INL/EXT-21-63894
Revision 0

Gap Assessment on Sensors and Instrumentation for Advanced Reactors

June 2021

Milestone Report—M2CT-21IN0701028

Pattrick Calderoni & Troy Unruh
Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/EXT-21-63894
Revision 0

Gap Assessment on Sensors and Instrumentation for Advanced Reactors

Milestone Report—M2CT-21IN0701028

Pattrick Calderoni & Troy Unruh
Idaho National Laboratory

June 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

ABSTRACT

The Sensor Technologies for Advanced Reactors Virtual Workshop—sponsored by the Gateway for Accelerated Innovation in Nuclear (GAIN), the Electric Power Research Institute, and the Nuclear Energy Institute—was held to exchange information on sensors and sensor technologies of interest to advanced nuclear technology developers, commercial instrument suppliers, and sensor researchers from Department of Energy (DOE) national laboratories, universities, and industry.

The workshop objectives were to discuss measurement requirements and sensor needs for advanced reactor concepts, understand current national laboratory capabilities and accelerated development approaches for sensors and instrumentation, and identify gaps so as to inform applicable DOE Office of Nuclear Energy (DOE-NE) research programs.

Due to the complexity of holding group discussions on individual gaps, a survey was sent to workshop participants, and personalized one-on-one feedback sessions were held to elicit additional information. Summaries of these sessions are provided in this gap assessment report.

Page intentionally left blank

CONTENTS

FIGURES

Page intentionally left blank

ACRONYMS

ASI	Advanced Sensors and Instrumentation
DOE	Department of Nuclear Energy
DOE-NE	Department of Energy Office of Nuclear Energy
FY	fiscal year
GAIN	Gateway for Accelerated Innovation in Nuclear
MTR	Material Test Reactor
NEET	Nuclear Energy Enabling Technologies
PWR	pressurized-water reactor

Page intentionally left blank

Gap Assessment on Sensors and Instrumentation for Advanced Reactors

1. INTRODUCTION

This report documents the outcomes of both the Sensor Technologies for Advanced Reactors Virtual Workshop—sponsored by the Gateway for Accelerated Innovation in Nuclear (GAIN), the Electric Power Research Institute, and the Nuclear Energy Institute—as well as personalized one-on-one meetings. The workshop was held to exchange information on sensors and sensor technologies of interest to advanced nuclear technology developers, commercial instrument suppliers, and sensor researchers from U.S. Department of Energy (DOE) national laboratories, universities, and industry.

The workshop objectives were to discuss measurement requirements and sensor needs for advanced reactor concepts, understand current national laboratory capabilities and accelerated development approaches for sensors and instrumentation, and identify gaps so as to inform applicable DOE Office of Nuclear Energy (DOE-NE) research programs.

Due to the complexity of holding group discussions on individual needs, a survey was sent to workshop participants, and personalized one-on-one feedback sessions were held to elicit additional information. Summaries of these sessions are provided in the following sections of this gap assessment report.

2. BACKGROUND

DOE-NE established GAIN to provide the nuclear community with the necessary technical, regulatory, and financial support to move innovative nuclear energy technologies toward commercialization while also ensuring continued safe, reliable, economic operation of the existing nuclear fleet. Through GAIN, DOE is making its state-of-the-art and continuously improving research development and deployment infrastructure available to stakeholders to achieve faster and cost-effective development of innovative nuclear energy technologies toward commercial readiness [1].

Initiation of the Sensor Technologies for Advanced Reactors Virtual Workshop was proposed by the DOE Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation (NEET-ASI) program in order to elicit feedback from national laboratories, universities, and industry on sensors and sensor technologies needed for advanced reactor developers. *While established nuclear utilities will likely benefit from the outcomes of this assessment, it was decided to focus the topics and discussions of advanced reactor developers, due to their early stage designs and deployment flexibility, neither of which is feasible with an established nuclear power plant.* Through GAIN, the NEET-ASI program contacted several advanced reactor developers to assess their sensor needs.

