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NEET Micro-Pocket Fission Detector - Final Project Report

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EXECUTIVE SUMMARY

This report documents results from research to develop and test a small, multi-purpose, robust, in-core flux and temperature sensor called the Micro-Pocket Fission Detector (MPFD). MPFDs are compact fission chambers capable of simultaneously measuring thermal neutron flux, fast neutron flux, and temperature within a single package. As discussed within this report, the small size, variable sensitivity, and increased accuracy of MPFDs represent a revolutionary improvement over current methods used to support irradiations in US Material Test Reactors (MTRs). To reap the benefits offered by MPFDs, a collaboration between the Idaho National Laboratory (INL) and the Kansas State University (KSU) to develop and test MPFDs was funded by the Nuclear Energy Enabling Technologies (NEET) program. Because of potential benefits of MPFDs, the French atomic and alternative energy commission, Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA), collaborated on MPFD research at their own expense.

The project objectives were carefully chosen to develop a sensor that would significantly advance flux detection capabilities for irradiation tests in US MTRs. These objectives, which were all successfully completed within this three year project, include:

- Redesign MPFDs to ensure survivability in US MTR irradiations for measurement of fast flux, thermal flux, and temperature.
- Select and procure new high temperature compatible materials for MPFD construction.
- Design and construct a new amplifier compatible with the MPFD.
- Develop deposition tools and methods for MPFD electrode deposition.
- Develop a fissile material deposition system and methods for MPFD fissile deposition.
- Develop construction methods for the new geometry of the MPFD.
- Assemble a non-fissile prototype MPFD.
- Perform leak rate evaluations of non-fissile prototype MPFD.
- Perform high temperature evaluations of non-fissile prototype MPFDs.
- Refine and improve prototype MPFD design as needed to develop an enhanced MPFD design.
- Characterize fissile deposition system for enhanced MPFD design.
- Select and procure new materials for enhanced MPFD design.
- Refine construction methods for enhanced MPFD design.
- Assemble enhanced MPFD with fissile deposit.
- Perform laboratory and radiation evaluations of enhanced MPFD.
- Submit final project report and publications on MPFD development and evaluations.

The development, testing and analysis completed in this project has provided the necessary 'proof-of-concept' data to demonstrate the viability of MPFDs for higher fluence irradiations. Highlights from our research accomplishments include:

- Redesigned MPFDs to fit inside a round geometry that is more suitable for installation in US MTR irradiation tests.
- Designed, built, and tested a new signal amplifier compatible with the MPFD.
- Designed and constructed specialized shadow masks in electron-beam evaporator for MPFD electrode deposition.
- Assembled electroplating system and characterized electroplating methods for MPFD fissile deposition.
- Developed unique construction methods to reduce the amount of welding and wiring connections for the round geometry MPFD.

- Assembled a non-fissile prototype MPFD to evaluate wiring connections and construction methods.
- Verified leak rate exceeded minimum acceptable requirements for MPFD prototypes.
- Successfully performed a high temperature evaluation of 1000 hours at 500 °C of non-fissile prototype MPFD.
- Developed a fissile material characterization system for enhanced MPFD design.
- Improved electroplating, welding and wire connections methods for enhanced MPFD design.
- Designed and assembled enhanced MPFD prototype using new construction methods with characterized fissile deposits.
- Performed neutron evaluations of enhanced MPFD prototype in-core at the KSU TRIGA reactor.

In summary, this project developed a new sensor that offers US MTR users enhanced capabilities for real-time measurement of the thermal and fast flux and of temperature with a single, miniature detector. In addition, the accomplishments of this project have attracted funding from other Department of Energy Office of Nuclear Energy (DOE-NE) programs for additional MPFD applications. This future work will build on current activities completed in this initial project, but the MPFD will be specifically tailored to survive higher temperature irradiations and transient testing irradiations.

This final project report summarizes activities completed to develop MPFDs. As documented in this report, all planned project objectives for developing this unique new, compact, multipurpose sensor have been completed.

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FIGURES

TABLES

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
EIL	Energy Innovation 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
IRP	Integrated Research Project
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
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 Final Project 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 the performance of new materials and fuels 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.

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 within many tests conducted in MTRs. This final project report summarizes activities completed to develop Micro-Pocket Fission Detectors (MPFDs) capable of measuring thermal neutron flux, fast neutron flux, and temperature within a single compact sensor. Information from FY12 and FY13 MPFD status reports is summarized in this final report for completeness, but can also be found in References 1 and 2.

