U.S. Department of Energy
Office of Nuclear Energy

Advanced Reactor Concepts Technical Review Panel Public Report

Evaluation and Recommendations for Future R&D on Seven Advanced Reactor Concepts, Conducted March through June 2014

October 2014

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FIGURES

Summary

This report documents the conduct of a technical review process and the findings of the Advanced Reactor Technology (ART) Technical Review Panel (TRP) for 2014. The technical review process and format of this report follows that used in 2012[1]. As was the case in 2012, the intent of the process is to identify R&D needs for viable advanced reactor concepts in order to inform Department of Energy (DOE) Office of Nuclear Energy research and development (R&D) investment decisions. A goal of the process is to facilitate greater engagement between DOE and industry. The process involved establishing evaluation criteria, soliciting concept inputs from industry entities, reviewing the concepts by TRP members and compiling the results and is described in Appendix A. A brief summary of the on-going research resulting from the 2012 Funding Opportunity Announcement is included in Appendix B.

Seven concepts were received from industry and they spanned a range of reactor types and coolant selections. The concepts included four fast reactors and three thermal reactors. As to reactor coolants, there were four gas-cooled reactors and three liquid metal-cooled reactors. Three reactors use Tristructural Isotropic (TRISO) fuels containing Uranium Dioxide (UO_2) or Uranium Oxycarbide (UCO), two reactors use nitrides of uranium or transuranics, one reactor uses Uranium Carbide (UC) and one uses metal fuel. The concepts also varied considerably in level of design maturity. Six of the concepts have power levels less than 300 MWe.

The objective of the TRP process was to evaluate the viability of the concepts, gain an understanding of their R&D needs and prioritize research that supports the commercialization of those concepts. The report identifies concept specific needs and needs of multiple concepts. The report then makes recommendations for advanced reactor R&D activities.

The overall outcome of the TRP process is a listing of R&D needs and recommendations that would be beneficial to industry and DOE. This information will be used to inform the Department of Energy Office of Nuclear Energy reactor technology funding decisions.

Interaction through this process can lead to an R&D program that has greater insight into industry, university, and national laboratory perspectives and potential opportunities for collaborative R&D projects.

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[1] *Advanced Reactor Concepts, Technical Review Panel Report, Evaluation and Recommendations for future R&D on eight Advanced Reactor Concepts, conducted April – September 2012,* November 2012

Technical Review Panel Report

1. OVERVIEW OF THE TECHNICAL REVIEW PANEL PROCESS

The U.S. Department of Energy (DOE) Office of Nuclear Energy sponsors a program of research, development, and demonstration related to advanced reactor concepts, both small modular reactors (SMRs) and larger systems. These advanced concepts encompass innovative reactor concepts such as fast reactors cooled by sodium, lead, or helium; high-temperature gas-cooled reactors; and fluoride salt-cooled high-temperature reactors.

1.1 Overview of the 2014 Technical Review Process

In April 2014, DOE Office of Nuclear Energy issued a Request for Information (RFI) to help inform development of the DOE reactor technology research portfolio. The RFI identified eleven criteria against which the concepts would be evaluated. Reactor vendors submitted seven concept proposals in response to the RFI and DOE Office of Nuclear Energy formed a Technical Review Panel (TRP) to evaluate the attributes, advantages, disadvantages, and relative benefits of the concepts and to identify research and development (R&D) needs based on the concept submittals. Appendix A shows the process flowchart followed to establish the TRP, obtain industry input, and evaluate that input. This report summarizes the results of the review panel's evaluation process.

As in 2012, the TRP consisted of nuclear reactor technology and regulation experts from national laboratories, universities and industry. The individual panel members reviewed the submitted information and conducted independent checks of the applicants' self-assessment conclusions and bases. The panel members were asked to use their expert judgment to evaluate the submitted reactor concepts against the set of eleven evaluation criteria and to identify R&D needs.

The following are the reactor concepts that were submitted in response to the RFI:

- AREVA (prismatic, high-temperature, gas-cooled reactor)
- Hybrid Power Technologies, LLC – Hybrid Nuclear Advanced Reactor Concept (gas-cooled reactor coupled with natural gas turbine)
- Gen4 Energy Reactor Concept (lead-bismuth fast reactor)
- LakeChime SSTAR (lead-cooled fast reactor)
- General Atomics – (high-temperature, gas-cooled fast reactor)
- X-Energy (pebble-bed, high-temperature, gas-cooled reactor)
- GE-Hitachi Nuclear Energy PRISM and Advanced Recycling Center (sodium fast reactor).

2. TECHNICAL REVIEW PROCESS

The RFI requested that the concept applicants submit concept descriptions and concept specific information responses for eleven categories. The TRP used this information for evaluation of concept viability and for identification of R&D needs.

2.1 Technical Criteria

In addition to concept descriptions, each applicant provided responses to the eleven categories listed in the following subsections. It was recognized that not all applicants have concepts at the development stage for which answers to all categories could be provided. While responses to these criteria served to allow TRP members and DOE to gain an understanding of the concepts, the key output of this effort was the identification of R&D needs in Category XI. The evaluation categories listed here are similar to that used in the 2012 RFI; however, the emphasis in this RFI was the identification and explanation of R&D needs.

2.1.1 Category I. Safety

This category is an assessment of defense-in-depth characteristics and the safety margins in the components and structures of the concept under review. Assessment of the defense-in-depth characteristics includes evaluating the main barriers to release of radioactive materials. The concepts are expected to provide enhanced margins of safety and/or use simplified, inherent, passive, or other innovative means to accomplish their safety and security functions. The purpose is to provide a basic understanding of the safety characteristics and demonstrate that the proposed concept can achieve the level of performance expected for future advanced reactors. Information on accident prevention, accident mitigation, emergency planning, shutdown heat removal and severe accident responses should be provided.

2.1.2 Category II. Security

This category is an assessment of the security capability of the plant, which may include features of the plant that reduce the likelihood or consequence of direct attack. The responses should provide a basic understanding of the security characteristics and demonstrate that the proposed concept can achieve the level of security expected for future advanced reactors. A description of features that will prevent or mitigate sabotage threats, aircraft impact and other relevant attack scenarios will provide insight into the concept's security performance. At a minimum, the concept should have the same degree of defense, security, and materials protection as is required for current generation Light Water Reactors (LWRs).

2.1.3 Category III. Ability to Improve Uranium Resource Utilization and Minimize Waste Generation

The purpose of this category is to provide a basic understanding of the performance features that can utilize uranium resources more efficiently to ensure long-term nuclear energy sustainability and reduce the environmental burdens of the fuel cycle. In the near and intermediate term, uranium resources are not expected to be a major limitation. The uranium enrichment and mass that would be required to operate the reactor are provided to understand the required fuel cycle inputs. An estimate of the discharged fuel content, volumes and mass are provided to understand waste and storage requirements.

2.1.4 Category IV. Operational Capabilities

This category provides a qualitative assessment of the operational capabilities of the proposed concept design. Electricity generation capabilities, flexibility in electricity generation, load following capability, fuel performance limitations, reactivity limitations, and mechanical and thermal stress in materials and components are addressed to understand operational performance. Outage requirements, maintenance and operating availability provide understanding of the concept's performance on the grid.

2.1.5 Category V. Concept Maturity, Operating Experience, Unknowns and Assumptions

This category provides a qualitative assessment of the maturity of the proposed concept design, associated technology readiness levels (TRLs), and relevant operational experience (including demonstration and/or test facilities). A description of the concept's level of design development, deployment schedule, operating experience, advanced materials, nuclear fuel and fuel design provides an understanding of the concept maturity.

