Advanced Reactor Concepts

Technical Review Panel Report

Evaluation and Identification of future R&D on eight Advanced Reactor Concepts, conducted April – September 2012

December 2012

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SUMMARY

This report documents the establishment of a technical review process and the findings of the Advanced Reactor Concepts (ARC) Technical Review Panel (TRP).[1] The intent of the process is to identify R&D needs for viable advanced reactor concepts in order to inform DOE-NE R&D investment decisions. A goal of the process is to facilitate greater engagement between DOE and industry. The process involved establishing evaluation criteria, conducting a pilot review, soliciting concept inputs from industry entities, reviewing the concepts by TRP members and compiling the results.

The eight concepts received from industry spanned a range of reactor types and coolant selections. The concepts included five fast reactors and three thermal reactors. As to reactor coolants, there were three sodium-cooled reactors, two gas-cooled reactors, one light water-cooled reactor, one lead-bismuth-cooled reactor and one salt-cooled reactor. Four reactors use uranium oxide or uranium metal fuel, one proposes use of uranium nitride fuel and three would use thorium fuel. The concepts also varied considerably in level of design maturity. Five 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 identifies priorities for advanced reactor R&D activities.

The overall outcome of the TRP process is a listing of R&D needs and priorities that would be beneficial to industry and DOE. This information will be used to inform 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.

[1] The TRP process generated three versions of reports. This report is the short public version. A longer detailed version for DOE and concept specific versions for concept providers were also prepared.

1. OVERVIEW OF THE TECHNICAL REVIEW PANEL PROCESS

The U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) 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.

In February 2012 DOE-NE 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 eight concept proposals in response to the RFI, and DOE-NE formed a Technical Review Panel (TRP) to evaluate the concepts, and to identify research and development (R&D) needs based on the concept submittals. The Appendix 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.

The TRP was made up of nuclear reactor technology and regulation experts from national laboratories, universities, industry, and consulting firms. The individual panel members reviewed the submitted information and conducted independent checks of the applicant's 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.

Following are the reactor concept titles that were submitted in response to the RFI:

- General Atomics – Energy Multiplier Module, (EM^2) [high temperature, gas-cooled fast reactor]
- Gen4 Energy Reactor Concept [lead-bismuth fast reactor]
- Westinghouse Electric Company - Thorium-fueled Advanced Recycling Fast Reactor for Transuranics Minimization [thorium-fueled sodium-cooled fast reactor]
- Westinghouse Electric Company Thorium-fueled Reduced Moderation Boiling Water Reactor for Transuranics Minimization [thorium fueled BWR]
- Flibe Energy- Liquid Fluoride Thorium Reactor (LFTR) [thorium-fueled liquid salt reactor]
- Hybrid Power Technologies, LLC – Hybrid Nuclear Advanced Reactor Concept [gas-cooled reactor / natural gas turbine combination]
- GE-Hitachi Nuclear Energy PRISM and Advanced Recycling Center [sodium fast reactor]
- Toshiba 4S Reactor [sodium fast reactor]

2. TECHNICAL REVIEW PANEL CRITERIA

The RFI requested that the concept applicants submit information for their concepts in the following eleven categories. The TRP then used this information to evaluate the concepts and to identify R&D needs.

1. **Safety:** Information in this category describes the safety aspects of the plant systems, defense-in-depth characteristics, and safety margins of the components and structures of the ARC submitted. The description of plant systems should include the safety features of the system designs and plant layout. The description of the defense-in-depth characteristics should address the main barriers to release of radioactive materials (e.g., fuel cladding, reactor coolant-system boundary, and containment structure). The discussion of safety margins should address the ability and means by which components and structures can withstand normal, transient, and postulated abnormal loads without exceeding design margins. The safety information should also include a discussion of the potential for adverse chemical interactions (e.g., sodium or alkali metal combinations with air or water).

2. **Security:** Information in this category describes the security capabilities of the ARC design and the inherent security features of the reactor technology employed, which may include features of the plant that reduce the likelihood or consequence of terrorist attack or deter the theft of nuclear materials.

3. **Uranium resource utilization and waste generation minimization:** The purpose of this category is to provide a basic understanding of performance features that can utilize uranium resources more efficiently to ensure long-term nuclear energy sustainability, and to provide a basic understanding of the performance features that can achieve overall reduction or minimization of waste requiring geologic disposition.

4. **Operational capabilities:** Information in this category describes the operational aspects of the ARC design such as control strategies, operating modes (e.g., base load versus load following capability), maintenance and inspection requirements, and refueling intervals.

5. **Concept maturity, operating experience, unknowns and assumptions**: The information provided in this category qualitatively describes the maturity of the proposed ARC design, associated technology readiness levels, and relevant operational experience (including demonstration and/or test facilities). The discussion should address the availability of advanced materials, fuels, and technologies currently under development.

6. **Fuel and infrastructure considerations**: The information provided in this category describes the reactor concept's compatibility with existing domestic and global nuclear infrastructures. Having high levels of current infrastructure compatibility could mean that a concept could be implemented in less time and with potentially lower costs than concepts requiring major infrastructure change and development.

7. **Assessment of market attractiveness**: The discussion in this category addresses the features that make the proposed concept attractive and competitive in the marketplace. This includes evaluating variables like efficiency, initial capital costs, application beyond electricity generation, and others. The market attractiveness of a reactor concept is determined by a wide range of factors, including economic factors (total costs of construction and operations, low capital costs, financing); nuclear safety considerations; commercial warranties; environmental factors; siting

requirements; and others. The timing of introducing the reactor concept into the market is an important factor, since it encompasses the prospects for public support and acceptance, political support, and favorable financing.