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 to overcome operational shortcomings associated with more complicated irradiation testing requirements. Recent interest in testing to support new reactor designs can require higher temperatures, higher fluxes, or 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 implemented; 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 high performance MTR 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 high performance MTR 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 multiple compact 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),[3,4] Advanced Reactor Concepts (ARC),[6 through 7] Light Water Reactor Sustainability (LWRS),[8,9] and Next Generation Nuclear Plant (NGNP) [10 through 15] 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.[16] 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.[17] 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. Currently, drop-in or static capsule experiments only allow data to be obtained at the endpoint of an experiment. Although visual examinations and 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 sensors in irradiation tests with instrumentation leads 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[3, 7, 8, 10 through 12] and cognizant technical experts were contacted[6,15,18 through 20] 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 8, 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 initial 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 Pressurized 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: radiation-induced hardening and embrittlement, phase instabilities from radiation-induced or radiation-enhanced segregation and precipitation, irradiation creep, volumetric swelling from cavity formation, and high temperature helium embrittlement due to formation of helium-filled cavities on grain boundaries.

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%	NA
	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.

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;[4, 5, 7 through 9, 11 through 14] and cognizant technical experts[6,15,20] 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	Desired 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, and 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 rely 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[21 through 29].

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 No power source Simple/robust	Need calibration No fast neutron response Low sensitivity Delayed response Need electrometer
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 methods 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.[21] 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 in appropriate fixturing (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: 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.

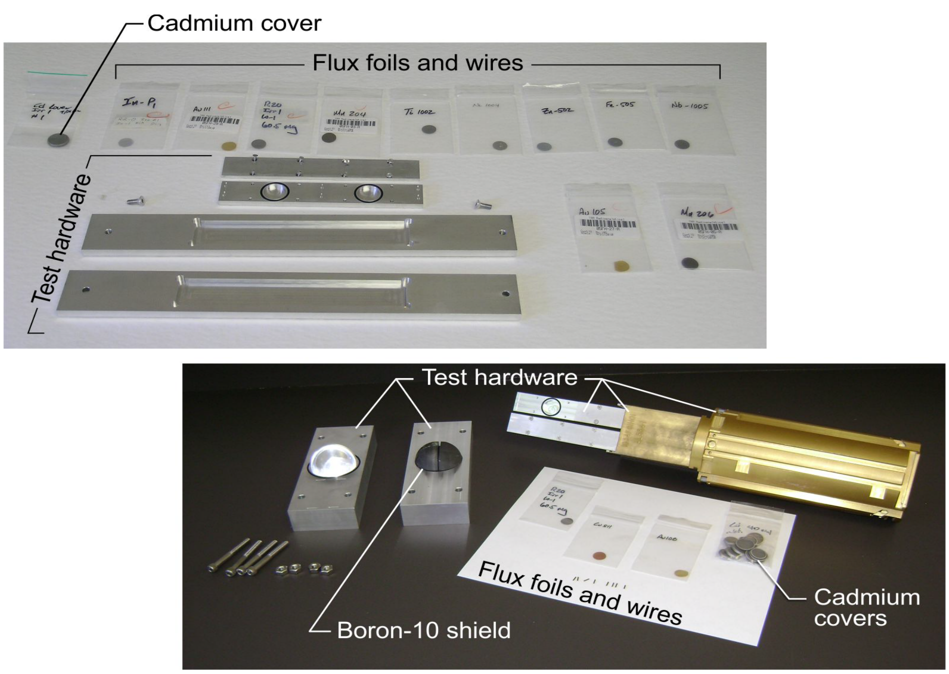

Figure 1. Representative flux wires, flux foils and test hardware used at INL.

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.[21] 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.

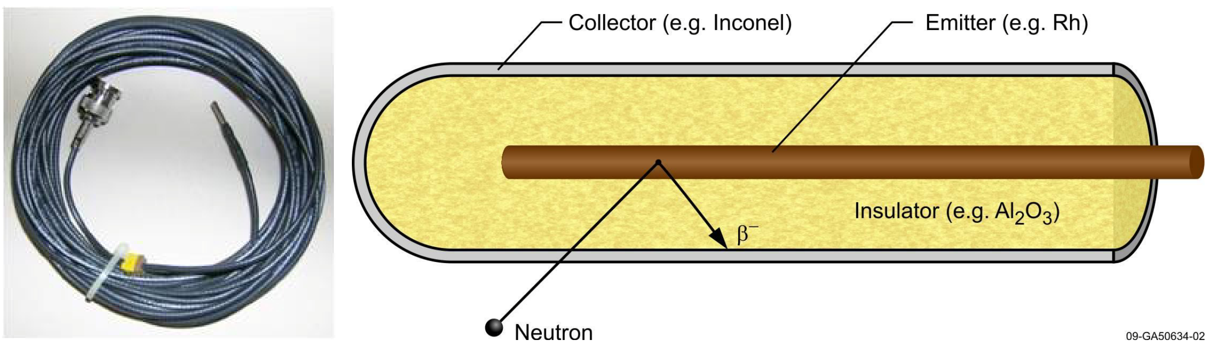

Figure 2. Representative Self-Powered Neutron Detector (SPND) and component sketch.

Table 4. Typical emitters for SPNDs[19].