2.1.6 Category VI. Fuel Cycle Considerations

This category examines a concept's compatibility with existing domestic and global fuel cycle nuclear infrastructures. Having high levels of current infrastructure compatibility, particularly fuel fabrication and material experience, could mean that a concept could be implemented in less time and with potentially lower costs than ones requiring major infrastructure change and development.

2.1.7 Category VII. Assessment of Market Attractiveness

This category provides a review of the features that make the proposed concept attractive and competitive in the marketplace. The market attractiveness of a reactor concept is determined by a wide range of factors, including revenue generation factors, nuclear safety considerations, commercial warranties, environmental factors, siting requirements, non-electric applications and others unique concept features. The timing of introduction of the concept into the market is an important factor, because it encompasses the prospects for public support and acceptance, political support, and favorable financing.

2.1.8 Category VIII. Economics

This category provides information related to a concept's economic factors (e.g., estimated capital requirements, manufacturing costs, operating costs, cost of electricity, and the cost, if any, of other products that may be produced such as hydrogen). The information allows an independent review of the potential economic performance of a concept system and its approach to materials, manufacturing, operations, fuel expenses, overnight capital costs, construction duration and levalized electrical cost.

2.1.9 Category IX. Potential Regulatory Licensing Environment

This category provides an indication of any potential challenges facing concept licensing by the U.S. Nuclear Regulatory Commission (NRC). The focus is on any unique design features that have not been subject to the licensing process for the current fleet of LWRs. Those concept features that have not been subject to the licensing process for the current fleet of LWRs are explained. The uncertainty and risks of features typically not found in LWRs are addressed. The features of the concept design and operational features that may positively or negatively impact licensing requirements are provided.

2.1.10 Category X. Nonproliferation

This category is relevant because advanced reactor concepts may be exported to non-nuclear weapon states. To assess nonproliferation, an understanding is obtained of the concept characteristics that impede the diversion, undeclared production of nuclear material or the misuse of technology by the host state seeking to acquire nuclear weapons or other nuclear explosive devices. Key considerations are the types and quantities of special nuclear materials used, whether the concept includes recycling of used fuel (and if so the characteristics of the recycling process), and any other technological aspects such as a high breeding ratio that might raise proliferation concerns.

2.1.11 Category XI. Research and Development Needs

This category solicits information on R&D needs and how the identified R&D would serve to advance the concept and associated technology. The response should provide relative prioritization from concept applicants, information on when R&D is needed, and a perspective of the dollar amount of R&D needed. The outcome from the TRP is identification of R&D needs by concept, identification of R&D support that could be of benefit to multiple concepts, and recommendations on prioritization of potential R&D activities.

3. CONCEPT SUMMARIES

3.1 AREVA High-Temperature Gas-Cooled Reactor Commercialization

The AREVA SC high-temperature gas-cooled reactor (HTGR) is an estimated 276 megawatt electric (MWe) prismatic high-temperature reactor using tristructural isotropic (TRISO) particle fuel. With a thermal power of 625 MWt, the reactor inlet temperature is 325°C and the outlet temperature is 750°C. The helium primary coolant has a pressure of 6 MPa and is circulated by two 4-MWe circulators to two 315-megawatt thermal (MWt) steam generators with outlet conditions of 556°C and 16.7 MPa. The reactor vessel material is SA508/533.

The configuration of the reactor and steam generators is shown in Figure 1. The reactor vessel contains the reactor core, reactor internals, and control rods. Each steam generator is housed in a separate steam generator vessel. A separate cross vessel connects each steam generator to the reactor vessel. Each cross vessel contains a hot duct that channels hot gas from the reactor outlet to the steam generator inlet. Cool return gas flows in the outer annulus between the hot duct and the vessel wall. The entire inner vessel surface is bathed in cool reactor inlet gas; therefore, conventional LWR vessel material can be used.

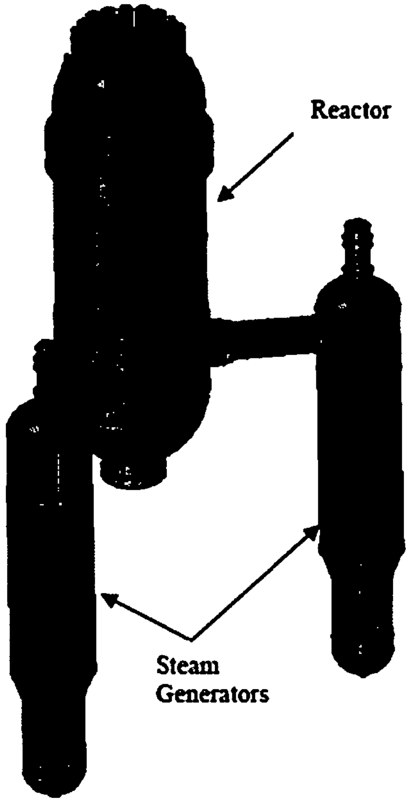


Figure 1. AREVA nuclear process steam supply system.

Each steam generator is a helical coil tubular heat exchanger. Feed water enters the bottom of the heat exchanger and flows upward through the tubes, while hot primary coolant flows downward over the tube bundle. This steam generator is very similar to those successfully employed in previous gas-cooled reactors.

The AREVA concept has three heat removal systems. The two main cooling loops transfer heat to the secondary circuit during normal operation. They also can provide cooling during refueling and other shutdown conditions. Heat is transferred from the vessel to the reactor cavity cooling system (RCCS) through thermal radiation and natural convection.

3.2 Hybrid Power Technologies, LLC -Nuclear Advanced Reactor Concept

The Hybrid Power Technologies, LLC Hybrid Nuclear Advanced Reactor Concept produces a total of 850 MWe, using 600 MWt from a helium-cooled, graphite-moderated reactor and 1,000 MWt from a natural gas-fired facility. The plant uses an integrated combined-cycle of a closed-system Brayton cycle with helium from the reactor, an open-system Brayton cycle combustion turbine, and a Rankine steam cycle as shown in Figure 2. The reactor outlet temperature is 838°C. Fifty-two percent net efficiency is expected. The reactor uses UO_2 in TRISO particles as fuel, with less than 19% enrichment and a 2-year refueling cycle. The plant design life is 40 years, with possible extension to 60 years. The design has three loops and utilizes rods for shutdown systems. The design utilizes active and passive decay heat removal from the reactor vessel with helium. Specific design features include operation as an intermediate load plant with the reactor powering the compressor for the natural gas combustion turbine. Transportability is limited, because the unit uses standard power plant and shipyard construction.

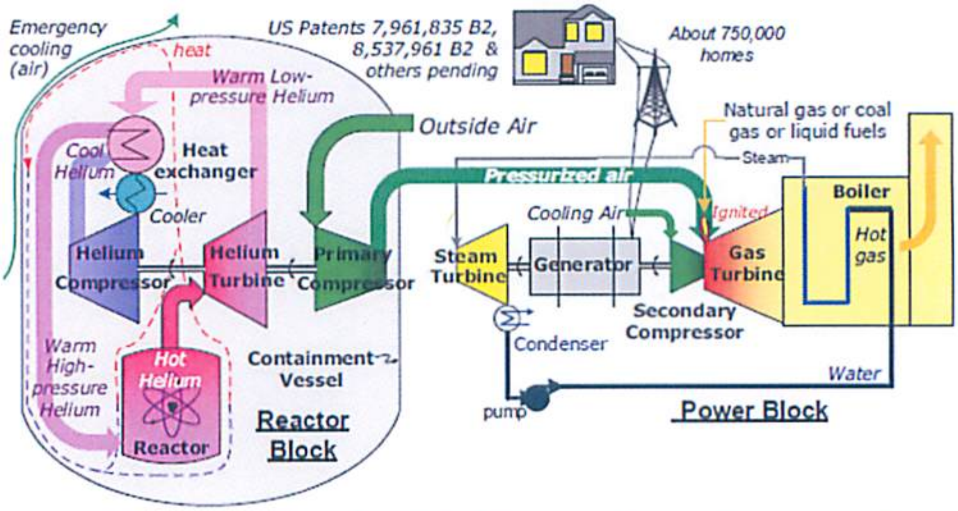


Figure 2. Hybrid Power Technologies, LLC Hybrid Nuclear Advanced Reactor configuration.

