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NEET Micro-Pocket Fission Detector – FY 2013 Status Report

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Idaho National Laboratory

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EXECUTIVE SUMMARY

A collaboration between the Idaho National Laboratory (INL), the Kansas State University (KSU), and the Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA), is funded by the Nuclear Energy Enabling Technologies (NEET) program to develop and test Micro-Pocket Fission Detectors (MPFDs), which are compact fission chambers capable of simultaneously measuring thermal neutron flux, fast neutron flux, and temperature within a single package.

When deployed, these sensors will significantly advance flux detection capabilities for irradiation tests in US Material Test Reactors (MTRs). Ultimately, evaluations may lead to a more compact, more accurate, and longer lifetime flux sensor for critical mock-ups and high performance reactors, allowing several Department of Energy Office of Nuclear Energy (DOE-NE) programs to obtain higher accuracy/higher resolution data from irradiation tests of candidate new fuels and materials. Specifically, deployment of MPFDs will address several challenges faced in irradiations performed at MTRs:

- Current fission chamber technologies do not offer the ability to measure fast flux, thermal flux, and temperature within a single compact probe; MPFDs offer this option.
- MPFD construction is very different than current fission chamber construction; the use of high temperature materials allow MPFDs to be specifically tailored to survive harsh conditions encountered in high performance MTRs.
- The higher accuracy, high fidelity data available from the compact MPFD will significantly enhance efforts to validate new high-fidelity reactor physics codes and new multi-scale, multi-physics codes.
- MPFDs can be built with variable sensitivities to survive the lifetime of an experiment or fuel assembly in some MTRs, allowing for more efficient and cost effective power monitoring.
- The small size of the MPFDs allows multiple sensors to be deployed, offering the potential to accurately measure the flux and temperature profiles in the reactor.

This report summarizes the status at the end of year two of this three year project. Highlights from our research accomplishments include:

- An updated design of the MPFD has been developed incorporating previous INL High Temperature Test Laboratory (HTTL) experience for developing robust sensors that are resistant to radiation and temperature degradation.
- Materials and tools to support the new design have been procured. Stainless steel tubes and custom alumina substrates and insulators have been used in support of new construction methods.
- Construction of the new design at INL's HTTL is underway using specialized new methods for cable construction and assembly.
- Electrical contact and fissile material plating methods have been explored and are being characterized at KSU to produce optimized, repeatable, and robust deposits.
- Updated detector electronics have been designed, built, and tested at the KSU (Electronics Design Laboratory (EDL). Furthermore, the electronics were tested with an older design of a MPFD installed in the KSU Training Research Isotope-production General Atomics (TRIGA) reactor.
- A project meeting was held at KSU to discuss the roles and responsibilities between INL and KSU for development of the MPFDs. In addition, a demonstration of newly designed electronics was given.
- A detector evaluation plan has been developed, and new testing capabilities in the ATRC have been used. The detector evaluation plan includes options for testing at the HTTL, Health Physics Instrumentation Laboratory (HPIL), and Adavnced Test Reactor Critical facility (ATRC), with potential testing at the KSU TRIGA reactor. It is expected this testing will lead to valuable insights to improve the MPFD design.

As documented in this report, all planned FY12 and FY13 accomplishments for developing this unique new, compact, multipurpose sensor have been completed.

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ACRONYMS

AFC	Advanced Fuel Cycle
ARC	Advanced Reactor Concepts
ASI	Advanced Sensors and Instrumentation
ATR	Advanced Test Reactor
ATRC	Advanced Test Reactor Critical facility
BTB	Back-to-Back
BWR	Boiling Water Reactor
CEA	Commissariat à l'Énergie Atomique et aux Energies Alternatives
DOE	Department of Energy
DOE-NE	Department of Energy office of Nuclear Energy
EDL	Electronics Design Laboratory
EGT	Experiment Guide Tube
FCRD	Fuel Cycle Research and Development
FNDS	Fast Neutron Detection System
FY	Fiscal Year
HFIR	High-Flux Isotope Reactor
HPIL	Health Physics Instrument Laboratory
HTGR	High Temperature Gas Reactor
HTIR-TC	High Temperature Irradiation Resistant Thermocouple
HTTL	High Temperature Test Laboratory
INL	Idaho National Laboratory
KSU	Kansas State University
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MPFD	Micro-Pocket Fission Detector
MTR	Material Test Reactor
NEET	Nuclear Energy Enabling Technology
NGNP	Next Generation Nuclear Plant
NIST	National Institute of Standards and Technology
NSUF	National Scientific User Facility
ORNL	Oak Ridge National Laboratory
PWR	Pressurized Water Reactor
REL	Research Education Laboratory
SFR	Sodium Fast Reactor
SMART	Semiconductor Materials And Radiological Technologies
SPND	Self Powered Neutron Detector
TRIGA	Training Research Isotope-production General Atomics

NEET ASI Micro-Pocket Fission Detector Annual Status Report

1. INTRODUCTION

Irradiation testing, which is often performed in harsh conditions (e.g., high flux, high temperature, etc.) in Materials Test Reactors (MTRs), is essential for evaluating materials or fuels performance prior to use in commercial reactors. Accurate monitoring of these harsh conditions with compact sensors, that are less likely to disturb the conditions of interest, is necessary to quantify any degradation that occurs during irradiation.

This report summarizes progress toward developing Micro-Pocket Fission Detectors (MPFDs) capable of measuring thermal neutron flux, fast neutron flux and temperature within a single compact sensor. Miniature fission chambers and thermocouples have been used in-core at research and test reactors throughout the world; however, none have been deployed in a single compact package to survive the harsh conditions that exist at high performance MTRs.

1.1. Motivation/Objective

During the last 40 to 50 years, various sensors have been developed to meet the needs of irradiation testing for materials and fuels in MTRs. Development of these sensors is an on-going process because they are continuously improved and refined as operational shortcomings are recognized for advanced testing requirements. The most recent addition of advanced testing for new reactor designs involves higher temperatures, higher fluxes and more corrosive test conditions. The next generation of sensors is under development that can survive these conditions.

In-core fission chamber design has remained relatively unchanged for decades. Improvements in performance, overall size and operational modes have been realized; however, all have been based on the same design that utilizes coaxial cylinders with a high pressure fill gas. These design considerations limit the robustness, lifetime, size, and operational performance of such sensors in advanced testing environments.

MPFDs utilize the same operational concept of existing fission chamber designs, but deploy a geometry with parallel plate electrodes instead of coaxial cylinders. The MPFD signal is not based on the full energy deposition from the fission products. This departure from conventional fission chamber design and operating characteristics allows the MPFDs to have a smaller chamber size with a lower fill gas pressure. The small size allows them to have a faster response time and thus, have the potential to achieve higher count rates than conventional fission chamber designs. The construction materials chosen for the MPFD include temperature and radiation resistant ceramics that can survive the harsh conditions of advanced irradiation tests. The small design also allows two or more neutron detectors and a thermocouple to be co-located within a single sensor sheath such that thermal flux, fast flux, and temperature can be simultaneously measured at very near the same location in the experiment.

MPFDs offer the potential for improved, high accuracy, and higher fidelity data of interest to Department of Energy office of Nuclear Energy (DOE-NE) programs. Deployment of several MPFDs in irradiation tests will provide much needed information for current efforts to develop and deploy high-fidelity, multi-scale, multi-physics computer codes.

1.2. Objectives of NEET MPFD Research

Several DOE-NE programs, such as the Fuel Cycle Research and Development (FCRD), [1,2] Advanced Reactor Concepts (ARC),[4 through 5a] Light Water Reactor Sustainability (LWRS),[6,7] and Next Generation Nuclear Plant (NGNP) [8 through 13] programs, are investigating new fuels and materials for advanced and existing reactors. The Nuclear Energy Enabling Technology (NEET) Advanced Sensor and Instrumentation (ASI) in-pile instrumentation development activities are focused upon addressing cross-cutting needs for DOE-NE irradiation testing by providing higher fidelity, real-time data with increased accuracy and resolution from smaller, compact sensors that are less intrusive.[14] In particular, flux sensors are required for characterizing fuel performance as a function of burnup and cladding and structural material degradation as a function of neutron exposure. The NEET ASI initiated the MPFD project because it addresses this cross-cutting need by developing, fabricating, and evaluating the performance of prototypes of compact multi-purpose fission chambers with integral temperature sensors.

A key objective of several DOE-NE programs is to understand the performance of candidate fuels and materials during irradiation. Hence, NEET research must produce sensors able to withstand the operating conditions of interest to these DOE-NE programs. It is also important that the enhanced sensors be able to measure test parameters with the desired accuracy and resolution required by these DOE-NE programs and that the sensors be compact to minimize their impact on irradiation test data. Recognizing that DOE-NE program needs change, the NEET program holds annual reviews to ensure that projects continue to meet DOE-NE program needs. Results from the 2013 review indicate that the MPFDs are still needed by DOE programs.[15] Specific details related to current requirements for thermal flux, fast flux, and temperature sensors requested by DOE-NE programs for fuels and material irradiations are summarized in this section.

1.2.1. Fuel

In-situ instrumentation is desired to provide real-time data on fuel performance phenomena. Without wireless transmission capabilities, drop-in or static capsule experiments only allow data to be obtained at the endpoint of an experiment. Although material property measurements may be made on samples at the end of the test, such measurements are subject to error because of handling and because measurements are not made under prototypic pressures, fluxes, and/or temperatures. Sensors included in such tests can only provide insights about the integral neutron fluence or peak temperatures. In-situ instrumentation in irradiation tests can provide data showing the evolution of particular phenomena over time.

Clearly, real-time data obtained during an irradiation are advantageous. However, it is important to understand what additional sensors are needed to obtain data with the required accuracy and resolution. As part of this NEET effort, appropriate documents were reviewed[1, 5, 6, 8 through 10] and cognizant technical experts were contacted[4,13,16 through 18] to gain insights related to the temperature, flux levels, and fluences proposed for fuel irradiation tests. Results from this review are summarized in Table 1.

1.2.2. Materials

As noted within Reference 6, there are many different types of materials within a Light Water Reactor (LWR); over 25 different metal alloys can be found within the primary and secondary systems, not to mention the concrete containment vessel, instrumentation and control, and other support facilities. Over the forty-year lifetime of a LWR, internal structural components may expect to see up ~10^{22} n/cm^2 in a Boiling Water Reactor (BWR) and ~10^{23} n/cm^2 in a Pressurised Water Reactor (PWR) (E > 1 MeV), corresponding to ~7 dpa and 70 dpa, respectively. The neutron irradiation field can produce large property and dimensional changes in materials. Such changes occur primarily via five radiation damage processes: radi-

a. The ARC program is limiting current research to evaluating advanced structural materials and relies on other DOE-NE programs for fuel development.

Table 1. Summary of desired parameters for detection during fuel irradiation tests[a]

Parameter	Representative Peak Value	Desired	
		Accuracy	Spatial Resolution
fuel temperature	Ceramic LWR - 1400 °C	2%	1-2 cm (axially); 0.5 cm (radially)
	Ceramic SFR - 2600 °C		
	Metallic SFR - 1100 °C		
	TRISO HTGR - 1250 °C		
cladding temperature	Ceramic LWR - <400 °C	2%	1-2 cm (axially)
	Ceramic SFR - 650 °C		
	Metallic SFR - 650 °C		
	TRISO GCFR	NA	NA
pressure in fuel rod plenum	Ceramic LWR - 5.5 MPa	5%	NA[b]
	Ceramic SFR - 8.6 MPa		
	Metallic SFR - 8.6 MPa		
	HTGR - NA		
LWR, SFR, and HTGR fission gas release (amount and composition)	0-100% of inventory	10%	NA
LWR and SFR fuel and cladding dimensions (includes fuel / cladding gap size); HTGR- NA	Initial Length, 1 cm	1%	NA
	Outer diameter/Strain, 0.5 cm/5-10%	0.1%	NA
	Fuel-Cladding Gap (0-0.1 mm)	0.1%	NA
LWR, SFR, and HTGR fuel morphology/microstructure/ cracking/ constituent redistribution	Grain size, 10 µm	5%	1-10 µm
	Swelling/Porosity, 5-20%	2%	
	Crack formation and growth	2%	10-100 µm
fuel thermal properties	Thermal conductivity Ceramic: < 8 W/mK; Metallic: < 50 W/mK; TRISO pebble/compact: 4-12 W/mK	4%	< 1 cm (radially)
	Density (inferred from changes in length, diameter, porosity, etc.) Ceramic: < 11 g/cm^3; Metallic: < 50 g/cm^3; TRISO pebble/compact: 2.25 g/cm^3[c]	2%	NA
real-time thermal and fast neutron flux for estimating fluence and fuel burnup for fuel irradiations	Thermal neutron flux - ~1-5 x 10^{14} n/cm^2-s	1-10%	5 cm (axially)
	Fast neutron flux (E> 1 MeV) - ~1-5×10^{14} n/cm^2-s	15%	5 cm (axially)

a. Representative peak values, accuracy, and resolution are based on engineering judgement by cognizant program experts.
b. NA-Not Applicable.
c. Value dependent upon particle packing fraction and matrix.

ation-induced hardening and embrittlement, phase instabilities from radiation-induced or -enhanced segregation and precipitation, irradiation creep due to unbalanced absorption of interstitials versus vacancies at dislocations, volumetric swelling from cavity formation, and high temperature helium embrittlement due to formation of helium-filled cavities on grain boundaries. Extending the service life of a reactor will increase neutron fluence and susceptibility to radiation damage (although new damage mechanisms are possible). Likewise, when one considers the additional conditions proposed within DOE-NE programs for NGNP and Sodium Fast Reactor (SFR) operation, material performance becomes more complex.