8. **Economics**: Information in this category addresses the reactor concept's economic factors such as construction, manufacturing, and operating costs and uncertainties; the resulting cost of electricity; and the value, if any, of other products that may be produced (such as hydrogen).

9. **Potential regulatory licensing environment**: Information provided in this category provides an indication of any potential challenges facing licensing the ARC by the Nuclear Regulatory Commission (NRC). The focus of this category would be on any unique design features that have not been subject to the licensing process for the current fleet of light water reactors (LWRs), or if the proposed design does not include features typically found in LWRs (e.g., lack of a primary containment structure).

10. **Nonproliferation**: Information in this category provides a basic understanding of some of the features and characteristics of the ARC design that minimize proliferation risks. It should be noted that technical measures alone will not be sufficient to address proliferation fully. So-called "extrinsic" measures are also vitally important. Extrinsic measures include international safeguards, treaties, organizations, trade practices, regional and multilateral security agreements, and institutional arrangements such as comprehensive international fuel services. This includes consideration of U.S. nonproliferation and policy objectives and the initiatives being undertaken by the National Nuclear Security Administration, U.S. Department of State, and the NRC. If possible, the concept or design being reviewed should be considered in this broader context. In many cases, the same extrinsic measures will apply across the board, but in other cases such as international safeguards there may be design-specific or facility-specific aspects that require attention.

11. **Research and Development Needs**: With the goal of supporting the commercialization of advanced reactor concepts, the focus of this category is to specifically solicit information on R&D needs from concept applicants, gain an understanding of the timeframe in which R&D is needed, and gain a perspective of the dollar amount of R&D needed. This includes 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

The submittals provided descriptions of the advanced reactor concepts. Following are summaries of the eight concepts submitted:

The ***Energy Multiplier Module*** (EM^2) is a 245 MWe, fast reactor that uses helium as its coolant. It uses a Brayton conversion cycle with a reactor outlet temperature of 850°C. 49% net efficiency is expected. The reactor uses uranium carbide (UC) fuel with 6.5% average enrichment and has a 30 year refueling cycle. The plant design life is 60 years. The design has one loop and utilizes two shutdown systems, control drums and separate shutdown rods. The design utilizes the power conversion system for normal decay heat removal from the reactor vessel with the passive direct auxiliary cooling system (DRACS). Specific design features include vented porous uranium carbide fuel, silicon carbide clad and a variable high speed turbine-generator set. The generator output would be rectified and then inverted to the grid frequency. Transportability is via truck. Special benefits of the design are process heat capability, the use of traditional LWR pressure vessel steel for the EM^2 reactor vessel and the modular construction below grade.

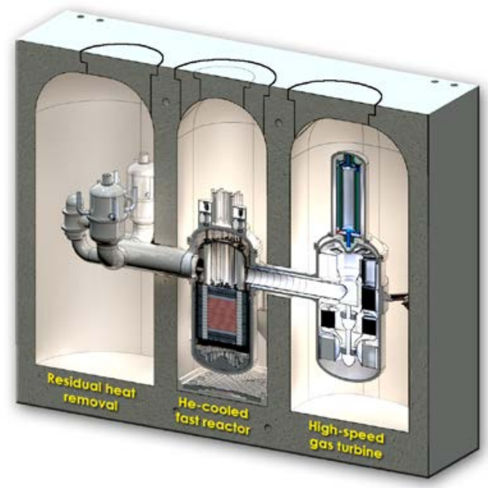


Figure 1. EM2 Advanced Reactor Design

The ***Gen4 Energy Reactor*** is a 25-MWe, fast reactor that uses lead-bismuth eutectic (LBE) as its coolant. It uses a Rankine conversion cycle with a reactor outlet temperature of 500°C. 30-35% 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 B_4C control rods and a secondary shutdown system having a central cavity into which a single B_4C control 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.

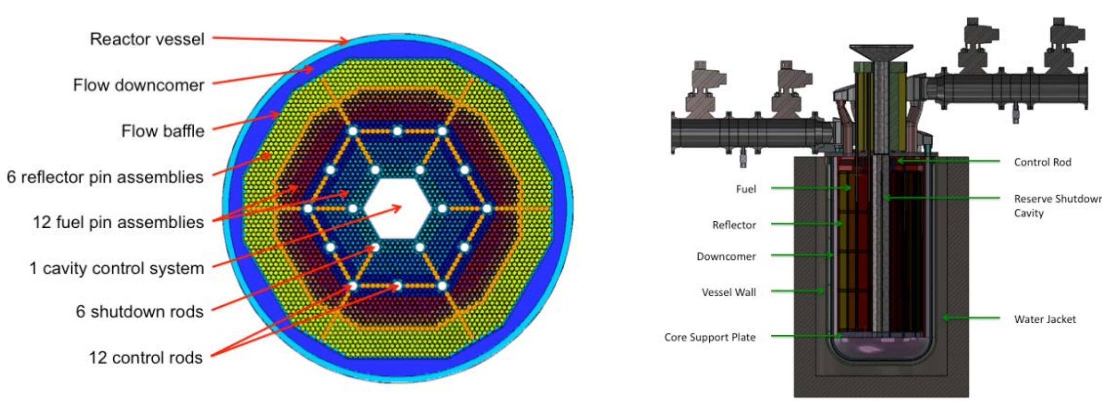


Figure 2. The plan view of the Gen4 Energy reactor core and the elevation view of the core and vessel.

