Versatile Irradiation Test Reactor User Needs Assessment

January 2017
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January 2017

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SUMMARY

An assessment of U.S. reactor vendor and developer’s versatile irradiation test reactor user needs has been completed. The assessment was performed through direct interaction with each vendor and developer under specific nondisclosure agreements for each organization. Key needs and objectives are discussed below.

From the assessed needs, a key point that all vendors and developers reinforced is the overall long-term benefit of a new test reactor to the U.S. program; this is a benefit that cannot be overemphasized. A new test reactor will be a tool available to all U.S. vendors and developers and will establish the basis for domestic and international transformational fuels and materials research. The ability of scientists to perform research and development consistently using the same tool is an overwhelming advantage from process efficiencies to analysis and data repeatability. For perspective, compare potential U.S.-based test reactor availability to utilization of the only fast-spectrum test reactor operating today, BOR-60 in Russia. The BOR-60 has been a workhorse but one where access is a long and difficult process. Irradiations research and development within foreign reactors have been limited for a number of reasons, including the high cost and long timeline to gain access to these reactors and the difficulty in transporting irradiation samples to and from the reactors. Hand-in-hand with test reactor availability are the long-term programmatic benefits, those that are not limited to a few irradiations or a single program, but a number of long and enduring irradiation programs that attract the “best and the brightest.”

The light-water reactor program is a good example; it is a long-term development program with major improvements and technology maturation. Fuels and materials development and testing are long-term tasks throughout the lifetime of a nuclear technology and span well beyond the initial testing period needed to demonstrate the technology. Continuous improvement has been the hallmark of the light-water reactor program. As one can expect, a new test reactor will be the basis for any number of decades-long irradiation programs that will be needed as the United States moves into a period of advanced reactor program deployment.

A final need of note is a shortened development cycle time, from idea to market deployment, another programmatic objective. The ability and importance of a new U.S. test reactor to shorten the development cycle time cannot be understated. This objective is feasible for an operating test reactor within the United States. Although current reactor developers are aggressively pursuing short development times outside of the United States, the level of success has been limited at best.
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<thead>
<tr>
<th>ACRONYMS</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRADA</td>
<td>Cooperative Research and Development Agreements</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>dpa</td>
<td>displacements per atom</td>
</tr>
<tr>
<td>FHRs</td>
<td>fluoride-salt cooled high-temperature reactors</td>
</tr>
<tr>
<td>GAIN</td>
<td>Gateway to Accelerated Innovation in Nuclear</td>
</tr>
<tr>
<td>HTGCFR</td>
<td>high-temperature gas-cooled fast reactor</td>
</tr>
<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
</tr>
<tr>
<td>LFR</td>
<td>lead-cooled fast reactor</td>
</tr>
<tr>
<td>LTA</td>
<td>lead test assemblies</td>
</tr>
<tr>
<td>LWR</td>
<td>light-water reactor</td>
</tr>
<tr>
<td>MSR</td>
<td>molten-salt reactor</td>
</tr>
<tr>
<td>NDA</td>
<td>nondisclosure agreement</td>
</tr>
<tr>
<td>NRC</td>
<td>U.S. Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>PIE</td>
<td>post-irradiation examination</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>research and development</td>
</tr>
<tr>
<td>SFR</td>
<td>sodium-cooled fast reactor</td>
</tr>
</tbody>
</table>
Versatile Irradiation Test Reactor User Needs Assessment

1. INTRODUCTION

Staff members of Idaho National Laboratory (INL), Argonne National Laboratory, and Oak Ridge National Laboratory completed an assessment of potential test reactor industry user needs. The needs of U.S. Department of Energy (DOE) research and development (R&D) programs have also been assessed and included in this report. A series of discussions with industry representatives conducted under nondisclosure agreements (NDAs) was undertaken during the last half of Calendar Year 2016. Contributors to this assessment were selected from a list of representative reactor vendor organizations. Because the time available to complete the assessment was short, not all reactor vendors were included, and some chose not to participate. However, the contributors represent well-established reactor vendors and developers working to bring new designs to the reactor market. Equally important was the breadth of the reactor technologies that are included in the assessment: sodium-cooled fast reactors (SFRs), lead-cooled fast reactors (LFRs), high-temperature gas-cooled reactors (HTGCFRs), light-water reactors (LWRs), and molten-salt reactors (MSRs). Throughout this report, the term molten-salt reactor or MSR is used to represent all variants of molten-salt-cooled reactors, including those using dissolved or solid fuel and in either a fast or thermal spectrum.

In an attempt to capture and define the market for a fast-spectrum test reactor, survey data were collected under NDAs to induce participants in the assessment to share potentially proprietary information falling under the following four categories:

- Specific needs related to key design parameters of the proposed technologies
- Development and demonstration needs to be addressed prior to test reactor operation
- Long-term technology improvements to improve the performance of technologically mature concepts as well as the significant testing needs for less mature concepts
- Clarified, detailed needs of the LWR community not met by existing test reactors.

All participating vendors and developers expressed needs that could be served by a new test reactor with appropriate experimental facilities. Organizations with high-maturity concepts expressed the need for testing in support of continuous improvement concurrent with prototype and demonstration plant operation, which are longer-term needs. Organizations with lower-level maturity concepts expressed needs for irradiation testing and development in the near term. Finally, all organizations envisioned longer-term test reactor needs consistent with the LWR community experience, where ongoing irradiation testing programs provided the basis for improvements ranging from safety to optimization of fuel. The need most often cited, consistent across all reactor vendors and developers, is for a well-informed and educated regulator. The regulator needs to be technically knowledgeable and cognizant of these various reactor types, according to the vendors and developers surveyed. A regulator who can, with confidence, contribute to certainty in the licensing process is an overwhelming need.