As part of this NEET effort, appropriate documents were reviewed;[2, 3, 5 through 7, 9 through 12] and cognizant technical experts[4,13,18] were contacted to gain insights related to the temperature, flux levels, and fluences proposed for irradiation tests to evaluate new high temperature alloys, candidate structural materials, and graphites. Currently, most material irradiations are relying on Post Irradiation Examination (PIE) to characterize material properties after an irradiation is completed. However, enhanced in-pile instrumentation offers the potential for increased accuracy, higher fidelity data since measurements are obtained at the conditions of interest. Currently-requested accuracies and resolutions for these materials are listed in Table 2.

Table 2. Summary of desired parameters for detection during materials irradiation tests[a,b]

Parameter	Representative Peak Values	Desired	
		Accuracy	Spatial Resolution
Material temperature distribution	LWRS Fuel Cladding - >1200 °C	2%	1-2 cm (axially); 0.5 cm (radially)
	LWRS Vessel and Internal Materials - 500 °C		
	HTGR and LWRS high temperature alloys - 950 °C		
	HTGR Graphite - 600 to 1200 °C	± 50 °C (axially) ± 40 °C (radially)	NA
Material dimensional changes due to swelling	Initial Specimen Length, HTGR Graphite - 2.54 cm	1%	NA
	Outer diameter/Strain, LWR vessel and internal materials - 0.5 cm/5-10%	0.1%	NA
Material morphology/ microstructure/cracking/ constituent redistribution	Grain size, LWR vessel and internal materials > 10 µm	5%	1-10 µm
	Swelling/Porosity, LWR vessel and internal materials 5-20%	2%	10-100 µm
	Crack formation and growth LWR vessel and internal materials > 10 µm	2%	10-100 µm
Material thermal properties	Thermal conductivity HTGR Graphite - ~80 W/m-K	4%	< 1 cm (radially)
	Thermal conductivity LWR vessel and internal materials ~50 W/m-K	5-20%	< 1 cm
	Thermal coefficient of expansion; HTGR Graphite - 5%	2%	NA[c]
	Density (estimated from changes in length, diameter, porosity, etc.) HTGR Graphite - 0.5%	0.2%	NA
Material mechanical/electrical properties	Irradiation creep HTGR Graphite - 3-4%	NA	NA
	Young's modulus HTGR Graphite - 3-4%	NA	NA
	Electrical resistivity HTGR Graphite - 3-4%	NA	NA
	Poisson's ratio HTGR Graphite - 3-4%	NA	NA
	Fracture toughness, shear strength HTGR Graphite - 3-4%	NA	NA
Material irradiation neutron flux for estimating fluence	Thermal neutron flux - ~1-5 x 10^{14} n/cm^2-s	1-10%	5 cm (axially)
	Fast neutron flux (E > 1 MeV) - ~1-5×10^{14} n/cm^2-s	15%	5 cm (axially)

a. Representative peak values, accuracy, and resolution are based on engineering judgement and are preliminary.
b. Only LWRS and NGNP irradiation information available for a limited number of parameters at this time.
c. NA-Not Available.

2. BACKGROUND

This section describes commonly used flux detection sensors in typical MTR irradiations. A brief overview discussing their theory of operation, basic construction, deployment considerations, data collection considerations, and basic advantages/disadvantages is given to emphasize advantages of the new, compact high performance MPFDs and how they uniquely address irradiation testing needs for DOE-NE programs.

2.1. Flux Sensors

Accurate measurement of the time-dependent neutron field, the neutron flux, the integral exposure, or the neutron fluence that a sample receives is needed in order to assess effects of neutron interactions on the sample under investigation. Some tests only require that the overall neutron fluence be known. Hence, passive methods are used to measure the neutron irradiation after the sample has been removed from the reactor. Many DOE-NE irradiation tests relay on passive neutron fluence measurement techniques. However, as discussed in Section 1, many DOE-NE programs have identified candidate new materials and fuels whose performance evaluations require high accuracy/high resolution real-time fast and thermal flux measurements. Such measurements are typically accomplished with Self-Powered Neutron Detectors (SPNDs) or fission chambers. As indicated in Table 3, there are advantages and disadvantages with each type of detector. This section describes typical examples of each type of sensor along with their limitations in irradiation tests to emphasize the need for this project to develop MPFDs for use in DOE-NE irradiation test programs in higher flux US MTRs, such as the 250 MWt Advanced Test Reactor (ATR) and the 100 MWt High Flux Isotope Reactor (HFIR).

Table 3. Summary of advantages and disadvantages of typical flux sensors[19 through 27]

Flux Sensor	**General description**	**Typical characteristics**	
		Advantages	**Disadvantages**
Flux Wires and Foils	Utilizes neutron activation of materials to emit measurable gamma-rays	Small Thermal/Fast neutron response No power source Simple/robust Easily installed	Not real time Rigorous post-analysis Integral measurement
Self Powered Neutron Detectors	Generates measurable electrical current under neutron irradiation	Real time Small Thermal neutron response Simple/robust	Need Calibration No fast neutron response Low sensitivity Delayed response
Fission Chambers	Fissionable material interactions provide measurable electrical pulses	Real time Small Thermal/fast neutron response Variable sensitivity	Need power source Fragile
Micro-Pocket Fission Detectors	Fissionable material interactions provide measurable electrical pulses	Real time Small Simple/robust Simultaneous thermal/fast neutron response with temperature measurement Variable sensitivity Low power requirements	Need power source

2.1.1. Flux Wires and Foils

Flux wires and foils are the most commonly used passive method for local neutron activation spectrometry. A flux wire or foil is simply a material of known composition and purity that is placed in a neutron field. When placed in a neutron field, different elements (and different isotopes of the same element) interact differently with respect to the energy of the incident neutron. When the interaction product is radioactive, the resulting induced activity can be measured and correlated to the integral incident neutron exposure.[19] This measurement and correlation can only be performed after the irradiation is complete, and the flux wire or foil is removed from the reactor.

Deployment simply requires that the flux wires or foils be securely placed in the reactor (Figure 1). Hence, they can be placed at nearly any location in the reactor. Some materials can be placed directly in contact with the reactor primary coolant, whereas other more fragile materials must be encased in low cross-section materials that don't affect their neutron exposure. Data collection requires removing the radioactive flux wires or foils from the reactor and placing them on a gamma ray detector and counting them for a specific amount of time. The counting information and material information along with the irradiation time, and the time since the end of the irradiation, can then be used to calculate the neutron flux. The advantages of this method are that very small sensors can be used; it is generally very accurate; it can be used for high and low flux levels; and it gives information about the incident neutron energy. The disadvantages are that it is not real-time and that it requires handling radioactive material.

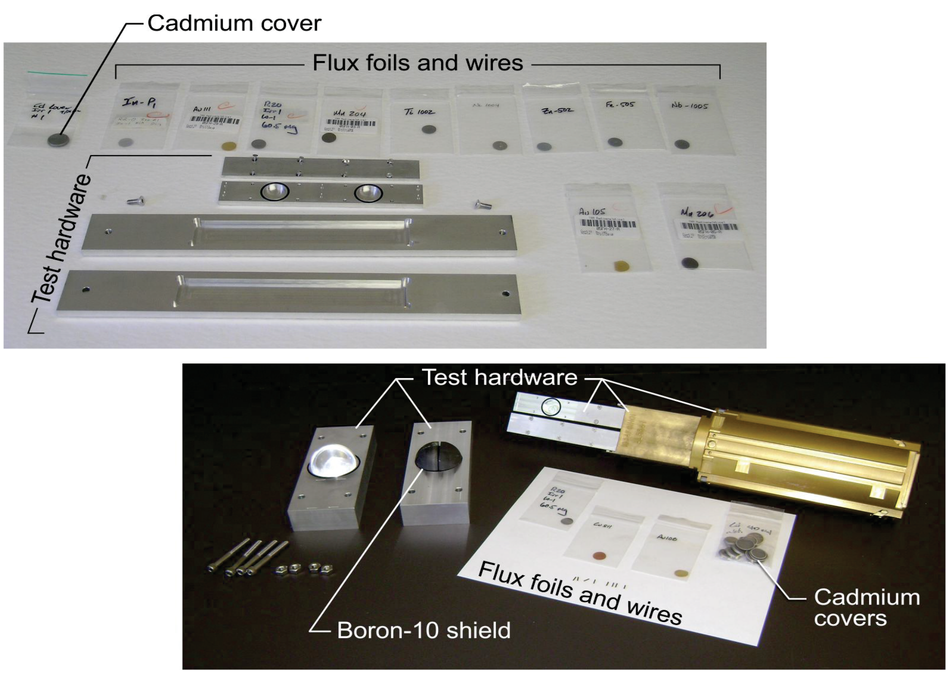

Figure 1. Representative flux wires, flux foils and test hardware used at INL

2.1.2. Self Powered Neutron Detectors

SPNDs are a commonly used real-time method for monitoring local neutron flux. SPNDs are built using materials that become radioactive in a neutron field and produce a small current which is correlated to the neutron flux (Figure 2). SPNDs are built around a central electrode, known as an emitter, which is composed of a metal with a relatively high neutron capture cross section.[19] Typical emitters and their properties are listed in Table 4. The central electrode is surrounded by an electrical insulator and an outer electrode, known as a collector. The outer electrode serves as a boundary between the reactor coolant and the emitter and insulator. The current between the emitter and collector is measured via external circuitry. It can take time for the current to build up in the SPND; hence, there is a delay time from several seconds to a few minutes before the signal is generated.

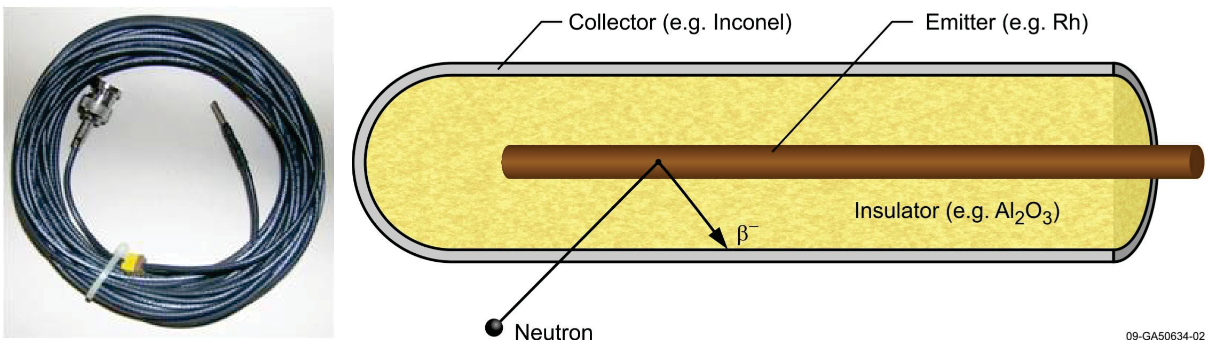

Figure 2. Representative Self-Powered Neutron Detector (SPND) and component sketch

Table 4. Typical emitters for SPNDs[19]

SPND Emitter	Sensitivity (A/m)/[2x10^{17} neutrons/(m^2 s)]	Response
Rhodium	2.4 x 10^{-6}	Delayed
Vanadium	1.5 x 10^{-7}	Delayed
Cobalt	3.4 x 10^{-8}	Prompt
Molybdenum	1.7 x 10^{-8}	Prompt
Platinum	2.6 x 10^{-7}	Prompt

Deployment requires a space large enough to fit the SPND, typically 1.5-6 mm in diameter, and the leads to be run from the experiment location to outside the reactor for signal processing; hence, SPNDs can only be deployed in specific experiment locations in the reactor. Data collection requires the SPNDs to be connected to sensitive low current measurement equipment. The SPNDs must be previously calibrated in a known neutron field so that the current response can be correlated to the incident neutron flux. The advantages of this method include that: it is self powered; it provides near real time neutron flux measurement; and it is a robust sensor. The disadvantages include: it has delays associated with its response; it requires a large neutron flux to generate a large current; it requires a calibration; it is generally limited to thermal neutrons; and it requires signal leads from the experiment to outside the reactor.[19]