2.1 Advanced Reactors Virtual Workshop

2.1.1 Introduction to the sensor gap assessment

A GAIN-sponsored workshop on sensors had been discussed among NEET-ASI program managers as early as 2018; however, planning for the workshop was not initiated until late 2019. The workshop was originally planned to be hosted at Idaho National Laboratory in June 2020, enabling participants to tour the Measurement Science Laboratories and observe many of the resources available for sensor fabrication and deployment. It was thought this would help foster discussions and collaborations. To discuss gaps, the organizers had planned to hold breakout sessions focused on measurement needs. However, the ongoing COVID-19 pandemic caused the meeting to be delayed until October 13, 2020, at which time it was hosted virtually. As part of this decision, the agenda was shortened from 2 days to a half-day overview to explain the gap assessment process, accompanied by a survey and personalized one-on-one meetings.

2.1.2 Sensor technologies for advanced reactors gap assessment survey

GAIN provided an extensive list of advanced reactor developers who had been emailed invitations to participate in the workshop. The email invitation and corresponding website each provided a link to the survey, as shown in Figure 1.

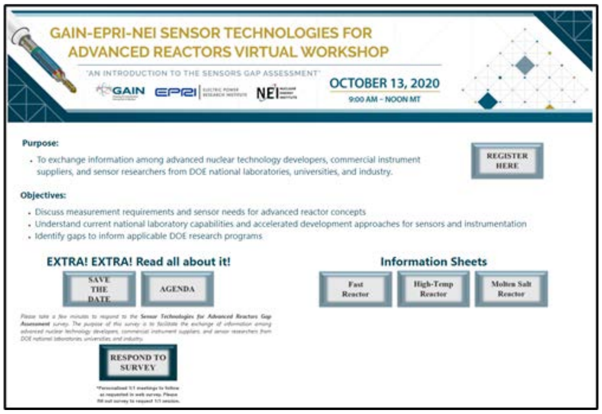

Figure 1. GAIN website.

The decision tree behind the survey was structured to categorize the feedback from national laboratory researchers, university researchers, commercial instrument suppliers, and nuclear technology developers. All users were asked to provide their contact information, as per the request form shown in Figure 2.

Figure 2. Contact information request form.

All users were able to provide comments and feedback; however, only those users who selected "nuclear technology developer" (see Figure 3) were asked if they wished to participate in a personalized one-on-one meeting to discuss the sensors and sensor technologies planned for their reactor designs.

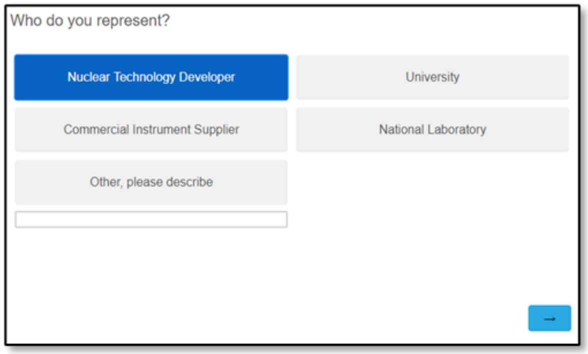

Figure 3. Example decision tree.

2.1.2.1 Workshop, survey, and NEET-ASI webinar attendance/feedback

Nearly everyone who received the GAIN email about the workshop registered to participate in it: a grand total of 144 persons. Ultimately, though, the actual number of workshop attendees was 106. Of these 106, 63 were sensor researchers from universities or national laboratories, 25 were nuclear technology developers, and 18 were commercial instrument suppliers (see the workshop participation chart in Figure 4).

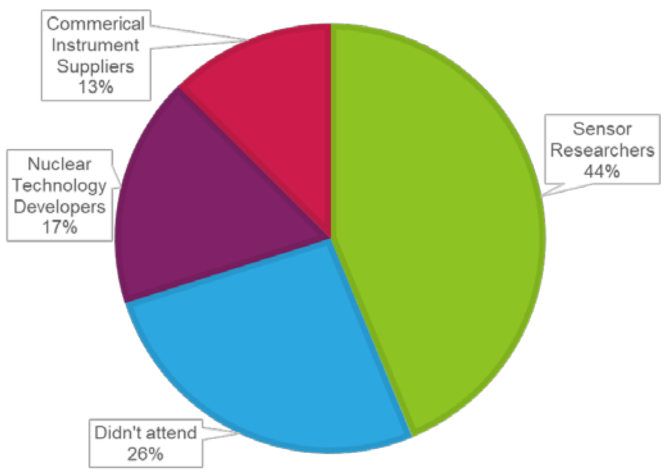

Figure 4. Workshop participation pie chart.