Because the Hybrid Nuclear Advanced Reactor concept is, in part, a combined-cycle power plant, a large number of applications are possible using natural gas or gasified coal as the hydro-carbon fuel source.

Multiple barriers are employed to prevent exposure of the public to radioactive material. The design also employs multiple and diverse active and passive measures to prevent the fuel from overheating. The underground reactor location is designed to provide security and protection against external threats, both natural and man-made. The reactor is designed to be fail-safe, even if no cooling water, electrical power, or plant personnel are available. The graphite/silicone reactor fuel is being considered for nuclear power designs located in both the United States and abroad.

The Hybrid Nuclear Advanced Reactor concept is designed to adopt proven components and designs to fit the characteristics of this new approach to nuclear energy. Additional developmental work could address technical, operational, and competitive capabilities and gain additional investor support.

3.3 Gen4 Energy

The Gen4 Energy Reactor (Gen 4Module (G4M)) is a 25-MWe, fast reactor that uses lead-bismuth eutectic (LBE) as its coolant. It uses a superheated Rankine cycle with a reactor outlet temperature of 500°C. Thirty to thirty-five percent net efficiency is expected. The reactor uses uranium nitride (UN) fuel with 19.8% enrichment and has a 10-year refueling cycle. The plant design life is 30 years. The design has one primary loop and one secondary loop and utilizes two independent shutdown systems. The design utilizes passive natural circulation for decay heat removal from the reactor vessel, with water as the ultimate heat sink. Specific design features include containing the reactor in a sealed cartridge to avoid onsite refueling, a primary shutdown system with inner and outer Boron Carbide (B_4C) control rods, and a secondary shutdown system having a central cavity into which a single B_4C control rod may be inserted. The plant is transported via truck, ship, or rail. Special benefits of the design include passive decay heat removal from the reactor vessel with a water jacket and the ability to operate in remote locations.

The basic layout of G4M is shown in Figure 3. There are two reactor containment vaults: one for the operating G4M and the other for a G4M that is cooling prior to shipment for disposition. The steam generator system is in a separate vault/containment. The reactor loop and steam generator system can be connected to either G4M. The reactor module has been sized to be transportable in a spent fuel transportation cask. The underground vaults provide containment and protection from external threats such as natural disasters and aircraft impacts.

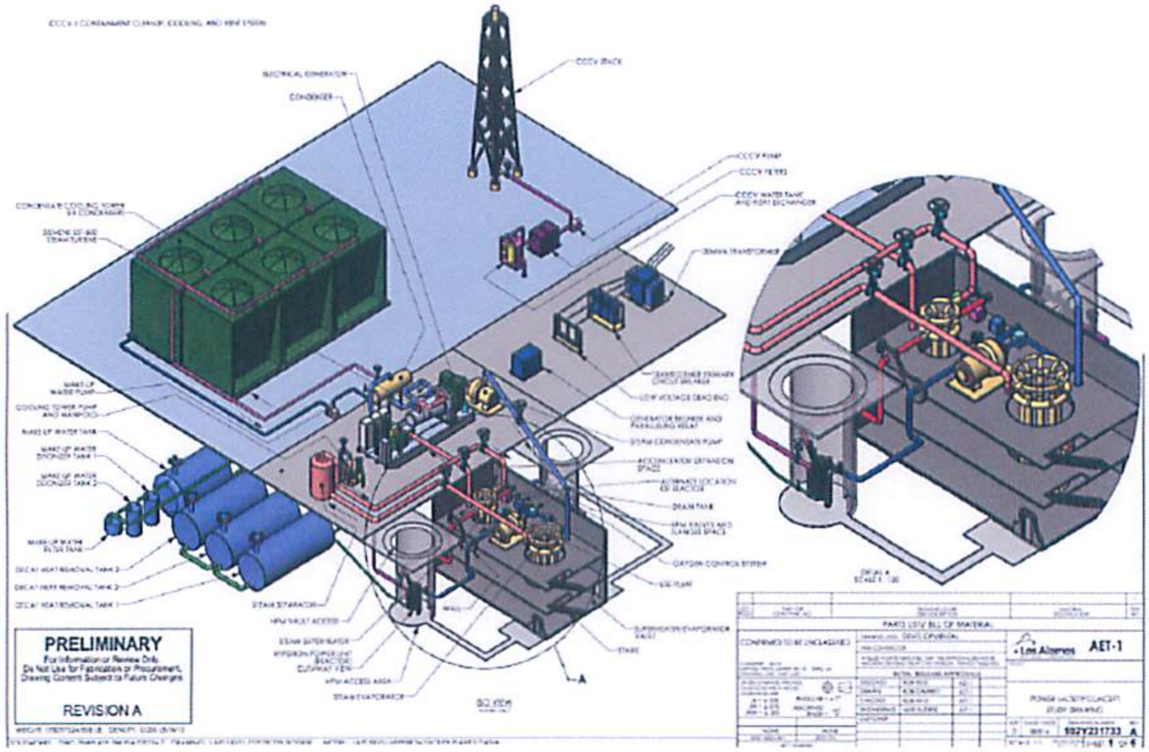


Figure 3. Gen4 plant layout.

3.4 LakeChime – University of Nevada Las Vegas-Argonne National Laboratory Small Secure Transportable Autonomous Reactor/Lead-Cooled Fast Reactor

The Small Secure Transportable Autonomous Reactor (SSTAR) is a small, 20-MWe (45-MWt), fast reactor and converter plant for international deployment (shown in Figure 4). SSTAR combines primary circuit natural circulation, lead (Pb) primary coolant, and transuranic nitride fuel in a pool vessel configuration inside of a small shippable reactor vessel. Energy conversion is accomplished with a supercritical carbon dioxide (CO_2) Brayton cycle power converter. The peak fuel cladding temperature is as high as 650°C for a core outlet temperature of 567°C and the net plant efficiency is 44%, taking advantage of the efficiency benefits of the supercritical CO_2 Brayton cycle.

One key achievement has been development of a control strategy for automatic control of the supercritical CO_2 Brayton cycle, in principle enabling autonomous load following over the full power range between nominal and essentially zero power. The SSTAR safety design approach is based on defense-in-depth providing multiple levels of protection against the release of radioactive materials and how the inherent safety features of the lead coolant, nitride fuel, fast neutron spectrum core, pool vessel configuration, natural circulation, and containment meet or exceed the requirements for each level of protection.