2.1.3. Fission Chambers

Fission chambers are another commonly used real-time method for monitoring local neutron flux. As shown in Figure 3, fission chambers are built using two electrodes; one which has a fissile material deposit that emits fission fragments when placed in a neutron field. These fission fragments produce an instantaneous current pulse between the electrodes that have a polarization voltage applied between them. The resulting pulse is measured via external counting electronics. The space between the electrodes must have a fill gas to aid detector performance. Like SPNDs, the outer electrode serves as a boundary between the reactor coolant and the inner materials. The fissile material deposit can be chosen such that the detector is sensitive to either thermal neutrons or fast neutrons. Fission chambers can be operated in three different modes: pulse mode for low power applications that measure the individual pulses, current mode for mid-range power applications where pulses are so frequent that they can’t be separated and produce a continuous current, and Campbelling mode for high power applications where the variance of the signal is characterized and correlated to the incident neutron flux.[19]

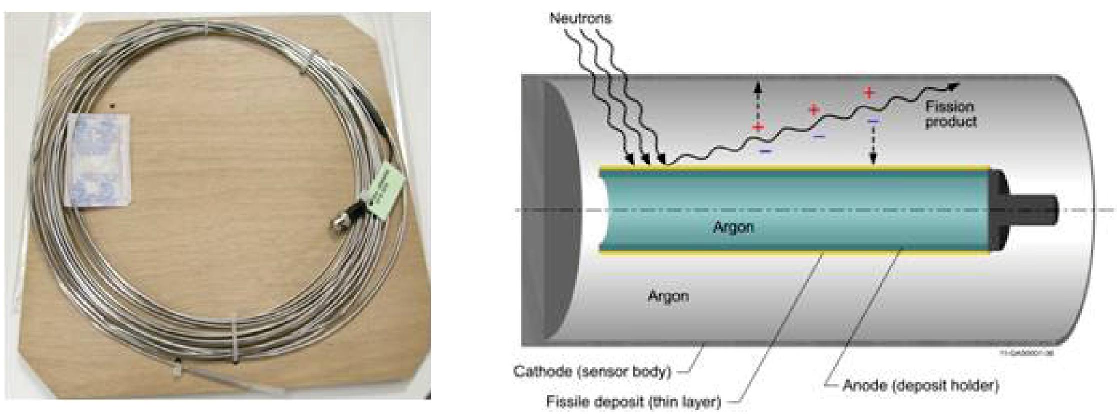

Figure 3. Representative fission chamber and component sketch

Deployment requires a space large enough to fit the fission chambers, typically 1.5-150 mm diameter, and leads from the fission chamber location to outside the reactor vessel for data display and storage. Hence, fission chambers can only be deployed in specific experiment locations in the reactor and sometimes are deployed outside the reactor core. Fission chamber response is correlated to incident neutron flux by accurate measurement of the fissionable deposit mass or by prior calibration in a neutron field. The advantages of this method include: it is real-time; it can be used for small and large neutron fluxes; it can be designed for thermal and fast neutron flux measurements; and it is more accurate then SPNDs.[19] The disadvantages include: it is more delicate; it can require a larger space in the reactor; and it requires signal leads from the experiment to outside the reactor.

Irradiations at US MTRs are typically performed at high fluxes using small samples with limited space for instrumentation. In addition, many DOE-NE irradiations must be performed at high temperatures (up to 2600 °C). Fission chambers must be sufficiently robust to survive these harsh conditions for the length of the experiment. As such, special fission chambers have been developed or are under development for use in US MTR experiments. The following section discusses several of these in-core fission chambers deemed most promising.

2.1.3.1. Miniature and Sub-Miniature Fission Chambers

The Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA) has over 40 years of experience in design, construction and use of miniature and sub-miniature fission chambers for MTR experiments (Figure 4).[26,27] CEA-developed fission chambers are as small as 1.5 mm diameter for sub-miniature fission chambers and 3 mm diameter for miniature fission chambers. The designs utilize two coaxial cylindrical electrodes of which the center electrode is covered with fissile material. The area between the electrodes is filled with argon gas between 1-10 atm pressure. The complexity of the coaxial design along with the potential for the high pressure fill gas to leak makes these miniature fission chambers more susceptible to damage during harsh irradiations.[26,27] The CEA fission chamber sensitivity to thermal and fast neutrons is increased by using different fissile material deposits. In addition, as part of the Joint Instrumentation Laboratory, CEA and Studiecentrum vor Kernenergie Centre d'Étude de l'Énergie Nucléaire(SCK•CEN) have also developed a Fast Neutron Detector System (FNDS) for monitoring fast neutron flux in large flux environments. Prior to the development of a new type of fission chamber, CEA models the expected response with specially developed software.[26,27]

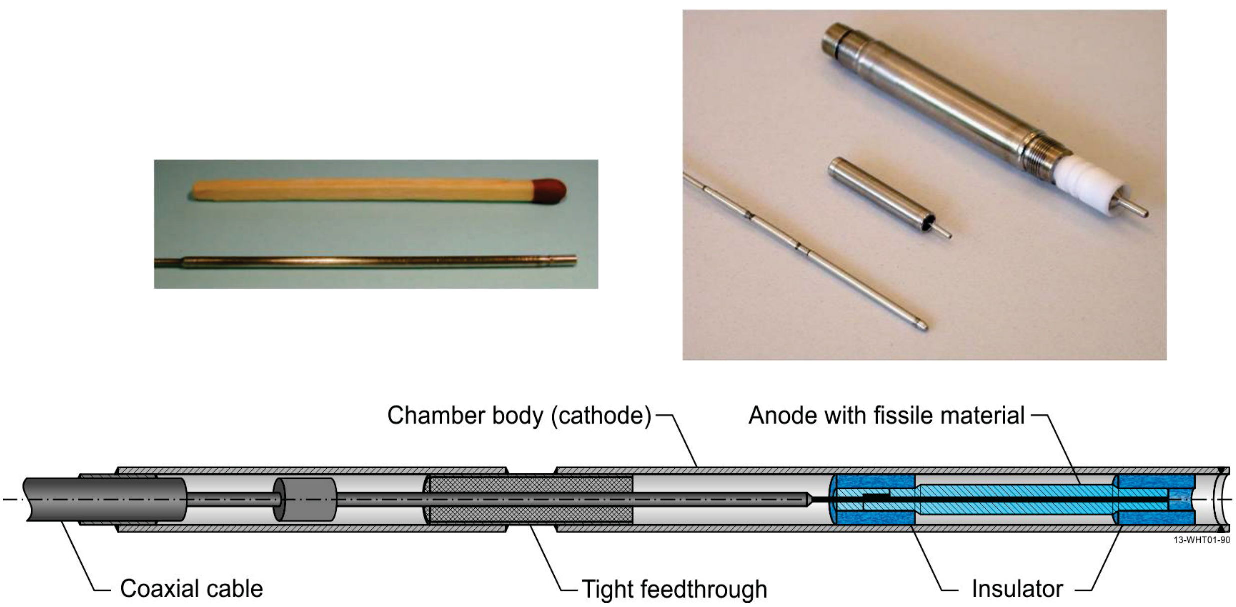

Figure 4. Representative CEA miniature fission chambers and component sketch[26,27]

2.1.3.2. Micro-Pocket Fission Detectors

Within the last decade, efforts were initiated by the Kansas State University (KSU) to develop MPFDs that have the potential to simultaneously detect thermal and fast flux along with temperature in a single miniature sensor.[20 through 25] Initial evaluations to demonstrate MPFD proof of concept have been performed at the KSU TRIGA reactor. However, prior to deployment of these new MPFDs in a US MTR, a more robust sensor design is required. MPFDs for MTR applications are currently under development in this joint INL/KSU/CEA NEET ASI project.

MPFDs utilize the same concept as coaxial fission chambers, but with a different geometry that uses parallel plate electrodes instead of coaxial cylinders. This design is known as a parallel plate fission chamber. However, the MPFD design is distinguished from other fission chambers because their signal is not based on the full energy deposition in the electrode gap from the fission products. This departure from conventional fission chamber design and operating characteristics allows the MPFDs to have a much smaller chamber size with a much lower fill gas pressure. The MPFD design has excellent discrimination characteristics because the energy deposited by the fission products is much greater than other types of background radiation interactions in the detector. Another benefit is that the small size allows them to have a faster response time. Thus, the smaller MPFDs have the potential to achieve higher count rates then conventional fission chamber designs. The construction materials chosen for the MPFD include temperature and radiation resistant ceramics. All of these characteristics make MPFDs well-suited to survive the harsh conditions present in DOE-NE MTR experiments.[20 through 25]

3. ENHANCED MPFD INVESTIGATION

This section presents the scope for this NEET project and summarizes the status of investigations completed during the first two years of this effort. To provide some perspective on why activities were able to move forward so rapidly, a brief review of prior KSU activities to design and test MPFDs is also presented.

3.1. Overall Plan and Schedule

This three year joint INL/KSU/CEA project consists of three tasks that will be completed within three years. Figure 5 illustrates activities that are performed each year of this project and the organizations participating in each activity. Task 1 of this project is devoted to enhancing the initial KSU-developed MPFD design to allow it to accommodate INL-developed High Temperature Irradiation Resistant Thermocouples (HTIR-TCs) and improve robustness for higher temperature, high flux, long-duration applications. Task 2 activities include selecting candidate materials and fabrication techniques to develop an optimized design required for higher flux US MTR testing. Results from initial Task 2 fabrication and evaluation activities will be considered to develop, fabricate, and verify the performance of a final MPFD design. In Task 3, investigators will refine the design and build a final MPFD. The final MPFD design will be evaluated in neutron and gamma fields using unique facilities available at INL and KSU. As discussed in this document, annual reports,[28] peer-reviewed archival journal articles and conference papers, and an invention disclosure record for a patent[29] have been completed throughout this project.

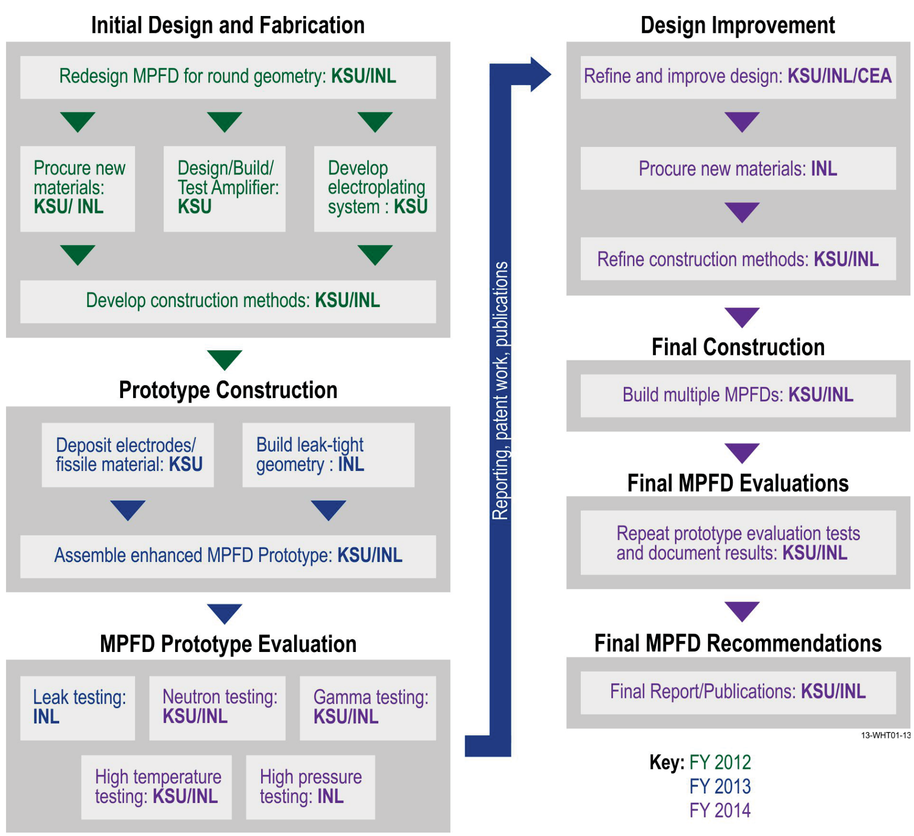

Figure 5. MPFD development tasks

Once completed, these tasks will provide new insights with respect to the performance of developmental and commercially-available flux detection sensors by comparing the accuracy, response time, and long duration performance of MPFDs to sub-miniature fission chambers, and SPNDs. Evaluation results will provide key insights about the feasibility of using these detectors in the higher flux ATR and HFIR reactors. Ultimately, evaluations will lead to a more compact, more accurate, and longer lifetime flux sensor for critical mock-ups, high performance MTRs, and commercial applications.