Fifteen nuclear technology developers requested a personalized one-on-one interview. But since several were from the same organization, only eight one-on-one interviews were initiated as a result of the survey sent to the 144 registered participants of the workshop. After completing the workshop, the eight organizations were sent emails to schedule the interviews. Two of the organizations did not respond, meaning that only six were ultimately interviewed. Interestingly, two other organizations indicated they had a sensor management plan, but did not request a follow-up interview. These data are summarized in the nuclear technology developer interviewee chart in Figure 5.

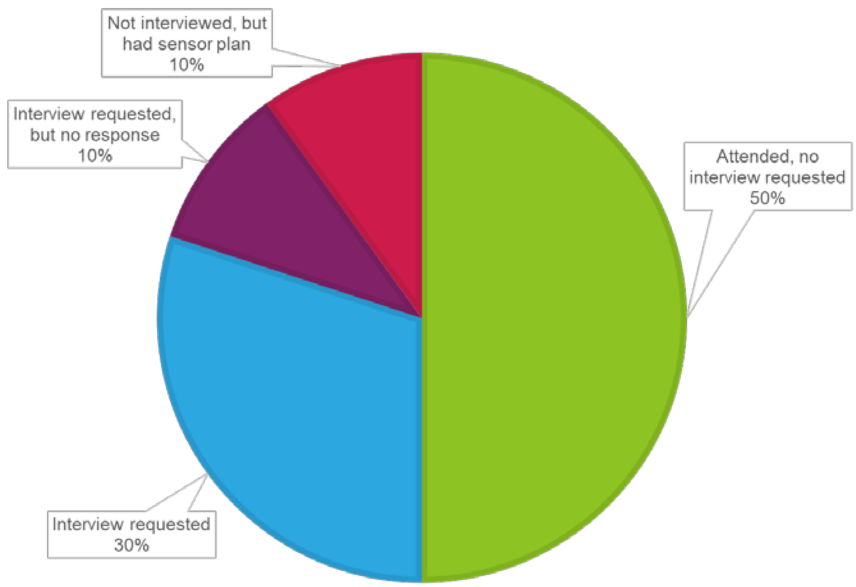

Figure 5. Nuclear technology developer interviewees.

In contrast to the GAIN workshop, registration and attendance for each of the 3 days of the NEET-ASI annual webinar were as follows:

Day 1: 127 registered, 119 attended

Day 2: 105 registered, 94 attended

Day 3: 97 registered, 89 attended

As can be seen, participation in the GAIN sensor workshop was similar to that in the NEET-ASI annual webinar, indicating that the participation aligned with expectations.

3. PERSONALIZED 1:1 MEETING OVERVIEW

Figure 6 shows the email request, titled “Sensor Technologies for Advanced Reactors Gap Assessment Personalized 1:1 Meeting,” sent to the eight nuclear technology developers (two of which did not respond), along with the three questions shown in Figure 7.

Dear ……,

Thank you for your interest in the GAIN-EPRI-NEI Sensor Technologies for Advanced Reactor Virtual Workshop and/or the Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation Annual webinars in 2020. These focused meetings were held to understand the current and future needs for the development of advanced sensor technologies for nuclear energy applications.

We would like to start a conversation pertaining to the Gap Assessment Survey your organization has completed as part of the virtual workshop. A preliminary discussion would be beneficial in order to assess the scope of the possible exchange and the process forward. I have attached a slide that highlights the information to be discussed.

Please let Kara in cc know your availability the week of ……, and we will schedule a 1 hour TEAMS web-meeting. You will be able to add other participants from your organization as needed.

We look forward to hearing from you.