The ***Westinghouse Thorium-Fueled Fast Reactor*** is a 410-MWe fast reactor that uses sodium as its coolant. It uses a Rankine conversion cycle with a reactor outlet temperature of 497°C. 41 % net efficiency is expected. The reactor uses (Th,TRU)-oxide, -nitride or -carbide fuel with the TRU coming from used LWR fuel. No additional enrichment is required. The reactor has a one-year refueling cycle and a plant design life of 60 years. The design has four water/steam secondary loops and utilizes three independent shutdown systems: primary using 24 control assemblies, secondary using six assemblies and the tertiary using B_4C or Hf balls in central locations (see Figure 4). The design utilizes passive decay heat removal from the reactor vessel with enhanced Reactor Vessel Auxiliary Cooling System (RVACS) and eventually supported by the Passive Reactor Auxiliary Cooling System (PRACS). Specific design features include the use of inner and outer fuel regions to flatten the radial power distribution and the use of three independent shutdown systems in an effort to design out the possibility of an anticipated transient without scram. Transportability is not discussed. Special benefits of the design are the use of electromagnetic sodium pumps, internal double-walled steam generators and a thorium-based fuel cycle with transuranic transmutation.

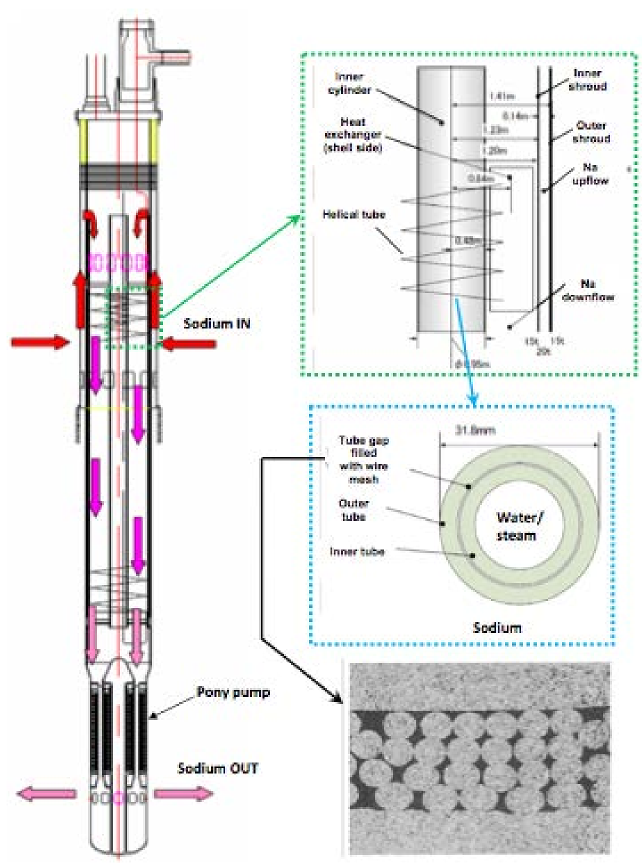


Figure 3. Westinghouse Thorium-Fueled Fast Reactor Double Wall Tube Steam Generator.

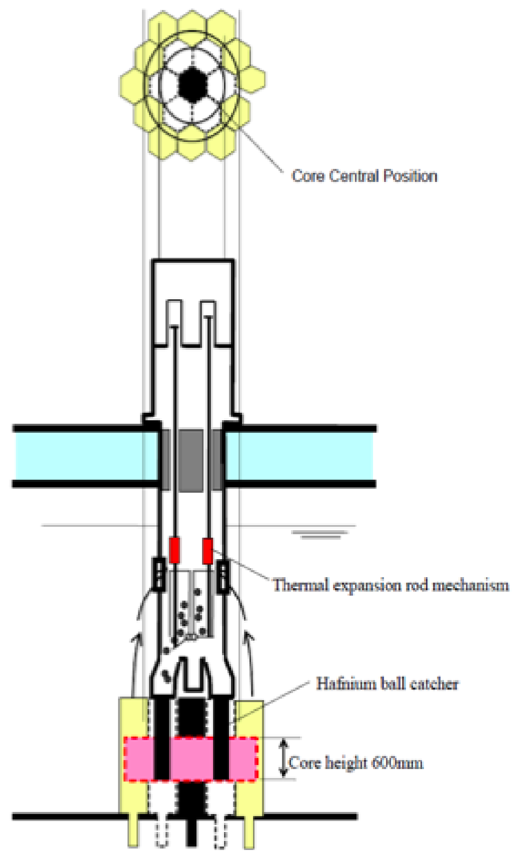


Figure 4. Tertiary Shutdown Concept

The ***Westinghouse Thorium-Fueled Reduced Moderated Boiling Water Reactor (Th-RMBWR)*** is a 1,356-MWe, epithermal advanced boiling water reactor. It uses a Rankine conversion cycle with a reactor outlet temperature of 288°C. 34 % net efficiency is expected. The reactor uses thorium –based transuranic fuel and has a one-year refueling cycle. The plant design life is 60 years. The majority of the ex-vessel design features are identical to the reference advanced boiling water reactor (ABWR) design. Safety characteristics of the Th-RMBWR should be comparable to, or better than, the uranium-fueled ABWR.