In summary, all survey responders indicated they would utilize irradiation services that a fast-spectrum reactor can provide with rapid accumulation of displacements per atom under prototypical conditions for qualification of fuel, qualification of fuel manufacturing processes, extension of the useful lifetime of cladding and structural materials under irradiation, study of corrosion behavior of materials and advanced coatings under irradiation, and demonstration of fuel performance. Specific needs are further discussed in Section 3 of this report. Of particular interest was clarification provided by an LWR fuel developer who identified needs that are not met by existing test reactors. The authors of this report are grateful to those who participated in this assessment. Participation required an investment in time and resources that was often a challenge.
NOTE: While conversing with users, those conducting the assessment had the opportunity to refine user needs and try to understand whether the needs have to be met prototypically in a test reactor, or whether carefully designed experiments in slightly non-prototypical conditions would be sufficient. An example of that process is the discussions the assessors had about full-length LWR testing. Note, however, that this effort was not by any means exhaustive, and significant work will need to be performed in the future to define approaches that can meet users' needs.

2. ASSESSMENT PROCESS DESCRIPTION

The assessment process began by INL, Argonne National Laboratory, and Oak Ridge National Laboratory staff members contacting reactor vendors and developers with a request to participate. The assessment participants are listed in Table 1. Positive responses were quickly followed by efforts to establish NDAs between one or more of the national laboratories mentioned above and the participant. It is notable that each national laboratory engaging with a participant needed an independent NDA with the participant. Although the possible use of a single NDA was discussed, it was quickly dismissed by the laboratories’ respective legal departments. This additional burden for any participant to establish an NDA limited the amount of laboratory participation in specific interactions. The additional time and effort required to establish individual NDAs between vendors and national laboratories (in some cases two or three times the NDA effort was needed to support a single conversation) suppressed the inclination to participate. Finally, concurrent efforts by the laboratories and several participants to establish NDAs and cooperative research and development agreements (CRADAs) supporting Gateway to Accelerated Innovation in Nuclear (GAIN) activities burdened the staffs of the various organizations. Consequently, execution of an NDA was often the critical-path activity leading up to the survey discussions.

After NDAs were in place, survey discussions were accomplished through in-person meetings or telephone conferences. Interviews or discussions were nominally engaged in by personnel from the three national laboratories, though in many cases discussions were performed by a staff member from only one laboratory. Specific data requirements or discussion checklists were not used, but rather an in-depth conversation was employed to engage industry personnel. This approach was successful in drawing out important considerations across a range of reactor types and implementation strategies without using a list of questions.

Table 1. Listing of reactor vendors participating in the needs assessment.

<table>
<thead>
<tr>
<th>Reactor Vendor</th>
<th>Reactor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westinghouse Electric Company</td>
<td>Lead fast</td>
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<tr>
<td>TerraPower</td>
<td>Sodium fast</td>
</tr>
<tr>
<td>General Atomics</td>
<td>High-temperature gas-cooled fast</td>
</tr>
<tr>
<td>General Electric-Hitachi</td>
<td>Sodium fast</td>
</tr>
<tr>
<td>Advanced Reactor Concepts</td>
<td>Sodium fast</td>
</tr>
<tr>
<td>Terrestrial Energy USA</td>
<td>Molten salt</td>
</tr>
<tr>
<td>Transatomic Power Corporation</td>
<td>Molten salt</td>
</tr>
<tr>
<td>Elysium Industries</td>
<td>Molten salt</td>
</tr>
<tr>
<td>AREVA</td>
<td>High-temperature gas-cooled</td>
</tr>
<tr>
<td>Oklo</td>
<td>Micro Rx</td>
</tr>
</tbody>
</table>

The discussions usually started with a description of possible test reactor concepts and their potential experimental capabilities. This approach proved to be a common ground that facilitated significant subsequent conversations lasting several hours.
3. INDUSTRY NEEDS

The needs expressed by the survey respondents are presented generically below to ensure protection of proprietary information. As shown in Table 1, vendors and developers represented include LFRs, SFRs, MSRs, and gas-cooled reactor types.

3.1 Summary of Generic Industry Needs

**Licensing:** Licensing through the U.S. Nuclear Regulatory Commission (NRC) is important to all vendors and developers, who expressed concern over uncertainty in the licensing process for advanced reactors. Overwhelmingly, there have been expressions of concern that the NRC is not or will not be appropriately informed and educated about the technology that supports development of advanced reactor applications, most of which are key to the economic performance of the technology. These comments were made in a positive context but reflected experience and history with the NRC and its (understandable) institutional emphasis on LWRs. The overall challenge to the NRC will be significantly larger and grow with each “new” or different advanced reactor license application. Although the NRC understands the potential problem facing it, the true magnitude of the problem will continue to be an unknown.

**Long-Life High-Burnup Fuels:** Developers of most advanced reactors seek to improve reactor economics through increased uranium utilization and less-frequent fueling, which requires utilization of long-life high-burnup fuels. Long-life high-burnup fuels are designed with improvements that increase the energy that can be extracted from fuel, prolong the service lifetime of the fuel, and reduce the associated volume of used fuel and waste. These fuel designs will employ previously unused cladding materials (such as silicon carbide composites and radiation-resistant stainless steels being developed today) and new fuel material compositions or configurations that offer reactor operation or fuel cycle advantages (such as vented fuel or transuranic-bearing fuel). These fuels require laboratory-scale R&D, qualification of manufacturing processes, and eventually qualification of fuel through the irradiation testing under representative service conditions and post-irradiation examination (PIE). In addition, experience has shown that fuel designs will be optimized throughout the advanced reactor life cycle, a decades-long process with a test reactor as the principal component.