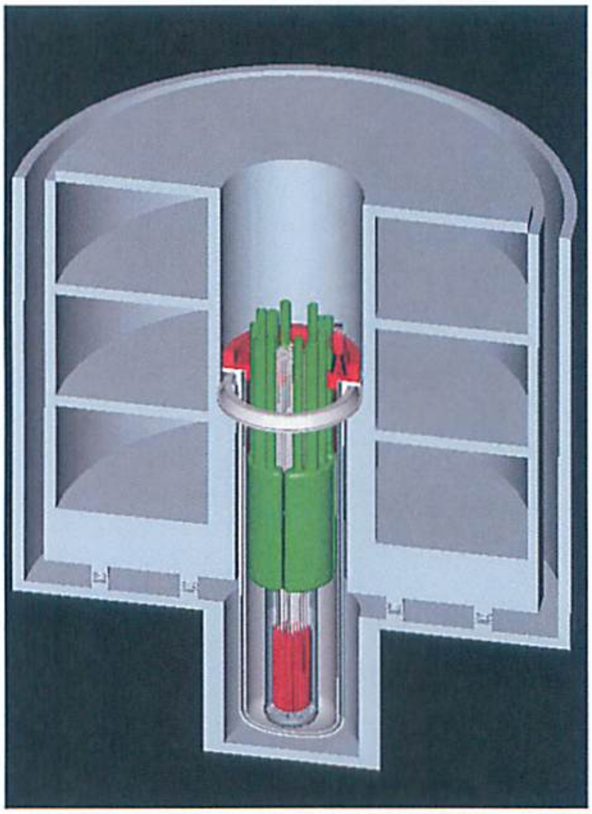


Figure 4. Partial power block conceptual design involving top support of SSTAR vessels from ledge inside seismically isolated reactor building.

3.5 General Atomics Energy Multiplier Module (EM^2)

The General Atomics EM^2 is a helium-cooled fast reactor with a core outlet temperature of 850°C. It is designed as a modular, grid-capable power source with a net unit output of 265 MWe. The baseline EM^2 plant consists of four modules. The reactor employs a "convert and burn" core design that converts fertile Uranium^{238} to fissile material and burns it in-situ over a 30-year core life without refueling or reshuffling. The core is divided into fissile and fertile sections. The fissile fuel can be low-enriched uranium with an average of 12% enrichment or mixed Plutonium (Pu) Uranium (U) with 9% fissile Pu. The fertile fuel can be natural or depleted uranium. The average burnup over the core life is 140 GWt/tonne. The reactor is sited in a below-grade sealed containment. The maintenance hall is at grade and covered by a protective shield against external impacts (such as a large aircraft). It uses passive safety methods for heat removal and reactivity control to protect the integrity of the fuel, reactor vessel, and containment. The plant also incorporates a below-grade, passively cooled spent fuel storage facility with capacity for 60 years of full-power operation. For electricity production, EM^2 employs a direct, closed-cycle gas turbine power conversion unit with a Rankine bottoming cycle for 53% net power conversion efficiency, assuming evaporative cooling. Figure 5 shows the plant process flow schematic with energy transfer and conversion. If abundant cooling water is not available, reject heat can be released directly to the atmosphere via dry towers with a 5-point reduction in net efficiency.

The baseline EM^2 plant is composed of four independent modules, each consisting of a complete powertrain from reactor to heat rejection; therefore, the modules can be built sequentially and operated independently. General Atomics, in cooperation with Chicago Bridge and Iron (CBI-Shaw), developed a modular construction approach that takes advantage of General Atomics' knowledge of serial production from its aircraft industry and CBI-Shaw's development of modular fabrication of AP1000 units in China, Georgia, and South Carolina. The estimated construction time for the four-unit plant is 42 months.

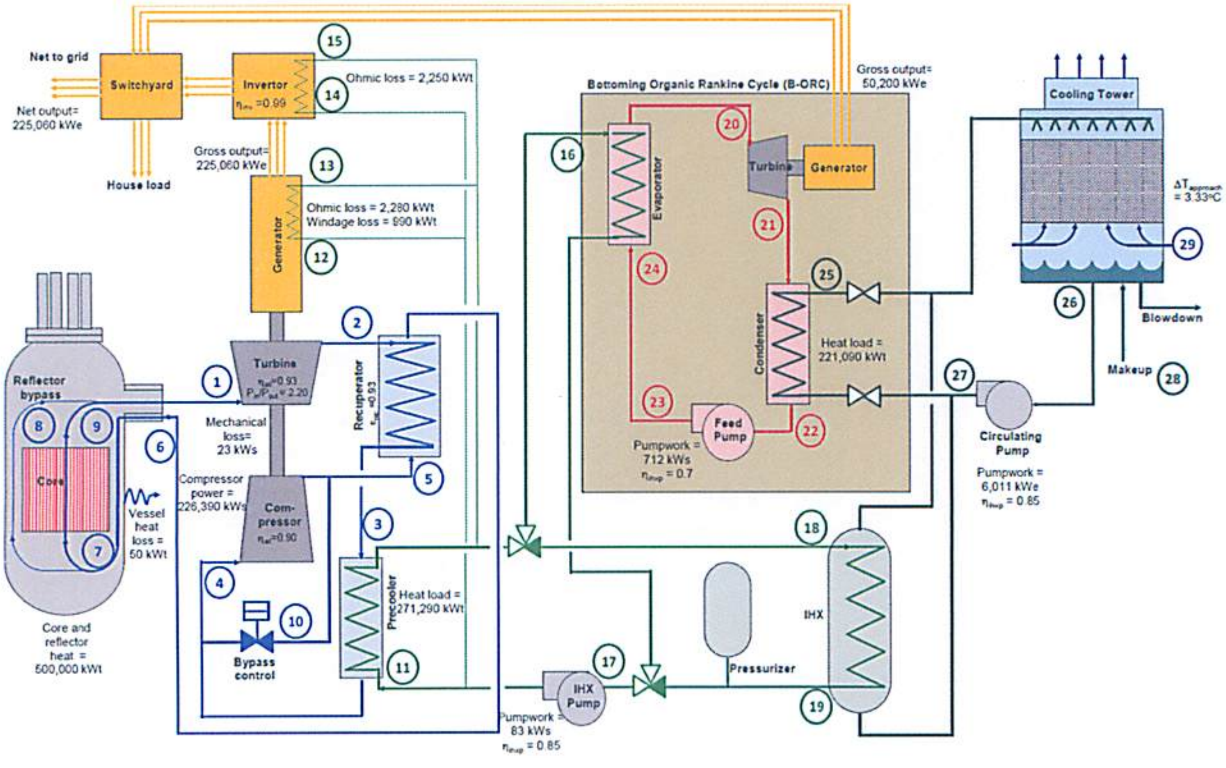


Figure 5. Process flow schematic for a single module.

3.6 X-Energy Xe-100™ Pebble Bed Temperature Gas Reactor (HTGR)

The Xe-100™ Nuclear Power Plant (NPP) is a modular, truck-transportable, pebble–bed, high-temperature, gas-cooled reactor that produces steam for either electricity generation or process heat. The thermal capacity of the plant is 100 MWt and when generating electricity, it can produce between 30 and 38 MWe, depending on the type of condensate cooling (i.e., evaporative wet cooling, sea water cooling, or dry cooling). When deployed for electricity generation, the Xe-100™ can be placed in close proximity to the power users due to its intrinsic safety that excludes the possibility of a core melt. Xe-100™ uses UCO fuel, is capable of reducing minor actinides in spent LWR fuel to less than 1%, and has the capability to reduce plutonium stockpiles.

Similar HTGRs have been safely operated for years in Germany (AVR and THTR) and have been, or are, pursued by South Africa (PBMR), China (HTR-10), and the Netherlands (Nereus). There are many industrial process heat applications of the Xe-100™.