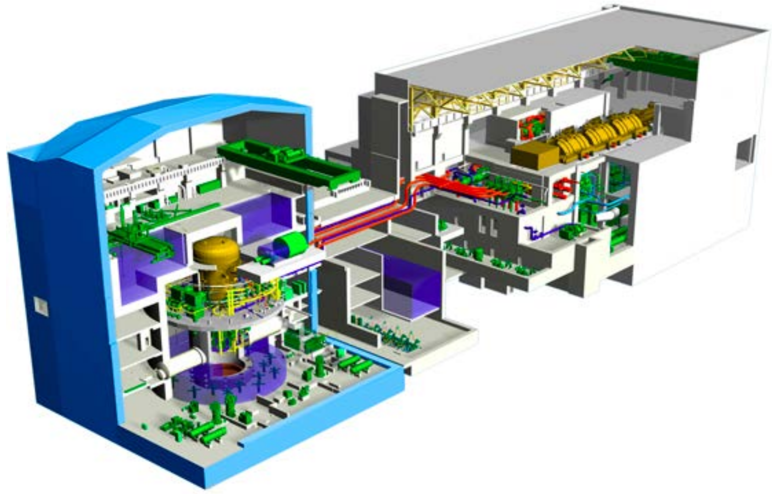


Figure 5. Plant Layout for the Th-RMBWR.

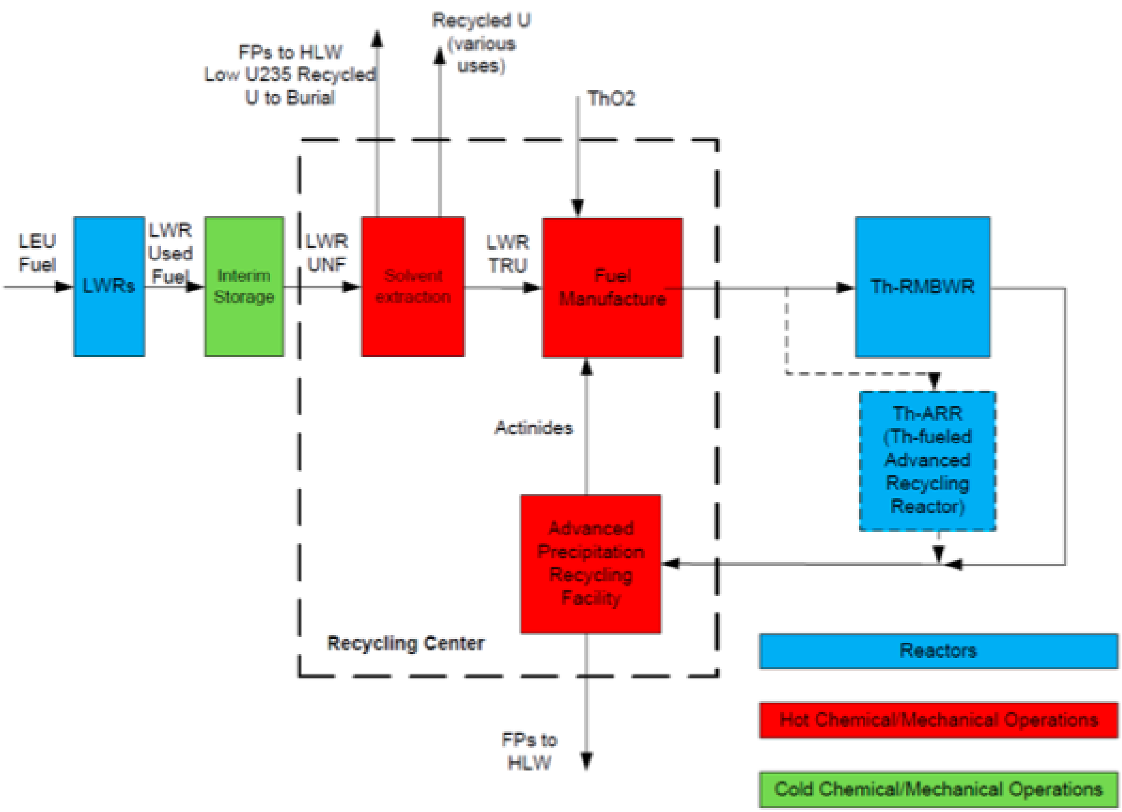


Figure 6. Back-end vision using thorium fuel.

The ***Flibe-Thorium Reactor Concept*** is a 40-MWe, thermal reactor that uses lithium fluoride/beryllium fluoride salt (FLIBE) as its coolant and graphite as its moderator. It uses a nitrogen Brayton conversion cycle with a reactor outlet temperature of >450°C. 40 % net efficiency is expected. The reactor uses UF_4 as the fuel, initially U-235 and later U-233. Thorium is continually added to the reactor and fission products are extracted. The plant design life is five to ten years. The design has one intermediate and one secondary loop and utilizes passively-cooled sub-critical fuel salt drain tanks as the shutdown system. The design utilizes passive decay heat removal from the reactor vessel with water in the underground silo as the ultimate heat sink. Specific design features include underground location of the reactor and primary heat exchanger is made of liquid-silicon-impregnated carbon-carbon composites. Transportability is via barge or truck. Many quantitative aspects of the design have not yet been determined.