SPND Emitter	Sensitivity (A/m)/[$2x10^{17}$ neutrons/(m^2 s)]	Response
Rhodium	2.4×10^{-6}	Delayed
Vanadium	1.5×10^{-7}	Delayed
Cobalt	3.4×10^{-8}	Prompt
Molybdenum	1.7×10^{-8}	Prompt
Platinum	2.6×10^{-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: 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.[21]

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 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 midrange 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.[21]

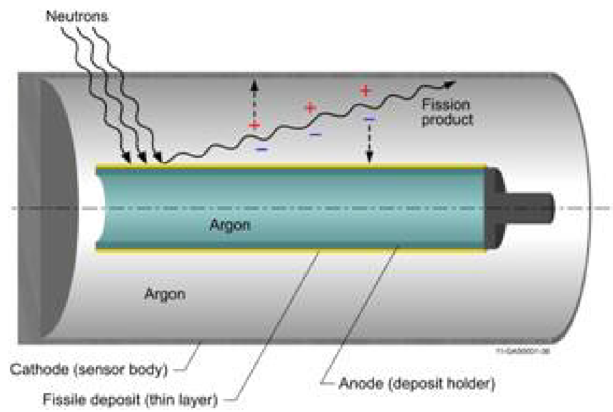

Figure 3. Representative fission chamber and component sketch.

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.[21] 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, some 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).[28,29] 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.[28,29] 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.[28,29]

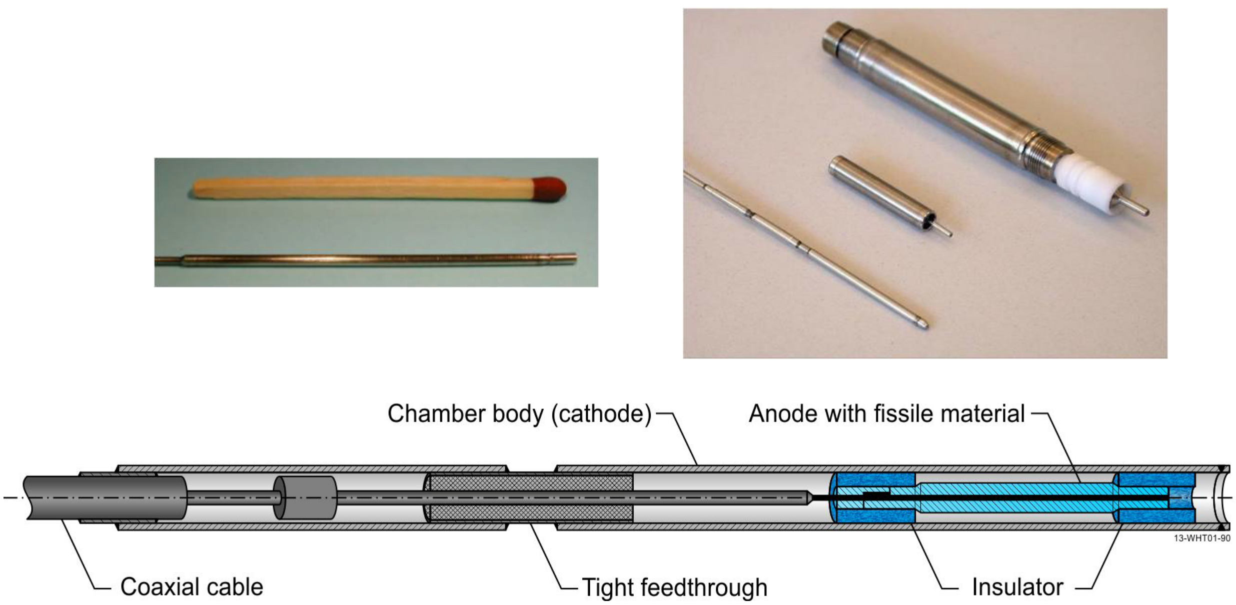

Figure 4. Representative CEA miniature fission chambers and component sketch[28,29].

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.[22 through 27] Initial 'proof-of-concept' evaluations to demonstrate MPFD performance were completed at the KSU TRIGA reactor. However, prior to deployment of these new MPFDs in a US MTR, a more robust sensor design was required. As discussed in Section 3, initial activities to develop MPFDs for high performance US MTR applications were completed 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.[22 through 27]

3. ENHANCED MPFD INVESTIGATION

This section presents the scope for this NEET project and summarizes investigation activities completed in this effort. A brief review of collaborator facilities and prior KSU activities to design and test MPFDs is also presented.

3.1. Overall Plan and Schedule

This joint INL/KSU/CEA project consisted of three tasks that were completed within three years. Figure 5 illustrates activities that were performed each year of this project and the organizations participating in each activity. Task 1 of this project was 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 included selecting candidate materials and fabrication techniques to develop an optimized design required for higher flux US MTR testing. Results from Task 2 fabrication and evaluation activities were considered to develop, fabricate, and verify the performance of the final MPFD design. In Task 3, investigators refined the design and built a final MPFD. The final MPFD design was evaluated in neutron and gamma fields using unique facilities at KSU. As discussed in this document, annual reports,[1, 2] peer-reviewed archival journal articles and conference papers, and an invention disclosure record for a patent[30] were completed throughout this project.

