NUCLEAR ENERGY ADVISORY COMMITTEE

MEMORANDUM FOR: Raymond V. Furstenau, Acting Assistant Secretary
Office of Nuclear Energy

FROM: Richard A. Meserve, Chair RAM
Joy L. Rempe, Co-chair JLR
Nuclear Energy Advisory Committee

DATE: February 24, 2017

SUBJECT: Transmittal of NEAC Report on the Test Reactor
Charge Report

NEAC has approved the report "*Assessment of Missions and Requirements for a New U.S. Test Reactor*" during its public teleconference meeting of February 16, 2017 and is hereby transmitting it to you.

This report was prepared in response to a request from Acting Assistant Secretary for Nuclear Energy, John Kotek. In a letter, dated July 29, 2016, he directed the Nuclear Energy Advisory Committee (NEAC) Chairs to form a team, comprised of members from NEAC subcommittees, "to assess the need and determine the requirements for an irradiation test reactor which would augment existing domestic capabilities to support the development and deployment of advanced non-light water reactors as well as to accommodate the future needs of light water reactor technologies."

Nuclear Energy Advisory Committee

Assessment of Missions and Requirements for a New U.S. Test Reactor

February 2017

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Acronyms

ANL	Argonne National Laboratory
ANSTO	Australian Nuclear Science and Technology Organisation
ATR	Advanced Test Reactor
BARC	Bhabha Atomic Research Centre
BNCT	Boron Neutron Capture Therapy
CAEA	China Atomic Energy Authority
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives
CNEA	National Atomic Energy Commission
DOD	Department of Defense
DOE	Department of Energy
DOE-NE	Department of Energy -Office of Nuclear Energy
dpa	displacements per atom
EBR-II	Experimental Breeder Reactor-II
GCR	Gas-Cooled Reactor
GIF	Generation IV International Forum
FFTF	Fast Flux Test Facility
FHR	Fluoride Salt-Cooled High Temperature Reactor
HFEF	Hot Fuel Examination Facility
HFIR	High Flux Isotope Reactor
HTGR	High Temperature Gas-cooled reactors
HTR-PM	High Temperature gas-cooled Reactor Pebble-bed Module
ICSA	In-Core Sample Assembly
IFE	Institute for Energy Technology
IGCAR	Indira Gandhi Centre for Atomic Research
IFEL	Irradiated Fuel Examination Laboratory
IKET	Institute for Nuclear and Energy Technologies
IMCL	Irradiated Materials Characterization Laboratory
IMET	Irradiated Materials Examination and Testing
ININ	Instituto Nacional de Investigaciones Nucleare

INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency (JAEA)
KAERI	Korea Atomic Energy Research Institute
KIT	Karlsruhe Institute of Technology
LANL	Los Alamos National Laboratory
LWR	Light Water Reactor
LFR	Lead Fast Reactor
LVXF	Large Vertical Experiment Facility
MITR	Massachusetts Institute of Technology Research Reactor
MNRC	McClellan Nuclear Research Center
MOST	Ministry of Science and Technology
MSR	Molten Salt Reactor
MTR	Material Test Reactor
NAS	National Academy of Science
NBSR	National Bureau of Standards Reactor
NEAC	Nuclear Energy Advisory Committee
NEI	Nuclear Energy Institute
NRT SC	Nuclear Reactor Technology Subcommittee
NASA	National Aeronautics and Space Administration
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NSUF	Nuclear Science User Facilities
ORNL	Oak Ridge National Laboratory
PAA	Państwowa Agencja Atomistyki
PIE	Post Irradiation Examination
PHWR	Pressurized Heavy Water Reactor
PWL	Pressurized Water Loop
RAL	Remote Analytical Laboratory
R&D	Research and Development
REDC	Radiochemical Engineering Development Center
RJH	Reactor Jules Horwitz

RPV	Reactor Pressure Vessel
SCK-CEN	Studiecentrum voor Kernenergie (Belgium Nuclear Research Center)
SEAB	Secretary of Energy Advisory Board
SFR	Sodium Fast Reactor
SLAC	Stanford Linear Accelerator Center
MURR	University of Missouri Research Reactor
NB	National Bureau of Standards Reactor
NCBJ	Narodowe Centrum Badan Jadrowych
NSC	Nuclear Science Center
OSURR	Ohio State University Research Reactor
OSTR	Oregon State University TRIGA Reactor
PSBR	Penn State University Breazeale Reactor
RCF	Rensselaer Polytechnic Institute Reactor Critical Facility
REDC	Radiochemical Engineering Development Center
SC-HTGR	Steam Cycle High Temperature Gas-Cooled Reactor
SFR	Sodium Fast Reactor
SNS	Spallation Neutron Source
SPL	Sample Preparation Laboratory
TMSR	Thorium Molten Salt Reactor
UFTR	University of Florida Training Reactor
UK	United Kingdom
UMLRR	University of Massachusetts at Lowell Research Reactor
UMRR	University of Missouri Science & Technology Research Reactor
UUTR	University of Utah TRIGA Reactor
VVER	Vod0Vodyan Energetichesky Reactor
WSUNRC	Washington State University Nuclear Radiation Center

I. Introduction

Nuclear power is an important carbon-free power source for the U.S. and the world. Beginning in 2030, a significant number of operating power reactors within the U.S. will reach 60 years of age and the end of their extended operating license; some of these reactors will not seek subsequent license renewal. In the draft report, “Vision and Strategy for the Development and Deployment of Advanced Reactors,”[1] the Department of Energy (DOE) indicates that replacement nuclear power options will include a combination of advanced Light Water Reactors (LWRs), small modular reactors, and advanced reactors technologies employing non-LWR coolants.

Advanced nuclear energy fuels and designs are being pursued in the U.S. by many commercial organizations (including a significant number of startup companies), DOE Laboratories, and universities. These efforts address both LWR and non-LWR systems. The latter differ significantly from LWRs in their materials of construction, design configuration and operating conditions. Most operate at significantly higher temperatures than LWRs. Some are fast-spectrum reactors targeting improved fuel-resource utilization and waste management. Their development and maturation requires an adequate infrastructure for experimentation, testing (including irradiation testing of fuels and materials), design evolution, and component qualification. Irradiation testing capabilities are also required for the continued development and improved operation of thermal reactors, including LWRs and advanced reactors employing graphite or other moderators. A high flux of neutrons (particularly fast neutrons) in a test reactor is valuable for reducing the potentially lengthy irradiation times needed to confirm the damage resistance of both thermal and fast-spectrum reactor materials when irradiated to high neutron doses.

Irradiation test reactors currently operated by DOE are thermal reactors built prior to 1970. Some DOE stakeholders have expressed concern about the ability of these DOE facilities, as well as other U.S. irradiation test reactors, to meet the needs of the existing fleet and development of advanced non-light water reactors. Recent reports[2,3] have differed in their assessment of the needs for a new U.S. irradiation reactor and potential users for such a facility, noting that some advanced reactor proponents indicate that their concepts could be deployed without a new test reactor.

The role of a test reactor is different than that of a demonstration or prototype of an advanced reactor. A test reactor provides necessary irradiation data for evaluating the performance of fuels, materials, components, and instrumentation used in existing and advanced reactors; whereas, construction and operation of a demonstration reactor establishes confidence in the viability of a new reactor design by providing data for assessing the integral behavior of the system prior to subsequent commercial offerings. A demonstration or prototype reactor could be designed to allow testing of fuels or materials in the specific environment of that reactor type, but would typically not provide the flexibility of a test reactor to serve the needs of a diverse set of users. The missions of a demonstration reactor and a test reactor are both important. It is unclear whether federal funding, which would be required for deploying most of the proposed advanced reactors or any new DOE test reactor, could be allocated for both the test and demonstration projects.

The Nuclear Energy Advisory Committee (NEAC) Chairs were charged to form a team, comprised of members from NEAC subcommittees, “to assess the need and determine the requirements for an irradiation test reactor which would augment existing domestic capabilities to support the development and deployment of advanced non-light water reactors as well as to accommodate the future needs of light water reactor technologies.” The full charge to the Task Force is found in Appendix A.1 of this report.

The charge letter emphasizes desired aspects of the requested independent NEAC review. Namely, the evaluation should determine “the requirements and overall capabilities (e.g., neutron spectrum/spectra, testing environments, etc.) for a new irradiation test reactor and compare these requirements with alternate existing facilities, methodologies, and approaches for meeting these needs.” The NEAC team was instructed to consider the needs of the entire user community including national laboratories, academia, industry, reactor vendors, supply chain manufacturers, material suppliers, the U.S. Government Agencies (DOE, NRC, NASA, NNSA, DOD, DOC, etc.), and the international community as well as the time frame that an irradiation test reactor capability would be required (if one is needed). Further guidance from DOE[a] emphasized that “need” is essentially asking that “in the expert judgment of NEAC, there is sufficient projected demand from the community of potential users (e.g., DOE, other government agencies, universities, industry, international) that can’t be filled using existing readily accessible capabilities (including alternate facilities, methodologies and approaches) to warrant DOE launching an effort that could lead to construction of a new test reactor.” It was noted that a more detailed discussion of capabilities would be useful, but is not essential for completing the charge and requested that we only call them out to the extent that we see “broad interest in a particular capability or set of capabilities from the potential user community.”

The approach adopted to address this charge is shown in Figure 1. Activities were completed by three NEAC subcommittees: the International Subcommittee, the Facilities Subcommittee, and a special Ad Hoc Subcommittee composed of members from the NEAC Reactor Technology and Fuel Cycle Subcommittees. Members participating in each of these subcommittees are listed in Appendix A.2. The International Subcommittee assisted by collecting information about international irradiation facilities that could meet some needs not currently met by U.S. irradiations facilities. The Facilities Subcommittee collected information related to existing US irradiation capabilities. Capabilities of existing and planned new irradiation facilities are summarized in Section II of this report. The Ad Hoc Subcommittee obtained input from possible domestic users of a new irradiation facility. As directed in the charge letter, this input was solicited from a broad spectrum of potential users. As discussed in Section III, this input was primarily collected at a meeting held in October 2016. The International Subcommittee also provided input related to international participation in and potential

[a] Email from J. Kotek, DOE, to J. Rempe, NEAC Co-Chair, dated November 17, 2016.

use of a new U.S. irradiation facility. Conclusions and recommendations from this effort are found in Section IV of this report.

Note that the conclusions and recommendations of this report are limited to the need for a new U.S. test reactor. NEAC members are not in a position to judge funding prospects. Furthermore, NEAC members did not assess the tradeoffs between a demonstration and a test reactor. Such an assessment would require additional information, such as business plans from advanced reactor designers and detailed knowledge about the technology readiness of their concepts.