Sincerely,

Figure 6. Sensor Technologies for Advanced Reactors Gap Assessment Personalized 1:1 Meeting email.

GAIN
Gateway for Accelerated Innovation in Nuclear

Engaging advanced reactor developers

Please be ready to discuss your company's measurement needs:

1. ***What physical parameters (i.e., temperature, pressure) will you need to measure in your systems?***
2. ***What are the main environmental conditions (i.e., neutron fluence, temperature chemical compatibility) and operational requirements for different components of your plant (i.e., core, in-vessel, primary/secondary loop, heat exchanger)?***
3. ***What are the main challenges to and planned qualification activities for instrumentation specific to your design solution (including data acquisition systems)?***

Figure 7. Questions on measurement needs.

3.1 General Feedback

During the interviews, a number of general feedback comments were received, and these are listed below. The comments were either discussed in more than one interview or are not specific to a reactor design. Hence, they are included here without the interviewee reference.

- ISO 17025 certified testing and calibration laboratories have limited capabilities for non-pressurized-water reactor (PWR) coolants and thus must use surrogates, bringing accuracy and relevance into question.
- Operational data for thermocouple performance evaluations are available from PWR operations or Material Test Reactor (MTR) irradiation experiments, albeit in temperature ranges irrelevant to the operations of many advanced reactors.
- Novel sensor technologies are tested in MTRs as well as in research reactors, which often fail to accumulate enough fluence (i.e. radiation damage) to characterize the sensors' lifetime performance when operating in advanced rectors.

- Novel sensor technologies are often tested in planned operational conditions. "Accident" condition testing (i.e., high-temperature/-pressure failures) is limited.
- There is general interest in the application of optical fiber technologies to advanced reactors. The technology is considered to potentially have a disruptive impact by decreasing the intrusiveness of the instrumentation in terms of size and vessel penetrations, and by providing multimode, multipoint, or distributed measurements. The main perceived challenge lies in the degradation of transmission performance in radiation fields (i.e. radiation-induced attenuation).
- Optimization of sensor location is an important part of the design process, and its importance increases the more the reactor's size and power are reduced. This assessment should be considered in plant design optimization, not as a subsequent activity.
- Instrumentation reliability data to support the development of advanced control systems are limited, creating a barrier in regard to licensing considerations.
- Modeling and simulation tools for advanced reactors require experimental data beyond what has been gathered from the operation of existing PWRs. Reliable instrumentation for the development of modeling and simulation tools is not commercially available.
- Advanced sensor technology should include the capability to perform online recalibration.
- Advanced sensor technology should include scalable solutions to ensure the transition from first-of-a-kind demonstrations of advanced reactor concepts to nth-of-a-kind commercial systems. This includes but is not limited to cost effectiveness.
- Advanced sensor technologies are often characterized in single effects testing and research reactor experiments. These experiments should include commercial sensors with traceable calibration and established quality assurance processes.

3.2 Feedback Summaries

Although the measurement needs of the advanced reactor developers were similar, each involved unique environmental conditions. However, the interviews were still useful for better understanding those areas in which cross-cutting research can impact advanced reactor developers. Note that the following information is not intended to strategically target the perceived gaps, but simply represents conclusions generated from the data captured.

The number of areas encompassing the discussions on the developers' measurement needs varied from interview to interview, ranging anywhere from three to sometimes more than 10. Figure 8 summarizes the feedback received on these various measurement needs. Of the areas considered during the interviews, four consistently stood out as being particularly cross-cutting. And while each reactor design may impose very different requirements regarding the measurement techniques utilized, the top four categories of measurement needs are as follows:

1. Temperature
2. Neutron flux
3. Flow
4. Pressure.

Temperature measurements are the most widely varied of the possible techniques usable for meeting the developers' measurement needs. A total of five different temperature measurement techniques were discussed (see Figure 9), with thermocouples being of primary interest, though many interviewees did not specify a particular temperature measurement technique. While neutron flux measurement techniques were less varied as a result of the limited maturity of commercially available techniques, the primary interest was in fission chambers (see Figure 10). Again, however, a significant number of interviewees did not specify a particular neutron-flux measurement technique.