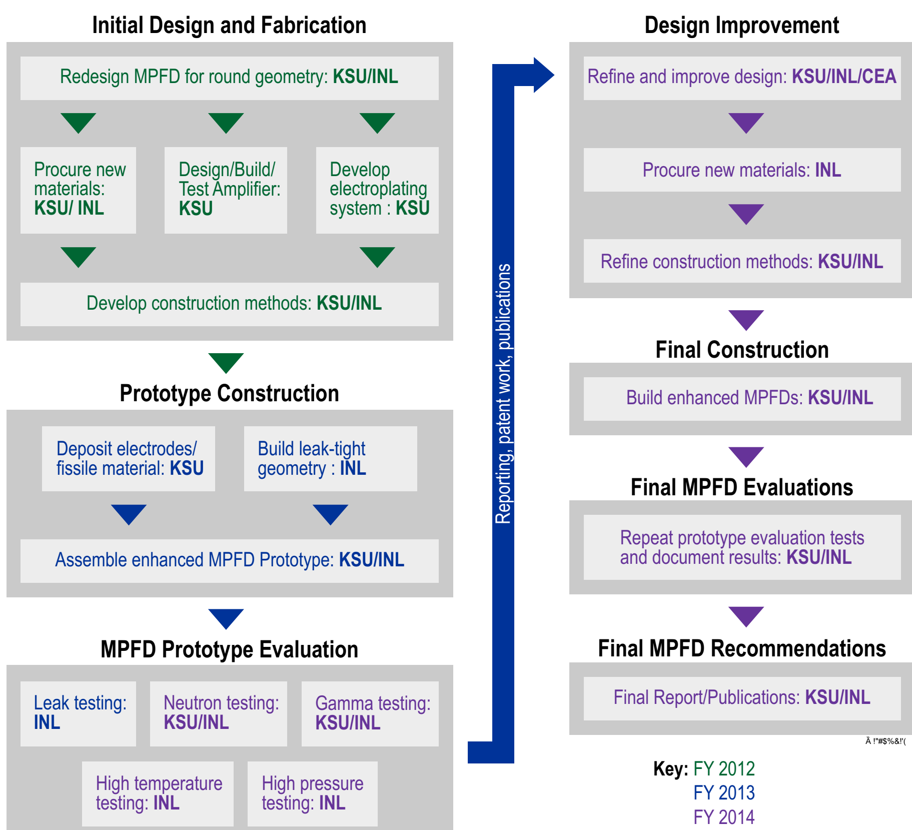

Figure 5. MPFD development tasks.

3.2. Prior Activities and Collaborator Capabilities

Research activities for the initial development of MPFDs at KSU is discussed in the following section. In addition, the capabilities of the collaborating organizations are summarized.

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).[22 through 27] 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

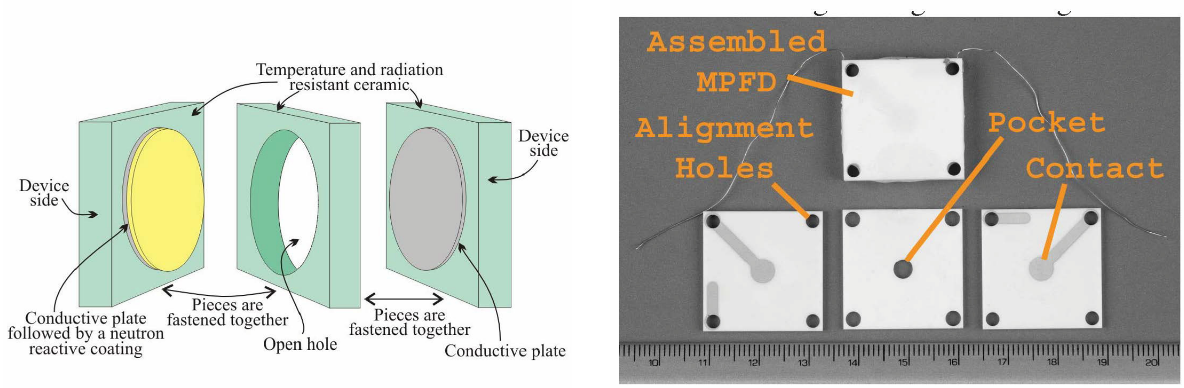

Figure 6. MPFD component sketch (left) and initial KSU prototype MPFD (right)[22 through 27].

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.[22 through 27] 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 with a K-type thermocouple wire bonded to the detector substrate was included; however, the attachment method was not ideal for optimal thermocouple performance.

