U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0001598
on
Enabling Technologies for Ultra-Safe and Secure Modular Nuclear Energy Systems

Objective:

ARPA-E seeks input from a broad range of disciplines and fields, including, but not limited to nuclear science and engineering, materials science and engineering, sensor science and technology, instrumentation and control engineering, automation science and engineering, power systems engineering, and safety by design for innovative concepts for technical innovation that will enable accelerated development and regulatory acceptance of modular[1] nuclear energy options involving either Gen III+ or Gen IV design features.[2] If made technically and economically viable, modular nuclear reactor technologies can augment large-scale reactors in providing clean, safe, secure, carbon-free electricity as well as heat energy for various non-electrical applications (e.g., industrial processes, mining activities, hydrogen production, and seawater desalination). ARPA-E is particularly interested in innovations that enable reactor designs to be: 1) inherently safe (beyond passive safety) with multiple safety mechanisms to prevent core melting in case of a loss of coolant accident (LOCA); 2) extremely secure without exposure of radioactive nuclides in case of LOCA or an enclosure breach with a zero or near zero emergency planning zone (EPZ); 3) quickly responsive to external load variations with control mechanisms that can also add safety beyond passive cool down; 4) long-lasting with operational durations of 10 to 20 years without refueling; 5) substantially autonomous in operations with minimal operator intervention; and 6) proliferation resistant. Consistent with the agency's mission, ARPA-E is seeking information on disruptive, novel technologies, relatively early in the R&D cycle, and not integration strategies for existing technologies.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below, and note in particular: the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

Background:

Nuclear power plants currently provide nearly 20% of the total U.S. electricity generation, or some 797.2

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[1] The DOE is supporting the design and licensing activities of advanced light water small modular reactor (SMR) concepts that feature passive safety systems and offer modular designs with single reactor units, each generating less than 300 MWe. Such SMR power plants are seen as alternatives to fossil-fired power plans of similar size, which include many of the U.S.'s aging coal-fired plants. For this RFI, we will define modular reactors broadly, in the power range of 1 to 300 MWe.

[2] Generations of nuclear reactors are most commonly identified along their deployment timelines from the late 1940s and beyond 2030. Generation I (Gen I) (late 1940s to late 1960s) are early prototype reactors; Gen II (late 1960s to early 1990s) are commercial power reactors; Gen III (early 1990s to late 2000s) are advanced light-water reactors; Gen III+ (late 2000s to late 2020s) are evolutionary reactor designs; and Gen IV (late 2020s to beyond 2030) are revolutionary designs. There are six main Gen IV reactor types: sodium-cooled fast reactor, lead-cooled fast reactor, gas-cooled fast reactor, molten-salt reactor, very high-temperature reactor, and supercritical-water-cooled reactor.

billion kW-hr, with 99 operating nuclear reactors for a total installed capacity of 98.7 GW.[3] These nuclear plants are all of the conventional, light water cooled type (or light water reactors [LWRs]), which have been the workhorse of the nuclear industry for several decades now. Nuclear electricity generation accounts for about 63% of the total low-carbon electricity generation worldwide.[4] However, in recent years LWR operation has come under increasing strain due to various reasons, including competition from natural gas-fired plants, forthcoming retirements of older reactors as they reach their end of life and related potential rise in operational and maintenance costs. This strain has been compounded by high initial capital costs of new LWR plants and their long construction lead times. For these reasons, only 4 LWRs that feature passively safe designs[5] (i.e., Westinghouse's AP1000, 1,110 megawatt electrical (MWe) reactors) are on target to come online in 2016 and 2017 as projected by the U.S. Energy Information Administration (EIA).[6] Even with a license extension to enable 60-year operations of the existing U.S. nuclear fleet, scheduled retirements will start around 2020 and conclude around 2050, which is just about the time period when large amounts of carbon-free baseload power will be needed to balance the anticipated high percentages of intermittent solar and wind electricity.

To augment existing nuclear power generation and look to future needs for new and robust nuclear power beyond the 2030 timeframe, the U.S. and other countries are researching and developing small modular reactors and advanced reactors, also known as Generation IV (Gen IV)-type reactors.[2]

The motivation for small modular reactors includes the need to reduce overall capital and operational costs, while incorporating new safety features developed for Gen III+ reactors. There are several motivations for advanced reactors:

> First, a key motivation is related to enhanced passive safety features, building on those offered by the recently-deployed Gen III+ reactors. The majority of the new advanced concepts aim to be considered truly 'walkaway-safe' reactors for which, in case abnormal operation necessitates shutdown of the reactor, such a shutdown could be done with no human intervention.[7]
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> Second, some advanced reactor concepts feature load-following capabilities (i.e., quickly ramp up or down in power) for integration with intermittent solar and wind electricity and offer heat and electricity options to cogeneration applications, such as desalination and various process heat applications.
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> Third, some advanced reactors of the fast neutron spectrum type offer the ability to produce more fissile matter than they consume thus reducing the need for fresh fuel. Such reactors could also burn spent fuel and reduce overall spent fuel radioactivity, which could offer an attractive path for substantial nuclear waste reduction in addition to other advantages.[8]

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[3] U.S. Energy Information Administration (EIA), Nuclear Energy Overview (1957-2015), http://www.eia.gov/totalenergy/data/monthly/pdf/sec8.pdf

[4] Nuclear Energy Institute (NEI), http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Environment-Emissions-Prevented. Calculated from U.S. EPA and EIA data for 2014. Nuclear power amounted to some 595 million metric tons of avoided carbon dioxide emissions.