The ***Hybrid Power Technologies' Nuclear Advanced Reactor Concept*** has an 850 MWe output, using 600 MWt from a helium-cooled thermal reactor and 1,000 MWt of natural gas. It 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. The reactor outlet temperature is 838°C. 52% net efficiency is expected. The reactor uses UO_2 in TRISO particles as fuel with <19 % enrichment and has a two-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, since the unit uses standard power plant and shipyard construction.

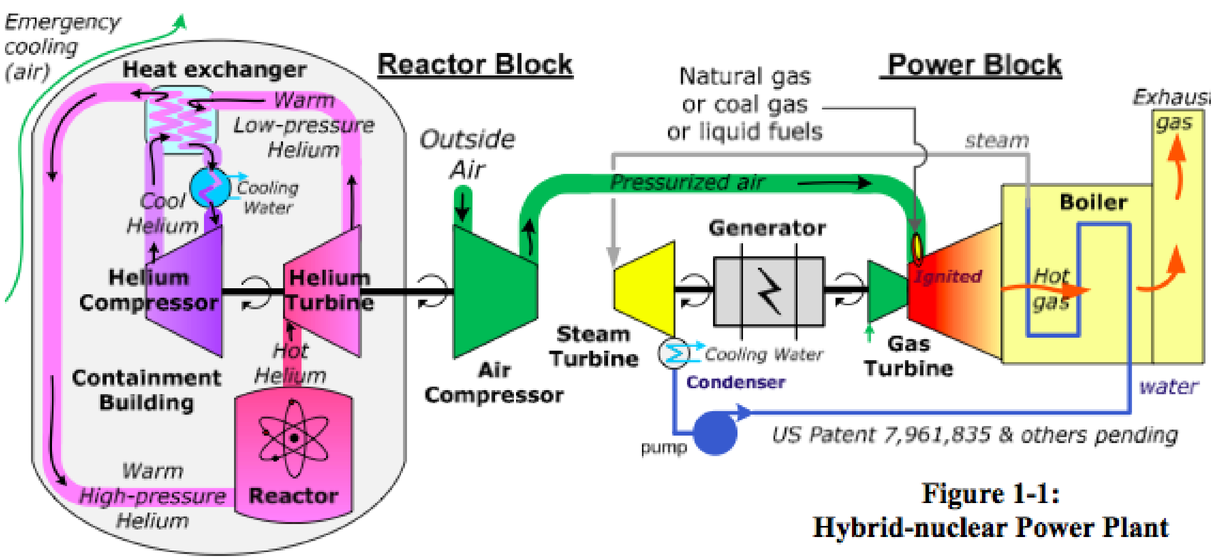


Figure 7. Hybrid Nuclear Advanced Reactor Overview.

The ***GE PRISM and Advanced Recycling Center.*** The PRISM reactor (Figure 8) is a 300 MWe, fast reactor that uses sodium as its coolant. It uses a supercritical Rankine conversion cycle with a reactor outlet temperature of 500°C. 39 % net efficiency is expected. The reactor uses U-TRU-10% Zr metal alloy fuel with 10.68 % Pu, 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 (RVACS) 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, the 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 the co-location of a small recycling center.

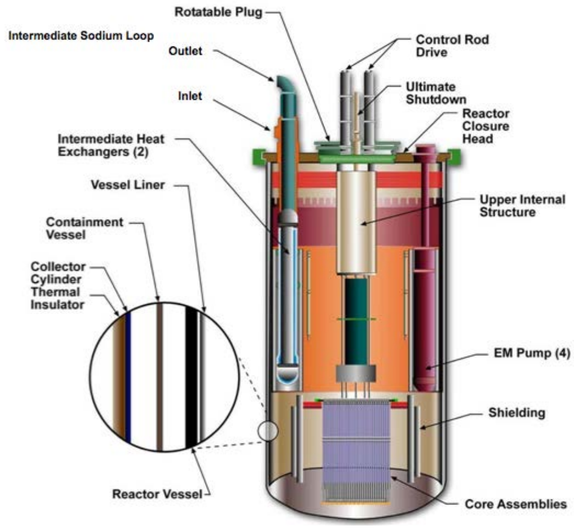


Figure 8. GE PRISM Reactor Module.

The *Toshiba 4S Reactor* is a 50-MWe, fast reactor that uses sodium as its coolant. It uses a Rankine conversion cycle with a reactor outlet temperature of 510°C. 37% net efficiency is expected. The reactor uses U-10% Zr metal alloy fuel with < 20 % enrichment and has a 10 year refueling cycle. The plant design life is 60 years. The design has one intermediate loop and one secondary loop and utilizes two independent diverse shutdown systems: the drop of the annular reflector, and the insertion of a central shut-down rod. The design utilizes passive decay heat removal from the reactor vessel with its Reactor Vessel Auxiliary Cooling System. Specific design features include operation underground in a sealed vault, negative reactivity feedback temperature coefficients and the high thermal conductivity of metallic fuel. Transportability is via truck or rail. Special benefits of the design are its focus on serving remote, distributed electricity customers where frequent fossil fuel deliveries are often impossible.