3.2. Summary of FY12 and FY13 Research

In this project, a robust and compact MPFD is being developed, fabricated, and evaluated using techniques perfected by INL's High Temperature Test Laboratory (HTTL) staff during development of other high temperature in-pile sensors, equipment and knowledged possessed by KSU for material depositions and electronics design, and the expertise in miniature fission chamber design possessed by CEA.

3.2.1. Initial KSU MPFD Design and Evaluation Activities (Prior to Start of Project)

Initial development of prototype MPFD designs began at KSU using large (~25 mm x 25 mm) alumina substrates with deposited electrical contacts (Figure 6).[20 through 25] Evaluations for depositing neutron reactive materials explored various methods, including boron with physical vapor deposition, uranyl nitrate solution with an eyedropper, and uranium and thorium coatings using electrolysis. After the neutron reactive material was applied, the detector substrates were bonded together using epoxy in an argon atmosphere. The first MPFD prototypes were tested in a neutron beam at the KSU TRIGA research reactor with successful results. However, it was recognized that the manufacturing process was not ideal to produce detectors for in-core applications

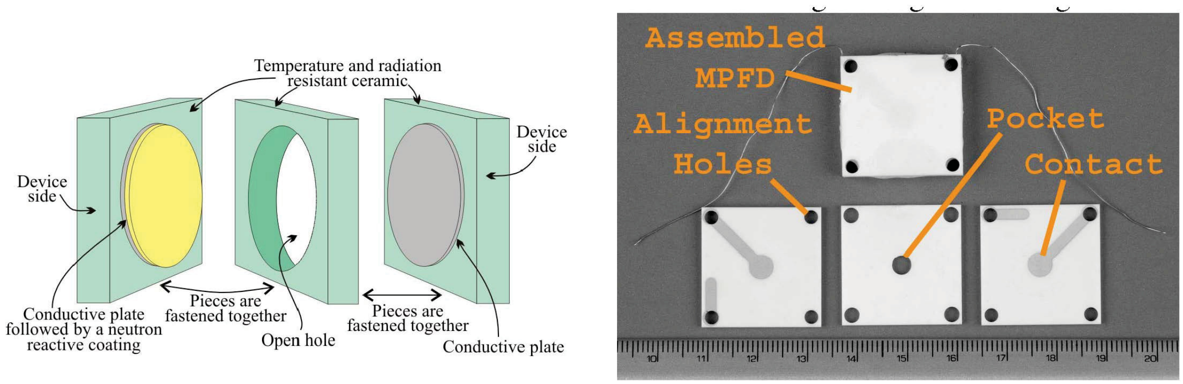

Figure 6. MPFD component sketch (left) and initial KSU prototype MPFD (right)[20 through 25]

Further refinements to the KSU MPFD design combined three chambers (one fast, one thermal, one background) and provided for a thermocouple all on a single substrate. Although the three chamber design incorporated multiple sensors in a single package, the new design was smaller (~25 mm x 6 mm) than previous designs.[20 through 25] Electroplating proved to be the most reliable method to deposit the neutron reactive materials. Uranium was used for thermal neutron detection and thorium was used for fast neutron detection. The background chamber was added to demonstrate that the neutron sensitive chambers were insensitive to background radiation. The provision for a temperature measurement was intended to have a K-type thermocouple wire bonded to the detector substrate; however, none were installed for testing.

Deployment of KSU MPFDs in their TRIGA reactor had limited success.[20 through 25] The testing resulted in the largest amount of MPFDs ever installed in a reactor core, 225 detectors. However, only about one third of them functioned; and the detectors that did function had issues with cross-talk between the output signals. The operational issues were due to water flooding into the probe tubes, wiring isolation issues, and improperly selected electronics. The probe tubes were constructed using three different diameters of aluminum tubes welded together using a TIG welder. The tubes were checked for leak tightness in a shallow water tank, but several tubes leaked when deployed in the KSU TRIGA reactor tank.

The wiring was required to exit the MPFD perpendicular to the substrate and immediately make a 90 degree bend to travel inside a protective metal sheath. The wires were separated from each other using wire guides, but were not shielded from each other for their entire length. After deployment in the reactor, it was discovered that several of the wires were in contact with each other and the outer sheath, rendering many detectors unusable.

In addition, multiple MPFDs utilized a single power source to reduce the amount of wires extending the length down to the reactor core. After deployment, it was determined that this arrangement introduced cross-talk issues that led to multiple pulses from a single detector that shared a power supply with other detectors.[20 through 25]

3.2.2. Enhanced Sensor Design for MTR Irradiations

DOE-NE programs require a robust and reliable sensor that will survive the harsh conditions of US MTRs. Hence, an enhanced version of the KSU MPFD is under development in this NEET project, which is a collaboration between INL, KSU and CEA. The enhanced MPFD utilizes design characteristics successfully deployed in other INL-developed high temperature in-pile sensors.

The new MPFD conceptual design developed as part of this INL/KSU/CEA collaboration, is based on a round stackable geometry (Figure 7). The round design characteristic solves three problems associated with the KSU design. First, a round geometry is more suitable for installation in leak-tight swaged, drawn, or loose assembly tubes, eliminating water ingress problems. Second, the round tube geometry includes insulation for the wires along their entire length from the reactor core to the data acquisition system, eliminating the potential for wire-to-wire contact. Third, the wire connections are made through the detector substrate, eliminating a 90 degree wire bend (Figure 8).

It was also determined that the third chamber used for detection of background radiation was unnecessary because prior KSU testing demonstrated the MPFDs are background insensitive. An additional benefit of the stackable design is the potential for multiple detectors of varying sensitivities to be added as customer requirements dictate. The thermocouple is placed directly above the fission chambers (Figure 9). This will eliminate the additional wire bonding required in the KSU design, thus improving thermocouple performance and robustness. However, as noted in Section 3.1, details of the MPFD conceptual design may change as the design is further developed and evaluated

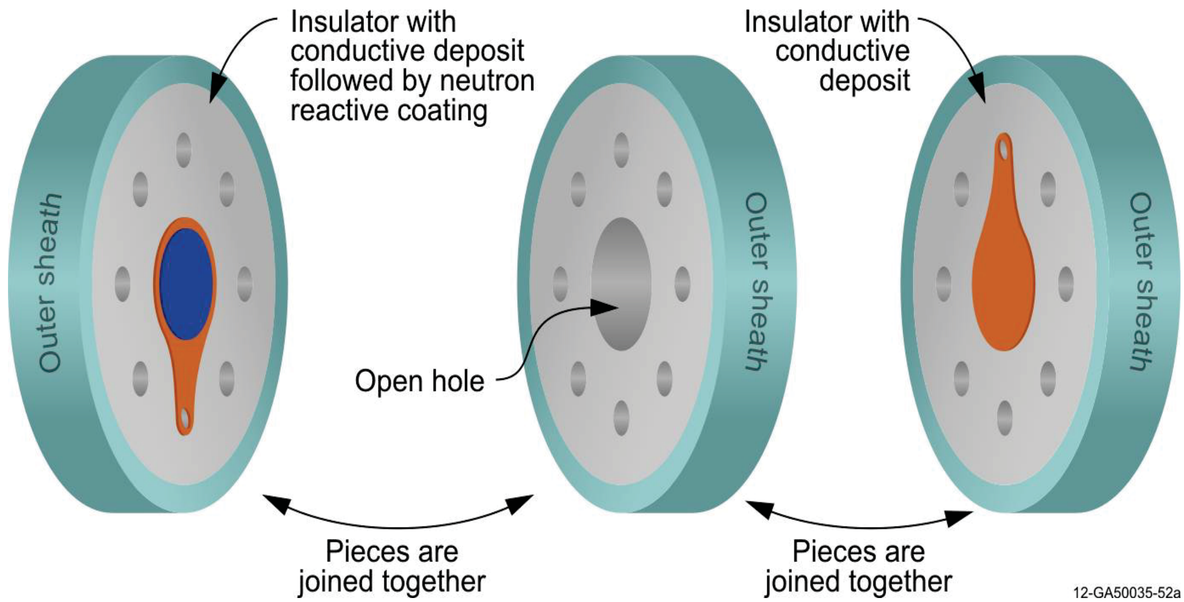

Figure 7. Round geometry MPFD conceptual design suitable for MTR irradiations

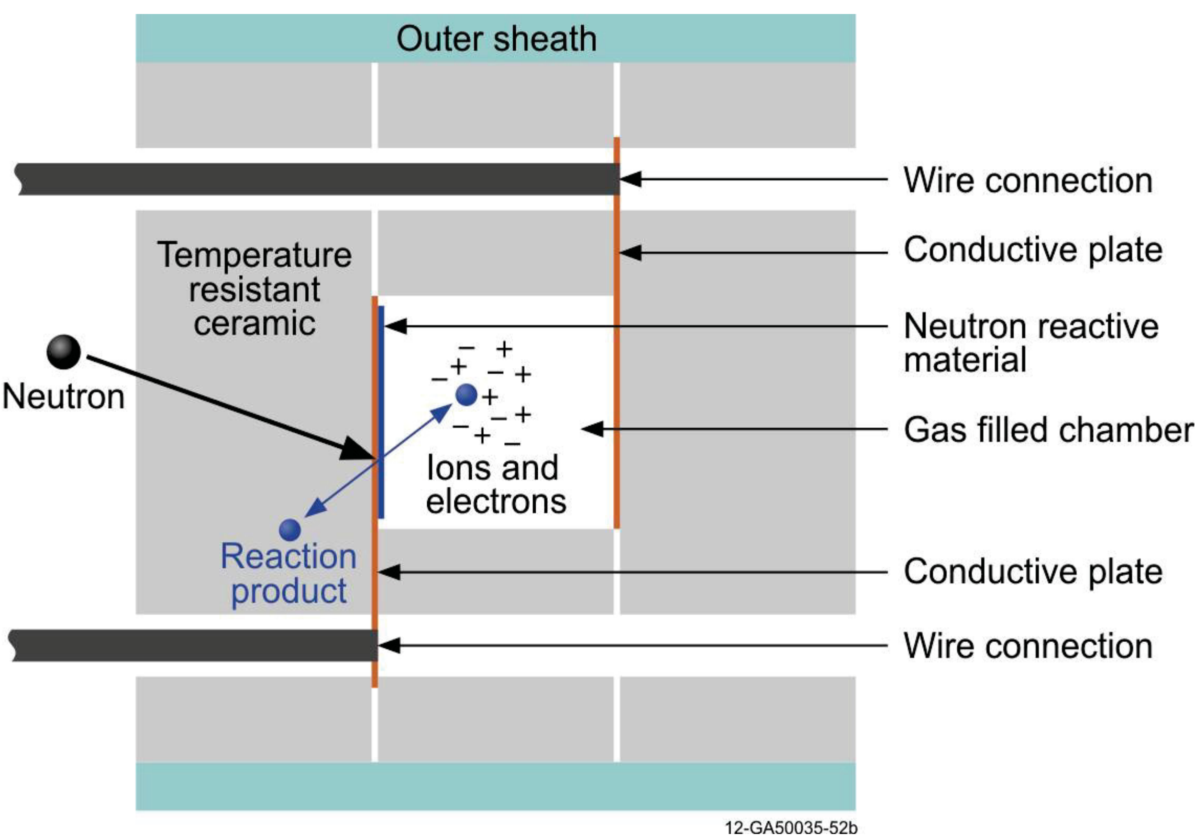

Figure 8. Component diagram of MPFD conceptual design showing wire locations

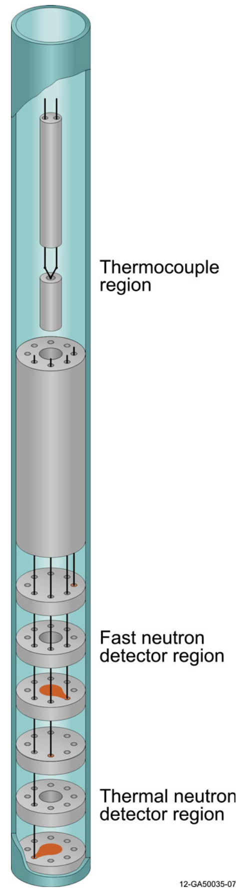

Figure 9. Enhanced MPFD conceptual assembly shown in tube with thermocouple above fission chambers

3.2.3. KSU Research

KSU experience in producing the initial MPFD prototypes is beneficial for producing an updated version of MPFDs. KSU tasks include building, testing, and optimizing detector amplifier boards for the new design, upgrading the fissile deposition system, and purchasing the required raw materials for detector substrate fabrication.