Deployment of KSU MPFDs in their TRIGA reactor had limited success.[22 through 27] 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.[22 through 27]

3.2.2. KSU Research Facilities

KSU experience in producing the initial MPFD prototypes was beneficial for producing an updated version of MPFDs. KSU has several specialized laboratories to aid in the construction and testing of MPFDs.[31 through 33] KSU tasks included: 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. This section summarizes KSU capabilities utilized for this effort.

3.2.2.1. SMART Laboratory

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 7), 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 completed construction of a new 1000 square foot class 100 clean room facility that has been fully operational as of March 2012.[31]

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.[31]

3.2.2.2. TRIGA Mark II Research Reactor

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 sensors and irradiation of materials. The KSU TRIGA is licenced to a 1.25 MW steady state operating power and has pulsing capabilities up to ~2 GW, making it ideally suited for testing sensors in high-power transients. The

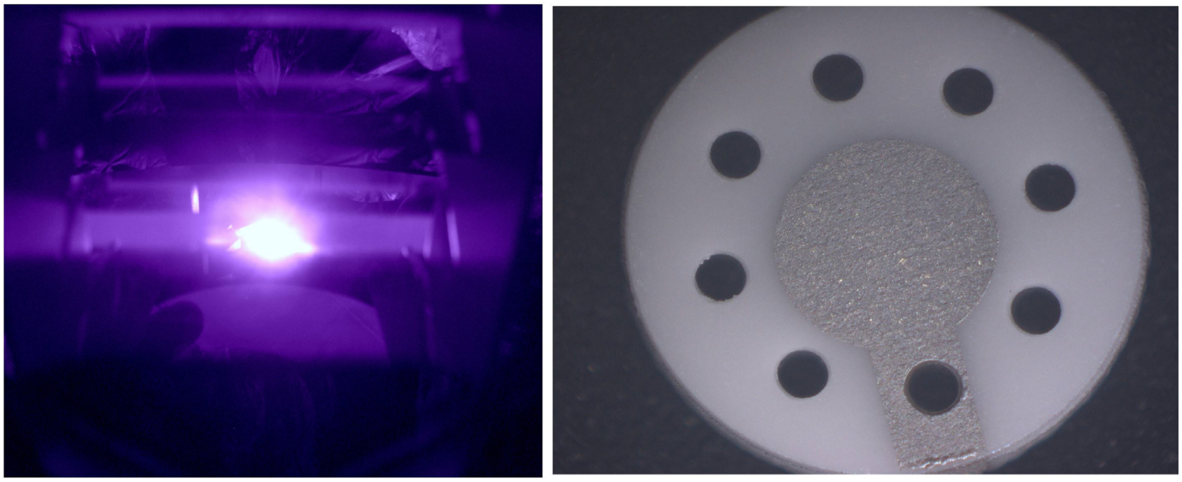

Figure 7. Electron-beam evaporator and MPFD sample at the KSU SMART Laboratory[31].

peak steady-state thermal flux and fast flux available in-core are approximately 2.50 x 10^{13} n/cm^2-s and 2.50 x10^{14} n/cm^2-s, respectively.[32] Sensors can be tested from source range to full power in reactor beam ports or directly in the reactor core. The ease of access to this reactor facility makes it an asset to the SMART Laboratory for neutron detector testing. [32]

3.2.2.3. Electronics Design Laboratory

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.[33]

3.2.3. INL Research Facilities

The INL's role in the NEET MPFD project utilizes 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 utilized for this effort.

3.2.3.1. High Temperature Test Laboratory

INL has several specialized facilities to construct and test MPFDs. The High Temperature Test Laboratory (HTTL) contains specialized equipment to design in-pile sensors and conduct high-temperature testing. HTTL's trained staff evaluates high-temperature material properties and develops 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. In addition, the 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 (see Figure 8). HTTL efforts support DOE-NE programs 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.[32]