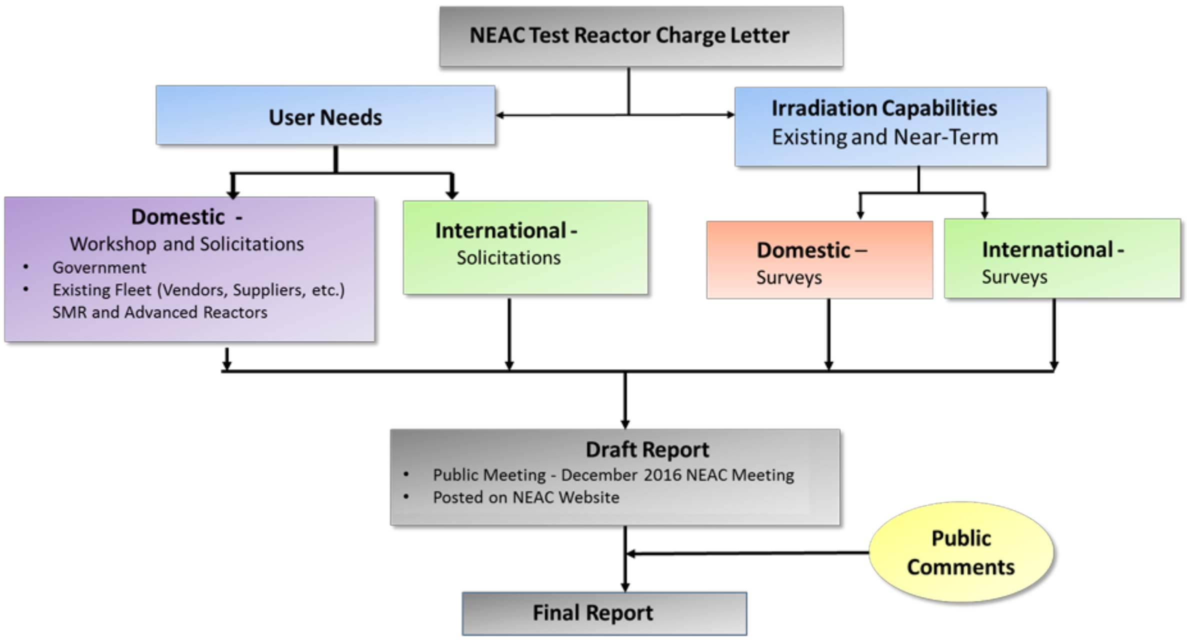

Figure 1. Approach to Complete Test Reactor Charge ([ ] – Activities completed by Facilities Subcommittee; [ ] – Activities completed by International Subcommittee; [ ] - Activities completed by the Ad Hoc Subcommittee; [ ] – Organizational and documentation activities led by NEAC Co-chairs)

We observe, however, that there are some U.S. benefits from either a new test reactor project or a demonstration reactor project that are not addressed by activities shown in Figure 1. These benefits apply to both projects. One of these benefits pertains to human capital. It is recognized that construction, startup, and operation of such facilities will stimulate the interest in and provide invaluable experience to the next generation of nuclear engineers. Second, as elaborated upon in Reference 2, the ability of the United States to reinforce safety, security and safeguards in foreign countries depends fundamentally on American example, influence, and assistance. Currently, the U.S. deploys more nuclear reactors than any other country and much of the international reactor fleet is based on the technology and analysis capability originated in the United States. However, foreign advanced nuclear reactor programs are larger than those in the United States, and several foreign countries have test reactors as well as demonstration and prototype facilities in operation or under construction. A new test reactor project or a demonstration reactor project would help the U.S. retain its capacity to influence the international community with respect to nuclear safeguards and security.

As shown in Figure 1, the approach provides several opportunities for public comment. Progress was reported at the December 2016 full committee meeting (allowing the public, as well as all NEAC members, to provide comments). A draft report, which incorporated comments obtained at the December 2016 NEAC meeting, was posted on the NEAC website in January 2017 to allow the public to provide comments prior to the final approval and issuance of this report in February 2017.

II. Current and Near Term Irradiation Capabilities

As historical evidence indicates, irradiation test reactors continue to play an important role for improving the performance of reactor plants well beyond the time they are first operated. Since the early days of the deployment of LWRs, several test reactors have been used to that end. For example, the Advanced Test Reactor (ATR) in the U.S., the Halden reactor in Norway, and in the future, the Reactor Jules Horowitz (RJH) in France, are supporting the advancement of LWR technologies. Further improvements will be needed in the future to enhance economic competitiveness and prospects for sustained commercial deployment of LWRs and non-LWRs. Targeted advances include increased power output, extended reactor/component lifetimes, increased reliability and operational flexibility, higher temperature operation for process heat applications and increased efficiency, improved characterization of reactor behavior, and increased safety margins.

Adequate capabilities for irradiation testing enable the demonstration of improvements not only for the materials and components employed in a reactor's initial design, but also for enhanced/improved fuel designs, advanced versions of replaceable reactor components, and the "permanent" structural components for reactor units subsequently built. The development and demonstration of such advances are greatly aided by the versatility that a test reactor facility offers for inserting and removing experimental hardware (materials, components, devices, instruments, etc.), varying operating conditions, accurately measuring these conditions and their impacts on performance, and validating analytical or computational models of behavior.

As discussed in Section I, two NEAC subcommittees evaluated the capabilities of existing and planned new irradiation test reactors. This section summarizes results for domestic facilities (by the NEAC Facilities Subcommittee) and for international facilities (by the NEAC International Subcommittee).

Current U.S. Irradiation Capabilities

The NEAC Facilities Subcommittee examined the capabilities and potential gaps in existing domestic facilities for irradiation testing of nuclear energy fuels, materials and components exposed to significant neutron doses. The domestic focus of this effort complements the NEAC International Subcommittee's focus on foreign facilities. We sought as part of this initiative to assess not only the current capability of existing facilities, but also what could be accomplished through upgrades. This provides a basis for evaluating the need for a new irradiation test reactor facility. All potentially relevant irradiation testing facilities in the U.S. were considered, including those operating at national laboratories, other government sites, universities, and industry.

Previous Assessments of Nuclear Energy Facilities

There have been many studies conducted to identify nuclear energy Research and Development (R&D) and technology testing facilities that exist within the DOE and university complex. The list of facilities is long. It is difficult to independently assess the capability and readiness of many of these facilities, not only because there are so many, but also because their use and availability changes as program priorities and needs change. The lack of a consistent long-term plan for nuclear R&D has hindered their maintenance and use. This is especially troubling since facilities important to nuclear R&D are expensive and, without consistent funding, will be lost. The U.S. at one time was the world leader in nuclear energy technology development, but its leadership position has declined. As observed in Section I, a new test reactor would help mitigate this decline, especially if effective use is made of capabilities that are already in place to support and utilize the new reactor.

The results of the prior assessments have been documented in the following reports:

- "Facilities for the Future of Nuclear Energy Research: A Twenty-year Outlook", DOE-NE, February 2009.[4]
- "2012 Annual Report for the Research Reactor Infrastructure Program", Idaho National Laboratory.[5]
- "Research and Test Facilities Required in Nuclear Science and Technology", NEA, Organization for Economic Co-operation and Development, ISBN 978-92-64-99070-8, NEQA No. 6293, OECD 2009.[6]
- "Nuclear Energy for the Future, Executive Recommendations for R&D Capabilities", Battelle, July 2008.[7]
- "A Strategy for Nuclear Energy Research and Development" EPRI and INL, INL/EXT-08-15158, December 2008.[8]
- "Required Assets for a Nuclear Energy Applied R&D Program" INL, 2008.[9]
- "Assuring a Future in U.S.-Based Nuclear and Radiochemistry Expertise", National Academy of Sciences, ID=13308, 2012.[10]

The information contained in these reports provides an extensive catalogue of capabilities, needs and priorities from several points of view. A consistent theme is the need to maintain U.S. expertise at a high level by conducting relevant research and technology development.

Conclusions from Previous Assessments

Perhaps the most relevant document among those listed above is the first one – "Facilities for the Future of Nuclear Energy Research: A Twenty-year Outlook".[4] This report is significant because it represents a consensus among experts and key stakeholders, and builds upon the preceding evaluations. To quote:

> Facilities for the Future of Nuclear Energy Research follows the recommendations of the National Academy of Sciences and is informed by several studies conducted in 2008, including those of DOE's national laboratory directors, DOE's Nuclear Energy Advisory Committee, and studies by the Battelle Memorial Institute that provide the foundation for the identification of core facilities.

Reference 4 addressed facility needs using the following priorities/considerations:

- Focus on the core set of materials test reactors, hot cells, and specialized facilities needed to support nuclear energy R&D for 20 years.
- Evaluate DOE's existing research facilities against needed capabilities, considering functionality, capacity and demand, operating status, adequacy of supporting infrastructure, and economy achieved through co-location with other needed facilities.
- Use the same criteria to assess university, industry, and international facilities.
- Consider facilities in standby when no suitable operating facilities exist.
- Building new facilities to satisfy capability requirements will be considered if no other reasonable alternative exists in the U.S. or internationally, and will be necessarily justified and funded by the sponsoring program.
- New facilities may best be located at remote sites, where existing infrastructure can support new capabilities.
- Facilities need not be co-located with research expertise, provided experts have access to the facilities.

The report identified several key U.S. and international facilities for irradiation (and transient) testing of nuclear energy materials.

Approach

In this effort, the NEAC Facilities Subcommittee reviewed the state of major U.S. irradiation test facilities identified in previous reports. Several important steps forward have been made in recent years. Restart of the TREAT reactor for transient testing is well underway and will provide a unique and important capability for the U.S. In addition, a major study has been completed for the ATR, addressing the potential lifetime of that facility and modifications needed to reach it. To support its review, the subcommittee developed a compilation of existing irradiation test reactors and their major characteristics. This compilation is found in Appendix B. While not exhaustive, it includes those facilities expected to be available and which provide sufficient neutron-flux intensities to meet anticipated testing needs. In addition, the Facilities Subcommittee considered two U.S. facilities no longer available for irradiation testing, the Experimental Breeder Reactor-II (EBR-II) and the Fast Flux Test Facility (FFTF), as well as foreign facilities that are potentially available today or in the future (e.g., the Jules Horowitz reactor). Many smaller research reactors in operation at several universities that could be employed for scoping irradiations to low levels of radiation damage (dose) were also considered.

Findings and Recommendations

Based on this review, and consistent with the prior assessments, the NEAC Facilities Subcommittee identified the following U.S. facilities as the primary candidates for irradiation testing of nuclear energy fuels and materials:

- ATR, Idaho National Laboratory
- High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory
- Massachusetts Institute of Technology Research Reactor (MITR)
- University of Missouri Research Reactor (MURR)
- National Bureau of Standards Reactor (NBSR)

Key characteristics for these reactors are summarized in Table 1. It is apparent that a significant national capability exists for irradiation testing in a thermal-neutron spectrum, particularly when the university facilities and expertise are included. On the other hand, the national capability for irradiation testing in a fast neutron spectrum is extremely limited. As can be seen from Table 1, the highest value of fast flux among all domestic irradiation reactors is provided by HFIR. This facility's maximum fast flux (for neutron energies exceeding 0.1 MeV) is approximately 1×10^{15} n/cm^2/s. However, the highest fast flux in an experimental location of useful volume is about half this value and corresponds to a damage rate of approximately 6 dpa (displacements per atom) per year of irradiation. This rate is too low for attaining damage doses exceeding 100 dpa (typically desired damage resistance value for advanced structural materials) in a reasonable irradiation time.

The attainment of increased fast flux levels in these U.S. "high performance" irradiation test reactors, using new fuels or core designs, does not appear to be a realistic possibility. In fact, their current flux intensities are achieved using highly enriched uranium, and the development and qualification of higher density fuels enabling their conversion to low-enrichment uranium for non-proliferation reasons (while preserving their flux intensities) has proven to be a significant challenge.[10]

A second key consideration is the flexibility of the existing reactors to support testing in different coolant environments and at elevated temperatures, particularly for coolants other than light water, such as pressurized helium gas, liquid sodium, liquid lead or lead-alloy, molten salt, etc. The subcommittee has explored this question only in a preliminary manner and tentatively concludes that the incorporation of loops enabling the irradiation testing of materials in (flowing) coolants other than light water would involve significant challenges.

A third consideration is the age of the candidate irradiation facilities. Each is approximately 50 years old or more, but is expected to operate to 2040 (or beyond).[b] Appropriate investments in maintenance and replacement of aging components are required for their continued operation.

[b] For example, the ATR is designed to have an essentially unlimited lifetime. There is a large distance between the fuel and the reactor vessel, which is made of SS (to minimize any vessel embrittlement), and approximately every 10-15 years, a core internals change-out is completed in which the entire core and its beryllium reflector is replaced.