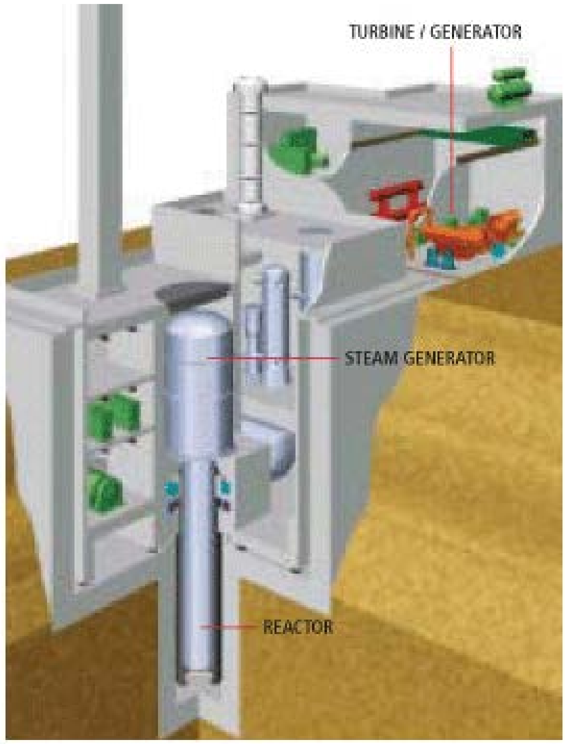


Figure 9. Plant Layout for the Toshiba 4S reactor concept

4. TECHNICAL REVIEW PANEL OBSERVATIONS

Each ARC submittal was assigned to four members of the TRP for review. The reviewers completed an evaluation summary sheet for each concept they reviewed. In the process of conducting their reviews, the TRP members found that not every information category described in Section 2 was meaningfully addressed by all submittals. A key factor in how well the eleven TRP criteria of Section 2 were addressed was highly dependent upon the level of readiness of the concept.

4.1 Summary Assessment

The panel evaluated the advanced reactor concepts as submitted by the vendors against the eleven criteria. The criteria included:

1. Safety
2. Security
3. Uranium resource utilization and waste generation minimization
4. Operational capabilities
5. Concept maturity, operating experience, unknowns and assumptions
6. Fuel and infrastructure considerations
7. Assessment of market attractiveness
8. Economics
9. Potential regulatory licensing environment
10. Nonproliferation
11. Research and Development Needs

There were few differences among the concepts with regard to their evaluations for safety, security, operational capabilities and nonproliferation. Where adequate information existed, there were notable differences with respect to fuel and infrastructure considerations, market attractiveness, economics and regulatory licensing environment. There were wide differences with regard to concept maturity and R&D needs. With respect to concept maturity, the concepts were categorized along a spectrum of maturity stages from Pre-conceptual, through Conceptual, Moderately Mature, and Mature to Highly Ready.

The Technical Review Panel provided specific comments on each of the eleven criteria for each of the eight reactor concepts. Because of the proprietary information contained in the vendors' submittals, and reflected in the TRP member reviews, those comments will not be released in their entirety.

5. R&D NEEDS

5.1 R&D Needs of Individual Advanced Reactor Concepts

The Technical Review Panel identified several key R&D needs for each of the eight concepts. Those unique R&D needs included concept specific issues such as reactor component development and testing, coolant related material testing and code qualification, safety system validation testing, natural circulation fluid dynamic testing, seismic evaluation and reflector evaluation. Because of the proprietary information contained in each of the vendor submittals, those R&D priorities are being conveyed to the vendors individually.

5.2 Common R&D Needs of Multiple Advanced Reactor Concepts

The advanced reactor concepts that were submitted rely on very specific technologies with relatively few truly crosscutting needs. However, it was noted that there are some common needs that are applicable to most of the concepts.

The TRP identified three need areas with issues that apply to a majority of the advanced reactor concepts:

- **Development of licensing approaches for advanced reactor concepts**: This will involve the development and implementation of an advanced reactor regulatory framework. It could also involve the development of advanced safety analysis tools and the development of a common verification and validation framework for these tools.
- **Accelerated development of Brayton cycle technologies:** This will involve efforts to accelerate the demonstration and deployment of Brayton cycle technologies. That program should focus on both the electricity producing technologies and on the coupling to the various advanced reactor technologies. The supercritical CO_2 cycle offers compelling reductions in size and cost of the power conversion system and should be a high priority.
- **Development of validated advanced reactor analysis methods**: This will involve the development of advanced neutronics, thermal-hydraulics, 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.

6. TECHNICAL REVIEW PANEL R&D PRIORITIES

This section provides the TRP priorities concerning future R&D activities for technologies associated with the specific concepts that were submitted to the TRP. The TRP process was strongly focused on the specific concepts that were submitted to the TRP, thus, the lack of support for R&D on a given technology/concept does not imply that pursuing work for the specific reactor technology is not valuable, rather it might reflect the fact that the specific concept associated with a technology is not the most representative of that technology, not as mature as other concepts, or seen as less marketable than other concepts.

To reach this set of priorities it was necessary for the TRP Chair, DOE Lead and laboratory staff to compile their sense of the collective view of the TRP. The existence of these priorities does not imply that a consensus view was obtained from TRP members.

It was determined that to address high priority R&D, a short term strategy is needed in which industry and national laboratories would conduct R&D efforts in specific, high priority areas.

It is recognized that the full R&D list associated with submitted concepts cannot be funded within current or planned budgets, and that a short list of priority items for which execution could be engaged in the short term would be useful. Consequently, a list of topics was developed that could be engaged in the short term and could have a strong impact on the concepts associated with the technologies indentified in this section. This list is organized in no priority order as R&D for specific technologies and R&D activities in support of multiple concepts. The technology specific R&D would be for gas-cooled fast reactors, LBE-cooled fast reactors and sodium-cooled fast reactors. Technology specific R&D for other concepts is not being supported at this time due to the long term fuel cycle development requirements that would be necessary for thorium fueled concepts and the lack of a compelling need to couple nuclear technology to a natural gas plant.