**Displacements per Atom:** Materials that are resistant to degradation under exposure to neutrons at high temperature are a prerequisite to any improvements to in-core component performance to allow long fuel life or to ensure component integrity with little to no maintenance. This leads to certain needs for all advanced materials and fuels development: high, fast-neutron flux displacement(s) per atom in prototypical conditions. Common to all advanced reactor concepts are exposures of fuel cladding and in-core components to high displacements per atom, in excess of 20 dpa/year. In this context, the benefit of a fast-spectrum reactor is apparent for ongoing and future LWR fuels and materials development. The desired acceleration in testing times over those available with thermal-spectrum test reactors is dramatic (as much as 3 times the displacements per year), and the LWR industry is extremely interested in such a capability.

**Irradiation Testing Capabilities:** Advances in sensors, digital processing systems, and data analytics to improve operational efficiency of new and existing reactors. Realizing this potential benefit will require advanced sensors for in situ measurements within the local irradiation environment: temperature, fluence, mechanical strains, and fission gas release. Developing such systems for incorporation into power reactors will begin with work in laboratories and university facilities; ultimate demonstration of these systems will be best accomplished in test reactors designed to accommodate such demonstration.
PIE: Vendors and developers place high importance on PIE capabilities for a number of reasons, but primarily the data developed during the examination process are key to licensing. High-reliability data generation and repeatability are important to fuels and materials development and qualification, because the process supports licensing activities. Specific needs include characterization of fuel and in-core component dimensional changes; fuel and materials microstructure evolution in-service and effects on component performance; and key properties of materials, including yield and ultimate strength, elastic modulus, fracture toughness, hardness, thermal conductivity, and chemical changes.

Component Testing: Several vendors and developers indicated a need to obtain performance data for reactor system components, for both primary and secondary systems, and to demonstrate advanced power-conversion technologies. An integrated test capability is desired for advanced power-conversion techniques, e.g., super-critical CO₂ Brayton Cycle and load following, with development of performance data in support of licensing.

Full-Core Testing: Certain concepts rely on unusual configurations for which partial or full-core prototypical configurations can be tested and demonstrated through mockup in a test reactor. Specific examples include demonstration of reactor response to perturbations or responses for large loading of a new fuel design, validation of reactor physics parameters and models through an integrated demonstration at the core-load scale, and demonstration of passive mechanisms (to the degree that the test reactor represents characteristics of a specific technology). Finally, the reliability of a fuel design can be demonstrated through sustained operation of a test reactor loaded with the fuel.

LWRs: LWR vendors and developers have expressed the need for fuel assembly testing as a means to continue advancements in fuel design previously considered to be achievable only through the testing of lead test assemblies, which are full-size pressurized-water or boiling-water reactor fuel assemblies. After several discussions and technical evaluations, the LWR fuel needs were clarified. Full-length, first-time, lead-test assembly irradiations can be replaced with shorter assemblies, e.g., 0.8 to 1.2 m in length and a 3 by 3 element matrix. Clearly, these requirements can be met in a number of existing water-cooled test reactors, including the Advanced Test Reactor at INL. As mentioned above, a fast-spectrum reactor brings other advantages to ongoing and future LWR fuels and materials development. The acceleration in testing times relative to that attained in thermal-spectrum test reactors is dramatic, as much as 3 times the displacements per atom rate.

MSRs: MSRs (such as the fluoride salt-cooled high-temperature reactors or molten-chloride fast reactors) utilize solid or dissolved fuel and may produce significantly higher displacements per atom than LWRs on structures operating at higher temperatures in a corrosive environment, with displacements per atom rate predictions exceeding 20 dpa/year. The materials utilized within these systems will require corrosion testing at service temperature in flowing molten salts under neutron irradiation. Some MSR vendors envision using advanced corrosion-mitigating coatings on structural materials that will need testing commensurate with other MSR materials.

In addition, physics data for salt constituents, validation of codes, assessment of materials performance and irradiation-assisted corrosion in loops of flowing salt at 550 to 750°C, assessment of liquid fuel salt performance and behavior through an operating cycle (with composition changes due to accumulation of soluble fission products), and testing and demonstration of salt system components under in-service conditions are needed.

LFRs and SFRs: In addition to the need for irradiation of fuel tests, and qualification and demonstration of fuel designs and core loads of fuel, reactor developers have additional need to assess length effects on fuel rods and assemblies that are longer than previously considered. Specific longer core length irradiation needs include requests for testing of fuel up to 2 m in length. Other testing, demonstration, and qualification needs include sensors and systems for viewing fuel and components in opaque coolants to facilitate fuel handling and in-service inspection.
**Gas-Cooled Reactors:** Gas-cooled fast reactor needs include high-burnup fuel and significant displacements-per-atom fuel cladding, and those efforts associated with advanced cladding and high burnup fuel cladding interactions. Very high-temperature gas-cooled reactors (thermal) can utilize fast-spectrum test reactor irradiation of structural materials.

**Schedules:** All participating vendors expressed strong support for a test reactor; however, specific schedules for utilization of the test reactor varied. For example, given the time needed to make a new test reactor operational and available, it was important to consider how each potential user would address development and demonstration needs during that lag time, assessing not only today’s needs but expected needs in the future. It is important to ascertain the role of a test reactor for mature technologies that possibly can be deployed in the short term but might need more testing to improve performance in the long term and, conversely, for less-mature technologies that cannot go to the prototype and deployment stage without significant testing. In summary, the need for a test reactor currently exists and extends well into the foreseeable future as advanced technologies are deployed and the test reactor role evolves into one of technology maturation, a life of well beyond 60 years.