Table 1. Characteristics of primary U.S. irradiation testing reactors.[a]

	Advanced Test Reactor (ATR)	High Flux Isotope Reactor (HFIR)	MIT Reactor - II (MITR-II)	University of Missouri Research Reactor (MURR)	National Bureau of Standards Reactor (NBSR)
Type	Light water tank	Light water tank	LW tank w/ heavy water outer tank	Light water tank	Heavy water tank
Owner	US DOE/Idaho National Lab	US DOE/Oak Ridge National Lab	Massachusetts Inst. of Technology	University of Missouri	US Department of Commerce/NIST
Power, MW_{th}	250[b]	85	6	10	20
Maximum Thermal Flux, n/cm^2-s	1.0E+15	3.0E+15	7.0E+13	6.0E+14	4.0E+14
Maximum Fast Flux[c], n/cm^2-s	5.0E+14	1.0E+15	1.7E+14	1.0E+14	2.0E+14
Irradiation Locations (in-core)	47	37	3	3	10
Core Height, cm	122	61.0	61.0	61.0	27.5x2 (split)
Loops (PWR/BWR/other)	6	0	1	0	0
Vertical Channels (replaceable fuel)	0	0	2	0	0
Rabbits (core/reflector)	1/0	1/2	0/2	0/2	5
Beam Ports	0	4	9	6	18
Irradiation locations (reflector/pool)	24/36	42	9/0	12/3	7
Highest Flux Large Experiment Position Diameter, cm Height, cm Fast Flux[b], n/cm^2/sec Thermal Flux, n/cm^2/sec	NE/NW Flux Trap (n=2) 13.7 122 5.0E+14 1.0E+15	Large Removable Beryllium Position (n=8) 4.64 61.0 5.3E+14 9.7E+14	LWR Loop Fixture 2.54 55.9 1.2E+14 3.6E+13	Center Test Hole Flux Trap 13.6 61.0 6E+13 6E+14	Small Removable Experimental Thimbles (n=4) 6.35 73.7 2E+14 (est) 3E+14 (est)
Largest Volume Experiment Position Diameter, cm Height, cm Fast Flux[b], n/cm^2/sec Thermal Flux, n/cm^2/sec	NE/NW Flux Trap (n=2) 13.7 122 5.0E+14 1.0E+15	Large Vertical Experiment Facility (LVXF) 7.2 61.0 1.3E+13 4.3E+14	In-Core Sample Assembly (ICSA) 4.57 55.9 1.2E+14 3.6E+13	Center Test Hole Flux Trap 13.6 61.0 6E+13 6E+14	Large Removable Experimental Thimbles (n=6) 8.89 73.7 2.0E+14 4.0E+14
Test Conditions	Gas-cooled (active), instrumented, static capsules (passive), PWR loops. Limited transient testing capabilities.	Gas-cooled (active), instrumented, static capsules (passive).	In-core flow loops at PWR or BWR conditions, HTGR materials loop up to 1600 C, gas-filled static capsule with instrumentation available.	Static capsules only.	Static capsules only.
Available Instrumentation	Passive: flux wires, melt wires (temperature), SiC temperature monitors. Active: neutron and gamma flux and temp.	Passive: flux wires, melt wires (temp.), SiC temperature monitors. Active: neutron and gamma flux and temperature plus 12 neutron scattering instruments in beamlines.	Instrumented gas-filled capsule (ICSA), instrumentation in PWR loop, passive temperature and neutron flux.	Triple axis spectro-meter on one beam port & high res. powder diffractometer on another; third beam port used for animal BNCT. Radiochemical analysis tools (MS, OES, etc.).	Passive: flux wires, melt wires (temperature).

[a]See list of acronyms.

[b]ATR is typically operated at a power level in the range of 110 to 120 MW_{th}.

[c]Fast flux is the flux of neutrons with energy exceeding 0.1MeV

Table 1. Characteristics of primary U.S. irradiation testing reactors. (continued)

	Advanced Test Reactor (ATR)	High Flux Isotope Reactor (HFIR)	MIT Reactor - II (MITR-II)	University of Missouri Research Reactor (MURR)	National Bureau of Standards Reactor (NBSR)
Utilization Trend (expected)	rising	rising	rising	rising	rising
Feasibility of incorporating one or more test loops, to enable irradiation testing pressurized water, pressurized helium gas, liquid sodium or lead-alloy, or molten salt	ATR has nine "in-pile tubes" that can hold flow loops. As of FY2017, six pressurized water loops (PWL) are installed in ATR with five used exclusively by Naval Reactors. The center flux trap PWL is available for DOE-NE use. The E, NE and S flux traps do not currently have loops installed.	No flow loops in the reactor or reflector. A small loop could possibly be built to fit in a LVXF. The ex-core loop equipment would have to be housed elsewhere in the facility. HFIR does have the capability to actively control temperature in irradiation experiments with a mixture of cooling gases.	The MITR-II has the capacity to install an LWR-condition loop. It also has a fixture for performing high-temperature irradiations under inert gas (He/Ne mixture) at 1000-1600C. Active gas cooling is available. Custom fixtures can be constructed as required.	It could be possible to install a flow loop in the center flux trap, with significant alterations to the reactor and facility. The flux trap is external to the RPV. MURR's main mission is isotope production, which utilizes this position almost exclusively.	The NBSR has no flow loops and it is unlikely that a flow loop could be designed and installed because of the core configuration and the small diameter of the experimental thimbles.
Initial Criticality/Operation	7/2/1967	8/1/1965	7/21/1958 (MITR-1) 8/14/1975 (MITR-II)	10/13/1966	12/7/1967
Facility Age, years	49.5	51.5	58.5 (MITR-I)	50	49
Facility Design Lifetime	≥ 2040	≥ 2050	≥ 2050	≥ 2056	≥ 2065
Feasibility and Prospects for lifetime extension	Life extension program completed in 2015 (core internals replacement scheduled for 2020).	Ongoing life extension program (core internals replacement 2023).	Ongoing life extension program in accordance with USNRC.	Ongoing life extension program in accordance with USNRC. All parts replaceable, including RPV.	Ongoing life extension program in accordance with USNRC. Aging management with upgrades as needed.
Hot Work Facilities	HFEF, IMCL, RAL, SPL (planned)	Nearby hot cells (REDC, IMET, IFEL)	Co-located small hot cells /hot boxes in reactor compartment.	State-of-the-art hot cells, shielded glove boxes, clean rooms, and laboratories. State-of-the-art hot cells, shielded glove boxes, clean rooms, and laboratories. Hot cells, glove boxes, clean rooms.	Limited
Associated Facilities	Gamma Irradiation Facilities. TREAT Reactor for transient testing.	Gamma Irradiation Facilities, neutron scattering beamlines, SNS and other ORNL resources.	MIT materials characterization laboratories, Gamma irradiation using spent fuel.	Neighboring Harry S. Truman Memorial Veterans Administration Hospital. 16.7 MeV cyclotron for radioisotope production and materials studies.	Extensive neutron technique beamlines.
PIE and Characterization Facilities	Materials and Fuels Complex, other INL facilities.	LAMDA, IMET, IFEL	Limited PIE capabilities; Neutron activation analysis.	University of Missouri facilities (limited radioactivity)	Extensive neutron detection instrumentation.

Finally, the availability and capacity of the existing irradiation facilities for new testing missions will require additional evaluation, considering the specific needs of the developers of advanced nuclear energy technologies. Each facility is currently operated to meet the needs of its owner and users, with the expectation of growing demand for its capabilities and services in the future. Limitations of available instrumentation and experimental support functions at existing facilities are key additional considerations. Additional investment is required for U.S. facilities to improve these capabilities so that they are at least comparable to options available at international facilities.

Conclusions

While existing operational facilities for irradiation testing in the U.S. provide significant capability for testing fuels and materials in a thermal neutron spectrum, they provide only a very limited capacity for testing in a fast neutron spectrum. Moreover, the existing reactors are not currently configured for irradiating fuels and materials in environments (thermal, hydraulic, mechanical, and chemical) representative of advanced liquid metal or molten salt reactors.

Capabilities for irradiation testing in a fast-spectrum and/or a prototypic operating environment will be needed to support the development, qualification and continued improvement of advanced fuels and materials. A significant flux of fast neutrons in a test reactor would also support the accelerated testing of advanced materials and fuels proposed for LWRs and other types of thermal reactors.

The construction of a new irradiation test facility would entail a significant financial investment. Both the magnitude and timing of this investment are important considerations that should be addressed as part of the decision process for the facility.

Current and Near-Term International Irradiation Capabilities

The NEAC International Subcommittee's contribution to the overall effort to assess the irradiation capabilities of existing and near-term international irradiation facilities was primarily obtained by utilizing existing information from publicly available prior assessments and databases, such as the Nuclear Science User Facilities (NSUF) database and the Generation IV International Forum (GIF) database. The Idaho National Laboratory (INL) assisted in collecting this information because of their ease of access to these databases. This information was augmented or updated in a few cases by responses to letters sent by the International Subcommittee to contacts in the international nuclear community requesting information on their potential user needs and their potential interest in participating in an U.S. advanced test reactor project. Appendix D.1 lists the organizations contacted within each country. Appendix D.2 also contains an example of a typical request letter.[c]

The capabilities of selected international research and test reactors are summarized in Table 2. A more extensive list is found in Appendix D.3. Most of these reactors are thermal spectrum reactors cooled with light water, although the Halden Boiling Water

[c]Some of the international respondents provided data to update information as to the characteristics of their facilities.

Reactor (HBWR) is cooled with heavy water. In addition, among the thermal test reactors, there are three helium-cooled reactors, one of which is a demonstration reactor consisting of two modules (HTR-PM). Finally, one of these reactors is cooled by molten salt with fixed pebble fuel (TMSR). It should be remembered that two of the advanced reactors that are of interest to U.S. developers are thermal reactors: high temperature gas-cooled reactors (HTGRs) and molten salt reactors (FHRs and MSRs). Testing of fuels and materials for these two reactor types can be performed in thermal spectrum test reactors, which are plentiful and relatively easy to access.

Table 2. Characteristics of selected international irradiation facilities.

Reactor	Halden BWR (HBWR)	Belgium Reactor-2 (BR2)	High Flux Reactor (HFR)	Japan Materials Test Reactor (JMTR)	JOYO	BOR-60	RJH (Reactor Jules Horowitz)
Country /Owner	Norway IFE	Belgium SCK-CEN	Netherlands EU	Japan JAEA	Japan JAEA	Russia ROSATOM	France CEA
Power, MW_{th}	20	100	45	50	140	60	100
Maximum Thermal Flux, n/cm^2-s	1.5 E+14	1.0 E+15	2.7 E+14	4.0 E+14	5.7 E+15	2.0 E+14	3.0 E+15
Maximum Fast Flux[d], n/cm^2-s	0.8 E+14	7.0 E+14	5.1 E+14	4.0 E+14	4.0 E+15	3.7 E+15	1.0 E+15
Initial Criticality	1959	1961	1961	1968	1977	1968	2018?
Irradiation capabilities	10 loops 40 in-core positions 5 reflector positions 0 rabbits 0 beam ports	1 loop 80 in-core channels[e] 0 rabbits 0 beam ports	0 loops 19 in-core positions 12 reflector positions 0 rabbits 12 beam ports	2 loops 20 in-core positions 40 reflector positions 2 rabbits 0 beam ports	0 loops 21 in-core positions 1 reflector positions 0 rabbits 0 beam ports	0 loops 15 in-core positions 10 reflector positions 0 rabbits 0 beam ports	1 corrosion loop 10 in-core positions 26 reflector positions 0 rabbits 0 beam ports
Largest thermal flux test volume (thermal flux, n/cm^2-s)	7.0 cm dia. (open D_2O) 3.5-4.5 cm dia. (test capsule)	90 cm height 8.0 cm dia. 20 cm dia.	60 cm height (2.9 E+14)	3.6 cm dia. 85 cm height (4.0 E+14)			Special LWR experiment rigs (MICA, CALIPSO, ADELINE, MADISON, etc.)
Largest fast flux test volume (fast flux, n/cm^2-s)	High power booster rigs (4 - 6 E+13)		60 cm height (1.8 E+14)		60 cm height Fuel bundle-sized capsules (4.0 E+15)	4.4 cm width, 45 cm height 3.7 E+15	
Test Conditions[f]	PWR, BWR GCR, HWR, VVER	PWR	PWR, BWR, GCR	PWR, BWR, GCR	SFR	SFR	PWR, BWR, GCR, SFR

[d]E > ~ 0.1 MeV (location dependent).
[e]Some channels in reflector, depending on core configuration.
[f]BWR-Boiling Water Reactor, GCR-Gas Cooled Reactor
PHWR - Pressurized Heavy Water, PWR-Pressurized Water Reactor
SFR - Sodium Fast Reactor, VVER- Vod0Vodyan Energetichesky Reactor

Of more direct interest to the NEAC charge from DOE "to support the development and deployment of advanced non-light water reactors" are the fast-spectrum test reactors, typically cooled with liquid sodium. As indicated in Table 2 (and shown in Appendix D.3), there are far fewer of these than the thermal test reactors. The fast neutron spectrum of these reactors is usually about 10 times greater than the equivalent fast-spectrum in the thermal test reactors. This means that it would take significantly longer time to achieve the desired neutron damage if the irradiations were performed in thermal test reactors. In addition, most of these fast-spectrum test reactors are not readily available to U.S. developers to perform irradiation experiments for a variety of reasons: some are currently shutdown, not yet constructed, or in countries with which the U.S. has problematic civil nuclear relationships.