[5] Passive safety systems rely almost exclusively on natural forces, such as density differences, gravity, and stored energy, to supply safety injection water and provide core and containment cooling. These passive systems do not include pumps. However, they do include some active valves, but all the safety-related active valves require either dc safety-related electric power (supplied by batteries), are air operated (and fail safe on loss of air), or are of the check valve type. U.S. Nuclear Regulatory Commission (NRC), http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1793/initial/chapter22.pdf.

[6] EIA, 2015 Annual Energy Outlook, p. 25.

[7] R. Lester, A Roadmap for U.S. Nuclear Energy Innovation, Issues in Science and Technology, National Academies of Sciences, Engineering, and Medicine, The University of Texas at Dallas and the Arizona State University, Winter 2016.

[8] Technology Roadmap Update for Generation IV Nuclear Energy Systems, OECD Nuclear Energy Agency for the Generation IV International Forum, January 2014: https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf

However, several technical and economic challenges stand in the way of commercialization of advanced nuclear reactors. The technical challenges that have persisted over the years include many that are tied to materials and systems engineering issues. Essentially all advanced reactor types operate at very high temperatures; their core components are exposed to extremely corrosive environments and are subjected to the high-energy neutrons generated during nuclear reactions. Table 1[9] illustrates the range of harsh operating conditions for the main advanced reactor types.

Table 1 Approximate operating environments for Gen IV systems

Reactor Type	Coolant Inlet Temp (°C)	Coolant Outlet Temp (°C)	Maximum Dose (dpa*)	Pressure (Mpa)	Coolant
Supercritical Water-cooled Reactor (SCWR)	290	500	15-67	25	Water
Very High Temperature gas-cooled Reactor (VHTR)	600	1000	1-10	7	Helium
Sodium-cooled Fast Reactor (SFR)	370	550	200	0.1	Sodium
Lead-cooled Fast Reactor (LFR)	600	800	200	0.1	Lead
Gas-cooled Fast Reactor (GFR)	450	850	200	7	Helium/ SC CO_2
Molten Salt Reactor (MSR)	700	1000	200	0.1	Molten Salt
Pressurized Water Reactor (PWR)	290	320	100	16	Water

* dpa is displacement per atom and refers to a unit that radiation material scientists used to normalize radiation damage across different reactor types. For one dpa, on average each atom has been knocked out of its lattice site once.

These materials challenges create significant uncertainty in the pathways for licensing and deployment of such advanced reactors. There has been tremendous progress in the development of new materials for higher temperature capabilities and higher resistance to neutron radiation damage;[10] however, none of these materials have been included in the new reactors under construction. (The materials used in new reactor construction are still those certified before the 1960’s.) This is due to the challenges associated with new materials certification for which there is insufficient existing data on performance under operating conditions.

ARPA-E is seeking input from the broad research and development communities with regard to needs and opportunities for transformational *enabling technologies* to address certification challenges for modular reactors, including the possibility of modular reactors based on next generation designs. Emphasis is placed on those technologies that can benefit a wide-range of reactor types, which include both advanced (Gen-IV) reactors and emerging advanced light-water reactors.

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future programs intended to create transformative enabling technologies that would greatly contribute to the future deployment of modular reactors, based on future advanced nuclear fission reactors or today’s emerging reactor technologies. Of particular interest are those technologies that would enable features such as (i) mostly autonomous operation, (ii) ‘walkaway-safe’ power plants, (iii) refueling cycles of 10 years or longer, (iv) load-following, (v) the highest possible physical security, and (vi) proliferation resistance. Technologies of interest could include advanced sensors and controls (both hardware and software components); advanced materials (both existing and emerging); and systems integration platforms that allow for advanced modeling, simulation and pilot scale demonstration of fully integrated technologies.

ARPA-E will not pay for any information submitted under this RFI. Based on the input provided in response to this RFI and other considerations, ARPA-E may decide to issue a FOA. If a FOA is published, it will be issued under a new FOA number. No FOA exists at this time. ARPA-E reserves the right to not

[9] T. Allen, J. Busby, M. Meyer, and D. Petti, Materials challenges for nuclear systems, *Materials Today*, 13 (12) (2010) 14-23.
[10] S. Zinkle and G. Was, Materials challenges in nuclear energy, Acta Materialia, 61 (2013) 735-758.

issue a FOA in this area.