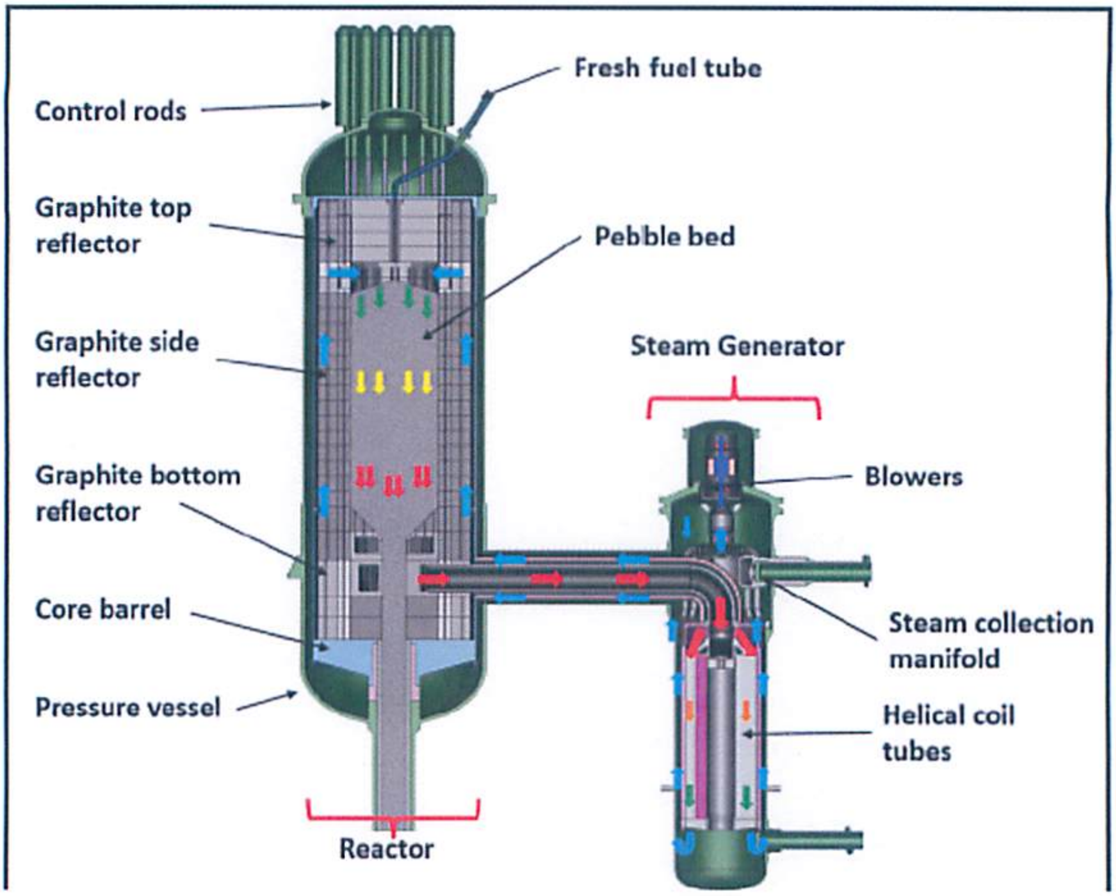


Figure 6. Xe-100 helium gas flow path in the primary coolant loop.

3.7 General Electric – Hitachi-PRISM

The General Electric PRISM reactor (Figure 7) is a 300-MWe, fast reactor that uses sodium as its coolant. The Sodium Fast Reactor (SFR) uses a supercritical Rankine conversion cycle with a reactor outlet temperature of 500°C. Thirty-nine percent net efficiency is expected. The reactor uses Uranium Transuranic (U-TRU) -10% (Zirconium) Zr metal alloy fuel with 10.68% Pu and 14.42% total fissile content and has a 1.33-year refueling cycle. The plant design life is 60 years. The design has two intermediate and two secondary loops and utilizes two independent, diverse design control rod groups of its shutdown systems. The design utilizes a reactor vessel auxiliary cooling system for passive decay heat removal from the reactor vessel, with air as the ultimate heat sink. Specific design features include a pool configuration for the primary sodium, use of electromagnetic pumps throughout, and two intermediate sodium loops. Transportability is enhanced by the modular construction sized for trucks and rail. Special benefits of the design are flexibility, allowing use for either waste management or resource utilization missions, and co-location of a small recycling center.

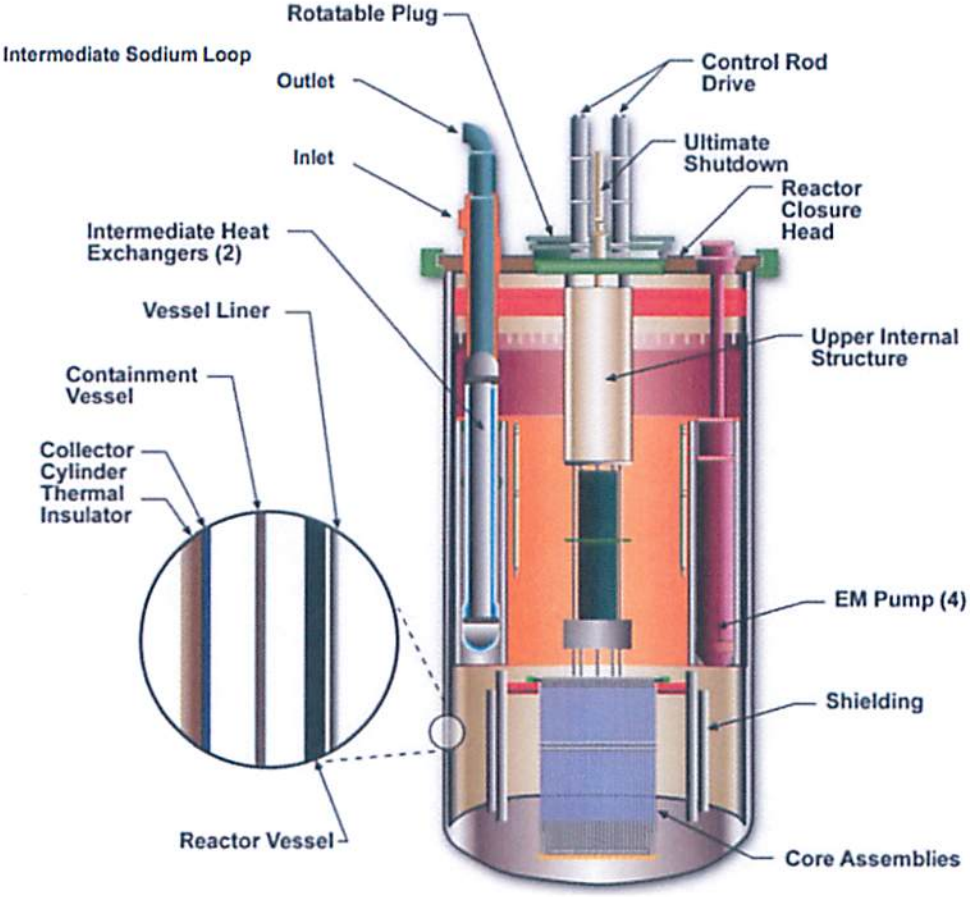


Figure 7. General Electric PRISM reactor module.

4. IDENTIFICATION OF RESEARCH AND DEVELOPMENT NEEDS BY CONCEPT

Technical Review Panel members were requested to review vendor inputs and provide R&D recommendations by concept. Each advanced reactor concept submittal was assigned to four members of the TRP for review. R&D needs were the key pieces of information requested of the vendors in the RFI. The reviewers completed an independent evaluation summary sheet for each concept they reviewed. In the process of conducting their independent reviews, the TRP members identified detailed R&D needs for each vendor concept they evaluated. A TRP member meeting was held where the evaluations were discussed and individual R&D needs identified by the vendors and TRP members were compiled.