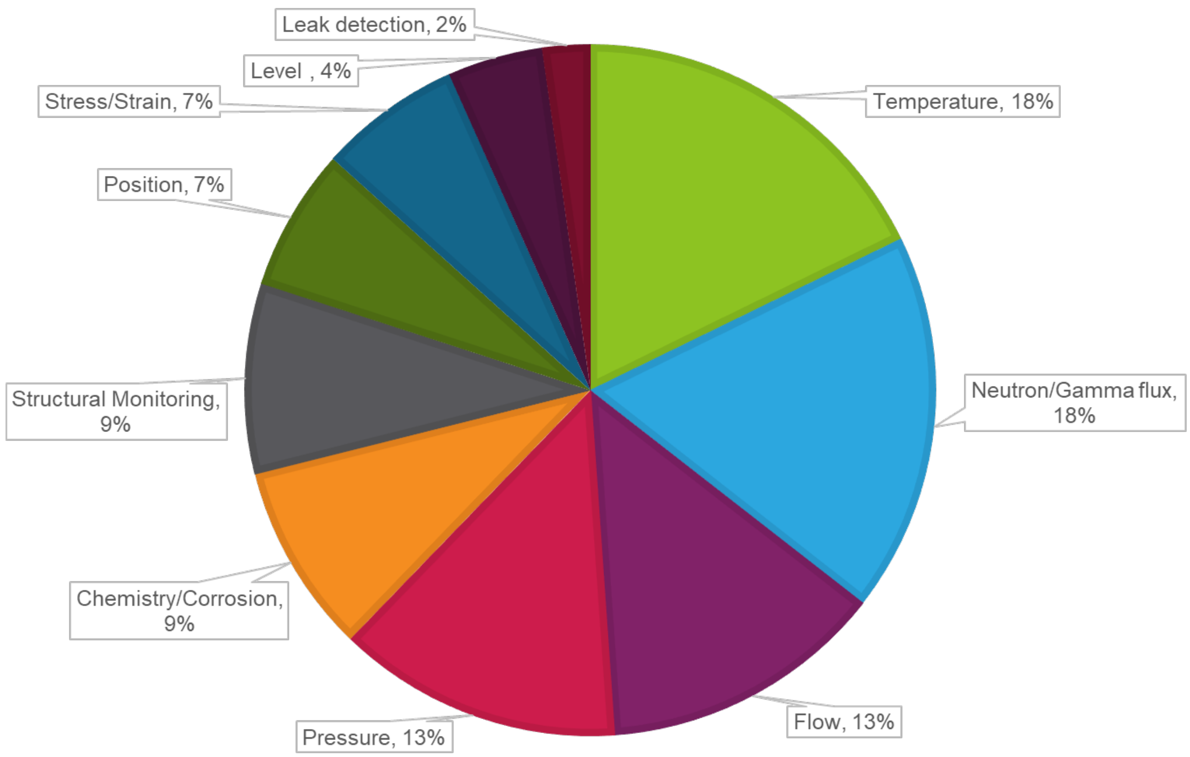

Figure 8. Summary of discussed areas of measurement needs.