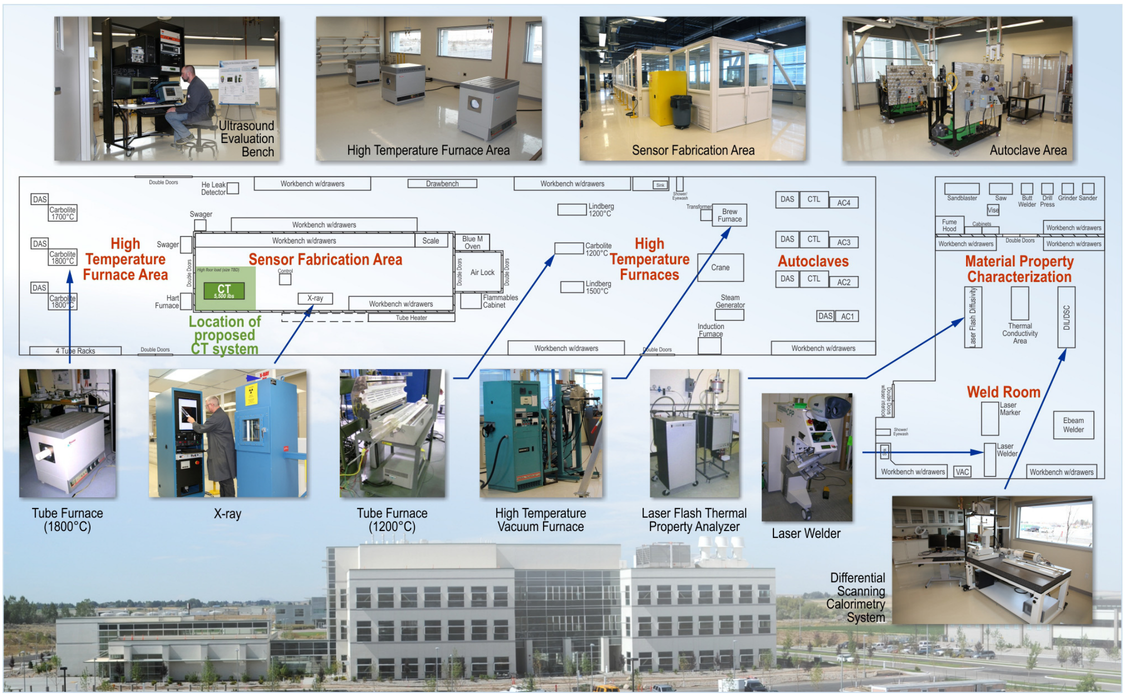

Figure 8. HTTL layout in the new Energy Innovation Laboratory.

In FY14, the HTTL was relocated to a new state-of-the-art facility at INL, the Energy Innovation Laboratory (EIL) (see Figure 8). The inclusion of a clean room capability and additional new state-of-the-art equipment including a recently awarded three-dimensional computed tomography system furthers HTTL's role as a world-class in-pile instrumentation development and testing facility.[35]

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. In addition, calibration activities performed at the ATRC are presented.

3.2.3.2. ATRC Facility

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 (Figures 9 and 10). This recently developed specialized fixturing provides INL a unique capability for comparison evaluations of real-time neutron flux detectors.[36]

3.2.3.3. HPIL Facility

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 dose rates, respectively.

These irradiators and the ATRC were not able to be incorporated into evaluations for this project due to time constraints associated with evaluations scheduled at the KSU TRIGA reactor. It is planned that recently awarded research will use the irradiators and the ATRC to test the neutron sensitivity and the gamma-ray insensitivity of the MPFDs.[37]

3.2.3.4. Flux Detector Calibrations at ATRC

As noted in Section 3.2.3.2, 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, SPNDs and back-to-back (BTB) fission chambers 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 9.

The in-core sensors were inserted into the ATRC using EGTs and also installed in the northwest in-pile tubes. 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. 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 10 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 in FY13. 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 unbal-

	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

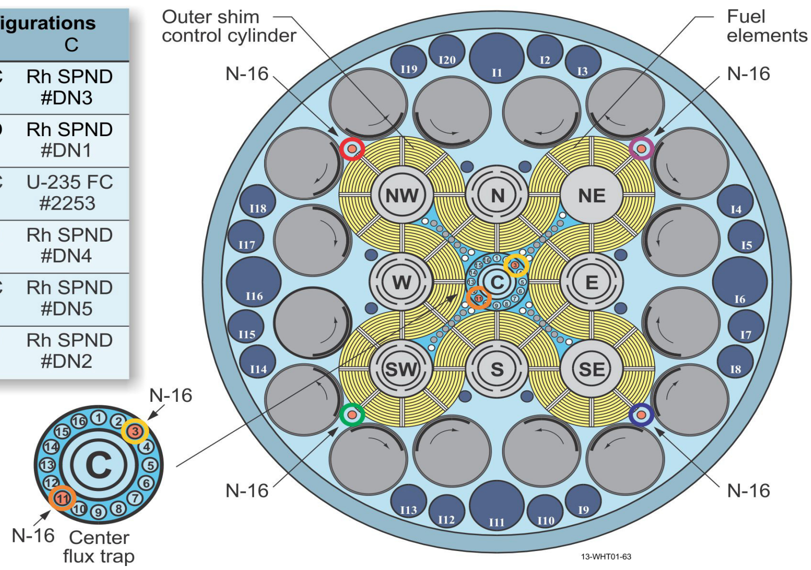

Figure 9. ATRC in-core sensor locations.

