactor development, but are already operating near full capacity. However, accumulating peak doses typical of advanced fast reactors (200 to 500 dpa) using a water- cooled MTR would take 20 to 50 years. Advanced fast neutron reactor systems experience neutron damage rates that are significantly higher because the neutrons are typically not thermalized and the magnitude of the fast neutron flux is much higher than for thermal systems. Fast neutron irradiation capability is largely lacking worldwide.

A water-cooled reactor therefore cannot meet the needs to support research and development of advanced fast reactor designs because the fast fluence rates are insufficient to achieve damage rates in materials (especially cladding) that would support proposed fast reactor deployment schedules. Furthermore, Generation IV concepts using coolants other than water may require fast neutrons for the study of materials, fuels and corrosion control. Closed test loops with such coolants must be carefully designed so as not to significantly perturb the spectrum of the driver core, and thus are generally unavailable and expensive to install in existing water-cooled MTRs.

Mature technologies are required for reliable operations of an irradiation test reactor. Thus, only SFR and a HTGR were examined to determine their ability to provide neutron irradiation services to support nuclear fuels and materials testing for advanced reactor systems. A summary of the key design parameters for these test reactor options is shown in Table 2. The mean raw scores for each metric obtained for the two test reactor designs are presented in Table 6, and goal level scores are summarized in Table 7.

Table 5 . Mean test reactor raw scores.

Metric	Description	HTGR	SFR
T1.1.1	Fast flux conditions	1.0	9.0
T1.1.2	Thermal flux conditions	5.0	9.0
T1.1.3	Irradiation volumes and length	9.0	6.8
T1.1.4	Cycle length	9.0	9.0
T1.1.5	Prototypic and bounding conditions	6.5	9.0
T1.2.1	Number of test zones	9.0	9.0
T1.2.2	Number of test loops	6.1	9.0
T1.2.3	Specimen retrievability at power	9.0	9.0
T2.1.1	Project cost	4.6	5.0
T2.1.2	Project schedule	4.6	4.6
T2.2.1	Annual operating costs	5.0	5.0
T2.3.1	Availability factor	5.0	7.9
T3.1.1	Number of secondary missions	9.0	9.0

Table 6. Mean weighted scores per metric for the TRs against Strategic Objective 4.

Goals	**Strategic Objective 4**	
	HTGR-TR	SFR-TR
1	47.3	67.2
2	13.5	16.6
3	5.0	5.0
Total	**65.9**	**88.9**
1σ	**5.5**	**3.9**

The assessment for the irradiation test reactor objective identified two discriminators between point designs: fast flux levels and irradiation volumes. Overall, the SFR irradiation test reactor design is the preferred option, because only it can provide very high fast neutron flux as well as high-thermal neutron flux in moderated zones to meet many of the needs of both the fast and thermal reactor developers. Being a thermal system, the HTGR does not provide a high fast flux, but the large size and inert coolant accommodates testing of a wide array of fuels and materials at a very large scale, including half-scale LWR fuel assemblies. Both systems can incorporate multiple test loops to test fuels and materials under different coolant conditions. The impact of the closed loops on the safety and operation of the reactors cannot be fully ascertained until more details about the specific loops are developed. Both point designs produce enough power at relevant temperatures to produce electricity to offset some of the operating costs. Both systems could be licensed under an NRC Class 104(c) license for irradiation test reactors.

A follow-on study is currently in the planning stage to take the next step and evaluate in more detail the need, capabilities and testing requirements, as well as the time frame, for a new test reactor to support the broad user community (National Laboratories, academia, industry, reactor vendors, supply chain manufactures, material suppliers, the U.S. Government, and the international community).

5. Summary and Conclusions

An assessment of advanced reactor technology options was performed to provide a sound comparative technical context for future decisions by the DOE concerning these technologies. Over the course of this study, the assessment team:

- Assembled a broad team of stakeholders from industry, academia, and government
- Chose a set of strategic objectives that support both innovation and the long-term commercialization of advanced reactor systems
- Considered a broad set of potential reactor technologies and selected a set for evaluation
- Commissioned point designs to develop the technical basis for evaluation
- Developed a comprehensive set of goals, criteria, and metrics to evaluate advanced test and demonstration reactor concepts ability to meet the strategic objectives
- Solicited extensive stakeholder input to evaluate candidate designs with respect to the goals, criteria, and metrics
- Identified pathways to deployment for concepts of varying technical maturity.

The study compared different technology options and identified the tradeoffs that exist when trying to meet the strategic objectives. Timelines and costs were estimated for the different demonstration systems, including perspectives on possible licensing approaches. It also presented the tradeoffs that exist among the different test reactor options in terms of the ability to conduct irradiations in support of advanced reactor R&D and to serve potential secondary missions. The findings of the study are summarized as follows for the most promising options for each strategic objective:

Objective 1 – Process heat: High-Temperature Gas-cooled Reactor

Objective 2 – Resource utilization/waste management: Sodium-Cooled Fast Reactor

Objective 3 – Maturation of less mature technology: Evaluation results did not identify any advantages between a Fluoride Salt Cooled High Temperature Reactor and a Lead-Cooled Fast Reactor

Objective 4 – Test Reactor: Sodium-Cooled Fast Reactor

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