6.1 Advanced Reactor R&D Activities in Support of Specific Technologies/Concepts

6.1.1 Priority R&D for Gas-Cooled Fast Reactors

In 2010 the Department completed a thorough technical review of the EM2 design. In 2011, GA submitted a status report documenting changes to the design and R&D progress. The EM2 description document submitted in April 2012 for the Technical Review Panel process shows that additional features have been added that address some of concerns identified in the Department's 2010 review. For example, a Direct Reactor Auxiliary Cooling System (DRACS) has been incorporated to provide added protection during depressurized loss of forced cooling events. Further development of this concept needs to include flow sheets for the fuel conditioning and processing schemes in order to validate the recovery fractions assumed in GA's calculations.

- TRP identifies the need for the development of a fuel cladding system with the objective of obtaining a fuel that can withstand high burnup, high damage, and high temperature, while accommodating both uranium and transuranic compositions. In addition, the safety case for that fuel needs to be demonstrated.
- TRP identifies the need for a program to develop, demonstrate, and validate the safety system of a GFR. That program should comprise the safety system and component design and testing, and an integrated analysis approach.

- Once the basic feasibility of the concept is demonstrated and its economic viability is established, TRP identifies the need for a program to design and test reactor components. That program should comprise the design and identification of key R&D needs for performance and safety, and execution of that R&D.

6.1.2 Priority R&D for Lead-Bismuth Eutectic-cooled Reactors

- The TRP identifies that a more in-depth design review of the LBE fast reactor concept should be performed. Numerous unanswered questions arose during the TRP review that must be resolved to provide sound recommendations concerning the proper R&D program going forward.
- TRP identifies the need for development of a program to evaluate erosion/corrosion mechanisms and the implementation of control approaches. This program will focus on demonstrating licensable pathways for these technologies.
- In addition to that erosion/corrosion control program, TRP identifies the need for a program focus on developing advanced structural materials resistant to erosion/corrosion by LBE be implemented. The objective of that program is to develop new steels that would not require active control mechanism during the lifetime of the reactor.
- The TRP identifies the need for a trade study to look at the pros and cons associated with the use of both oxide and nitride fuel for the LBE reactor. If oxide fuel is found to be too much of a penalty, only then would the TRP recommend that a program focused on developing, testing, and licensing nitride fuels be implemented. The objective of that program would be to obtain a safe nitride fuel that can be fabricated for long term fueling of small deployed LBE reactors.
- The TRP identifies that once the basic feasibility of the concept is demonstrated and its economic viability is established, that a program is needed to support the design and testing of LBE reactor components. That program should comprise the design, identification of key R&D needs for performance and safety, and execution of that R&D.

6.1.3 Priority R&D for Sodium-cooled Reactors

- The TRP identifies that continued support should be provided for the design and testing of sodium reactor components. That program should comprise the design and identification of key R&D needs for performance and safety, and execution of that R&D.
- TRP identifies the need for a program devoted to the demonstration of advanced fuels for sodium cooled reactors, with an emphasis on the demonstration of their safety behavior.
- TRP identifies the need for continued support for the design and demonstration of technologies for under sodium viewing.

6.2 Advanced Reactor R&D Activities in Support of Multiple Concepts

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

6.2.1 Development and Implementation of Advanced Reactor Licensing Framework

One key need identified by the TRP for all advanced reactor concepts was development of a licensing framework. Also, a method to interact with the NRC in advance of a commercial application is vital to identify any safety challenges and 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. The safety characteristics and off-normal behavior of these systems are therefore different from LWRs. There is a need to establish a licensing framework for advanced reactors that allows credit for the unique characteristics of the advanced reactor yet provides the NRC a sound technical framework within which to issue a license. 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.

A review of advanced reactor concepts reveals a number of technical issues that will require resolution. For example:

- Implementation of Defense-in-Depth in a manner that is different than in current LWRs
- Implementation of Functional Containment in a design as opposed to the traditional containment approach of LWRs
- Passive system behavior and reliability
- Establishment of mechanistic source terms
- Licensing basis event selection
- Size of Emergency Planning Zone
- Multi-module control
- Staffing of smaller units or modules.

Some of these issues are generic to many of the concepts and are currently under review with the NRC and as part of the Nuclear Energy Institute SMR initiative.

6.2.2 Accelerated Deployment of Brayton cycle technologies

TRP identified that a program is needed, on the basis of the existing Advanced Reactor program, to accelerate the demonstration and deployment of Brayton cycle technologies. That program should focus on both the electricity producing technologies and on the coupling to the various advanced reactor technologies. The supercritical CO_2 cycle offers compelling reductions in size and cost of the power conversion system and should be first priority. For a helium-cooled Brayton cycle, the global work underway should be reviewed and the capabilities that exist in US industry should be evaluated to make an informed decision about the proper next step in Helium Brayton cycle R&D.

6.2.3 Development of Advanced Reactor Analysis Methods

TRP identifies the need for a program to accelerate the development and validation of advanced methods for the analysis of advanced reactors; this program would include methods for core analysis, reactor and system analysis, and their validation. Its emphasis would be on domains that are judged to be weakest today and will deliver fully validated code packages.

This activity will involve the development of advanced neutronics, thermal-hydraulics, 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 (NEAMS) program.