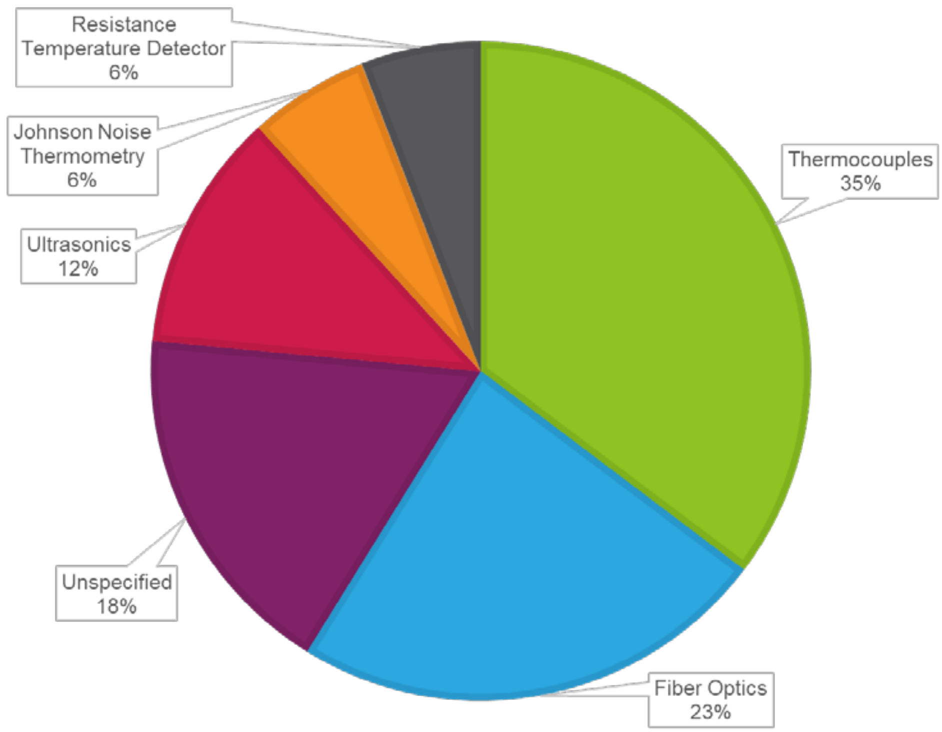

Figure 9. Temperature techniques discussed.

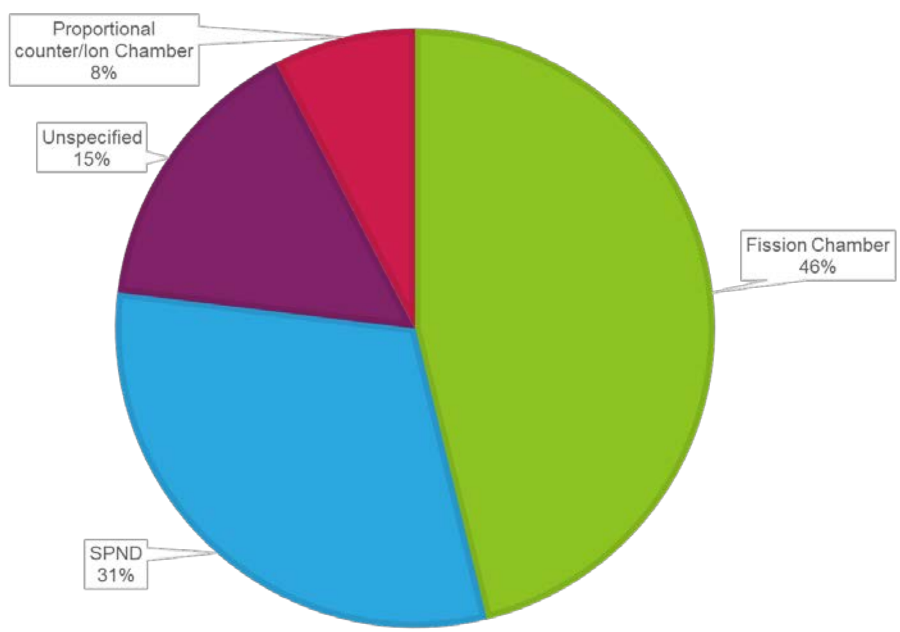

Figure 10. Flux measurement techniques discussed.

Each of the limited-distribution appendices at the end of this report further detail the discussions held during the one-on-one meetings, provide a short summary, and highlight the five following topics:

1. Measurement type
2. Identified techniques
3. Sensor characteristics
4. Known challenges.

The last category includes a description of alignment from the NEET-ASI national technical director, along with a four-category color map for quickly identifying alignment with the recent NEET-ASI portfolio. The legend and description for this alignment is shown in Figure 11.

Aligned with current ASI roadmap
Requires minor additions to current ASI roadmap
Requires substantial additions to current ASI roadmap
Outside ASI scope

Figure 11. NEET-ASI alignment categories covered in the appendices.