**DOE Nuclear Energy R&D Needs:** The DOE Nuclear Energy R&D programs have traditionally maintained advanced fuels and materials research either in support of short-term industrial demonstration and deployment or in support of long-term prospective research for innovative concepts. Similarly, for industrial programs, DOE fuel and reactor development programs could have benefited from the unavailability of fast irradiation capabilities in the United States; while some irradiations can be realized in foreign facilities, the processes that have to be engaged before using those facilities are lengthy and cumbersome, and access to foreign facilities is very limited.

Likewise, a number of irradiations can be realized in U.S. thermal test reactors in conditions approaching fast test reactor conditions—for example, through the use of neutron filters. Unfortunately, these tests are never sufficiently representative of fast-reactor conditions to allow for licensing of these innovative fuels. Also, typically, the fast component of the flux in these facilities is not sufficient to get high displacements per atom in a reasonable time.

DOE also maintains a “science-based” approach toward developing predictive fuels-modeling capabilities; the final objective of that development is to create tools that will accelerate the development of innovative concepts in the future. This approach requires a number of focused irradiations, either long or short term, with heavily instrumented experimental devices or the possibility to do in situ measurements and quick extraction of samples—for example, with rabbit-type devices. Some space-power and propulsion technologies are dependent on fast-reactor concepts. However, there are essentially no irradiation data on the fuels of interest. A fast-spectrum irradiation capability at temperatures approaching 2,600°C is needed. Irradiation and performance data on full-length space nuclear fuel elements could be attained with the use of a high-temperature loop within a fast test reactor. Consideration of other technologies that could use the facility or test loop is important, given the low-frequency use of a near-term fast-reactor development program.

Minimum key DOE needs can be summarized as follows:

- **Fast flux level:** 4E15n/cm²s
- **Flux spectrum:** flexible from pure fast to epithermal to thermal
- **Displacements per atom per year:** 20
- **Coolants:** complete spectrum (including hydrogen and lithium closed-loop systems)
- **Temperatures:** up to 2,600°C
• Experimental devices: complete range from capsules to closed loop, with the ability to test single fuel elements and small fuel element bundles

• Instrumentation: in situ measurements; out-of-core measurements with quick retrieval of samples.

### 3.2 Test Reactor Capability Serving Participating User Needs

The translation of stated user needs to test reactor capability are mostly straightforward. The following is not meant to be definitive but to represent a distillation of many needs into an unambiguous listing of potential test reactor requirements. The following is also listed in Table 2.

- **Neutron flux:** 
  \[ >5 \times 10^{15} \text{ n/cm}^2\text{s} (\geq 0.1 \text{ MeV}) \]

- **Spectrum:** Fast and thermal

- **Temperature range:** 500 to 2,600°C (depending on coolant, including both static and transient profiles)

- **Displacements per atom:** \( \geq 20 \text{ dpa/year}, \text{ total up to 400 to 500 dpa (nonmetallic cladding)} \)

- **Irradiation length:** \(< 1.0 \text{ to 2 m} \)

- **Irradiation volume:** \( \leq 7 \text{ L (0.1-m loop diameter by } \leq 1\text{-m length)} \)

- **Irradiation duration:** One reactor cycle (typically 100 days) to years and very short tests for model validation

 Irradiation testing environments:

- Sodium
- Lead
- Helium
- Light water
- Molten salts (various compositions)

Testing configurations: open-core irradiation testing for fuels and materials with and without instrumentation, capsules filled with various media, and closed test loops.

Measurement techniques: traditional measurement of local neutron flux and coolant temperature; in situ measurement of fuel temperatures, fuel rod internal pressure, fuel rod and component deformation (e.g., plastic deformation and flow-induced vibration-induced displacement); and capability for quick sample introduction and extraction, such as with rabbit tubes and prompt fuel handling.

Table 2. Test reactor experimental requirements and potential test vehicle configurations.

<table>
<thead>
<tr>
<th>Experimental Parameter</th>
<th>Requirement</th>
<th>Test Loop Description</th>
<th>Potential Test Loop Coolants</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Flux</td>
<td>( \geq 5 \times 10^{15} \text{ n/cm}^2\text{s} (&gt;0.1 \text{ MeV}) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron Spectrum</td>
<td>Thermal and fast</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Range</td>
<td>500 to 2,600°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental Parameter</td>
<td>Requirement</td>
<td>Test Loop Description</td>
<td>Potential Test Loop Coolants</td>
<td>Comments</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Irradiation Duration</td>
<td>Very short, single cycle (~3 months) to multi-year</td>
<td></td>
<td></td>
<td>Very short tests for model validation, reconstitution and reinsertion after PIE</td>
</tr>
<tr>
<td>Irradiation Length</td>
<td>&lt;1.0 to 2 m</td>
<td>Two vendors requested longer core length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irradiation Volumes</td>
<td>≤7 L</td>
<td></td>
<td>0.1-m outside diameter, 0.1- to 1.0-m length</td>
<td></td>
</tr>
<tr>
<td>In Situ Measurements</td>
<td>Temperature, fluence, mechanical strains, fission gas release</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential Experimental Vehicles</td>
<td>Closed test loop</td>
<td>Loop is cooled externally and independent of the reactor primary coolant. Heavily instrumented and controlled.</td>
<td>Sodium, lead, helium, light water, molten salts (various compositions)</td>
<td>One or two experimental vehicles in test reactor, dependent on a number of technical factors. Loops containing coolants not compatible with sodium would employ a double-wall arrangement with integral leak detection.</td>
</tr>
<tr>
<td></td>
<td>Open test loop</td>
<td>Loop is cooled by reactor primary coolant, and experimental section is cooled by dedicated coolant volume isolated from reactor coolant. Heavily instrumented and controlled.</td>
<td>Sodium, lead, helium, light water, molten salts (various compositions)</td>
<td>Two to four experimental vehicles in test reactor</td>
</tr>
</tbody>
</table>
### Table 2. (continued).