The individual needs by concept are not identified in this public report. However R&D needs applicable to technologies associated with the concepts are identified in Section 5 and were included in the Funding Opportunity Announcement.

How well the eleven TRP categories were addressed was highly dependent on the level of maturity of the concepts. With respect to design maturity, the concepts were categorized along a spectrum from pre-conceptual, conceptual, moderately- mature, mature, to highly ready. Generally pre-conceptual designs were evaluated as needing significant R&D and highly ready designs were noted to need only limited R&D.

5. RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

This section provides the TRP recommendations concerning future R&D activities for technologies associated with the specific concepts that were submitted to the TRP. TRP members were knowledgeable of advanced reactor technologies and the work performed under the Generation IV International Forum over the last decade; therefore, their understanding was beneficial in their individual assessment of the proposed concepts. While the TRP members were focused on the specific concepts that were submitted to the TRP, they did identify R&D needs for the reactor technology areas that would be beneficial to the examined concepts and other related concepts.

The TRP did not attempt to reach a consensus. The opinions of the members diverged in some areas but not significantly. The recommendations presented here generally represent the views of the TRP, but necessarily are the result of discussions with the TRP by the TRP chair, the DOE TRP lead, and laboratory staff.

The RFI asked for information and research needs for the near term. Because fuel development and testing campaigns are lengthy, fuel R&D needs were not requested. For completeness, R&D needs related to fuel, as identified by either the vendors or members of the TRP were noted by DOE. However those fuel-related R&D areas are not included in the high priority recommendations for future research in Section 5.1.

It is recognized that not all R&D recommended by this process can be supported by current R&D funding. As a consequence, a short list of high-priority R&D items was prepared. This high priority R&D list is described in Section 5.1. Section 5.2 describes advanced reactor needs of multiple concepts as identified by the TRP review.

5.1 TRP Comments and High Priority Research and Development Needs

Technical Review Panel General Comments:

Members of the TRP identified two concerns associated with R&D on advanced reactor concepts that are not specific areas of research, but have impacts on the conduct of such R&D. The first concern is that in some cases there is limited access of concept providers/vendors to DOE national laboratories facilities. Many of the DOE facilities for irradiation, post-irradiation examination, thermal-hydraulic testing, and materials examination are unique in the world and are of a caliber that private industry has not been able to maintain in recent decades.

The second, somewhat-related concern is that there is limited funding for experimental work in facilities constructed by DOE, either at the national laboratories or at universities. Facilities, such as the High-Temperature Test Facility at Oregon State University, are important national capabilities, but they cannot be fully maintained and utilized without support from DOE. Many of these facilities are too small and/or specialized to survive as "User Facilities" in the conventional sense, but they could carry out industry identified DOE-funded R&D work done in collaboration with industry.

Both of these issues were taken into consideration in the determination of the high-priority R&D shown below.

(For the purpose of this set of recommendations, the term "TRP" refers to the collective view of the TRP, TRP Chair, DOE lead, and laboratory staff. The existence of these recommendations does not imply that a consensus view was obtained from TRP members.)

Technical Review Panel Concept Related Comments:

In examining the concepts identified in section 1.1, TRP members individually provided overall comments and scores. From these independent scores they indicated that SFR and HTGR R&D should be of a higher priority, and noted value in performing R&D for GFRs and LFRs.

TRP members also noted that the range of submitted concepts can provide for a number of future applications for advanced reactors, thus enabling the penetration of nuclear energy into a larger share of the market. This could include reactors with long life cores that can be deployed in remote locations; reactors that provide high temperature heat that could be used for non-electric applications; and reactors that significantly extend current resources and reactors that can be used to reduce high level radioactive waste production. This TRP evaluation process noted that there is a range in the technical maturity among the various concepts, with the HTGR and PRISM concepts being the most mature and the Gen4 Energy, SSTAR and EM^2 concepts needing more R&D on key technology issues.

The TRP also noted that higher expected performance is correlated with innovative approaches which tend to be less mature; the members view this as a very positive trend and are optimistic about the general trends in innovation. All the concepts were generally regarded as safer and more secure than current LWR designs; while various technical approaches were used to reach these higher levels of safety and security, the TRP did notice trends towards more passive safety, and deeper intrinsic features that increase security; the TRP also observed that certain of these features can also be used to bring incremental improvements to existing LWR designs.

Uranium utilization showed significant variation with fast reactors being better than other designs. This is strongly correlated to basic physics and will be a future differentiator between concepts if there is a need for resource extension (the same arguments would apply if waste transmutation became a mission). Operational capabilities also showed significant variation with the hybrid system showing a significant benefit in flexibility. The TRP noted that flexibility, including the ability to integrate renewable energy supplies or facilitate penetration of the non-electric market, is not yet a well-defined objective. The growing need for energy integration among clean energy baseload power sources and energy use and storage capabilities is the topic of a hybrid energy analysis currently underway. The results of this review, while not focused on flexibility, seem to indicate that opportunities for greater flexibility exist.

The concept fuel cycle evaluations were rated as similar to the current LWR reactors. Economics were typically less favorable than the current LWR fleet with the exception of the of the EM^2 reactor; nevertheless, the TRP also believes that economic evaluations are necessarily very uncertain for reactors that are in the conceptual stage, and also believes that pathways for improved economics will appear during the research, design, development and deployment phases. Regarding regulatory environment, the TRP noted that the X-Energy pebble-bed concept and the PRISM sodium-cooled fast reactor have greater readiness for licensing than the other concepts. The TRP also mentioned the current effort by DOE to obtain a regulatory process that is adapted to advanced concepts, and gave credit to concept features that provide increased safety and security performance.

In evaluating the market attractiveness of the concepts, the members rated all of the concepts similar to the current LWR technology, except for the X-Energy reactor which was somewhat more attractive; the TRP noted that the evaluation is relevant to the current market conditions, and to the fact that there is a significant short-term barrier to entry: future market conditions might modify the evaluation and support advanced concepts.

The evaluations gave all of the concepts overall ratings similar to that of current LWR technology.

Details on high priority advanced reactor R&D needs are as follows:
(These needs were used in a funding opportunity announcement for cost-shared R&D)

A. **Post-Accident Heat Removal System Testing.**

Importance: R&D is needed to substantiate the viability of passive decay heat removal safety systems, for various scenarios, for long-term decay heat removal for gas-cooled and liquid-metal reactors. Decay heat removal during station blackout depends on natural circulation for several advanced reactor concepts.

Examples: Conduct R&D to examine air-cooled or water-cooled reactor cavity cooling systems for decay heat removal at facilities such as the High-Temperature Test Facility at Oregon State University or the Natural Circulation Shutdown Test Facility at Argonne National Laboratory (ANL). Conduct R&D to explore system performance characteristics during passive cooling scenarios in addition to those with potential ingress of water or air into the reactor vessel. Data should be generated over a wide range of conditions in order to expand the validity of models and correlations used in decay heat simulations.

B. **Fluid Dynamics Modeling and Code Validation.**

Importance: R&D is needed to provide sufficient design information for operating conditions or shutdown and decay heat removal systems to allow an assessment of their effectiveness and reliability. A range of scaled fundamental, separate, and mixed effects experiments are needed to complement integral tests being performed at some universities and national laboratories. Experimental data should cover the range of parameters (e.g., pressure drops, flow rates, etc.) that will be seen in normal and off-normal operating situations, and the experimental data should provide a high quality reference that the regulator and designers can both use as a verification point for the system's performance. The experimental data should enable the validation of system and multidimensional Computational Fluid Dynamics (CFD) models and codes used for simulating natural circulation heat transfer in low (transition) flow regimes.