REQUEST FOR INFORMATION GUIDELINES:

ARPA-E is not accepting applications for financial assistance or financial incentives under this RFI. Responses to this RFI will not be viewed as any commitment by the respondent to develop or pursue the project or ideas discussed. ARPA-E may decide at a later date to issue a FOA based on consideration of the input received from this RFI. No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E reserves the right to contact a respondent to request clarification or other information relevant to this RFI. All responses provided will be taken into consideration, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the email address ARPA-E-RFI@hq.doe.gov by June 17th, 2016. ARPA-E will not review or consider comments submitted by other means. Emails should conform to the following guidelines:

- Please insert "Responses for RFI for FOA DE-FOA-0001598" in the subject line of your email, and include your name, title, organization, type of organization (e.g. .. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 10 pages in length (12 point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.
- **Questions:** ARPA-E encourages responses that address any subset of the following questions of relevance to the respondent and encourages the inclusion of references to important supplementary information.

1) Reactor Context for Enabling Technologies

a. What aspects of different possible reactor design features have the best potential for use in modular nuclear energy systems? For instance, are there innovative combinations of non-water heat conduction systems and coolants (e.g., heat pipes, helium, CO_2, supercritical CO_2, molten metals, liquid salts, and others), nuclear fuel forms, and heat to electricity power conversion devices that are best suited for applications in modular reactors that can be sited in a wide range of environments?

b. How do the optimum aspects of the reactor design vary with the scale of the modular reactor between 1 and 300 MW? How would the scale affect the choice of materials, sensing, monitoring, and control systems? Which scale would be most amendable to load-following capabilities?

c. What are the crucial technical needs and opportunities associated with active sensing, monitoring, and control of a reactor in order to enable load-following capabilities?

d. What are the crucial technological needs and opportunities associated with active sensing, monitoring, and control of an integrated reactor design in order to enable operational safety? Think beyond commonly-accepted passive safety design features. What are the technical challenges in implementing such systems? Are there concepts that would completely eliminate the need of evacuation at and beyond the site boundary?

e. Should a target of power production efficiency from nuclear energy be specified (e.g. 45%) to be above the state-of-the-art? Would an ambitious target necessitate adoption of new high-performance materials and technologies that are not yet nuclear grade certified?

2) **Materials**

a. What are the specific materials challenges of vital reactor components that would enable very high temperature tolerance for enhanced safety, high neutron radiation resistance, compatibility with coolant/heat transfer media, the fuel, and others? Is there much to gain in terms of safety margins by enabling high temperature-tolerant core materials?
b. How could state-of-the-art computer modeling and simulation codes be leveraged to support materials optimization for different modular reactor types?

3) **Sensors and Controls**

a. What type of operational modes and conditions of modular nuclear reactor systems would qualify as “substantially” autonomous? What technological innovations could enable substantially autonomous operation of nuclear reactor systems, and what are the related technology gaps?
b. Are there available sensors and imaging and monitoring technologies that could enable marked improvements in safety and autonomous operations of nuclear reactor systems? If not, what are the technology gaps and opportunities for future development of such technologies and devices?
c. If ARPA-E were to support development of resilient, robust in-core sensors, what specific data should those sensors monitor and record? What are the challenges (i.e. environmental robustness, noise, sensor lifetime, etc.) of designing and deploying new sensors? How would a control system or a human operator make use of data from new sensors to drive decision making and improve safety?

4) **Safety and Security: Leveraging Non-Nuclear Experiences**

a. Could safety, security and/or non-proliferation experience from outside the nuclear power industry be leveraged to make transformational improvements to the advanced modular nuclear energy systems?
b. Are there specific external threats that particular reactor designs or materials combinations are exceptionally good or bad at countering?

5) **Market Considerations**

a. How can the development of enabling technologies for enhanced safety, security and proliferation resistance of nuclear reactor systems (if at all) improve economics of present-day and future reactors of all types and sizes? Please be as specific as possible.
b. Are there markets where the economic viability of small modular reactors is realized from their benefits in generation of both electricity and process heat in the next 10-20 years?

6) **Diagnostic Platform**

a. Consider an integrated diagnostic platform that is designed to provide opportunities for development and testing of various enabling technologies under conditions relevant for operational use to provide essential data that will accelerate the regulatory certification work. For such a platform, what would be the optimal size and design requirements? What key features (e.g. high neutron flux, extreme temperatures) should be included? Please explain your rationale for the platform size and design features.

b. With the diagnostic platform in mind, should a "common solid core" (i.e., a solid core that is agnostic to both nuclear fuels and heat to electricity/power devices) be used for testing? Such a core may, for example, allow design and testing of various heat to power conversion systems, such as closed-loop helium turbines, closed-loop supercritical CO_2 turbines, and open-loop steam turbines for various end-use applications (e.g., heat and electricity cogeneration).
c. How could state-of-the-art, high-fidelity computer modeling and simulation codes be leveraged and integrated for reduction of diagnostic testing?