Recommendations

The recommendations provided for the international irradiation needs focus primarily on the need for a more complete picture of the situation outside the U.S. Specifically, DOE should:

- Utilize the ongoing activity of GIF to catalogue international test reactor capabilities (as well as other advanced reactor development activities) to periodically update the NSUF database, which is already continuously maintained;
- Engage in more detailed dialog with those international organizations that already have advanced irradiation facilities or are currently planning to build such facilities to determine the detailed testing capabilities of these facilities and their availability for potential use by U.S. companies; and
- Based on potential emerging policy changes by the new administration, consider engaging organizations in Russia and India to determine if their existing or planned advanced irradiation facilities could be available to U.S. companies.

III. User Needs

Approach

As noted above, the Ad Hoc Subcommittee was formed from the NEAC Nuclear Reactor Technology and Fuel Cycle Subcommittees to identify domestic user needs for a new test reactor. This subcommittee decided that the most effective method to gain user information would be to invite potential users from industry and from government to a meeting to obtain their views of the need for a test reactor and to specify desired test reactor capabilities. This allowed interested users to participate in an open discussion and to help this subcommittee understand commonalities among users and develop findings for NEAC. The Ad Hoc Subcommittee invited over twenty organizations from industry, government and laboratories (see Appendix C.1). A wide range of companies were invited based on their expressed interest to DOE-NE for test reactor usage; government agencies that have used test reactors for their irradiation testing activities in the past were also invited.

The meeting was held on October 28, 2016, at ANL. The agenda for the meeting and list of attendees are provided in Appendix C.2. Most government agencies did not respond to this request. While representatives of Naval Reactors attended, they declined to make a formal presentation. The U.S. NRC representatives were observers at the meeting. The representatives from AREVA were unable to attend, but did provide a formal response. In addition to AREVA, TerraPower, Advanced Reactor Concepts (ARC), Westinghouse, and the Fast Reactor Working Group[g] submitted letters to DOE or the NEAC Ad Hoc Subcommittee.

All meeting presentations and letter reports from industry representatives are available at the NEAC website: https://www.energy.gov/ne/services/nuclear-energy-advisory-committee.

Requested Potential User Information

Each organization that presented was asked to address their required user capabilities for an irradiation test reactor. The Ad Hoc Subcommittee provided a suggested listing of possible desired user capabilities that included:

- Required neutron flux and fluence
- Materials to be tested (quantities, durations, test article sizes)
- Fuels to be tested (quantities, durations, test article sizes)
- Test environment (test volume, ambient fluid, flows, temps, pressures, chemistry)
- Fission gas sampling and removal
- Data requirements: temperature, flux, fluence, cladding stress, coolant flow

To the extent possible, the subcommittee sought an understanding of the desired real-time measurements (e.g., elongation/swelling, fission gas release, thermal conductivity degradation, etc.) during irradiation. In addition, the Ad Hoc Subcommittee requested that potential users describe prior testing (general types of data obtained, such as material or component survivability, fuel performance testing, etc.; irradiation conditions such as thermal/fast flux and associated fluence, test environment such as coolant, etc.) and planned tests.

Summary of Presentation and Discussions

The consensus of received input was that a test reactor would support many specific missions, including:

- Fast reactor fuel and materials development needs;
- Accelerated materials radiation damage tests (e.g., higher dpa/yr);
- Sufficient fuel and materials test volume needs;

[g]In its letter, the Fast Reactor Working Group indicated that it consists of the following developers and industry leaders: Oklo, GE Hitachi Nuclear Energy, TerraPower, ARC, Westinghouse, General Atomics, Southern Company, Duke Energy, and Exelon.

- Improved real-time data acquisition (at least comparable to foreign test reactors);
- Avoiding difficulties with fuel and materials testing at foreign test reactors.

Some of the industry representatives (e.g., AREVA, GE-Hitachi, TerraPower, Westinghouse, and Terrestrial Energy), who have an interest in pursuing advanced reactors, were of the view, however, that a test facility was not essential for the commercial advancement of their technology. Each industry presentation provided a list of suggested test reactor capabilities that are detailed in their presentations. Appendix C.3 provides the General Atomics response as a representative example of the range of needed capabilities, i.e., multiple small test volumes, as well as large test volumes or flow loops under prototypic conditions. Written input from AREVA indicated that a new test reactor was not required for deployment of their thermal spectrum SC-HTGR, but observed that a new test reactor, with enhanced capabilities, would be of interest for longer-term SC-HTGR and accident tolerant fuel evaluations.

For those industry vendors supporting fast reactor development and deployment (e.g., General Atomics, GE-Hitachi, TerraPower, and Westinghouse Electric), the test reactor must be a fast-spectrum test reactor, one with a high fast neutron flux (0.5E14 - 1.0E16 n/cm^2-sec, E > ~0.1 MeV) with a large test volume (>10 liters and > 1 meter length). GE-Hitachi noted that it could proceed without such testing if past fuel and material qualifications at EBR-II were sufficient for regulatory review and approval; however, additional testing would be desirable. TerraPower stated that a letter of support for a test reactor was sent to the DOE-NE Assistant Secretary. TerraPower indicated that they were currently relying on testing in foreign test reactors, but noted that this approach was becoming quite problematic, i.e., significant delays were encountered for a range of technical and non-technical reasons.

For those industry developers exploring innovative reactor concepts (e.g., Elysium Industries, Oklo, Terrestrial Energy, and Transatomic Power), a fast-spectrum test reactor was preferred to accelerate materials and fuels testing. A fast-spectrum allows materials to experience a larger damage rate and is an accepted technical approach to study radiation damage of materials. This benefit was also noted in the DOE AT/DR Options Study.[3] While a test reactor was desirable, Terrestrial Energy stated that its first prototype could be used for any materials qualification testing required for its reactor concept.

Several vendors developing non-LWR concepts (e.g., TerraPower, GE-Hitachi, GA, AREVA, Westinghouse Electric, etc.) expressed interest in having loops containing coolant that will be used in their reactor design (e.g., sodium, molten salt, helium, lead, etc.).

For those industry vendors that are developing LWR innovative fuels or high-burnup fuels (e.g., Lightbridge, GE-Hitachi, AREVA and Westinghouse Electric), the test reactor would need to provide accelerated testing in larger volumes than ATR or HFIR, i.e., tens of liters of test volume space with flow loop or test assembly lengths more than 1 meter. These large test volumes would also be important for those organizations wishing to evaluate the performance of large components and advanced instrumentation. Several potential users also noted difficulties in getting needed testing time in foreign test reactors.

Finally, all potential users noted the desire to have advanced instrumentation development as part of any new test reactor, i.e., real-time measurements not available at ATR or HFIR to support data collection during irradiation testing. Additionally, the potential users noted the need to have a test reactor with high reliability and availability with appropriately trained staff.

Finding and Recommendation

Input collected by the Ad Hoc Subcommittee led to one finding and one recommendation.

Finding: There are several missions that a fast-spectrum test reactor could provide.

The Ad Hoc Subcommittee found that a fast test reactor can provide the needed capabilities for prototypic test conditions as well as accelerated fuel and material testing. In addition, a domestic fast test reactor would eliminate the notable difficulties in being able to schedule materials and fuel testing in foreign reactors. These difficulties involve reliable scheduling at these facilities as well as bureaucratic delays due to export control requirements for material transfers to and from the foreign test reactor site. Finally, the Ad Hoc Subcommittee notes that to provide support for the DOE-NE Advanced Reactor Strategy for advanced non-LWR demonstration by 2030, a test reactor program plan (design, review, and construction) needs to begin now to be available for timely operation for materials and fuel qualification testing.

Recommendation: The Ad Hoc NEAC Subcommittee recommends that DOE-NE proceed immediately with pre-conceptual design planning activities to support a new test reactor (including cost and schedule estimates). These activities should expeditiously lead to the preparation of a mission need document. The planning activities would summarize the test reactor capability gap, describe why current facilities are not sufficient to address the gap, and discuss why a new test reactor is needed to support the DOE-NE strategic plan and its overall R&D program for advanced reactor concepts, as well as provide a pre-conceptual design of the reactor to meet stated technical objectives.

International User Needs and Interest in Collaboration

Approach

The information request letters sent by the International Subcommittee to international organizations requested information about their desired capabilities in a new U.S. test reactor (see Appendix D.1 and Appendix D.2). Of the 47 information request letters issued by the NEAC International Subcommittee, which were sent to 31 organizations in 24 countries, only 18 organizations responded.

Findings and Recommendations

Appendices D.3 and D.4 summarize the written responses. Most organizations did not provide a response that answered all the detailed technical questions that were asked in the information request letters. Rather, most responders provided high-level comments and/or indicated their interest in participating in a U.S. advanced test reactor project if approved.

A concise summary of the responses on a country-by-country basis follows:

- Japan is well positioned with their own SFR and HTGR test reactors for the next 30 years.
- The Republic of Korea plans to build a SFR by 2028 and currently uses the BOR-60 reactor in Russia, but would be interested in participating in a new U.S. irradiation facility if it is based on sodium technology.
- China already has a SFR test reactor with no plans to add a new one, but it would be interested in participating in a new U.S. irradiation test reactor program.
- The United Kingdom does not have any test reactors at this time; it uses the HBWR now and plans on using the RJH in the future. However, the fast flux is not adequate for advanced fast reactor (GFR, SFR, and LFR) testing. Currently all its planned experiments are in the HBWR, but would be interested in a new U.S. irradiation facility in 2030 if the fast reactor capability of the RJH does not materialize.
- The European Commission is interested in lead-bismuth, SFR, and GFR, but planning is "not well advanced." Future interest in a new U.S. irradiation facility depends on the EU circumstance at that time.
- The Czech Republic has no plans for a new irradiation facility and would utilize the RJH when available. It would be interested in exploring collaboration with the U.S. on an advanced irradiation facility. Their existing LVR-15 test reactor can be utilized in non-LWR areas to complement a new irradiation facility.
- Argentina, Brazil, and Poland are not interested in a new fast flux U.S. irradiation facility; they are focused on LWRs.
- France has plans for a new SFR, but has indicated that they would be interested in participating in a new fast flux U.S. irradiation facility. They suggested several potential forms of participation.

It is difficult to draw firm conclusions from the responses received from the international organizations. Those that answered to the detailed questions were generally consistent in their user needs with those from the potential U.S. user community and some other countries might be interested in using a new U.S. facility. Some international organizations pursuing irradiations in a new U.S. facility may encounter difficulties similar to those encountered by U.S. organizations in pursuing irradiations abroad. In the absence of binding financial commitments from international partners, the decision to proceed with a new advanced test reactor should be based solely on its ability to address U.S. needs. The potential for binding international commitments should be evaluated and pursued if compatible with U.S. needs.

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IV. Summary and Recommendation

This document summarizes the response to a charge requesting that NEAC chairs form a team "to assess the need and determine the requirements for an irradiation test reactor which would augment existing domestic capabilities to support the development and deployment of advanced non-light water reactors as well as to accommodate the future needs of light water reactor technologies." DOE guidance for this charge emphasized the need for an independent evaluation as to whether there is sufficient projected demand from the community of potential users (e.g., DOE, other government agencies, universities, industry, international) that can't be filled using existing readily accessible capabilities (including alternate facilities, methodologies and approaches) to warrant launching a U.S. effort that could lead to construction of a new test reactor.

Three NEAC subcommittees completed activities to address this charge:

- The International Subcommittee collected information about international irradiation facilities and solicited information from international organizations about their interest in participating in and using a new U.S. fast-spectrum test reactor,
- The Facilities Subcommittee collected information related to existing U.S. irradiation capabilities, and
- A special Ad Hoc Subcommittee composed of members from the NEAC Reactor Technology and Fuel Cycle Subcommittees obtained input from a broad spectrum of possible domestic users of a new irradiation facility.

Interim results from the three subcommittees were discussed at the December 2016 NEAC meeting. Consensus findings and recommendations from this effort are highlighted in this section.