3.2.3.1. KSU Facilities

KSU has several specialized laboratories to aid in the construction and testing of MPFDs.[30 through 32] The Semiconductor Materials and Radiological Technologies (SMART) Laboratory at KSU is a unique facility dedicated to the research and development of new and innovative radiation detector technologies. The SMART Laboratory houses specialized equipment to support that work, including clean rooms, a fission chamber plating station, a linear drive diamond cutting wheel, a diamond wire saw, precision lapping and polishing machines, a 6-pocket e-beam evaporator (Figure 10), an ion mill, a vacuum annealing chamber, microscopes, ovens, grinders, an assortment of furnaces for annealing, sintering, diffusions, and oxidations, a scanning electron microscope, an Auger electron analyzing system, IV and CV tracers, radiation sources and NIM electronics to test and characterize radiation detectors and materials. In addition, the

SMART Laboratory just completed construction of a new 1000 square foot class 100 clean room facility that has been fully operational as of March 2012.[30]

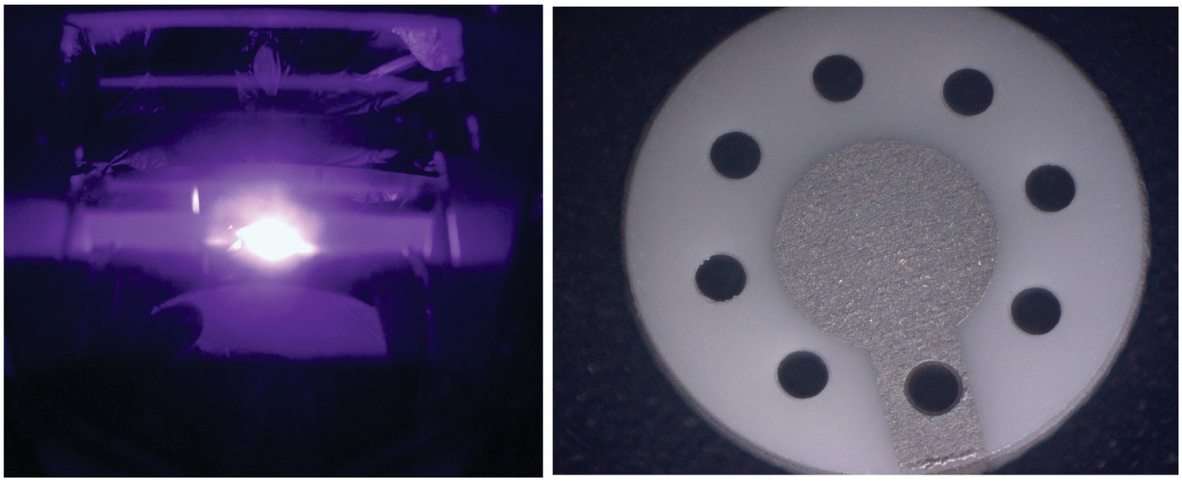

Figure 10. Evaporator and sample at the KSU SMART Laboratory[30]

The facility is available to students and faculty for research and development of sensors. The SMART Laboratory serves as a center for undergraduate and graduate student education as well as a facility to accommodate funded research projects from various government and industrial sponsors.[30]

The TRIGA Mark II research reactor at KSU supports education, research, training, and regional industries. The reactor is used extensively by the SMART Laboratory for testing of radiation senors and irradiation of materials. The KSU TRIGA has a 1.25 MW steady state operating power and has pulsing capabilities up to ~2 GW, making it ideal suited for testing sensors in high-power transients. Sensors can be tested in reactor beam ports or directly in the reactor core. The ease of access to the facility makes it an asset to the SMART Laboratory for neutron detector testing.

The KSU Electronics Design Laboratory (EDL) works closely with the SMART Laboratory to develop the required electronics needed to support sensor research and development. EDL's focus is to provide researchers access to advanced electronics and assist with integrating electronics technology into research programs. EDL is an in-house design service for KSU researchers. The staff has both industry and research experience with analog instrumentation and digital design, as well as software development, system engineering, system construction, and project management.[32]

3.2.3.2. Electronics for Enhanced MPFD

Electronics used in initial MPFD tests suffered from high-frequency noise being passed between channels through a shared high voltage line between several detectors. To avoid this problem with the enhanced MPFD design being developed in this project, the high voltage lines on the amplifier board were separated using low-pass filters. The new amplifier board is powered by ±12V and +5V and incorporates 5V logic signals outputting two channels of analog pulse, analog current and digital timing, that can each output, with 50 Ohm impedance. A prototype amplifier has been assembled at the KSU EDL and tested successfully with an older MPFD installed in the KSU TRIGA reactor. However, it is recognized that some component values on the amplifier board may require a minor adjustment to match the capacitance of the new MPFD design. These changes will be made when the new MPFDs are assembled and tested for capacitance.

3.2.3.3. New MPFD Plating System

The KSU SMARTLab is responsible for plating all coatings required for MPFD construction. Two plating steps are required; the first step is to plate the electrical contacts or electrodes on the alumina substrates. The second plating step is to deposit the fissile material on one of the electrical contacts. The initial plating to deposit the electrical contacts is performed using an electron-beam evaporator (Figure 10). The plating requires custom shadow masks for the new design of MPFDs to be machined using a micro-milling machine at KSU. The purpose of the shadow masks is to selectively deposit the contact material that defines the electrical contacts and wire-bonding pad. Titanium and platinum have been explored as possible contact materials; and platinum has provided the best contact.

Once the electrical contacts are in place, the second plating step will deposit the material (uranium-235 for thermal neutron detection and thorium-232 for fast neutron detection). Two methods for fissile material deposition have been investigated. The first method is standard electroplating as was used with previous designs of MPFDs (Figure 11). The small substrates and thin depositions utilize a specialized nA-current micro-electroplating system at KSU. The second method utilizes electroless plating that does not require an electric current to be applied to the plating solution. Both methods will require a dissolvable resin to be applied to select locations of the electrical contact to avoid fissile material from plating on the wire-bond pad and path of the detector. Evaluations completed in FY13 using the electroless plating method was shown to work, but did not deposit the required amount of material on the detector. Hence, the standard micro-electroplating method was chosen for future depositions.

Figure 11. Micro-electroplating uranium at KSU

Initial electrical contact depositions were successful. However, FY12 evaluations found that many of the alumina substrates were cracked between the outer wiring holes and would lead to poor detector electrodes. It is suspected that the cracks are a result of the manufacturing process required to harden the alumina. In FY13, an alternative vendor was located to provide alumina substrates that had smoother surfaces without any cracks. Contact deposition quality has greatly improved with characterization activities underway using an optical profilometer (Figure 12), x-ray fluorescence analyzer (Figure 13), and electrochemical analyzer. Investigations to develop and characterize a robust electrical contact with a fissile material deposition will be completed in FY14.

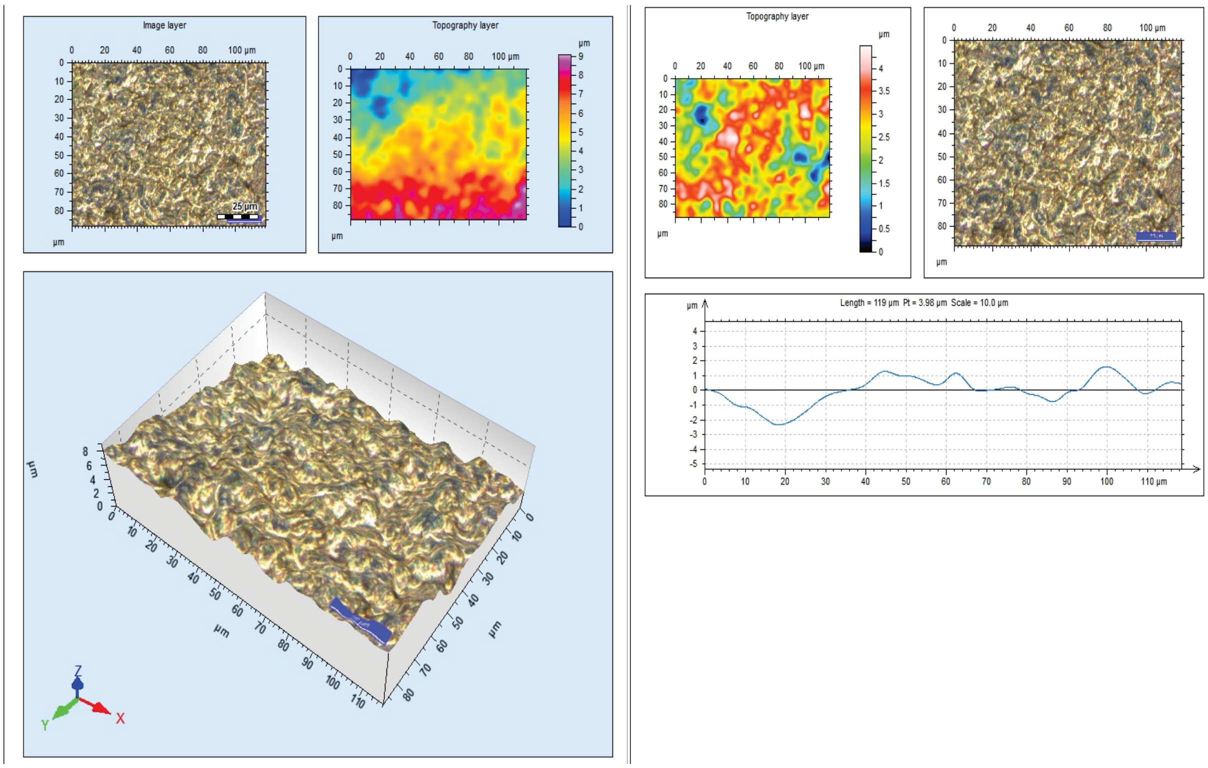

Figure 12. Electroplated sample of uranium under analysis with optical profilometer

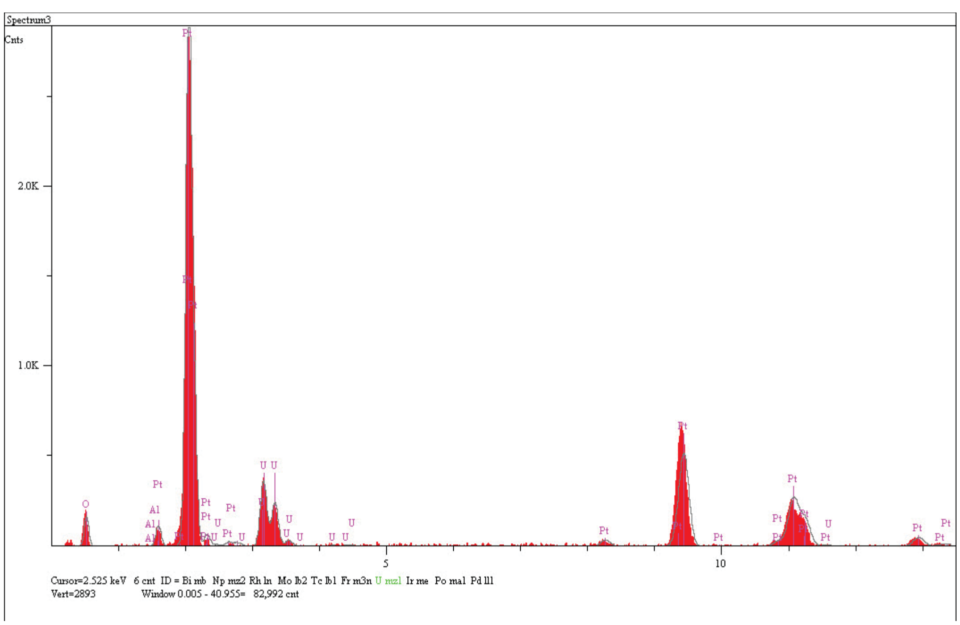

Figure 13. X-ray fluorescence spectrum of uranium coated sample

3.2.3.4. Project Meeting at KSU

As part of the FY12 activities, a project meeting was held at KSU on May 11, 2012, to discuss the new MPFD design and the challenges associated with its construction. Several options for alternate construction methods and equipment were discussed that are currently being explored by KSU and INL. During this meeting, KSU demonstrated the new amplifier board at the KSU TRIGA reactor (Section 3.2.3.2). Analog and digital signals (Figure 14) were identified during TRIGA reactor operation at 100 kW, using one of the previous-generation detectors remaining in the reactor core. In addition, INL provided prototypic detector test pieces to KSU to ensure that the new MPFD parts will be compatible with KSU construction methods and equipment. A second project meeting is planned in FY14 to finalize project planning of activities required to complete this project.