<table>
<thead>
<tr>
<th>Experimental Parameter</th>
<th>Requirement</th>
<th>Test Loop Description</th>
<th>Potential Test Loop Coolants</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrumented open-core test</td>
<td>Experiment is cooled by primary coolant flow through the assembly; experiment is instrumented.</td>
<td>Sodium</td>
<td>Two to four experimental vehicles in test reactor</td>
<td></td>
</tr>
<tr>
<td>Open-core test</td>
<td>Experiment is cooled by primary coolant flow through the assembly; limited experiment instrumentation.</td>
<td>Sodium</td>
<td>Many experimental vehicles (limited by reactor physics)</td>
<td></td>
</tr>
<tr>
<td>Hydraulic transfer system</td>
<td>Irradiation within a sealed capsule</td>
<td>As supported by materials of construction and volume constraints</td>
<td></td>
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</tr>
</tbody>
</table>

The following Table 3 is a summary of vendor non-proprietary requirements that are further summarized in Appendix A.
### Table 3. Summary of non-proprietary requirements.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>SFR</td>
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<tr>
<td>Neutron Flux</td>
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<td>Fuel</td>
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<tr>
<td>Support evolution from UZr to UPuZr</td>
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<td>Cladding</td>
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<tr>
<td>HT-9 Cladding Qualification</td>
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<tr>
<td>Component Demonstration</td>
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<td>Power Conversion</td>
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<td>Neutron Flux (max ( E &lt; 0.1 ) MeV)</td>
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<td>3( \times 10^{15} \text{n/cm}^2\text{s} (&gt;50 \text{dpa/yr})</td>
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<td>500 to 350 W/cm (instrumented pellets)</td>
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<td>( \text{O}_2 ) sensors, getters, PbO mass exchange, ( \text{H}_2/\text{Ar}/\text{O}_2 ) injectors</td>
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<td>Flux, power, clad and fuel temperatures, lead mass flow, pressure, and strain page</td>
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<tr>
<td>HTGCFR</td>
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<td>Test Sample Temperatures, Pressures, and Power Outputs</td>
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<td>Helium ( \geq 600 \text{ to } 1,800°C ), internal capsule pressure ( \leq 1 \text{ atm} ). Cold, capsule power ( \geq 6.10 \text{ kW} ).</td>
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<td>Helium Loop</td>
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<td>Mass flow at 100 g/s. Pressure at 13 MPa. Helium temperature 550 to 1,000°C.</td>
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<td>Outer diameter ( \approx 100 \text{ mm} ). Height ( = \text{full core height} ).</td>
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<td>Temperature, fluence, mechanical strains, fissile gas release</td>
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<td>PFR: dimensional changes, microstructure, mechanical strength, elastic modulus, fracture toughness, hardness, thermal conductivity, chemical changes</td>
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Table 3. (continued).

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</table>

- **HTGCTR** Neutron Flux: Slightly harder than a LWR spectrum.
- **MSR** Neutron Flux: >1E15 n/cm²s (>0.1 MeV).
- **LWR** Neutron Flux: 2 to 5E13 n/cm²s (E<0.3 eV).

- **HTGCTR» Temperatures**: 800 to 1,000°C.
- **MSR» Temperatures**: 550 to 750°C.
- **LWR» Temperatures**: Prototypical pressurized-water reactor: 15.5 Mpa, <Tsat 250 to 350°C.

- **HTGCTR» Irradiation Volume**: 0.5m × 1.0m × 0.5m.
- **MSR» Irradiation Volume**: 3 × 3 rod array × 500 to 800 mm.
- **LWR» Irradiation Volume**: 0.05m × 0.05m × 1.0 m minimum.

- **HTGCTR» Pressure, Temperature**: 8.5m × 1.0m × 0.5m.
- **MSR» Pressure, Temperature**: Prototypical pressurized-water reactor: 15.5 Mpa, <Tsat 250 to 350°C.
- **LWR» Pressure, Temperature**: 800 W/cm (Average=400 W/cm).

- **HTGCTR» Comments**: Inert atmosphere irradiation, structural and nonstructural components; materials irradiation under static and flowing salt environments.
- **MSR» Comments**: Large composite structures.
- **LWR» Comments**: Tritium management is an experimental concern.

- **HTGCTR» Instrumentation**: Power and power distribution, flux and flux distribution, rod geometry, T (clad, fuel, coolant), coolant mass flow and pressure, clad strain gages.
- **MSR» Instrumentation**: Power and power distribution, flux and flux distribution, rod geometry, T (clad, fuel, coolant), coolant mass flow and pressure, clad strain gages.
- **LWR» Instrumentation**: Power and power distribution, flux and flux distribution, rod geometry, T (clad, fuel, coolant), coolant mass flow and pressure, clad strain gages.