Examples: This work could include R&D to update thermal fluids and multi-physics methods to more modern tools and data; therefore, a validated computational suite is available for detailed design and licensing. Additionally, accident analysis codes could be updated to include the effects of radiative heat transfer, thermal fluids, and structural effects. Validated and verified computer models could be developed that describe the natural circulation flow and experimental data.

C. **Silicon Carbide (SiC) Reactor Internals Component Development and Testing.**

Importance: R&D is needed to optimize the processes for fabricating and joining SiC-SiC parts for use as reactor internals. In addition R&D is needed to develop the capabilities to produce affordable large and complex parts and to test SiC-SiC components.

Examples: Conduct R&D on fabricating high-purity SiC-SiC parts by various techniques and demonstrate techniques for making SiC joints that will be suitable for use in very high-temperature and high-neutron environments expected in high-temperature thermal and fast reactor cores. Conduct appropriate testing to demonstrate viability of economical manufacturing and joining methods for use in these environments.

D. **Corrosion Control with LBE Coolant.**

Importance: R&D is needed to develop an improved understanding of the mechanisms of corrosion and for corrosion control in LBE. This additional insight into LBE corrosion is needed to establish a viable operating scheme for corrosion control on a reactor-system scale, including margins and operating constraints for structural components in this coolant. Oxygen has been found to be a potentially effective non-metallic corrosion-inhibitor in liquid lead and LBE systems. By controlling the oxygen concentration in LBE, it may be possible to maintain a protective iron and chromium based oxide film on some structural material surfaces, while keeping lead and bismuth from excessive oxidization that can lead to precipitate contamination.

Examples: Testing to determine corrosion rates and mechanisms for materials as a function of the oxygen content of the LBE and its velocity could provide data needed for oxygen-level corrosion control approaches and seek to gain an understanding of the optimum coolant corrosion control for LBE reactor components. If a viable scheme for reactor-scale corrosion control is established, a roadmap to establish the pathway for any selected alloy that is not yet American Society of Mechanical Engineers (ASME) codified for high-temperature construction should be developed.

E. Helical Coil Steam Generator Development.

Importance: R&D is needed to improve the designs of helical coil steam generators in order to improve safety of plant designs and to improve economics of the concepts. Primary to secondary boundary integrity can present challenges for plant operation and reliability. Steam generator leak uncertainty could be reduced by development of welded steam generator connections and research on thermal steam generator stresses.

Examples: This R&D may include analysis of existing procedures for dissimilar metal weld joint fabrication or improvement of those procedures. Improve methods for steam generator leak recovery to mitigate the consequences if a primary to secondary boundary leak occurs.

F. Development/Qualification of High-Temperature Instrumentation and Control Systems.

Importance: R&D is needed for the development and qualification of high-temperature instrumentation. Advanced reactor control systems will utilize state-of-the-art architecture, hardware, and software technology. It is anticipated that some advanced reactor concepts will require specialized instrumentation to operate in a high-temperature environment.

Examples: Conduct R&D in support of development and qualification of high-temperature instrumentation for advanced nuclear reactor applications. Conduct R&D in support of reactor control systems and advanced technology.

G. Development/Modernization of Probabilistic Risk Assessment (PR).

Importance: R&D is needed to bring any of the safety-related technologies used in the design of advanced nuclear reactor concepts to a sufficient level of maturity to allow for industrial use.

Examples: Develop PRA methodologies and tools to modernize existing analysis and to incorporate risk-informed design methods. Modernizing PRA would include internal, external, and reactor-specific hazards. Models could be built in a modern PRA code (i.e., a computer-aided fault tree analysis system) that would use the non-LWR PRA standard as a guide.

H. Advanced Reactor Component Development and Testing.

Importance: R&D is needed for development and testing of components for use in an advanced reactor. Development of components such as heat exchangers may have significant benefit to advanced reactor designs (such as potential use in advanced energy conversion applications).

Examples: Development or activation of a test advanced reactor loop and conduct of component testing would provide data needed to examine possible pump, heat exchanger, and steam generator performance capabilities. Development of heat exchangers for advanced reactor designs to allow utilization of advanced energy conversion systems.

Conduct power conversion unit development and testing. Conduct R&D for in-vessel components. This component development R&D effort is intended to provide an opportunity that may not be captured in the other R&D topics, but it is for application in advanced reactor designs.

I. Development of Electromagnetic Pumps.

Importance: R&D is needed for development of electromagnetic pumps for various advanced reactor applications. Nuclear qualification of reliable, long-life pumps is needed in order to provide technical assurance for long-term, safe operations.

Examples: Testing of electromagnetic pump concepts under various thermal transient conditions is required to confirm predicted reliability. This may include pump performance, longevity, and cavitation (and associated erosion) issues.

J. Development of Multi-Physics Tools/Modeling and Simulation Upgrades.

Importance: R&D is needed to provide updated modeling tools for advanced liquid metal reactor technologies.

Examples: Development of multi-physics tools that could be used to optimize overall system performance, including core physics, safety, operability, material performance, and economics. Upgrade/update the plant models such as the ARIES, neutronic, and thermo hydraulic methodologies to more modern tools and data; therefore, a validated computational suite is available for detailed design and licensing.

5.2 Advanced Reactor Research and Development Needs in Support of Multiple Concepts

5.2.1 Development of Licensing Approaches for Advanced Reactor Concepts

5.2.1.1 Development and Implementation of Advanced Reactor Licensing Framework.

One key need identified by the TRP for all advanced reactor concepts was to develop a licensing framework. Advanced reactor technologies need regulatory guidance in support of commercial licensing applications to clarify regulatory requirements including those that could impact performance and/or cost.

Advanced reactors use different coolants, different structural materials, and different fuels in different configurations and under different service conditions than conventional LWRs. Therefore, the safety characteristics and off-normal behavior of these systems are different than LWRs. Establishing a licensing framework for advanced reactors that allows credit for the unique characteristics of the advanced reactor yet provides NRC a sound technical framework within which to issue a license is needed. The framework could include both technology-neutral and concept-specific sections. However, only when a license application is actually pursued will the details and technical issues that require resolution to support this framework be worked out.

The TRP reaffirmed the need for the Advanced Reactor Licensing Initiative that is currently being pursued as a joint project with the NRC to develop General Design Criteria for Advanced Reactors. The TRP noted the positive progress being made on the Joint effort which has developed draft design criteria, held public workshops and solicited industry inputs.

5.2.1.2 Development of Advanced Reactor Analysis Methods

The development of modeling and simulation tools was noted as another need applicable to multiple advanced reactor concepts. This activity could involve development of advanced neutronics, thermal hydraulic and mechanical analysis tools and their validation to modern standards. These tools will provide credible capabilities to design advanced concepts and understand the design margins. This development could be included in the advanced reactor plans for the Nuclear Energy Advanced Modeling and Simulation Program. The advanced methods developed should be capable of being qualified for licensing applications.

5.2.2 Development and Testing of Advanced Materials

Development and testing of advanced materials was an R&D need identified by several of the concept providers. Advanced materials are a key element for the success of advanced reactors. Either in collaboration with the Nuclear Energy Enabling Technologies Program or as add-ons to existing materials testing programs, a roadmap for incorporation of selected materials needs should be initiated.