4. CONCLUSION

As expected, each nuclear technology developer had unique needs, and individual attention was required to assess how NEET-ASI cross-cutting projects will fulfill those needs. Despite many of the instrumentation development plans not being fully matured, it was apparent that the largest contribution to NEET-ASI program prioritization arose from advanced reactor developers in the process of maturing their instrumentation and controls design strategies and testing them in demonstration facilities. In other words, the more prior interaction between laboratory researchers and vendor designers, the more useful this coordination exercise. Recent activities pertaining to the DOE Advanced Reactor Demonstration program serve as a good example of a framework in which this interaction worked to achieve a common understanding of needs, capabilities, and opportunities. The most relevant technical discussions on prioritization and alignment came from vendors already engaged with national laboratories in the definition of work scopes as part of Advanced Reactor Demonstration awards. This indicates the necessity of periodically engaging in such gap analysis in order to better guide the NEET-ASI program research plan. The main conclusion of this report is that *the static gap assessment performed in fiscal year (FY) 2021 which stemmed from the GAIN workshop should be converted into a periodic gap analysis for execution as part of the updating to the NEET-ASI research plan*. As part of this exchange, development of templates to elicit specific feedback is recommended—whenever possible—at reoccurring one-on-one meetings, in addition to documents summarizing NEET-ASI program strategy and ongoing activities.

The NEET-ASI program was created in FY 2012 as part of the NEET Crosscutting Technology Development element of the DOE nuclear energy portfolio [2]. The program initially focused on the execution of competitively awarded projects targeting laboratory proof of concept of advanced technologies with a high potential for disruptive transformation and a low Technology Readiness Level. Funding allocation was implemented mainly through the Nuclear Energy University Programs, the NEET program, and the Nuclear Science User Facilities program, all of which were later grouped into the Consolidated Innovative Nuclear Research Funding Opportunity Announcement. In this phase, the NEET-ASI program engaged primarily with national laboratories and universities via active research activities in the area of nuclear instrumentation. Starting in FY 2017, a second element was added to the program, targeting the maturation of in-core instrumentation for use in irradiation experiments conducted in MTRs which are operated on behalf of DOE. This new focus enabled the most promising sensor technologies to undergo maturation toward the development and demonstration of instruments with high Technology Readiness Levels. It also expanded NEET-ASI stakeholders into DOE-NE programs involving the execution of irradiation experiments, making the NEET-ASI scope effectively crosscutting across all DOE-NE missions. The objective of the gap assessment was to *optimize the NEET-ASI program stakeholders' engagement by initiating a direct dialog with industrial partners interested in the development of advanced reactor technologies. This report has shown that, in this sense, the gap assessment exercise in FY 2021 was successful in establishing such connections and creating the framework in which such engagement can be continuously strengthened and consolidated.*

The gap assessment discussed in this report aimed to collect feedback from advanced reactor developers in order to better inform NEET-ASI program priorities. Assessing the alignment of current and planned NEET-ASI activities via such feedback should be performed as part of developing the program strategic plan, and the consequent research roadmap and did not fall within this scope. However, preliminary comments in this regard from the NEET-ASI national technical director are included in the report's appendices, intended for limited distribution only. A brief summary of such comments, without reference to specific reactor technologies or related developers, is reported below for public distribution, in no specific order or priority. The following are the main technical areas within the NEET-ASI program scope that were identified as important in the gap assessment but have limited implementation in current NEET-ASI research activities:

- Structural health monitoring for nuclear reactor components, including reliable sensing solutions, methods for real-time data analysis, and the development of models and control algorithms to enable predictive maintenance
- Demonstration of the reliability of commercially available instruments for temperature and pressure measurement when operating in advanced reactor environmental conditions, including relevant neutron fluences, materials (coolant, structural) and design configurations (feedthroughs, welds)
- Reliable instruments and methods for flow and liquid level measurement, compatible with advanced reactor coolants and environmental conditions
- Reliable instruments and methods for real-time characterization of advanced reactor coolant chemistry.

5. REFERENCES

[1] https://gain.inl.gov/SitePages/Home.aspx

[2] https://www.energy.gov/ne/nuclear-energy-enabling-technologies-neet