- **HTGCTR» Data needs**: 15 to 30 years following a successful commercialization of near-term steam cycle high-temperature gas-cooled reactor.
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<td>Irradiation Temperature</td>
<td>≤2,625°C</td>
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<td>5 MW/L (prototypic power level)</td>
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<td>Power Level</td>
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<tr>
<td>Irradiation Volume</td>
<td>≤0.13 m (diameter) × 1.0 m long</td>
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<td></td>
<td></td>
<td>There are essentially no irradiation data on the fuels of interest. A fast-spectrum irradiation capability at temperatures approaching 2,900 K is needed.</td>
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</table>
Appendix A

Compilation of Non-Proprietary Summaries

NOTE: This appendix does not contain a listing of the needs compiled from all industry participant discussions. This appendix contains a compilation of non-proprietary needs from those industry participants who chose to provide a publicly releasable summary of needs. Those participants are:

- Westinghouse Electric Company Summary
- Advanced Reactor Concepts Summary
- TerraPower Summary
- Transatomic Summary
- General Atomics Summary
Appendix A

Compilation of Non-Proprietary Summaries

Westinghouse Non-Proprietary Class 3

Westinghouse Electric Company
Global Technology Development
1000 Westinghouse Drive, Suite 305
Cranberry Township, Pennsylvania 16066
USA

Dr. Douglas C. Crawford
Director of Technology R&D Leader
Reactor & Nuclear Systems Division
Oak Ridge National Laboratory
PO Box 2008, MS6003,
Oak Ridge, TN 37831-6003

Dr. Phillip Finck
Sr. Scientific Advisor
Idaho National Laboratory
2525 North Fremont Ave
Idaho Falls, ID 83415-3634

Subject: Westinghouse Preliminary Feedback on Irradiation Testing Needs to Inform Advanced Test Fast Test Reactor (ATFR) Conceptual Design

October 10, 2016

Dear Dr. Crawford and Dr. Finck:

Attached you find Westinghouse preliminary feedback on our irradiation testing needs. Note that this information is provided with the sole scope of informing the conceptual design of the Advanced Test Fast Reactor (ATFR) currently under development by ANL and INL. Also note that the level of detail with which such information is provided is commensurate with the early stage of the discussion on the ATFR development and of Westinghouse involvement.

If you have any questions, do not hesitate to contact me.

Very truly yours,

Paolo Ferroni*
Principal Engineer
Westinghouse Electric Company LLC

cc: John Beatty*
Cindy Pezze
Sumit Ray
Ed Lahoda
Dave Mitchell
Fausto Franceschini

*Electronically Approved Records are authenticated in the Electronic Document Management System (EDMS)

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Westinghouse Electric Company LLC

Westinghouse preliminary feedback on irradiation testing needs to inform Advanced Test Fast Reactor conceptual design

RT-TR-16-20

October 10, 2016
1. Introduction

The Advanced Demonstration and Test Reactor (ADTR) study conducted by three major US national laboratories, i.e. INL, ANL and ORNL ("lab team"), and with input from various stakeholders, evaluated specific advanced reactor concepts on the basis of "strategic objectives" established by the U.S. DOE, for potential development of Demonstration Reactor(s) and/or of a Test Reactor in the U.S. (Ref. 1).

In regard to the Test Reactor option, a peer design review took place on August 4-5, 2016, at ORNL, where two conceptual designs for an Advanced Test Fast Reactor (ATFR), both sodium-cooled and developed by ANL and INL, respectively, were discussed. General considerations beyond the specific designs were also made, and emphasis was put on the need for considering a tradeoff between the testing capabilities sought with the ATFR, its complexity in operation, its availability and ultimately its cost. During the review, it became clear that in order to inform the design, a more precise understanding of the irradiation testing needs of the various stakeholders is needed, especially as the ATFR design moves forward. Such understanding should be "progressive," in the sense that it will move from an early stage – when necessary testing capabilities are distinguished from unnecessary ones, to successive stages when knowledge of technical specifications for the necessary capabilities will be required to properly design the ATFR.

This report is intended to provide the lab team with information on the irradiation testing capabilities that Westinghouse deems important to be implemented in the ATFR, based on the needs that the company envisions for testing products of interest (both LWR- and non-LWR-related), in the ATFR. It should be stressed that the level of detail with which such information is provided is commensurate with the early stage of ATFR development and of Westinghouse involvement in such program.

2. Westinghouse irradiation testing needs

The irradiation testing capabilities to be implemented in the ATFR should include those in support of both non-LWR (LFR) and LWR technologies. Westinghouse believes that the ATFR is needed to accelerate development and deployment of advanced technologies that are promising, especially from the standpoint of commercial viability. Westinghouse, however, also believes that LWR testing capabilities should be included as well, for the following reasons:

- LWR technology will continue to be the backbone of nuclear energy for many decades to come;
- LWR technology is still innovative by stakeholders interested in achieving enhanced performance in terms of safety, economics and operability of their products, and it will continue to be so in the future. The Westinghouse Accident Tolerant Fuel (ATF) program is a prime example of innovation in LWR technology and even though our ATF products will be commercially available well before ATFR operation, follow-on irradiation testing in this reactor will contribute to enhance the robustness of the ATF irradiation database. It is also anticipated that similar programs will continue to exist in the future, which will benefit from the availability of state-of-the-art irradiation testing capabilities such as the ATFR;
- Testing and instrumentation capabilities in existing test reactors, such as ATR and HFIR, play a central role in various ongoing technology development programs but are sometimes constrained.
by the design of the reactors themselves. Enhanced irradiation testing capabilities will allow performing tests in more prototypical and/or predictable conditions, e.g. longer testing zones with relatively uniform axial power profile, and with state-of-the-art instrumentation, thus better responding to 1) generally stricter regulator’s requirements and 2) the higher resolution needed for validating advanced modeling and simulation tools.

- Enhanced testing capabilities and instrumentation could accelerate qualification of new fuel designs by potentially allowing Lead Test Rod testing, typically performed in commercial reactors and as such in need for extra preparatory work to avoid any “interference” with plant operation, to be conducted in the ATFR (followed by Lead Test Assembly testing “only” in commercial plants). This could potentially save 4-6 years of fuel development time.

Sections 2.1 and 2.2 provide some information on the desired irradiation testing capabilities to support innovation/development of LWR and LFR technologies, respectively.

2.1 Desired LWR testing capabilities

Table 1 summarizes key information that Westinghouse deems important to provide to the lab team, at this stage of ATFR development and of Westinghouse involvement in the program, for informing the design of the ATFR LWR testing capabilities.