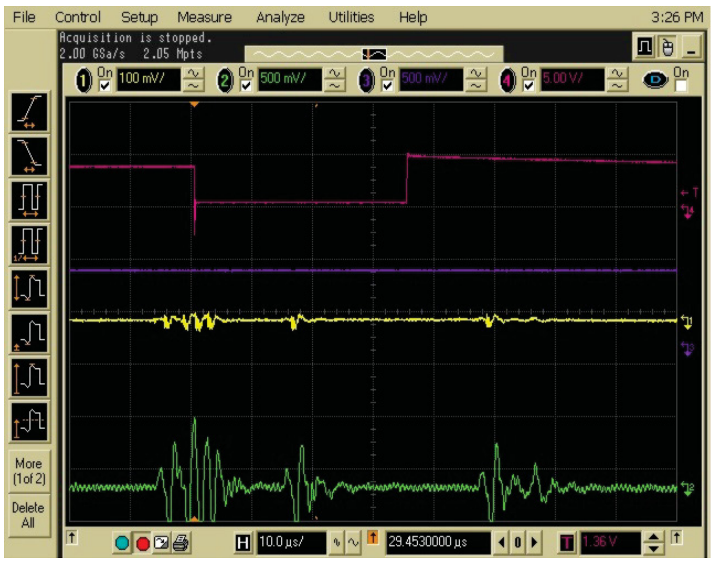

Figure 14. Analog and digital signals from MPFD in KSU TRIGA reactor

3.2.4. INL Research

The INL's role in the NEET MPFD project stems from its experience in developing and deploying unique in-pile instrumentation suitable for irradiation testing programs that operate in high flux and high temperature conditions. This section summarizes INL capabilities and progress toward completing this effort.

3.2.4.1. INL Facilities

INL has several specialized facilities to constructed and test MPFDs. The HTTL contains specialized equipment to design in-pile sensors and conduct high-temperature testing. HTTL's trained staff evaluates high-temperature material properties and develop custom high-temperature instrumentation for nuclear and non-nuclear applications, including new methods for measuring temperature, thermal conductivity, localized heating, and sample deformation in MTRs. HTTL houses specialized equipment to support such work, including high-temperature tube furnaces, a high-temperature vacuum furnace, swagers, a draw bench, a laser welder, a helium leak detector system, a real time X-ray imaging system, several autoclaves, and various high-temperature material property measurement systems to provide comparison data. HTTL's efforts support INL initiatives that require specialized in-pile sensors for fuels and materials irradiations, such as the ATR National Scientific User Facility (NSUF), NGNP, Advanced Fuel Cycle (AFC), and LWRS programs.[33]

The HTTL will be relocated to a new state-of-the-art facility at INL, the Research Education Laboratory (REL), which is estimated to be fully constructed and ready for occupancy in October 2013. (Figure 15). The inclusion of a clean room capability and additional new state-of-the-art equipment will make the HTTL a world-class in-pile instrumentation development and testing facility.[34]

INL capabilities also include two unique facilities for testing in neutron and gamma fields, the ATR Critical facility (ATRC) and the Health Physics Instrument Laboratory (HPIL). A brief description of each of these facilities is provided below.

The ATRC core is a nearly-identical full-scale nuclear mock-up of the ATR core and can provide valuable insight into the use of advanced sensors prior to deployment in the ATR. The current mission of the ATRC is to obtain accurate and timely data on nuclear characteristics of the ATR core, such as rod worths and calibrations, excess reactivities, neutron flux distribution, gamma-heat generation rates, fuel loading requirements, and effects of the insertion and removal of experiments. The ATRC provides a necessary supplement to analytical reactor methods that support ATR operation. Although the ATRC typically operates at power levels of 600 watts or less, its authorized maximum power level is 5 kW. The core power is maintained at low levels to minimize radiation exposures during manual operations required to unload experiments and fuel. As discussed within this section, an ATR NSUF project has recently developed and installed Experiment Guide Tubes (EGTs) into ATRC irradiation positions. This recently developed specialized fixturing provides INL a unique capability for comparison evaluations of real-time neutron flux detectors.[35]

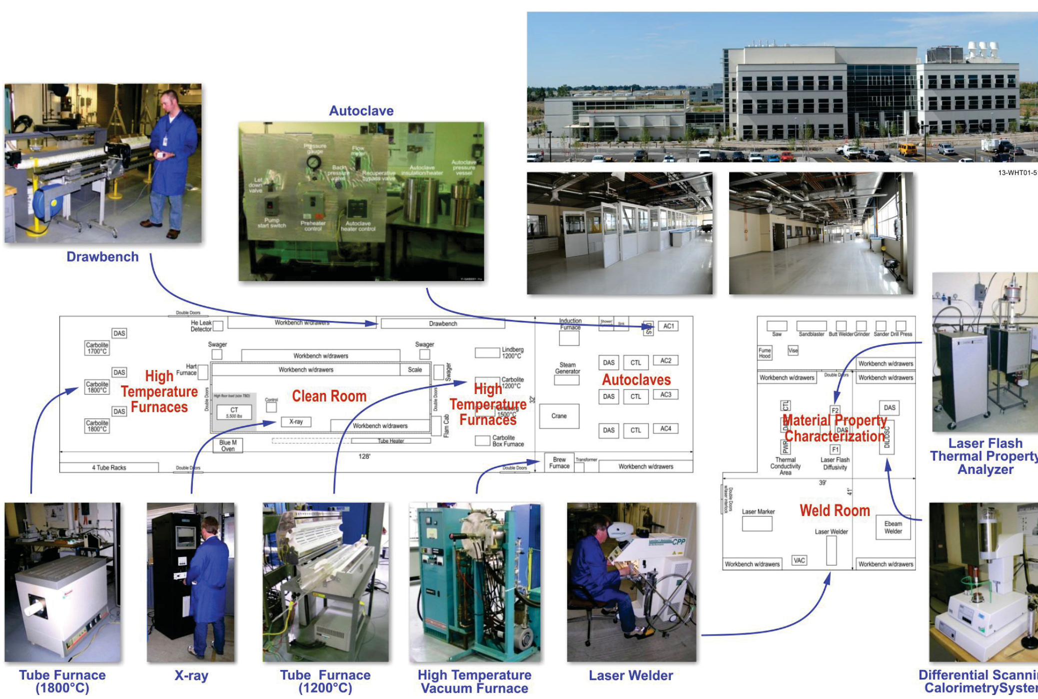

Figure 15. Research Education Laboratory and Equipment

The HPIL is the primary radiation protection instrumentation calibration facility at the INL. The HPIL includes two irradiators for detector evaluations. The first irradiator at the Low Scatter Facility houses a National Institute of Standards and Technology (NIST) traceable Cf-252 neutron source that provides a 10 rem/hr neutron dose rate. The second irradiator, the Gamma Beam Irradiator houses NIST traceable Cs-137 and Co-60 gamma sources of 800 R/hr and 400 R/hr does rates, respectively. These irradiators will be useful to test the neutron sensitivity and the gamma-ray insensitivity of the MPFDs.[36]

3.2.4.2. Materials

During FY12 and FY13, INL procured the materials needed for construction of the MPFD prototypes. Initial evaluations are focused on building a robust prototype using less expensive, commercially-available materials. However, it is recognized that prior to deployment in a high temperature/high flux MTR experiment, high temperature and radiation resistant materials suitable for the harsh environment must be utilized. It is also recognized that the design will be further enhanced and miniaturized once the construction techniques have been developed and refined.

The main components of the initial MPFD detector and extension cable are specially manufactured hard-fired alumina substrates and crushable alumina insulators (Figure 16), respectively, all housed within leak-tight stainless steel tubing. A "loose assembly construction" is used,with a rigid stainless steel tube containing hard-fired alumina substrates for fission chamber electrodes and fissile depositions (Figure 10), a thermcouple, and wire contacts. The crushable alumina insulators serve as an insulator for the 6 wire extension cable with a stainless steel outer sheath (Figure 17). The extension assembly is drawn to the desired length and diameter to provide flexibility for installation in the reactor tank.

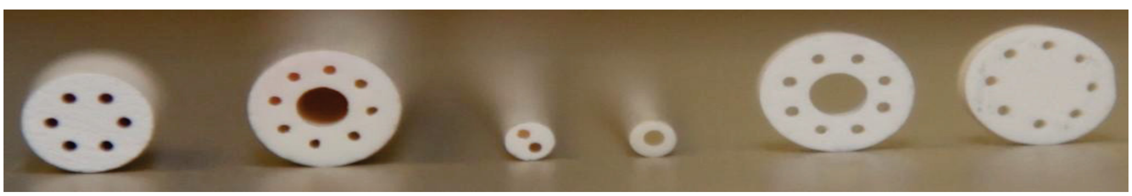

Figure 16. MPFD alumina substrates and insulators

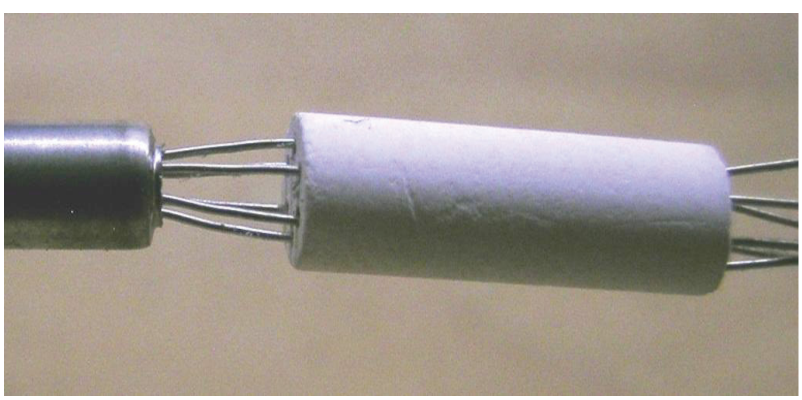

Figure 17. Extension cable with 6 wires threaded through insulation

3.2.4.3. Construction Methods

MPFD construction is underway using equipment and techniques perfected by INL's HTTL staff.[1] The unique design of the MPFD requires several construction steps that aren't required for conventional in-pile sensor fabrication. Specifically, specialized techniques have been developed that emphasize robustness (e.g., minimizing the number of wire splices and component embrittlement associated with welding). Figure 18 shows some of the specialized HTTL equipment used in MPFD fabrication. After the parts are assembled (Figure 19), it is inserted into the outer sheath, and welded together (Figure 20). The final step to insert the fill gas, typically argon, is performed by sealing a portion of the loose assembly in specialized fixturing at the HTTL prior to performing the final weld.

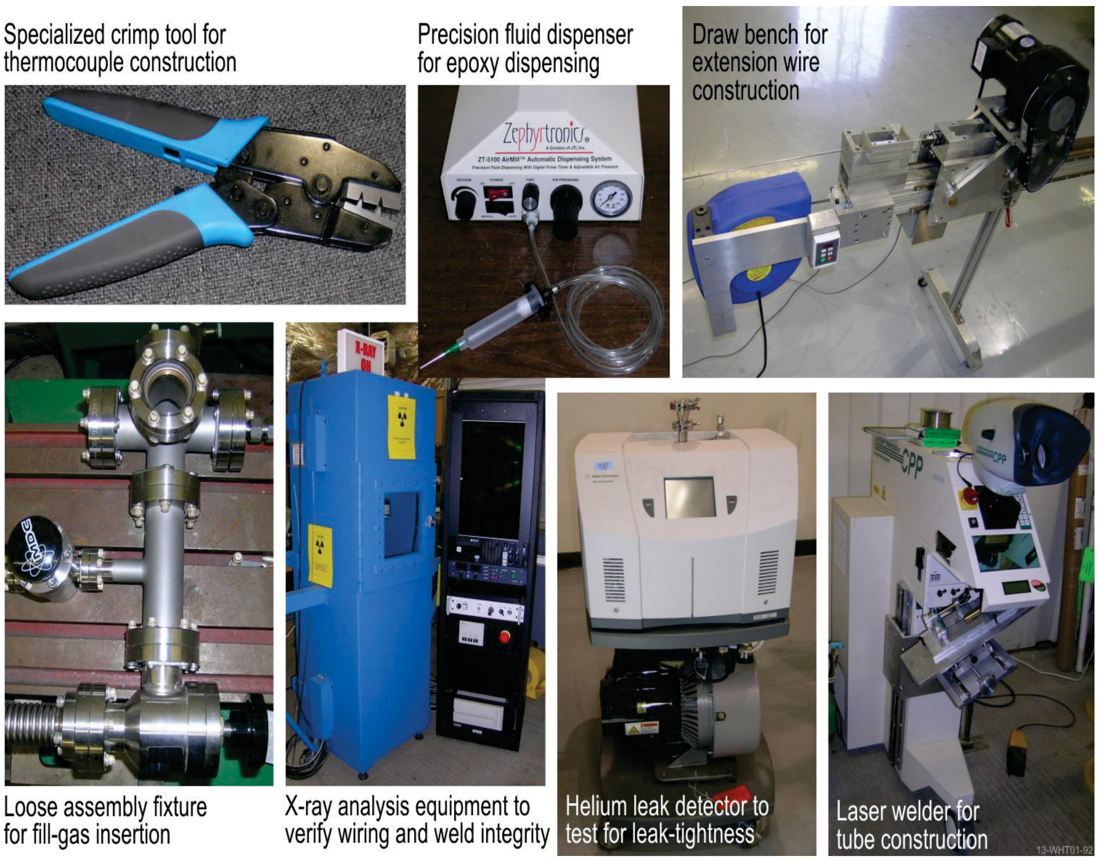

Figure 18. Various HTTL equipment for MPFD fabrication

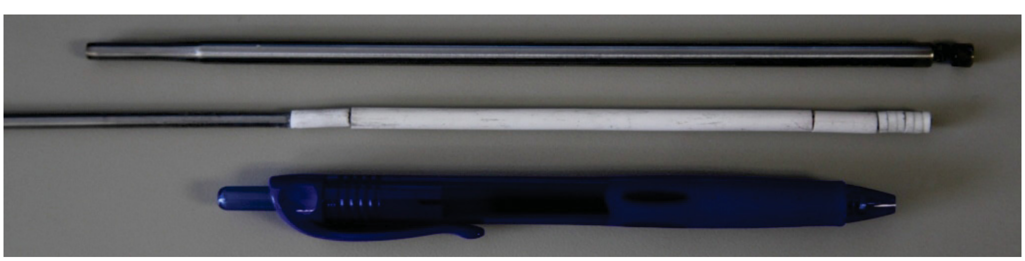

Figure 19. Exploded view of prototype MPFD versus standard ballpoint pen

Figure 20. Assembled prototype MPFD versus standard ballpoint pen

3.2.4.4. Evaluations

Testing of the new MPFD design is underway to evaluate the robustness of the epoxy wire connections, thermocouple performance, and the weld integrity. The evaluation schedule is outlined in Table 5. High temperature evaluations are performed in HTTL furnaces. Sensor performance is assessed in the HTTL by considering thermocouple response, x-ray observations, helium leak checks, and resistance and continuity measurements. Weld integrity is evaluated by using the HTTL helium leak testing equipment to verify that the assembly meets requirements for the ASTM leak rate of sheathed thermocouples.[1]