Irradiation Capabilities

Finding: *Appropriate investments are required for continued operation of U.S. test reactors. Furthermore, limited instrumentation and experimental support capabilities are available at existing U.S. facilities. Additional investment is required for U.S. facilities to offer capabilities that are sought by users.*

Existing U.S. test reactors provide significant capability for testing fuels and materials in a thermal neutron spectrum, but provide limited capacity for testing in a fast neutron spectrum. Fast fluxes are limited to 5×10^{14} n/cm^2/s, E > 0.1 MeV or 6 dpa per year. Existing U.S. facilities are not currently capable of irradiating fuels and materials in thermal, hydraulic, mechanical, and chemical environments representative of advanced liquid-metal or molten-salt reactors. Furthermore, U.S. facilities are approximately 50 years old.

Finding: *There is significant capability in existing international test reactors not available in U.S. facilities. However, this international capability can be difficult to access.*

Most international facilities are thermal spectrum reactors cooled with water; but several have or plan to include loops containing sodium or molten salt. There are fast-spectrum test reactors that are already operational (or expected to become operational) in several countries. Experience indicates that reliance on data obtained from a test reactor located in another country can be problematic due to bureaucratic delays and costs associated with export control and international shipping requirements, as well as due to schedule delays associated with the high demand for the limited number of available fast-spectrum facilities.

User Needs

Finding: *There are several missions that a fast-spectrum test reactor could provide.*

A fast test reactor can provide the needed capabilities for prototypic test conditions as well as accelerated fuel and material testing. In addition, a domestic fast test reactor would eliminate difficulties associated with accessing and utilizing foreign test reactor sites.

Finding: *The decision to proceed with a new test reactor should not be contingent on international participation.*

Although international participation is of interest, the decision to proceed with a new advanced test reactor should be based on its ability to address U.S. needs absent binding commitments for funding by international partners. International organizations desiring irradiations in a new U.S. irradiation facility will encounter similar difficulties encountered by U.S. organizations pursuing irradiations in international facilities. The potential for binding international commitments should be evaluated and pursued if compatible with U.S. needs.

Finding: *Implementation of the DOE-NE Advanced Reactor Strategy requires immediate development of a program plan.*

The DOE-NE Advanced Reactor Strategy[1] calls for an advanced non-LWR demonstration by 2030. Two of the advanced reactors that are of interest to U.S. developers are thermal reactors: high temperature gas-cooled reactors (HTGRs) and molten salt reactors (FHRs and MSRs). Testing of fuels and materials for these two reactor types can be performed in thermal spectrum test reactors (although it may be necessary to have loops containing coolants associated with such technologies). However, other advanced reactor designs will require irradiation data in international facilities, a new advanced test reactor, or a design-specific demonstration/prototype reactor. A test reactor program plan (design, review, and construction) needs to begin now to be available for timely operation for materials and fuel qualification testing of a broad range of advanced non-LWR demonstration reactors.

Recommendation: *The Ad Hoc NEAC Subcommittee recommends that DOE-NE proceed immediately with pre-conceptual design planning activities to support a new test reactor (including cost and schedule estimates).*

These activities should expeditiously lead to the preparation of a mission need document. The planning activities would summarize the test reactor capability gap, describe why current facilities are not sufficient to address the gap, and discuss why a new test reactor is needed to support the DOE-NE strategic plan and its overall R&D program for advanced reactor concepts, as well as provide a pre-conceptual design of the reactor to meet stated technical objectives.

The above findings and recommendation are limited to the need for a new U.S. test reactor. It is unclear whether federal funding, which would be required for deploying most of the proposed advanced reactors or any new DOE test reactor, can be available for both test and demonstration projects. NEAC members are not in a position to judge funding prospects. Furthermore, we did not assess the tradeoffs between a demonstration and a test reactor. Such an assessment would require additional information, such as business plans from advanced reactor designers and detailed knowledge about the technology readiness of their concepts.

V. References

[1] US DOE, “Vision and Strategy for the Development and Deployment of Advanced Reactors”, Version 21, Unpublished Draft, May 27 2016.

[2] J. Deutch, et al., “Secretary of Energy Advisory Board Report on the Task Force on the Future of Nuclear Power”, September 22, 2016

[3] D. Petti, et al., Advanced Demonstration and Test Reactor Options Study, INL/EXT-16-37867, Rev. 1, July 2016.

[4] “Facilities for the Future of Nuclear Energy Research: A Twenty-year Outlook”, DOE-NE, February 2009.

[5] “2012 Annual Report for the Research Reactor Infrastructure Program”, Idaho National Laboratory.

[6] “Research and Test Facilities Required in Nuclear Science and Technology”, NEA, Organization for Economic Co-operation and Development, ISBN 978-92-64-99070-8, NEQA No. 6293, OECD 2009.

[7] “Nuclear Energy for the Future, Executive Recommendations for R&D Capabilities”, Battelle, July 2008.

[8] “A Strategy for Nuclear Energy Research and Development” EPRI and INL, INL/EXT-08-15158, December 2008.

[9] “Required Assets for a Nuclear Energy Applied R&D Program” INL, 2008.

[10] “Assuring a Future in U.S.-Based Nuclear and Radiochemistry Expertise”, National Academy of Sciences, ID=13308, 2012.

Appendix A – Charge Letter and Contributors

A.1 Charge Letter (page 1 of 2)

Department of Energy
Washington, DC 20585

July 29, 2016

Dr. Richard Meserve
Covington & Burling LLP
850 Tenth Street, NW
Washington, D.C. 20001-4956

Dr. Joy Rempe
360 Stillwater
Idaho Falls, ID 83404

Dear Dr. Meserve and Dr. Rempe:

I request that you form a team, comprised of members from the Nuclear Energy Advisory Committee's (NEAC's) Nuclear Reactor Technology, Facilities and International subcommittees, to assess the need and determine the requirements for an irradiation test reactor which would augment existing domestic capabilities to support the development and deployment of advanced non-light water reactors as well as to accommodate the future needs of light water reactor technologies. Nuclear power is an important carbon free power source for the U.S. and the world. Beginning around 2030 a significant number of operating U.S. nuclear reactors will reach 60 years of age and questions exist over the ability to extend operation to 80 years. Interest is increasing in exploring the development and deployment of advanced reactor technologies using non-light water coolants. These interests, coupled with draft legislation under consideration by the United States Congress, point to a growing interest in the construction of an irradiation test reactor capability in the U.S.

The purpose of this review is to independently determine the requirements and overall capabilities (e.g., neutron spectrum/spectra, testing environments, etc.) for a new irradiation test reactor and to perform a comparison with alternate facilities, methodologies, and approaches for meeting these needs and providing these capabilities. The needs, capabilities and options should be examined from the long term perspective (2030 and beyond).

The requirements review team should consider the needs of the entire user community including National Laboratories, academia, industry, reactor vendors, supply chain manufactures (fuels, I&C, heat exchangers), material suppliers, the United States Government (DOE, NRC, NASA, NNSA, DOD, etc.), and the international community as well as the time frame, if needed, that an irradiation test reactor capability would be required. The needs of the user community should be obtained via one-on-one meetings and/or the use of questionnaires or other communication mechanisms. In this context, the evaluation of the need for a US facility should include consideration of whether US needs can be met by facilities that exist or that are planned abroad. This evaluation should be

A.1 Charge Letter (page 2 of 2)

coordinated with the NEAC International Subcommittee's effort identify international nuclear facilities that the U.S. nuclear industry could leverage to support the further development of the GAIN Initiative and complement existing U.S. facilities.. A summary of this information should be presented in a public workshop in order to further facilitate feedback from the community on the needs of the users.

In parallel with the collection of the user community needs, the National Laboratories will be tasked with examining the range of technical options that could best meet the requirements of the user community, including an assessment of the cost, schedule and key risks associated with those technical options. Resources from the National Laboratories will also be made available to conduct meetings and/ or workshops and support the review team, as needed.

The team/sub-committee should conduct its meetings and or workshops as needed over the next several months with a status report provided during the late 2016 full NEAC meeting and final report delivered March 1, 2017. John Herczeg from my staff will provide assistance and coordination for the sub-committee, as well as coordination with our National Laboratories. The final report should recommend what capabilities, if anything, are required to address the perceived need for an irradiation test reactor, and when these capabilities should be available.

Sincerely,

John F. Kotek
Acting Assistant Secretary
for Nuclear Energy

cc: Dr. Michael Corradini
Chair, NEAC Nuclear Reactor Technology Subcommittee

Dr. John Sackett
Chair, NEAC Infrastructure Subcommittee

Dr. John Kelly
Deputy Assistant Secretary for Nuclear Reactor Technologies

Thomas J. O'Connor
Director, Office of Advanced Reactor Technologies

John Herczeg
Deputy Assistant Secretary for Fuel Cycle Technologies

Regis Matzie
Chair, NEAC International Subcommittee

A.2 Participants in each NEAC Subcommittee

Name	Position(s)
NEAC Oversight	
Richard A Meserve*	NEAC Co-Chair
Joy L. Rempe*	NEAC Co-Chair
Ad Hoc Subcommittee	
Michael L. Corradini	Chair, Nuclear Reactor Subcommittee
Alfred Sattelberger*	Chair, Fuel Cycle Subcommittee
Doug Chapin	Member, Nuclear Reactor Subcommittee
Ron Omberg	Member, Fuel Cycle Subcommittee
Burt Richter*	Member, International Subcommittee
Joy Rempe*	Member, Nuclear Reactor Subcommittee and Fuel Cycle Subcommittee
John I. Sackett*	Member, Infrastructure Subcommittee
John Stevens	Member, Fuel Cycle Subcommittee
Karen Vierow Kirkland*	Member, Nuclear Reactor Subcommittee
Facilities Subcommittee	
John I. Sackett*	Chair
Dana Christensen*	Member
David Hill	Member
Michael Corradini	Member
Hussein Khalil	Member
Andy Klein	Member
Paul Murray	Member
Mark Rudin*	Member
Alfred Sattelberger*	Member
Andrew Sherry	Member
International Subcommittee	
Regis Matzie*	Chair
Matthew Bunn*	Member
Tom Cochran	Member
Sue Ion*	Member
Thomas Issacs*	Member
Maria Korsnik*	Member
William Martin	Member
Lee Peddicord	Member
Burt Richter*	Member
Allen Sessoms	Member