Individual members of the TRP identified two areas of reactor materials R&D where increased funding might be applied in the future. First, advanced reactor materials R&D is needed to develop the basis for ASME Code qualification of additional commercial materials not currently included within the ASME Code for construction of high-temperature reactor components. These additional high-temperature construction materials could include either advanced commercial materials, such as newer generation ferritic-martensitic or austenitic steels with enhanced elevated temperature strength (e.g., optimized Grade 92 or Alloy 709), or mature commercial alloys with special qualifications for specific high-temperature reactor systems (e.g., Hastelloy N for corrosion resistance in salt-cooled systems or HT-9, which has a very extensive irradiation-effects database for fast reactor applications).

The second area in which advanced materials R&D is needed concerns SiC reactor internal components. Development and testing are needed to optimize the processes for fabricating and joining SiC-SiC parts for use as reactor internals. In addition, R&D is needed to develop the capabilities to produce affordable large and complex parts and to test SiC-SiC components.

Specifically, R&D is needed for fabricating high-purity SiC-SiC parts by various techniques and for demonstrating techniques for making SiC joints that will be suitable for use in the very high-temperature and high-neutron environments expected in high-temperature thermal and fast reactor cores.

5.2.3 Recommendations Concerning Supercritical Carbon Dioxide (sCO_2) Energy Conversion

The TRP noted interest by multiple concepts in advanced energy concepts such as the (sCO_2) Brayton Cycle. The TRP and DOE stated that other reactor concepts not represented in this TRP review also were looking carefully at sCO_2 energy conversion. DOE is exploring sCO_2 energy conversion through an initiative coordinated among the Offices of Nuclear Energy, Fossil Energy, and Energy Efficiency and Renewable Energy. DOE has requested funding for the Supercritical Transformational Electric Power Generation Project which envisions a pilot-scale, cost-shared demonstration project to accelerate pre-commercial development and validation of the (sCO_2) Brayton cycle energy conversion technology.

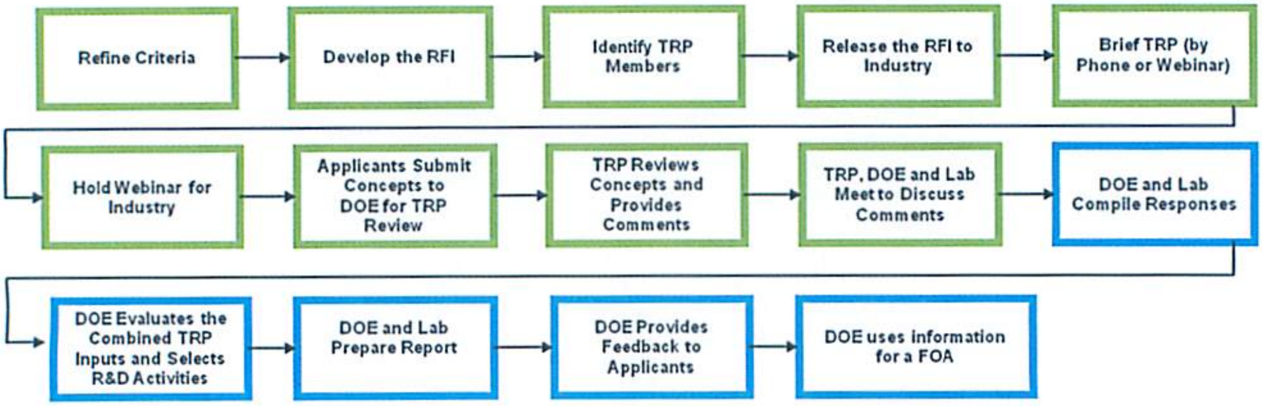
ACKNOWLEDGEMENT AND DISCLAIMER

This report was compiled by Dr. Phillip Finck-TRP Chair, Mr. Martin Sattison, Dr. George Griffith and Dr. Steve Herring of Idaho National Laboratory and by Mr. Craig Welling-TRP Federal Lead and Mr. Steven Reeves of U.S. Department of Energy and based on the comments provided by the Technical Review Panel (TRP) members. This document also includes comments and recommendations from Dr. Robert Hill of Argonne National Laboratory and Dr. Dave Petti of Idaho National Laboratory. This report is a compilation of opinions and recommendations reflecting the individual views of the TRP members. The TRP process purposely did not seek to obtain a consensus view from TRP members.

ACRONYMS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
DOE	U.S. Department of Energy
EM^2	Energy Multiplier Module
G4M	Gen4 Energy Gen4 Module
HTGR	high temperature gas reactor
LBE	lead-bismuth eutectic
LWR	light water reactor
MWe	megawatt electric
MWt	megawatt thermal
NRC	U.S. Nuclear Regulatory Commission
PRA	probabilistic risk assessment
R&D	research and development
RFI	request for information
SiC	silicon carbide
SFR	sodium fast reactor
SSTAR	small secure transportable autonomous reactor
TRISO	tristructural isotropic
TRL	technology readiness level
TRP	technical review panel

Appendix A Technical Review Panel (TRP) Process



A-1. ASSESSMENT PROCESS

A-1.1 Advanced Reactor Concept Applicant

For a design to be considered by DOE, the advanced reactor concept applicant submitted a concept input that provided DOE with relevant design information. The concept inputs submitted to DOE included a concise description of the concept and responses to each of the request for information items in the Request for Information (RFI) document.

A-1.2 Advanced Reactor Concept Technical Review Panel

The advanced reactor concept TRP is made up of experts in nuclear reactor technologies and regulation from national laboratories, universities, the industry, and consulting firms. The individual TRP members reviewed the information submitted to DOE and provide their individual views on R&D needs.

The objective of the review of the individual members of the TRP was to identify viable advanced reactor technologies for the future and to identify key R&D activities for developing these technologies. In carrying out this objective, TRP members used their expert judgment to apply the evaluation criteria to each advanced reactor concept. The TRP members made their judgment on the technology gaps and uncertainties and the R&D activities needed to address them.

In summary, each individual TRP member reported to the DOE Office of Nuclear Energy his/her findings and recommendations concerning the concepts and their R&D needs. The TRP did not provide the Office of Nuclear Energy with a consensus view of any advanced reactor concept.

A-1.3 Advanced Reactor Concept Laboratory Support Panel

Upon completion of reviews by TRP members, a separate, small panel of national laboratory experts and DOE personnel compiled TRP responses and prepared this report for DOE. That panel reviewed submittals from the TRP and was responsible for consolidating them into a unified set of comments with respect to the evaluation criteria. The report reflects TRP member comments, identifies R&D needs, and offers recommendations on future R&D activities

Appendix B Summary of the 2012 Technical Review Panel Process

In February 2012, the DOE Office of Nuclear Energy issued an RFI to help inform development of the DOE reactor technology research portfolio. The RFI identified eleven criteria against which the concepts would be evaluated. Reactor vendors submitted eight concept proposals in response to the RFI, and the DOE Office of Nuclear Energy formed a TRP to evaluate the attributes, advantages, disadvantages, and relative benefits of the concepts and to identify R&D needs based on the concept submittals.

Three general areas were identified by the 2012 TRP where R&D activities could support multiple concepts. The most crucial need for multiple concepts was development, with NRC, of a regulatory framework for advanced reactors. Other areas of R&D needs were in accelerated development of Brayton cycle technology and development of advanced reactor analysis methods.

As a result of the 2012 TRP process and the 2013 Funding Opportunity Announcement, the Department of Energy provided awards totaling $3.5 million (DOE amount of the cost-share) for four advanced nuclear reactor projects. These projects, led by General Atomics (Silicon carbide testing R&D), General Electric-Hitachi (Electromagnetic pump R&D), Gen4 Energy (Lead bismuth natural circulation R&D), and Westinghouse (Modeling and validation of sodium plugging in heat exchangers) address key technical challenges to designing, building, and operating the next generation of nuclear reactors.