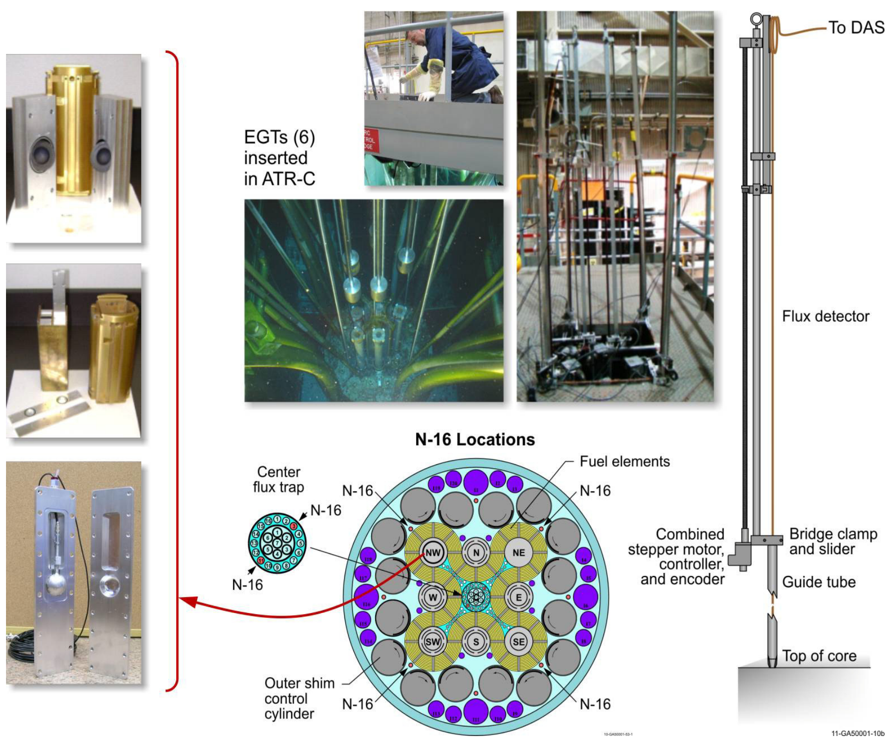

Figure 10. EGTs in ATRC.

anced condition, meaning the reactor power in the NW lobe was purposely changed from the nominal critical power level.

Initially, the flux sensors were verified to be operational; then, the detectors were used to track reactor power. Typical data obtained from axial flux testing and power level testing is shown in Figure 11. In addi-

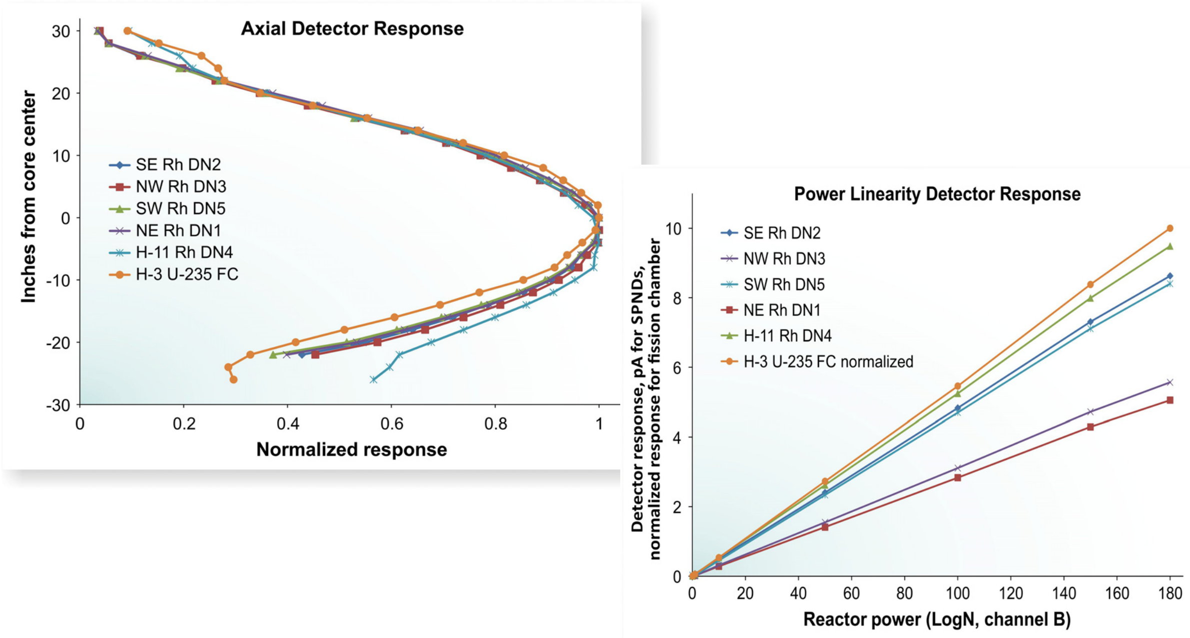

Figure 11. Axial flux profile and power measurements obtained from rhodium SPNDs and a fission chamber from experimental configuration C.

tion 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 References 38 and 39.

Other cross-calibration fixtures for ATRC were tested in FY14. Specialized fixtures (Figure 12) allowed a 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 measure of fission reaction rates and provide accurate cross-calibrations of other detectors such as an enhanced MPFD. 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 13. Detector response to Log N reactor power is shown in Figure 14. Further experimental details can be found in Reference 40.