*NEAC Member

Appendix B – Facilities Subcommittee Supporting Information

B.1 U.S. Test Reactor Characteristics and Capabilities

	Advanced Test Reactor ATR	High Flux Isotope Reactor HFIR	MIT Reactor - II MITR-II	University of Missouri Research Reactor MURR	National Bureau of Standards Reactor NBSR	Fast Flux Test Facility FFTF	Experimental Breeder Reactor - II EBR-II
Type	LWR Tank	LWR Tank	LWR Tank with heavy water outer tank	LWR Tank	Heavy Water Tank	Fast Reactor, Liquid sodium coolant	Sodium cooled fast reactor
Owner	US DOE/Idaho National Laboratory	US DOE/Oak Ridge National Laboratory	Massachusetts Inst. of Technology	University of Missouri	US Department of Commerce/NIST	US DOE/Hanford Site	US DOE/Idaho National Laboratory
Country	USA	USA	USA	USA	USA	USA	USA
Power, MW_{th}	250	85	6	10	20	400	62.5
Maximum Thermal Flux, n/cm^2-s	1.0 E+15	3.0E+15	7.0E+13	6.0E+14	4.0E+14		
Maximum Fast Flux, n/cm2-s	5.0 E+14	1.0E+15	1.7E+14	1.0E+14	2.0E+14	4.6E+15	2.5E+15
Irradiation locations (in-core)	47	37	3	3	10	91	22
Core Height [in]	48	20	24	24	11x2		
Loops (PWR/BWR/other)	6	0	1	0	0		
Vertical Channels (replaceable fuel)	0	0	2	0	0		
Rabbits (core/reflector)	1/0	1/2	0/2	0/2	5		
Beam Ports	0	4	9	6	18		
Irradiation locations (reflector/pool)	24/36	42	9/0	12/3	7	108	
Test Conditions	Gas-cooled (active), instrumented, static capsules (passive), PWR loops. Limited transient testing capabilities.	Gas-cooled (active), instrumented, static capsules (passive	PWR loop, gas-filled static capsule with instrumentation available,epithermal BNCT, in-core flow loops at LWR conditions, high temp gas reactor materials loop up to 1600C	static capsules only	static capsules only		
	Advanced Test Reactor	**High Flux Isotope Reactor**	**MIT Reactor - II**	**University of Missouri Research Reactor**	**National Bureau of Standards Reactor**	**Fast Flux Test Facility**	**Experimental Breeder Reactor - II**
Available Instrumentation:	Passive: flux wires, melt wires (temperature), SiC temperature monitors Active: neutron and gamma flux and temperature.	Passive: flux wires, melt wires (temp.), SiC temp. monitors Active: neutron and gamma flux and temperature plus 12 neutron scattering instruments in beamlines.	Instrumented gas-filled capsule (ICSA), instrumenation in PWR loop, passive temperature and neutron flux.	Triple axis spectrometer on one beam port & amp; high resolution powder diffractometer on another with resolution of 0.0015 (del D/D), third beam port used for animal BNCT. Radiochemical analysis tools (MS, OES, etc.)	Passive: flux wires, melt wires (temperature).		
Hot Work Facilities:	HFEF, IMCL, RAL, SPL(planned).	Nearby hot cells (REDC, IMET, IFEL).	Co-located small hot cells /hot boxes in reactor compartment.	state-of-the-art hot cells, shielded glove boxes, clean rooms, and laboratories. state-of-the-art hot cells, shielded glove boxes, clean rooms, and laboratories. hot cells, glove boxes, clean rooms.	limited	Handford Site facilities.	HFEF
Associated Facilities:	Gamma Irradiation Facilities. TREAT Reactor for transient testing.	Gamma Irradiation Facilities, neutron scattering beamlines, SNS and other ORNL resources.	MIT materials characterization laboratories, Gamma irradiation using spent fuel.	There is a neighboring Harry S. Truman Memorial Veterans Administration Hospital. 16.7 MeV cyclotron for radioisotope productions and materials studies.	Extensive neutron technique beamlines.	Handford Site facilities.	Materials and Fuels Complex facilities. TREAT Reactor for transient testing.
PIE and Characterization Facilities:	Materials and Fuels Complex.	LAMDA, IMET, IFEL	Limited PIE capabilities; neutron activation analysis.	University of Missouri facilities (limited radioactivity).	Extensive neutron detection instrumentation.	Handford Site facilities.	Materials and Fuels Complex facilities.

B.2 Other University Research Reactors (1 of 2)

- **Idaho State University AGN-201 reactor** is a 5 watt reactor used for training.
- **Kansas State University TRIGA,** a pulsing research reactor licensed for operation up to 1.25 MW. Its primary roles are research support, education, training and outreach. It includes significant in-core and out-of –core irradiation capabilities.
- **McClellan Nuclear Research Center** (**MNRC**) at UC – Davis. This facility includes a 2 MW TRIGA research reactor. Is relatively new, build in 1990 by the Air Force for neutron radiography and now used for general research. Capabilities include tomography, neutron activation analysis, radiation effects testing, research scale isotope production and silicon doping capabilities. It is the third largest university research reactors in the nation.
- **North Carolina State University PULSTAR,** a 2 MW pool type research reactor. Because of its fuel and core design, the reactor has dynamic characteristics similar to commercial LWR power reactors. Allows for teaching experiments to measure reactivity coefficients, for example. Has significant irradiation and neutron diffraction capability. It also includes capabilities for an intense positron source and an ultra-cold neutron source.
- **Ohio State University Research Reactor (OSURR)** operates a .5 MW pool-type reactor. It is fueled with MTR-type LEU fuel. It includes significant in-core and out-of-core irradiation capability serving a wide range of researchers.
- **Oregon State University TRIGA reactor (OSTR)** is a 1 MW facility with the capability of power “pulses” that can reach several thousand MW. It is used for a wide variety of applications including chemistry, physics, geology, archaeology, nuclear engineering and radiation health physics.
- **Penn State University Breazeale Reactor (PSBR),** a 1 MW TRIGA reactor with pulsing capabilities. It is the nations’ longest continuously operating university research reactor with extensive in-core irradiation capability as well as neutron radiography. New facilities and capabilities are routinely added, including a cold neutron source and cold neutron prompt gamma activation analysis.
- **Purdue University School of Nuclear Engineering PUR-1 reactor** is a 1 KW pool type reactor utilizing flat plate MTR type fuel. It is operated primarily for education.
- **Reed College Research Reactor**, a .25 MW TRIGA reactor used for instruction, research and analysis by faculty and students at Reed College. It provides in-core irradiation capability.
- **Rensselaer Polytechnic Institute Reactor Critical Facility (RCF)** is a zero-power critical facility used for training.
- **Rhode Island Nuclear Science Center** – University of Rhode Island. This facility includes a 2 MW reactor to be used as a tool for education, research and service work related to the nuclear industry and technology. The long-term vision is for it to become an integral part of the national infrastructure. Plans are to upgrade the reactor to 5 MW.

B.2 Other University Research Reactors (2 of 2)

- **Texas A&M University Nuclear Science Center (NSC),** includes a 1 MW TRIGA reactor. It is used to produce radioisotopes for commercial use, neutron activation analysis and support for the nuclear engineering department.
- **University of California at Irvine Nuclear Reactor** is a .25 MW TRIGA with pulsing capabilities to 1000 MW. The facility specializes in neutron activation analysis. It provides tracer radionuclides and activation analysis for a wide range of applications, including solvent extraction separations of actinides and lanthanides in spent fuel reprocessing.
- **University of Florida Training Reactor (UFTR)** is a .10 MW loop-type LWR. It is used to train students to operate reactors, and to support courses in physics, chemistry, geology, and mechanical engineering anthropology and environmental sciences. It is a radiation source for various research programs such as trace element analysis of ocean sediments, river sediments foods, plants and many other materials.
- **University of Maryland Training Reactor** is a .25 MW TRIGA. It operates as need to support the educational and experimental programs of the university.
- **University of Massachusetts at Lowell Research Reactor (UMLRR)** is a 1 MW pool type reactor. Its design power capability is 5 MW which could be achieved with a licensing upgrade. It provides multidisciplinary capabilities for use in nuclear related education and research. Includes significant in-core and out-of –core irradiation capability, including fast neutrons for radiation effects research.
- **University of Missouri S&T Research Reactor (UMRR)** is a .20 MW pool type reactor. It has gamma and alpha spectroscopy capabilities and state-of-the art data acquisitions and spectrum analysis software. They provide research opportunities for faculty and students from non-reactor owning universities.
- **University of New Mexico AGN-201M reactor** is a low power reactor used for training.
- **University of Texas at Austin – TRIGA II at the Nuclear Engineering Teaching Laboratory (NETL)**, a reactor licensed for 1.1 MW operation and power pulses. Includes a cold source, 6-meter neutron guide tube, and a capillary focusing device. It is the newest U.S. University reactor, licensed in 1993.
- **University of Utah TRIGA Reactor (UUTR)** is a .10 MW reactor used for research, training and education. Supports a new nuclear engineering curriculum. Includes radiation services.
- **University of Wisconsin TRIGA Reactor,** a 1 MW facility, is an integral part of the nuclear engineering program and supports work-force development for the nuclear industry. Provides capabilities in neutron activation analysis as well as neutron radiography and radiolysis.
- **Washington State University Nuclear Radiation Center (WSUNRC)** includes a 1 MW TRIGA reactor. It provides irradiation services, radioisotope production and analytical services for researchers at PNNL as well as for the radiochemistry program at WSU. Produces radioisotopes for national laboratory and business clients. Includes a power pulsing capability (to 1000 MW) which has been frequently used in cooperation with PNNL). It has been used extensively for research in boron neutron capture therapy.

Appendix C – Ad Hoc Subcommittee Supporting Information

C.1 List of Invitees and Sample Invitation Letter to Workshop

List of Invitees

Company or Institution	Reactor Type
Advanced Reactor Concepts	Sodium Fast Reactor
AREVA	Modular High Temperature Gas Reactor
Elysium Industries	Molten Salt Reactor
Flibe Energy	Molten Salt Reactor
EPRI	Generation IV Reactor Concepts
Gen4 Energy	Lead Fast Reactor
General Atomics	Gas Fast Reactor
GE-Hitachi	Sodium Fast Reactor
Lightbridge	LWR Advanced Fuel
Oklo	Advanced non-LWR
NEI	Advanced non-LWR
Southern Company	Advanced non-LWR
Terrapower	Sodium Fast Reactor
Terrestrial Energy	Molten Salt Reactor
Transatomic Power	Molten Salt Reactor
X-Energy	Modular High Temperature Gas Reactor
Westinghouse Electric	Lead Fast Reactor
Department of Commerce	NIST Reactor
Department of Defense	Military Reactors
Department of Homeland Security	Irradiation Testing
Naval Reactors	Irradiation Testing
NNSA	Irradiation Testing
U.S. Nuclear Regulatory Commission	Safety and Regulation

Sample Invitation Letter

Alfred P. Sattelberger
Deputy Laboratory Director for Programs &
Chief Research Office (CRO)

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439-4844

1-630-252-3504 phone
1-630-200-8439 cell
1-630-252-5318 fax
asattelberger@anl.gov

September 20, 2016

Advanced Reactor Concepts
2 Wisconsin Circle, Suite 700
Chevy Chase, MD 20815

The Nuclear Energy Advisory Committee (NEAC) has been asked by DOE-NE to assess the user needs and determine the requirements for an irradiation test reactor. This would augment existing domestic capabilities to support the development and deployment of advanced non-light water reactors as well as to accommodate the future needs of LWRs.

As part of this effort, we have formed an ad-hoc committee from the NEAC Nuclear Reactor Technology and Fuel Cycle subcommittees to meet with potential users for such a facility to determine their needs and test requirements. We have scheduled a meeting for interested parties (industry and government agencies) to discuss their needs on Friday, October 28th, at Argonne National Laboratory, outside Chicago, IL.

We are contacting you to see if a representative from your organization would like to attend this one-day meeting and make a presentation about your users' specific needs for such a test reactor facility. We are still developing an agenda but envision each potential speaker would be given 30 minutes to make their presentation. The objective is to offer all attendees an opportunity to discuss with each other their requirements for a test reactor facility.

Please confirm that someone from your organization will be able to attend and who that would be no later than October 1st to Michael Corradini at corradini@engr.wisc.edu and Donna Shaw at dshaw@anl.gov.

We will provide details on the workshop as soon as possible after we assess who is attending and who will present.

We enclose the charge given to NEAC from Assistant Secretary Kotek, as well as a listing of possible requirements that would be provided by the users attending the meeting.

Sincerely,

Al Sattelberger
Deputy Laboratory Director for Programs &
Chief Research Officer

Mike Corradini
Nuclear Engr. & Engr. Physics
University of Wisconsin-Madison

APS/ds

File: 09-16-230

Potential User Needs:

Required Neutron flux and fluence

Materials to be tested (quantities, durations, test article sizes)

Fuels to be tested (quantities, durations, test article sizes)

Test Environmental Conditions (test volume, surrounding fluid, flows, temps, pressures, chemistry)

Fission gas sampling and removal

Data Requirements: Temperature, fluence, cladding stress, coolant flow

To the extent possible indicate:

- Desired real-time measurements (e.g., elongation/swelling, fission gas release, thermal conductivity degradation, etc.) during irradiation (so that test reactor designers will realize the types of test rigs that must be included in their designs).
- Describe prior testing (focus, obtained general types of data, such as material /component survivability, fuel performance testing, etc. thermal/fast, fluence, etc.) and planned tests.