2.2 Desired Lead Fast Reactor testing capabilities

In addition to the availability of testing zones for insertion of lead-filled capsules, Westinghouse strongly supports the implementation, in the ATFR design, of a testing loop for materials to be tested in high-temperature, flowing liquid lead under well-controlled chemistry conditions. When provided with such a loop, the ATFR will support the development and qualification of materials, mainly fuel and fuel rod cladding, for use in LFR systems. Since significant experience already exists with UO₂, including in a fast neutron spectrum, and since extensive testing campaigns have already demonstrated promising performance by several materials to reliably operate for long time in liquid lead below about 480°C, the ATFR will be particularly useful to support the development of higher-performance LFRs operating with advanced, non-UO₂ fuel and with lead temperatures above approximately 500°C.

Table 2 summarizes key information that Westinghouse deems important to provide to the lab team, at this stage of ATFR development and Westinghouse involvement in the program for informing the design of the ATFR LFR testing capabilities.

2.3 Additional desired capabilities

An effective fuel qualification is the result of effective irradiation testing but also of effective Post-Irradiation Examination (PIE). On this regard it is important to ensure that the time between the completion of irradiation testing and PIE is minimized, for example by reducing cooling times and ensuring effective transportation of samples from the ATFR to the PIE facilities.
Acknowledgments

Westinghouse would like to acknowledge the input provided on LFR testing capabilities by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA).

References

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<th>Value/range</th>
<th>Notes</th>
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<td>Irradiation testing zone dimensions</td>
<td>Cross section</td>
<td>Able to accommodate at least a 3x3 rod array (with the potential of at least 1 unfueled position), with rod OD and pitch representative of commercial designs (e.g. OD=9.5mm and P=12.6 mm)</td>
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<td>Height</td>
<td>500-800 mm (irradiated length), plus entry region not necessarily irradiated to capture entry effect and ensure fully developed flow</td>
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<td>Pressure, temperature</td>
<td>Prototypical of PWR conditions (15.5 MPa; up to Tsat) with capability to cover BWR conditions as well</td>
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<td>Water velocity</td>
<td>Up to 6 m/s</td>
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<td>Rod peak linear power</td>
<td>Up to ~800 W/cm. Length-averaged up to about 400 W/cm</td>
<td>Need to reach values higher than peak values in current LWRs, to test more resilient fuels. Also, need to know linear power that each pellet &quot;sees&quot;, either by making the axial power profile as flat as possible, or by finely (axially) instrument rods</td>
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<td>Peak linear power rate of power change</td>
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<td>Water mass flow/velocity</td>
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<td>Strain gages and associated ports</td>
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<td>Rod peak linear power</td>
<td>300-350 W/cm²</td>
<td></td>
</tr>
<tr>
<td>Fast neutron flux (&gt;0.1 MeV)</td>
<td>High-dpa region</td>
<td>At least 3-4×10¹⁶ n/cm² s (&gt;30 dpa/yr)</td>
</tr>
<tr>
<td></td>
<td>Mid-dpa region</td>
<td>~10¹⁶ n/cm² s (~1 dpa/yr)</td>
</tr>
<tr>
<td></td>
<td>Low-dpa region</td>
<td>10⁸-10¹¹ n/cm² s (10⁻⁵ - 10⁻³ dpa/yr)</td>
</tr>
<tr>
<td>Oxygen control system, and chemistry control system</td>
<td></td>
<td>Oxygen getter (Zr, Ti, Ta, Mg...)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass exchanger (PbO)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H₂/Ar/O₂ injectors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Filters (preferably mechanical, e.g. cold traps)</td>
</tr>
<tr>
<td>Other instrumentation to measure:</td>
<td>Power and power distribution (axial and radial)</td>
<td>At multiple axial elevations</td>
</tr>
<tr>
<td></td>
<td>Neutron flux and spectrum (the latter desirable)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rod geometrical configuration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temp. (Pb and cladding mandatory, fuel recommended)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pb mass flow/velocity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressure, including differential pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain gages and associated ports</td>
<td>For on-line monitoring cladding swelling vs BU</td>
</tr>
<tr>
<td>Other</td>
<td>Testing loop should have a zero, or very low, neutron flux region where reference samples (exposed to the same conditions as those in the core with the exception of irradiation) can be tested. This region can be above the active region, or in the loop piping outside of the vessel.</td>
<td></td>
</tr>
</tbody>
</table>

* Because of the higher damage resulting, for the same fluence, from exposure to lower neutron flux than to higher neutron flux, providing the ATFR with low-fast flux testing zones, in lead, will prevent obtaining results that are not conservative. In absence of prototypical conditions characterizing components such as the vessel or the inner vessel (low fast flux in lead), testing in high fast flux region but for very short time may lead to results which are not conservative.
Advance Reactor Concepts, LLC.- Test Reactor Needs (Non-Proprietary Summary)

Licensing

Both educating the regulator about the technology and demonstrating that it can be successfully licensed. Uncertainty in licensing has been a major impediment for private financing and success with the test reactor would remove that uncertainty.

Data

- Availability of existing information and data
- Qualification of existing data for NRC use is an important for licensing

Advanced Fuels and Fabrication

- Long residence time fuels supports innovation in fuels and materials
- 20 year life fuel, peak Burnup ~14%, Tmax 500°C
- Advance fuel fabrication processes will require development and qualification of fabrication processes
- Test Rx should be prepared to support change in fuel compositions, e.g., UZr to UPuZr

Cladding and Duct Materials

- Low swelling cladding and duct materials:
  - HT-9 is best (current) alloy available
  - Determine adequacy of HT9 in service for extended use, ~20 years (need 200dpa total)
  - BOR-60 @ 15 dpa/year is too slow for development
- No full core demonstration of HT9 cladding and duct – assumed as the only potential alloy with any irradiation history.