Table 5. FY14 MPFD evaluation schedule

Evaluation Type	Comments	Dates	
		Start	Finish
Leak Rate	Meet ASTM standard	9/1/2012	11/1/2012
High Temperature 1	Test limits of materials and construction methods with non-fissile samples	11/1/2013	4/1/2014
Gamma Response	Verify gamma insensitivity	12/1/2013	4/1/2014
Neutron Response	Verify neutron response	2/1/2014	4/1/2014
High Temperature 2	Test temperature limits with fissile samples	4/1/2014	5/1/2014
Reactor Testing	Low power in-core testing, Transient Testing	5/1/2014	7/1/2014

Further evaluations are scheduled that will test the integrity of the electrode (non-fissile) deposition under high temperatures once materials are received from KSU.

In addition, efforts have been initiated to develop an evaluation plan to test the MPFD performance in radiation fields. The evaluation plan will be dependent on availability of INL facilities such as the HPIL irradiators and the ATRC reactor. Other options under consideration include testing at the KSU TRIGA reactor.

3.2.4.5. ATRC Evaluations and Testing Results

As noted in Section 3.2.4.1, ATRC research funded by an ATR NSUF program has resulted in neutron detector evaluation capabilities at INL that are beneficial to MPFD development. The project, a joint ISU/CEA/INL collaboration, was initiated to investigate the feasibility of using neutron sensors to provide online measurements of the neutron flux and fission reaction rate in the ATRC. The project cross-calibrated various activation detectors (foils and wires), miniature fission chambers, and SPNDs in the ATRC. The SPNDs under evaluation had hafnium, gadolinium and rhodium emitters for thermal neutron detection. The fission chambers under evaluation had U-235 fissile deposits for thermal neutron detection and U-238 fissile deposits for fast neutron detection. Test locations for the real-time detectors are shown in Figure 21.

	Experimental Configurations A	B	C
Red	U-235 FC #2253	U-238 FC #4	Rh SPND #DN3
Purple	Hf SPND #658	Rh SPND #DN1	Rh SPND #DN1
Yellow	U-235 FC #2252	U-235 FC #2253	U-235 FC #2253
Orange	U-238 FC #4	Hf SPND #657	Rh SPND #DN4
Green	Gd SPND #663	U-235 FC #2252	Rh SPND #DN5
Blue	Hf SPND #657	Hf SPND #658	Rh SPND #DN2

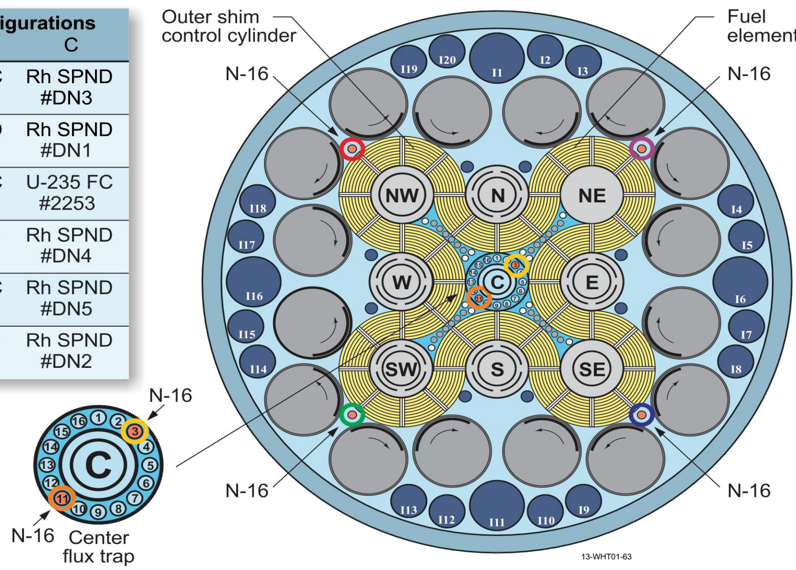

Figure 21. ATRC in-core sensor locations

The in-core sensors were inserted into the ATRC using EGTs. The EGTs were placed in the ATRC's N-16 positions, which are re-entrant tubes used to determine lobe power in the ATR core. However in ATRC a lobe power measurement system does not exist, so the N-16 positions have removable dummy fillers that allow for in-core detector testing. The EGTs are primarily fabricated from aluminum to minimize their weight. However, selected components, such as the guide tube shown in Figure 22 are made from stainless steel 304 for additional robustness. The six EGTs mechanically position detectors at a specified vertical location in the four N-16 exterior positions and two center flux trap N-16 positions. The EGTs were supported above the reactor by attaching them to the reactor control bridge. The position control and detector response are controlled and measured via LabView software to allow all sensors to either individually or simultaneously move and detect the local neutron flux for calibration purposes.

Detector evaluations were performed for a variety of operational conditions. The reactor was brought to specified power levels between 0.01W and 600W. In addition, measurements were taken with the reactor shut down prior to startup and with the reactor shut down after startup. In order to assess if the detectors could be used to monitor various power splits, the reactor was purposely operated in an unbalanced condition, meaning the reactor power in the NW lobe was purposely changed from the nominal critical power level.

Initially, the sensors were verified to be operational, then the detectors were used to track reactor power. Typical data obtained from power level testing is shown in Figure 23. Representative data obtained from axial flux testing is shown in Figure 24. In addition to data collection, various insights were gained during the testing of the in-core sensors related to installation, operation, and data analysis. Additional details related to this testing are documented in Reference 37.

Other cross-calibration fixtures for ATRC were approved for use in FY13. Specialized fixtures have been fabricated (Figure 25) to allow a back-to-back (BTB) fission chamber to be inserted into the ATRC. The BTB fission chambers, which are often called 2π fission chambers because they are designed to count almost all fission fragments emitting from a thin deposit in a 2π solid angle, provide the most accurate

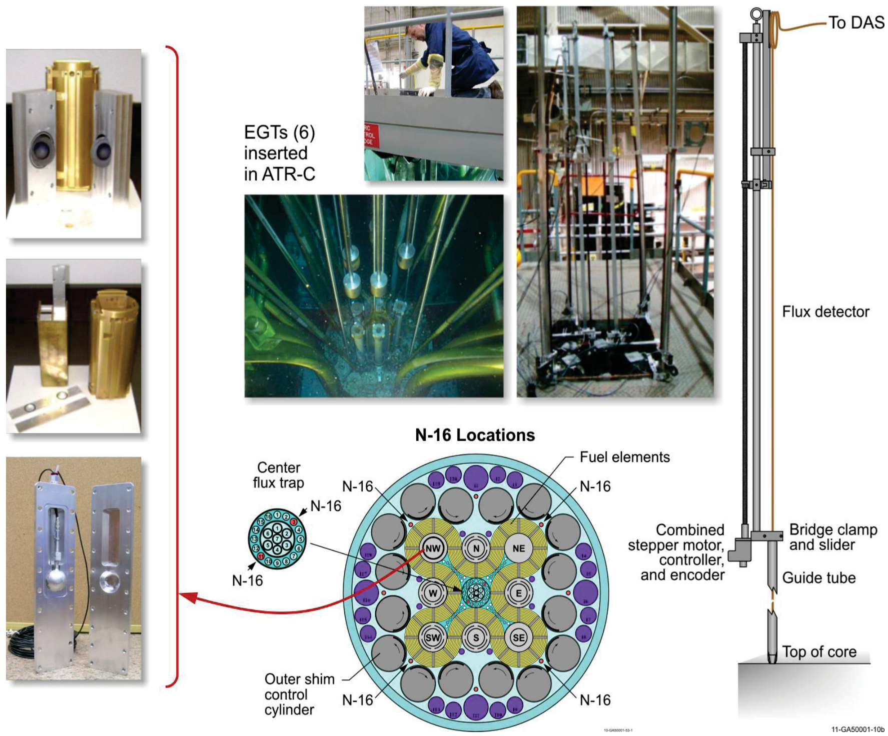

Figure 22. EGTs in ATRC

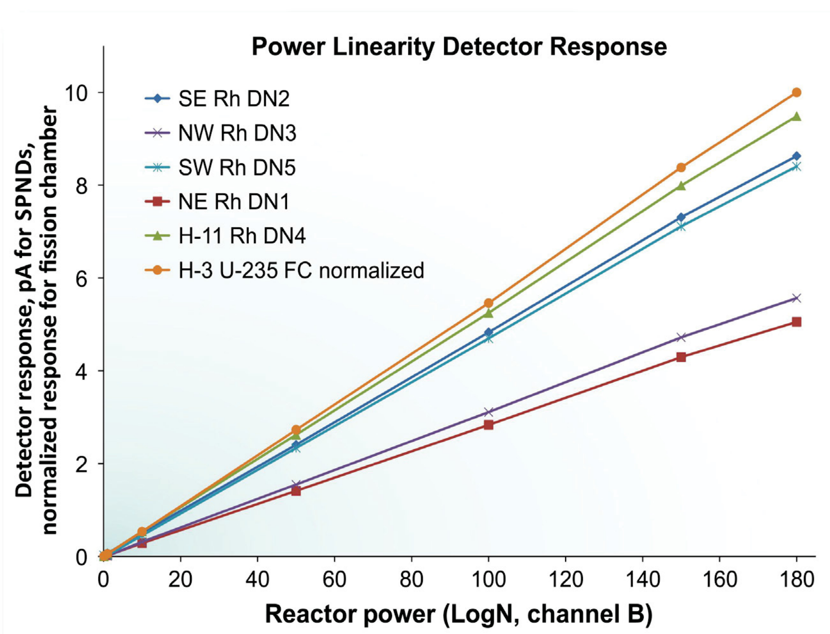

Figure 23. Comparison of power measurements obtained from rhodium SPNDs and a fission chamber from experimental configuration C

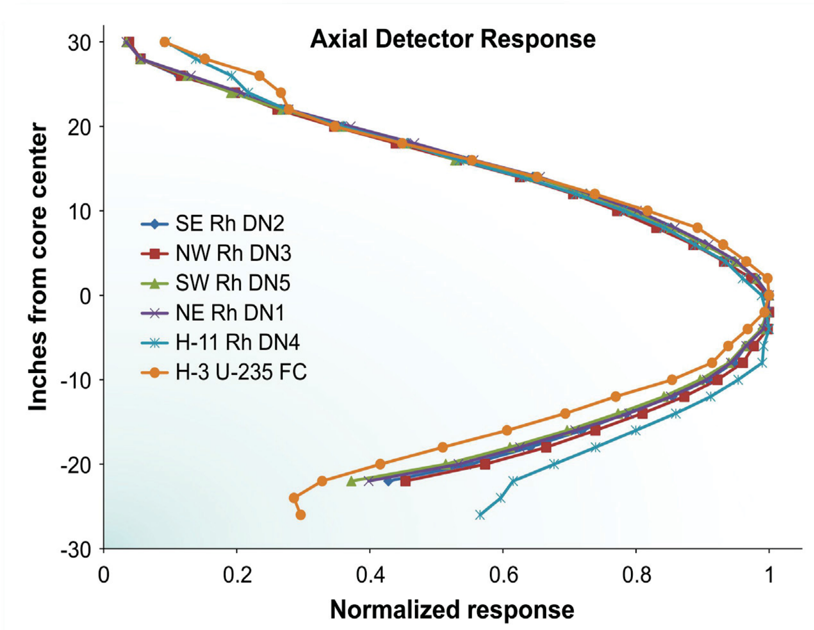

Figure 24. Axial flux profile from rhodium SPNDs and a fission chamber from experimental configuration C

measure of fission reaction rates and provide accurate cross-calibrations of other detectors. These fixtures place a BTB fission chamber in the ATRC core alongside other in-core sensors to compare their response in near-identical flux conditions. The layout of the test fixture used to insert these BTB fission chambers into the ATRC is shown in Figure 26. Depending on ATRC and funding availability, these BTB fixtures would be ideal for MPFD calibration.