C.2 Agenda and List of Attendees at Ad Hoc Subcommittee Meeting

Agenda

Test Reactor User Needs Meeting Agenda

ARGONNE LAP BLDG. 446 AUDITORIUM OCTOBER 28th, 2016

Each presenter should plan for 20 min with 10 min for Q&A

8:00 am: Welcome and Introductions – Mike Corradini

8:15 am: NEAC Charge and Background – Al Sattelberger

8:30 am: AREVA – Lew Lommers (unable to attend)

9:00 am: General Atomics – Hangbok Choi

9:30 am: General Electric – Eric Loewen

10:00 am: Terrapower – Kevan Weaver

10:30 am: Westinghouse – Paolo Ferroni

11:00 am: EPRI - Cristian Marciulescu (oral comments)

11:30 am: Working Lunch

12:30 pm: Elysium Industries – Roger Stoller

1:00 pm: Lightbridge – James Malone

1:30 pm: Oklo – Jacob DeWitte

2:00 pm: Terrestrial Energy – John Kutsch

2:30 pm: Transatomic – Sean Robertson

3:00 pm: Open Discussion

4:00 pm: Adjourn

Test Reactor Users Meeting Attendees: October 28, 2016

Name	Affiliation	Email
Speakers		
Hangbok Choi	General Atomics	hangbok.choi@ga.com
Paolo Ferroni	Westinghouse	ferronp@westinghouse.com
John Kutsch	Terrestrial USA	jkutsch@terrestrialUSA.com
Eric Loewen	General Electric	eric.loewen@ge.com
James Malone	Lightbridge	jmalone@ltbridge.com
Cristian Marciulescu	EPRI	cmarciulescu@epri.com
Josh Richard	Oklo	joshrich@oklo.com
Roger Stoller	Elysium Inc.	stollerre@mindspring.com
Kevan Weaver	Terrapower	kweaver@terrapower.com
NEAC Subcommittee		
Al Sattelberger	ANL	asattelberger@anl.gov
Doug Chapin	MPR	dchapin@mpr.com
Mike Corradini	UW-Madison	mlcorrad@wisc.edu
Ron Omberg	PNNL	ron.omberg@pnnl.gov
Joy Rempe	Rempe & Assoc.	jlrempe@cableone.net
Burt Richter	SLAC	brichter@slac.stanford.edu
Additional Attendees		
Jake Ballard	Naval Reactors	jake.ballard@unnpp.gov
Doug Crawford	ORNL	crawforddc@ornl.gov
Phillip Finck	INL	phillip.finck@inl.gov
Chris Grandy	ANL	cgrandy@anl.gov
Florent Heidet	ANL	fheidet@anl.gov
Bob Hill	ANL	bobhill@anl.gov
Stuart Maloy	LANL	maloy@lanl.gov
Vivian Sullivan	ANL	Vivian.sullivan@anl.gov
Amir Afzali	Southern Co.	aafzali@southernco.com
Everett Redmond	NEI	elr@nei.org
John Adams	US NRC	john.adams@nrc.gov
Matt Mitchell	US NRC	matthew.mitchell@nrc.gov
Alice Caponiti	US DOE	alice.caponiti@nuclear.energy.gov
Janelle Eddins	US DOE	Janelle.zamore@nuclear.energy.gov
John Herzeg	US DOE	john.herzeg@nuclear.energy.gov
William McCaughey	US DOE	bill.mccaughey@nuclear.energy.gov
Patricia Paviet	US DOE	patricia.paviet@nuclear.energy.gov
Becky Onuschak	US DOE	jrebecca.onuschak@nuclear.energy.gov

C.3 Example Response Listing Needed Test Reactor Capabilities (GA EM2)

Characteristic	GA Requested Specifications
1. Fast and thermal neutron flux levels, n/cm^2-s	Neutron flux (>1. MeV) in the range of 3E15 to 1E16
2. Fast fluence	Up to 6E23
3. Test duration	Most tests from 3-12 months. Some material tests may be longer
4. Test sample materials	SiC, UC, Si_2Zr_3, IN617, IN800, C-C
5. Test sample temps, pressures and power outputs	Test samples in helium at 1000-1800^{o}C; cold pressure at 1 atm; thermal power at 0-5kW
6. Need to sample fission gas during irradiation	Desirable to have option to sample release of fission gas by isotope from fuel pellets as function of fuel burnup
7. Size of test capsule	15-30 mm OD by 100-200 mm length. Material capsules are smaller; fuel capsules are larger
8. Measurements of test sample conditions	Temperature, fluence, cladding stress
9. Anticipated number of test capsules per year	5-20 fuel capsules and 5-10 material capsules
10. Flowing coolant loops including physical envelope, power, temps and instrumentation	Flowing re-entrant helium loop with in-core diameter of 100 mm. inlet temp at 500-600^{o}C. Pressure up to 1950 psia; test article power up to 30 kW and outlet helium temp up 1000^{o}C
11. Test sample characterization support	It is helpful to perform some pretest measurements with similar methods, instruments and personnel as post-test measurements
12. Test capsule fabrication support	This is helpful, particularly if there is a set of standard capsules that have been qualified for testing in the reactor
13. Test planning and execution support	It would be helpful to have a test reactor staff member available to help the experimenting organization with the necessary planning and preparation
14. Types of post-irradiation examinations	Dimensional changes, microstructure, mechanical strength, fracture toughness, hardness, thermal conductivity, chemical changes

Appendix D –International Subcommittee Supporting Information

D.1 List of Contacted Organizations and Sample Request Letter

Country	Organization
Argentina	National Atomic Energy Commission (CNEA)
Australia	Australian Nuclear Science and Technology Organisation (ANSTO)
Belgium	Studiecentrum voor Kernenergie (SCK•CEN)
Brazil	Eletronuclear
Canada	Chalk River Laboratories
Czech Republic	Nuclear Research Institute Řež
France	Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)
Germany	Institute for Nuclear and Energy Technologies (IKET)
	Karlsruhe Institute of Technology (KIT)
India	Indira Gandhi Centre for Atomic Research (IGCAR)
	Bhabha Atomic Research Centre (BARC)
Japan	Japan Atomic Energy Agency (JAEA)
Mexico	Instituto Nacional de Investigaciones Nucleare (ININ)
Norway	Institute for Energy Technology (IFE)
Poland	Państwowa Agencja Atomistyki (PAA)
	Narodowe Centrum Badan Jadrowych (NCBJ)
People's Republic of China	China Atomic Energy Authority (CAEA)
	Ministry of Science and Technology (MOST)
	Tsinghua University
Republic of Korea	Korea Atomic Energy Research Institute (KAERI)
Republic of South Africa	Department of Energy
Sweden	Studsvik AB
Switzerland	Paul Scherrer Institut
Turkey	Hacettepe University Rector Sanitary
Ukraine	Kharkiv Institute of Physics and Technology
United Kingdom	National Nuclear Laboratory
International Organizations	Euratom, European Commission, Joint Research Centre
	Organization of Economic Cooperation and Development Nuclear Energy Agency

D.2 Sample Request Letter (page 1 of 3)

Nuclear Energy Advisory Committee
International Subcommittee

November 4, 2016

Mr. Osvaldo Azpitarte
National Atomic Energy Commission (CNEA)
Av. Del Libertador 8250 (1429)
Buenos Aires, Argentina

Dear Mr. Azpitarte:

The United States Department of Energy (US DOE) has been evaluating the need for an advanced test reactor that could supplement the capabilities that currently exist both domestically and internationally. DOE has asked its Nuclear Energy Advisory Committee (NEAC) to provide an independent assessment of the need for and requirements of an advanced irradiation test reactor that can be used to support the development and deployment of advanced non-light water reactors as well as to accommodate the future testing needs of light water reactor technologies, e.g., fuels development. Typical of the advanced reactor technologies being considered for such a test reactor are those that are included in the Generation IV International Program. The specific technology has not been selected at this time, but will be based on several factors, including readiness level, user needs, flexibility, etc.

The International Subcommittee of NEAC has been explicitly asked to reach out to international partner organizations with which the US already has collaborations or might in the future engage in significant collaborations in nuclear energy. There are several elements in this outreach initiative which are contained in the following questions:

- Can your existing facilities complement those operating in the US today to meet our future needs in the advanced reactor (i.e., non-LWR) area?
- Are you planning on adding new facilities in the future that would meet these needs?
- If the US moves ahead with an advanced test reactor, would your organization be interested in participating in such a project and in what manner?
- If the US moves ahead with an advanced test reactor, what would be your user needs? (See attached potential user needs list.)

To facilitate your responses to these questions, I have included several attachments:

1. List of Potential User Needs (you can supplement this list with others as you see appropriate)
2. Charge Letter to NEAC from the Assistant Secretary of Nuclear Energy, John Kotek
3. A Gap Analysis of Test Reactor Capabilities for Advanced Reactor Testing that was developed jointly by US national laboratories

Your help in responding to the above four (4) questions is greatly appreciated. We would like your response by November 18, 2016, if at all possible. I understand that some of these questions may be difficult to answer in such a short time, but whatever input you can give would be greatly

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D.2 Sample Request Letter (page 2 of 3)

appreciated.

For your information, a paper copy of this letter and the associated attachments will be mailed to you shortly. This will provided a more formal route if needed by your organization. However, I would hope that you can answer the above requested information by email to speed our processing; this is important to the US DOE.

If you would like clarification on any points in this letter or have questions that need to be answered before you can respond, feel free to contact me. My contact information is:

Dr. Regis A. Matzie
Chair, NEAC International Subcommittee
Email: regismatzie@gmail.com
Phone: +1 (860) 997-5350

Sincerely,

Regis A. Matzie

Regis A. Matzie

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D.2 Sample Request Letter (page 3 of 3)

Attachment
List of Potential User Needs

1. Required neutron flux (fast and thermal) and fluence
2. Materials to be tested (e.g., quantities, durations, test article sizes)
3. Fuels to be tested (e.g., quantities, durations, test articles sizes)
4. Test environmental conditions (e.g., test volume, surrounding fluid, coolant flows, temperatures, pressures, chemistry)
5. Fission gas sampling and removal
6. Data requirements (e.g., temperature, fluence, cladding stress, coolant flow)

To the extent possible indicate:

1. Desired real-time measurements (e.g., elongation/swelling, fission gas release, thermal conductivity degradation, etc.) during irradiation (so that test reactor designers will realize the types of test rigs that must be included in their designs).
2. Describe prior testing (focus, general types of data obtained, such as material/component survivability, fuel performance testing, etc.) and planned tests.

Have you used a U.S. test reactor for irradiation services in the past? If yes, when?

When might you need an advanced test reactor as described in the cover letter?

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D.3 International Research and Test Reactors (Thermal)

Name	Type	Location	Power and Maximum Flux (n/cm^2-s)	Comment
International Thermal Test Reactors[a,b]				
HFR (Petten)[c]	Thermal Neutron Material Test Reactor (MTR)	Netherlands	45 MW 2.7×10^{14} Thermal 5.1×10^{14} Fast 5.6×10^{14} Flux (In-Core)	Two core loops. Light water cooled. Nineteen in-core irradiation channels. Twelve reflector irradiation channels. Use: Solid state physics, neutron radiography, BNCT, NAAHY, NAA Modest volumes and high flux.
SAFARI	Thermal Neutron MTR	South Africa	20 MW 2.4×10^{14} Thermal 2.8×10^{14} Fast 4.0×10^{14} Flux (In-Core)	Light water cooled. Twelve in-core irradiation channels. Two reflector irradiation channels. Use: Isotope production, neutron beam research, radiography, diffraction. Small volume high flux.
BR-2	Thermal Neutron MTR	Belgium	100 MW 1.0×10^{15} Thermal 7.0×10^{14} Fast 7.0×10^{14} Flux (In-Core)	Has water loops. Has done HTGR and SFR fuels testing and material testing in LBE. Operation likely until 2036. Light water cooled. Be, water as moderator material. Variable core (control rods, power, fuel element type, experiments). Eighty in-core irradiation channels. Some channels in reflector depending on configuration. Use: neutron radiography, fuel and material testing, isotope production, silicon doping, instrument irradiations.
HBWR (Halden)	Boiling HWR	Norway	20 MW 1.5×10^{14} Thermal 8.0×10^{13} Fast 1.5×10^{14} Flux (In-Core)	History of LWR testing. Ten Loops. Heavy water cooled. Forty in-core irradiation channels. Five reflector irradiation channels. Use: Fuel and core material performance studies, fuel and core material studies: BWR, pressure water reactor (PWR) conditions.
HANARO	Thermal Neutron MTR	Korea	30 MW 4.5×10^{14} Thermal 2.0×10^{14} Fast 4.5×10^{14} Flux (In-Core) 1.6×10^{14} Flux (Reflector)	Light water cooled. Seven in-core irradiation channels. Twenty-five reflector irradiation channels. Use: Beam experiments, isotope production, NAA, material testing, NTD, fuel testing, 3-PIN PWR and CANDU fuel irradiation. One pressurized loop in reactor core. Modest volume and high flux. Fuel test loop.
IVV-2M	Pool Type	Russia	15 MW 5.0×10^{14} Thermal 2.0×10^{14} Fast 5.0×10^{14} Flux (In-Core)	Light water cooled. Be, water as moderator material. Five loops in core. Thirteen in-core irradiation channels. Thirty-six reflector irradiation channels. Use: Fuel and structure materials test. Has one loop with reduced flux.