Component demonstration and development

- Primary and secondary components- design data needed
  - Fuel handling
  - Core Restraint is an important issue
    — Flexibility
    — Passive feedback
  - Zenon feedback
- Advanced sensors, instrumentation and control
- Power conversion demonstration at representative power levels
  - Test reactor should provide a readily available source of heat; supercritical CO₂, Brayton cycle with bottoming cycle testing will need 10 to 100 MWt source
  - Load following and bottoming cycle demonstration
TerraPower Requirements Summary: SFR (Non-Proprietary Summary)

- **Irradiation Needs:**
  - Fast Flux (> 0.1 MeV, $4 \cdot 10^{15}$ n·cm$^{-2}$·s$^{-1}$),
  - >20 dpa/year,
  - specific fuel design demonstration/validation of high burnup and in-situ breeding

- **Test Reactor Needs**
  - Support over power conditions
  - Fueled assembly irradiated in various positions
  - Experiment Loops (1 or 2)
    - Instrumented
    - Molten salt loop at 650° to 700°C
Acting as a response to the request for information by the DOE test reactor design group, this document outlines several potential experimental conditions and characteristics that would be of use to the Transatomic MSR design process.

Temperature

- The effect of temperature on material properties under neutron irradiation
  - Experimental range: 550 to 750°C

Neutron Fluence (> 0.1 MeV)

- High neutron fluence for evaluation of structural and non-structural components (including salt) over the course of life
  - Experimental range: $1 \cdot 10^{21}$ to $1.5 \cdot 10^{22}$ n·cm$^{-2}$
  - A neutron flux of roughly $1 \cdot 10^{15}$ n·cm$^{-2}$·s$^{-1}$ would allow for fairly rapid experimental trials (on the order of months).

Experimental Setup Considerations

- Inert atmosphere materials irradiation capabilities for structural and non-structural components (including salt)
- Materials irradiation capabilities under a static salt environment
- Materials irradiation capabilities under a flowing salt environment
  - Flowing experiments can be performed with natural circulation, however, forced flow capabilities are desirable.

General Considerations

- As lithium based salts result in substantial tritium production, tritium management and control must be taken into account.
- On-site post irradiation facilities that would be appropriate for structural and non-structural component (including salt) analysis
- Removable test loops for analysis of larger scale piping components
- Ideally the analyzed salt would be LiF-UF$_4$; the uranium component can be strictly $^{238}$U as $^{235}$U is not necessary for these tests.
## General Atomic- Sample Customer Requirements for National Fast Test Reactor

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>GA Request</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Test types</td>
<td>Helium test loop for fuel samples. Static in-core locations for material samples.</td>
</tr>
<tr>
<td>2. Helium test loop thermal-fluid parameters</td>
<td>Mass flow at 100 g/s. Pressure at 13 MPa. Helium temperature 550 to 1000°C</td>
</tr>
<tr>
<td>3. Helium test loop envelope</td>
<td>Outer diameter = ~100mm. Height = full core height.</td>
</tr>
<tr>
<td>4. Helium test loop features</td>
<td>Multiple capsules per loop. Ability to insert and extract test capsules without removing loop.</td>
</tr>
<tr>
<td>5. Helium test loop construction materials</td>
<td>Double wall vessel of HT-9</td>
</tr>
<tr>
<td>6. Fast and thermal neutron flux levels, n/cm²-s</td>
<td>Neutron flux (&gt;01. MeV) in the range of 3E15 to 1E16 n/cm²-s</td>
</tr>
<tr>
<td>7. Test duration</td>
<td>Most tests from 3-12 months. Some material tests may be longer</td>
</tr>
<tr>
<td>8. Test sample materials</td>
<td>SiC, UC, Zr₃Si₂, Be₂C, IN617, IN800, C-C</td>
</tr>
<tr>
<td>9. Test sample temps, pressures and power outputs</td>
<td>Test samples in helium at 600-1800°C. Capsule internal pressure = 1 atm cold. Fuel capsule thermal power at 0-10 kW.</td>
</tr>
<tr>
<td>10. Need to sample fission gas during irradiation</td>
<td>Desirable to have option to sample release of fission gas by isotope from fuel pellets as function of fuel burnup</td>
</tr>
<tr>
<td>11. Size of test capsule</td>
<td>15-30 mm OD by 100-200 mm length. Material capsules are smaller, fuel capsules are larger</td>
</tr>
<tr>
<td>12. Measurements of test sample during irradiation</td>
<td>Temperature, fluence, mechanical strains, fission gas release</td>
</tr>
<tr>
<td>13. Anticipated number of test capsules per year</td>
<td>5-20 fuel capsules and 5-10 material capsules</td>
</tr>
<tr>
<td>14. Test sample pre-irradiation characterization support</td>
<td>It is helpful to perform some pretest measurements with similar methods, instruments and personnel as post-test measurements</td>
</tr>
<tr>
<td>15. Test capsule fabrication support</td>
<td>This is very helpful, particularly if there is a set of standard capsules that have been qualified for testing in the reactor</td>
</tr>
<tr>
<td>16. Test planning and execution support</td>
<td>It is essential to have a test reactor staff member available to help the experimenting organization with the necessary planning, preparation and safety analysis.</td>
</tr>
<tr>
<td>17. Types of post-irradiation examinations</td>
<td>Dimensional changes, microstructure, mechanical strength, elastic modulus, fracture toughness, hardness, thermal conductivity, chemical changes</td>
</tr>
</tbody>
</table>