Figure 25. Fabricated back-to-back fission chamber fixtures

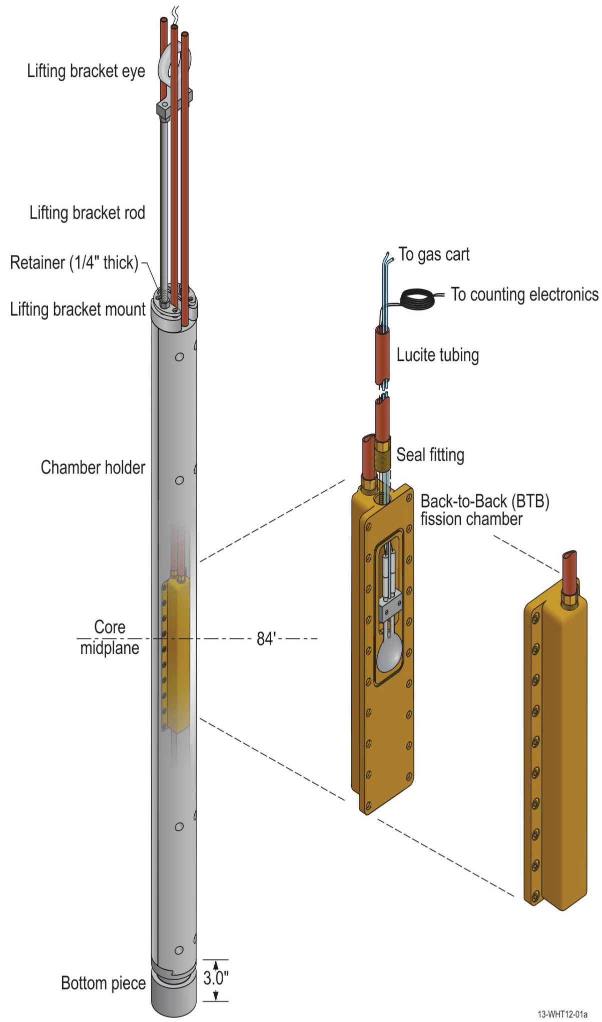

Figure 26. Back-to-back fission chamber fixture assembly

3.3. Summary

In summary, all planned FY12 and FY13 activities have been completed. The joint work between INL and KSU has produced an updated design with supporting materials, equipment, and electronics. KSU efforts have focused on the plating system to manufacture the electrical contacts and deposit the fissile material. KSU has also redesigned the detector electronics to provide more reliable signals from the MPFDs. INL efforts have focused on redesigning the MPFD for MTR irradiations by altering the design to be more robust and deployable for harsh in-pile environments. Materials have been procured for construction and construction methods have been developed for the MPFD construction. Evaluations are underway to test the high temperature robustness and leak-tightness of the new construction methods. It should be noted that the originally proposed planned workscope for FY13 was reduced due to a reduced FY13 funding allocation. However, it is currently anticipated that the FY14 funding allocation will allow all planned tasks for fabricating MPFDs to be completed.

4. FUTURE WORK

Work in out years will build on current activities that are focused on producing a robust MPFD for MTR irradiation tests. The following section summarizes research activities to ensure this goal.

During FY14, all the remaining required detector prototype fabrication and high temperature and neutron flux evaluations will be completed at INL and KSU. High temperature evaluations will be performed at the HTTL. Simple response testing may be performed at KSU using their TRIGA research reactor and at the HPIL panoramic irradiator. Although not originally planned for this NEET effort, the potential for more complex evaluations will be explored that use new specialized fixturing installed at the ATRC. As noted in Section 3.2.4.5, this fixturing allows characterization and cross-calibration of a wide range of flux detectors, including SPNDs, CEA-developed fission chambers, and specially-developed BTB fission chambers. In addition, CEA, using their own funding, will model the detector response and compare calculation predictions to actual results. Available CEA results will be incorporated into final recommendations for an enhanced MPFD design.

Table 6. MPFD FY14 responsibilities

Task	INL	KSU	CEA
Finish prototype construction	X	X	
High temperature evaluation	X		
Neutron flux evaluations	X	X	
Model detector response			X
Smaller, improved design development	X	X	X
Enhanced design fabrication and evaluation	X	X	
Complete annual status report	X	X	

4.1. Final Construction and Evaluations

Construction of a MPFD prototype will be completed in FY14. The prototype construction will focus on refining the construction methods for the MPFDs. INL construction methods are not expected to deviate significantly from what has been outlined in Section 3.2.4.3. Special focus will be given to alternative wire connections and tube-to-tube welds and end-cap weld integrities.

KSU construction will focus on providing repeatable electrode and fissile material deposition procedures. In particular, the fissile material deposition must be uniform to provide the optimized detector response. Characterization of the fissile material deposition will also be performed so that detector response can be accurately modeled.

4.2. Future Evaluations

Assuming that the balance of the requested project funding is provided in FY14, MPFD prototype evaluations will be completed. The testing will demonstrate that the MPFDs can survive the high temperatures and respond as expected to neutron irradiations. Comparisons will be made between other thermocouples and real-time flux sensors.

4.2.1. HTTL

Testing at the HTTL will focus on evaluating the mechanics of the detector design without a fissile material to avoid handling radioactive materials. The HTTL will confirm the leak-tightness of the MPFD assembly by using helium leak testing equipment to verify it meets the ASTM leak rate of sheathed thermocouples. After leak testing is completed, high temperature evaluations will be completed using existing high temperature furnaces at the HTTL. The epoxy wire connections will be tested using X-ray evaluations and resistivity measurements to verify the connections and wires survive the high temperature environment. The response of the thermocouple will be tested by comparison to a calibrated thermocouple.

Further testing with a fissile material deposit will utilize a combination of equipment and capabilities at the HTTL and HPIL as discussed in the following section.

4.2.2. HPIL

The gamma-ray sources at the HPIL will be used to characterize the gamma insensitivity and background noise to properly select the low level discrimination threshold for a completed MPFD. After the lower level discriminator has been adjusted, response testing will be performed at the low scatter facility at the HPIL (Figure 27) to verify MPFD response to neutrons. The low scatter facility will provide a low neutron fluence to the MPFD, however the purpose of the evaluation is only to verify response to neutrons. It is expected that a neutron moderator, such as a block of high density polyethylene, will be needed to improve the response to thermal neutrons. After MPFD response testing is complete, HTTL tube furnace evaluations will be conducted (Figure 27) to evaluate the thermocouple performance and robustness of the wiring connections and fissile deposit. During the high temperature testing, the MPFD will be returned periodically returned to the HPIL low scatter facility to verify the response remains unchanged to neutrons after various heating cycles. This process will be repeated to characterize the high temperature limits.[1, 36]

Figure 27. Tube furnaces (left) and neutron irradiator (right) for MPFD response testing[1, 36]

4.2.3. Reactor

Subsequent evaluations will focus on characterizing the in-core detector response. The KSU TRIGA reactor has the ability to perform in-core testing of the MPFDs in the central thimble irradiation housing. The measurement campaign will characterize detector response in relation to reactor power. In addition, the KSU TRIGA has the ability to pulse the reactor to approximately 2 GW in 0.35 seconds to test the time-dependent MPFD response to short high power transients.[31]

Reactor performance and characterization at the INL will depend on the availability of the ATRC. A testing program is being developed that will utilize recently deployed EGTs that place the MPFDs in several different locations and elevations throughout the ATRC core.[35,37,37] The data will be compared to integral flux measurements from previously completed reactor flux profile characterizations. In addition, evaluations will be performed using specialized fixturing to cross-calibration the MPFDs with SPNDs, CEA-developed fission chambers and specially developed BTB fission chambers, pending funding and ATRC availability.[35]

4.2.4. CEA Detector Modeling

In addition to HTTL/HPIL/ATRC/TRIGA evaluations, the prototype MPFD will also be modeled by CEA for detector response. CEA has over 40 years of experience in fission chamber research and development and has developed several fission chamber physics codes to model detector response. Their codes are based around standard fission chamber designs that use coaxial cylinders and not the parallel plate design that MPFDs use. As such, some modifications to the geometry definitions in the CEA computer codes will be required.[26, 27]

4.2.5. MPFD Enhancements

The final evolution in MPFD design will be realized in FY14. The data from the evaluations will be used to refine the MPFD conceptual design so that it is more deployable in MTR irradiations. It is expected that the overall size can be reduced so that the sensor is less intrusive to MTR irradiation experiments. During this redesign, it is expected other design changes will be identified that will improve construction techniques to make the MPFD easier to assemble. It is also expected that design changes will be identified to improve robustness by utilizing high temperature sheaths, insulators, wiring and wire connections that can survive the harsh conditions in MTR irradiations. Finally, design changes to improve signal response and signal processing will be addressed in the MPFD and the accompanying electronics.

4.2.6. Follow-on MTR Irradiations

It is currently anticipated that one of the many DOE-NE programs evaluating new fuels and materials requesting an enhanced flux and temperature sensor will deploy a MPFD in a higher flux reactor irradiation test. The testing and analysis completed in this project will provide the necessary 'proof-of-concept' data to demonstrate the viability of MPFDs for higher fluence irradiations, offering ATR and HFIR users enhanced capabilities for real-time measurement of the thermal and fast flux and of temperature with a single, miniature detector.

5. SUMMARY

The NEET program is currently funding a program for developing and testing compact miniature fission chambers capable of simultaneously measuring thermal neutron flux, fast neutron flux and temperature within a single package. When implemented, these sensors will significantly advance flux detection capabilities for irradiation tests in US MTRs.Ultimately, evaluations may lead to a more compact, more accurate, and longer lifetime flux sensor for critical mock-ups, high performance reactors and commercial nuclear power plants. Deployment of MPFDs in US DOE-NE program irradiation tests will address several challenges:

- Current fission chamber technologies do not offer the ability to measure fast flux, thermal flux, and temperature within a single compact probe; MPFDs offer this option.
- MPFD construction is very different than current fission chamber construction; the use of high temperature materials allow MPFDs to be specifically tailored to survive harsh conditions encountered in-core of high performance MTRs.
- The higher accuracy, high fidelity data available from the compact MPFD will significantly enhance efforts to validate new high-fidelity reactor physics codes and new multi-scale, multi-physics codes.
- MPFDs can be built with variable sensitivities to survive the lifetime of an experiment or fuel assembly in some MTRs, allowing for more efficient and cost effective power monitoring.
- The small size of the MPFDs allows multiple sensors to be deployed, offering the potential to accurately measure the flux and temperature profiles in the reactor.

As part of this effort to develop a new sensor, a joint collaboration is underway between INL, KSU, and CEA to produce MPFDs capable of surviving the harsh environment of DOE-NE MTR irradiations. Highlights to-date for this effort include:

- An updated design of MPFD has been developed incorporating previous INL HTTL experience for developing robust sensors that are resistant to radiation and temperature.
- Materials and tools to support the new design have been procured. Stainless steel tubes and custom alumina substrates and insulators have been used in support of new construction methods.
- Construction of the new design at INL's HTTL is underway using specialized new methods for cable construction and assembly.
- Electrical contact and fissile material plating methods have been explored and are being characterized at KSU to produce optimized, repeatable, and robust deposits.
- Updated detector electronics have been designed, built, and tested at the KSU EDL. Furthermore, the electronics were tested with an older MPFD design that was installed in the KSU TRIGRA reactor.
- A project meeting was held at KSU to discuss the roles and responsibilities between INL and KSU for development of the MPFDs. In addition, a demonstration of newly designed electronics was given.
- A detector evaluation plan has been developed, and new testing capabilities in the ATRC have been used. The detector evaluation plan includes options for testing at the HTTL, HPIL, and ATRC, with potential testing at the KSU TRIGA reactor. It is expected this testing will lead to valuable insights to improve the MPFD design.

As noted within this report, this is year 2 of a 3 year project. During the first two years, all planned work was accomplished within the allocated budget. Planned FY14 allocations will allow all remaining workscope to be completed for developing and evaluating MPFDs. Once NEET program evaluations are completed, the final MPFD will be ready for deployment in MTR irradiations, providing DOE-NE programs a unique new capability for evaluating the performance of candidate new fuels and materials to better characterize irradiation test conditions.

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