Name	Type	Location	Power and Maximum Flux (n/cm^2-s)	Comment
International Thermal Test Reactors[a,b]				
MIR.M1	Thermal MTR	Russia	100 MW 5.0×10^{14} Thermal 1.0×10^{14} Fast 5.0×10^{14} Flux (In-Core)	Light water cooled. Be, water moderator material. Eleven in-core irradiation channels. Seven loops. Use: fuel and material tests, reactor material test, isotope production. Water loops; gas loop; ramp, LOCA and RIA testing.
SM-3	Thermal MTR	Russia	100 MW 5.0×10^{15} Thermal 2.0×10^{15} Fast 1.9×10^{15} Flux (In-Core) 1.4×10^{15} Flux (Reflector)	Classified as a pressure vessel reactor. Light water cooled. Six in-core irradiation channels. Thirty reflector irradiation channels. Use: Irradiation, testing materials, transuranic isotopes, testing reactor materials, isotope production, both high and low temperature. Irradiation positions, flux trap, and water loops.
OPAL	Thermal Neutron MTR	Australia	20 MW 2.0×10^{14} Thermal 2.1×10^{14} Fast 2.0×10^{14} Flux (In-Core)	Light water cooled. No in-core irradiation channels. No core loops. Seventy-eight reflector irradiation channels. Use: Neutron beam science, condensed matter studies, RI production, NTD of Si, NAA, Limited volume; beams, isotopes and Si irradiation.
LVR-15	Thermal Neutron MTR	Czech Republic	10 MW 1.5×10^{14} Thermal 3.0×10^{14} Fast	Materials and fuels tests. Isotope production. Neutron scattering
TRIGA II Pitesti SS Core	Thermal Neutron TRIGA	Romania	14 MW 2.6×10^{14} Thermal 1.8×10^{14} Fast	Materials and fuels tests. Isotope production. Neutron scattering
MARIA	Pool Type	Poland	30 MW 3×10^{14} Thermal 1.5×10^{14} Fast	Isotope production. Neutron scattering. Transmutation. Radiography. Undergoing upgrade for fusion material sample 14 MeV irradiation research.
BRR	Thermal Tank WWR	Hungary	10 MW 2.5 x 1014 Thermal 1.0 x 1014 Fast	Materials and fuels tests. Isotope production. Neutron scattering. Nuclear data measurement.
HTTR (High Temperature Test Reactor)	Prismatic graphite reactor	Japan	30 MW 7.5×10^{13} Thermal 2×10^{13} Fast	Data for design, safety & licensing; fuels and materials irradiation.
HTR-10	Pebble bed modular graphite reactor	China	10 MW (Flux not listed in IAEA database)	Demonstration of safety & reliability; testing digital I&C
JMTR	Thermal MTR	Japan	50 MW 4.0×10^{14} Thermal 4.0×10^{14} Fast 4.0×10^{14} Flux (In-Core)	*Temporarily shut down for refurbishing.* Light water cooled. Twenty in-core irradiation channels. Forty reflector irradiation channels. Two core loops. Use: One hydraulic rabbit device and one shroud facility.

Name	Type	Location	Power and Maximum Flux (n/cm^2-s)	Comment
International Thermal Test Reactors[a,b]				
RJH (Reactor Jules Horowitz)	Thermal Neutron MTR	France	100 MW 5.5×10^{14} Thermal 1×10^{15} Fast	*Under construction*. The 1st criticality is expected in 2016. Partners: Europe and OECD-NEA. Available 2019 (?). Large volume and high flux. Unique capsules for LWR testing.
TFHR (Thorium Pebble Bed Reactor)	Pebble Bed MSR	China	2 MW (Flux not listed in IAEA database)	*Planned. Available sometime after 2020.* Solid fuel. Molten salt cooled. Develop non-electric applications. Materials and fuels testing.
TMSR (Thorium Molten Salt Reactor)	Thermal Neutron MSR	China	2 MW (Flux not listed in IAEA database)	*Planned. Available sometime after 2020.* Fuel dissolved in salt. Molten salt cooled. Develop non-electric applications. Materials and fuels testing.
HTR-PM (High Temperature Reactor-Power Module)	2-unit Pebble bed reactor	China	250 MW each unit (Not listed in IAEA research reactor database)	*Under Construction*. He-cooled graphite pebble bed reactor. Research, design, manufacturing, construction, experiment, fuel fabrication, licensing, and operation.

a. Currently operating systems except as noted.
b. Data on most reactors from International Atomic Energy Agency (IAEA) database https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx. Fast flux for MYRRHA was estimated as flux with neutrons exceeding 0.75 MeV; for all others, fast flux is flux of neutrons with energy exceeding 0.1 MeV.
c. Nearing end of life, but replacement facilities are under discussion (e.g., Pallas to replace HFR Petten).

D.3 International Research and Test Reactors (Fast)

Name	Type	Location	Maximum Flux (n/cm^2-s) and Power	Comment
International Fast Reactor Systems				
BOR 60	Sodium Fast Reactor	Russia	60 MW 2.0×10^{14} Thermal 3.7×10^{15} Fast 3.7×10^{15} In-Core Flux	Fast breeder reactor. Liquid Na cooled. Fifteen in-core irradiation channels. Ten reflector irradiation channels. Use: Reactor material tests, isotope production.
FBTR	Sodium Fast Reactor	India	40 MW 3.3×10^{15} Fast Flux (SS) 3.3×10^{15} In-Core Flux	Fast Breeder type reactor. Sodium cooled. One in-core irradiation channel. Use: Isotope production, training, materials and fuel testing.
CEFR	Sodium Fast Reactor	China	65 MW (Flux not listed in IAEA database)	Fast Breeder Reactor. Fuels & materials irradiation; instrumentation & components testing; radioisotope production
JOYO	Sodium Fast Test Reactor	Japan	140 MW 4.0×10^{15} Fast 5.7×10^{15} In-Core Flux)	*Temporarily Shutdown*. Liquid sodium cooled. Twenty-one in-core irradiation channels. Uses: FBR fuel and material irradiation, teaching, training
MBIR	Sodium Fast Test Reactor	Russia	150 MW 5.5×10^{15} Fast	Fast Power reactor. *Planned to be constructed.* Liquid Na cooled. Three in-core irradiation channels. Three core loops. Expected availability 2020
MYRRHA	Accelerator-based Pb-Bi Cooled Subcritical System	Belgium	100 MW 1×10^{15} Fast	*Planned to be constructed* Fast test system*. Expected availability 2030.*To be a multipurpose hybrid research reactor for high tech applications, ADS system with spallation/fast reactorCoolant lead-bismuth.
CLEAR	Accelerator-based Lead Bismuth Cooled Subcritical System	China	10 MW	*Under construction*. *Operation expected in 2020*. Loops available for testing materials corrosion, thermal hydraulics, and safety.
Currently operating systems except as noted. Data on all reactors from International Atomic Energy Agency (IAEA) database https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx.				

D.3 International Research and Test Reactors (Transient Test Facilities)

Name	Type	Location	Steady State and Pulsed Power and Flux	Comment
International Transient Safety Test Facilities				
CABRI	Pulsed Water Pool-type Reactor	France	25 MW steady state 2.65×10^{13} thermal 7.34×10^{13} fast 20 GW pulsed power 2.12×10^{16} thermal 5.87×10^{16} fast	Materials and fuels tests.
Triga II Pitesti-Pulsed	Pulsed Water-cooled TRIGA Reactor	Romania	0.5 MW steady state 2×10^{13} thermal (SS) 2.5×10^{13} fast (SS) 20 GW pulsed power 1×10^{17} thermal 1×10^{17} fast	Materials and fuels tests. Neutron radiography
IGR	Graphite Pulsed Reactor	Kazakhstan	10 GW pulsed power 7×10^{16} thermal 2×10^{15} fast (Steady state data not included in IAEA database)	Materials and fuels tests.
NSRR	Pulsed Water-cooled TRIGA Reactor	Japan	0.3 MW steady state 1.9×10^{12} thermal (SS) 6.3×10^{12} fast (SS) 23 GW pulsed power 1.5×10^{17} thermal 3.0×10^{17} fast	Fuel behavior under transient conditions. Facility is temporarily shut down.
Data on all reactors from International Atomic Energy Agency (IAEA) database https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx.				

D.4 Summary Responses from International Organizations

Country[h] (Agency)	Reactor Technology Interests[i]	Current/Future Research Reactor Utilization	Interest in Collaboration on/Using a New U.S. Fast-Spectrum Test Reactor
Argentina (CNEA)	LWRs, SFRs, for long term		None
Australia (ASTO)	VHTRs, MSRs		Would be interested in utilizing through GIF
Belgium (SCK-CEN)	Provides irradiation services at BR-2	Operates BR-2 MTR. Will use MYRRHA (Mol) when available.	Response did not answer question regarding interest in collaboration.
Brazil (CNEN)	LWRs		None; would be an observer at best
Canada (CNL)			Official response being drafted by CNL.
China (China Institute of Nuclear Energy)	LWRs, SFRs, GCRs	Operates China Experimental Fast Reactor (SFR).	Possible interest in participating in a new U.S. test reactor for fuels, materials irradiation
Czech Republic (REZ)	Non-LWRs Gen IV reactors	LVR-15 for non-LWR R&D. Will use RJH when available	Possible for high fast flux fuels, materials testing. Interested in exploring collaboration
European Commission (Joint Research Centre)	Provides irradiation services at Petten HFR.	Operates Petten HFR. LWR, GCR R&D. Future PALLAS reactor may replace Petten HFR.	Any future interest in participating in a U.S. advanced test reactor would depend on EU circumstances at that time
France (CEA)	LWRs, SFRs, Gen IV reactors	Operates several research reactors. Building RJH and ASTRID SFR.	Yes, in the continuity of current bi-lateral with U.S. Several forms of participation suggested

[h] Original responses may be found at the NEAC website: https://www.energy.gov/ne/services/nuclear-energy-advisory-committee.

[i] GCR-Gas Cooled Reactor, LWR-Light Water Reactor, MSR- Molten Salt Reactor, PHWR-Pressurized Heavy Water Reactor, SFR-Sodium Fast Reactor, VVER- Vod0Vodyan Energetichesky Reactor

Country[h] (Agency)	Reactor Technology Interests[i]	Current/Future Research Reactor Utilization	Interest in Collaboration on/Using a New U.S. Fast-Spectrum Test Reactor
Germany (IKET, KIT)	SFRs	Uses neutron source FRM2 (Munich). Will use RJH, MYRRHA when available.	None
India (BARC)	HWR, LWR, SFR	Operates new SFR reactor.	No answers given. Referenced policy issues
Japan (JAEA)	LWR, SFR, HTGRs	Operates HTTR, JOYO, MONJU. Collaborating with CEA ASTRID design.	Would possibly be interested in a U.S. fast flux facility that is complementary to JOYO. Focus on capabilities not offered by JOYO.
Republic of Korea (KAERI)	LWR, SFR	Operates HANARO test reactor. Plans to build SFR by 2028. Uses BOR-60 for SFR fuel/cladding tests.	Yes. Currently irradiating SFR TRU fuel rods, and proposed fuel for the new Korean Kijang Research Reactor in ATR
Norway (OECD Halden)	Provides irradiation services at Halden	Operates Halden reactor. LWR R&D.	None
Poland (NCNR)	HTRs, Fusion R&D	Operates MARIA MTR. Planning Lithium-Deuterium Converter facility	None
South Africa	LWRs, GCRs		U.S. DOE contacting RSA DOE following protocol
Ukraine (KIPT)	Fuels, Materials, Gen IV, fusion R&D	Operates accelerators for materials, fuels, subcritical ADS,Conducting R&D on Traveling Wave Reactor.	Possible interest. Indicated that a coordinated response from KIPT is needed.
United Kingdom	LWRs, Gen IV reactors	Uses Halden now. May use Petten HFR and BR-2 (Belgium). Will use RJH.	May be interested if RJH not available (not until after 2030)