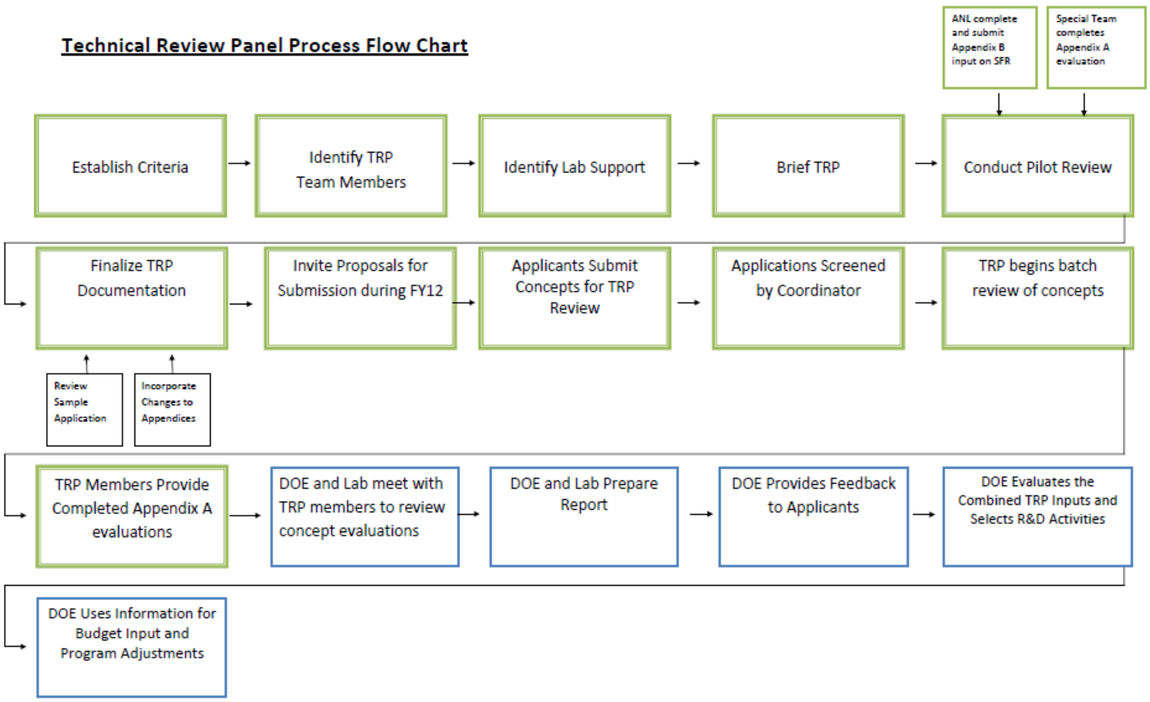
ACKNOWLEDGEMENT AND DISCLAIMER

This report was compiled by Dr. Phillip Finck-TRP Chair, Mr. Martin Sattison, Mr. Douglas Burns and Dr. Steve Herring of the Idaho National Laboratory and by Mr. Craig Welling – DOE Lead, and Mr. Jason Tokey of the Department of Energy, based on the comments provided by the Technical Review Panel members. This document also includes comments and recommendations from Dr. Robert Hill of Argonne National Laboratory and Dr. Dave Petti and Dr. Roald Wigeland of the Idaho National Laboratory. This report is a compilation of opinions and recommendations reflecting individual views of TRP members. The TRP process purposely did not seek to obtain a consensus view from TRP members.

ACRONYMS

ANS	American Nuclear Society
ARC	advanced reactor concepts
BARS	Toshiba BWR with Advanced Recycle System
BWR	boiling water reactor
CASL	Consortium for Advanced Simulation of Light-Water Reactors
DOE	U.S. Department of Energy
EM^2	Energy Multiplier Module
FCT	Fuel Cycles Technologies
GE	General Electric
GFR	gas fast reactor
HCSG	helical coil steam generator
HTGR	high temperature gas-cooled reactor
ISI	in-service inspection
LBE	lead-bismuth eutectic
LFR	lead-bismuth fast reactor
LWR	light water reactor
MSR	molten salt reactor
MWe	megawatt electric
MWt	megawatt thermal
NE	Office of Nuclear Energy
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEET	Nuclear Energy Enabling Technologies
NGNP	Next Generation Nuclear Plant
NRC	U.S. Nuclear Regulatory Commission
PRA	probabilistic risk assessment
R&D	research and development
RFI	request for information
SAFR	Sodium Advanced Fast Reactor
SiC	silicon carbide
SFR	sodium fast reactor
SMR	small modular reactor
Th-RMBWR	Thorium-Fueled Reduced Moderated Boiling Water Reactor
TRP	technical review panel
UNF	used nuclear fuel
VHTR	very high temperature reactor

Appendix - Technical Review Panel Process



A.1 Assessment Process

A.1.1 ARC Applicant

For a design to be considered by DOE, the ARC applicant submitted a concept input that provided DOE and the ARC TRP members with relevant design information. The concept inputs that were submitted to DOE included a concise description of the concept and responses to each of the requests for information items in the RFI document.

A.1.2 ARC Technical Review Panel

The ARC 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 submitted information 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, the 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 DOE Office of Nuclear Energy his/her findings and recommendations concerning the concepts and their R&D needs. The TRP did not provide NE with a consensus view of any ARC concept.

A.1.3 ARC 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 a 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. That report reflects TRP member comments, identifies R&D needs, provides an understanding of the time frame in which the R&D is needed and offers recommendations on future R&D activities.