3.2.4. CEA contributions

The CEA has over 40 years of experience in design, construction and use of miniature and sub-miniature fission chambers for MTR experiments. The CEA has developed many specialised computed modeling codes to aid in fission chamber research and development. The CEA contribution to this project was to provide technical guidance and modeling capabilities as needed.

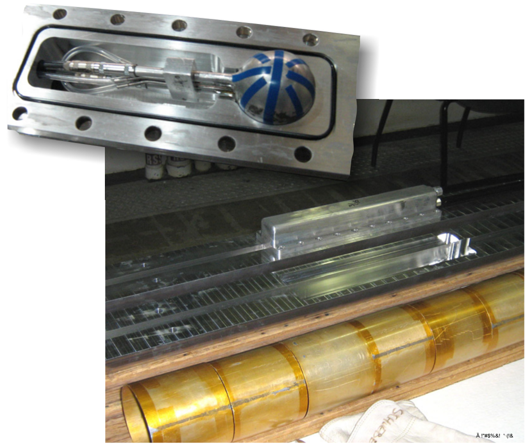

Figure 12. Fabricated back-to-back fission chamber and fixtures being assembled for testing in ATRC.

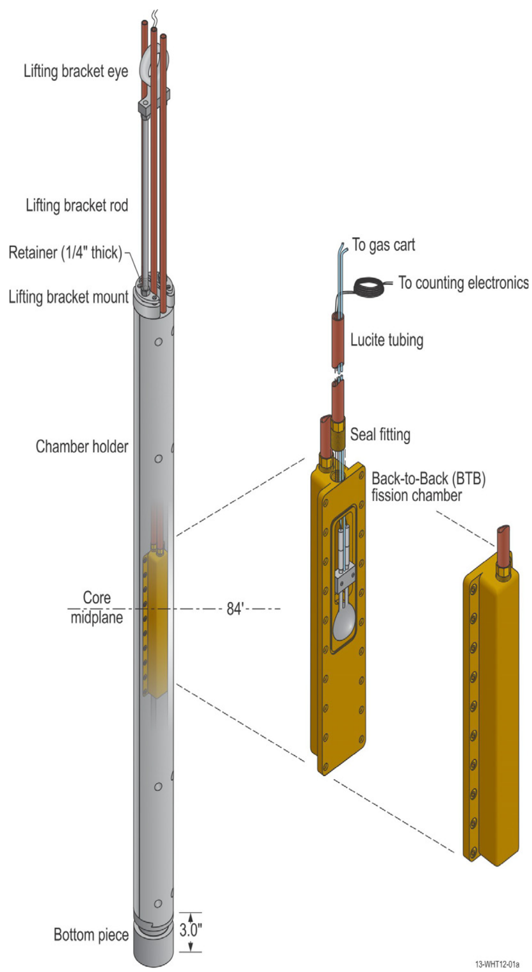

Figure 13. Back-to-back fission chamber fixture assembly.

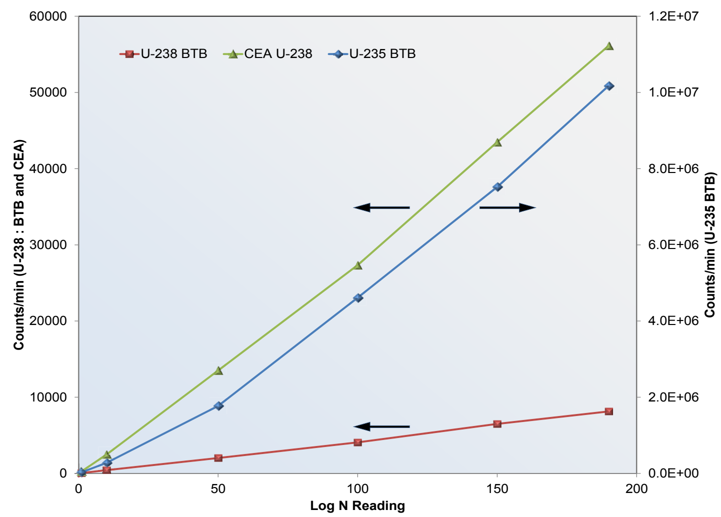

Figure 14. Back-to-back fission chamber representative data.

3.2.5. Project Meeting

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 by KSU and INL. During this meeting, KSU demonstrated the new amplifier board at the KSU TRIGA reactor (Section 3.2.2.2). Analog and digital signals 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 were compatible with KSU construction methods and equipment.

3.3. MPFD Development and Evaluation

In this project, a robust and compact MPFD was developed, fabricated, and evaluated using techniques perfected by INL's 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.

3.3.1. Enhanced Sensor Design for MTR Irradiations

DOE-NE programs require a robust and reliable sensor that will survive the harsh testing conditions possible in US MTRs. Hence, an enhanced version of the KSU MPFD was developed in this NEET project, as 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 design uses a round stackable geometry (Figure 15). 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 used in the original KSU MPFD design (Figure 16).

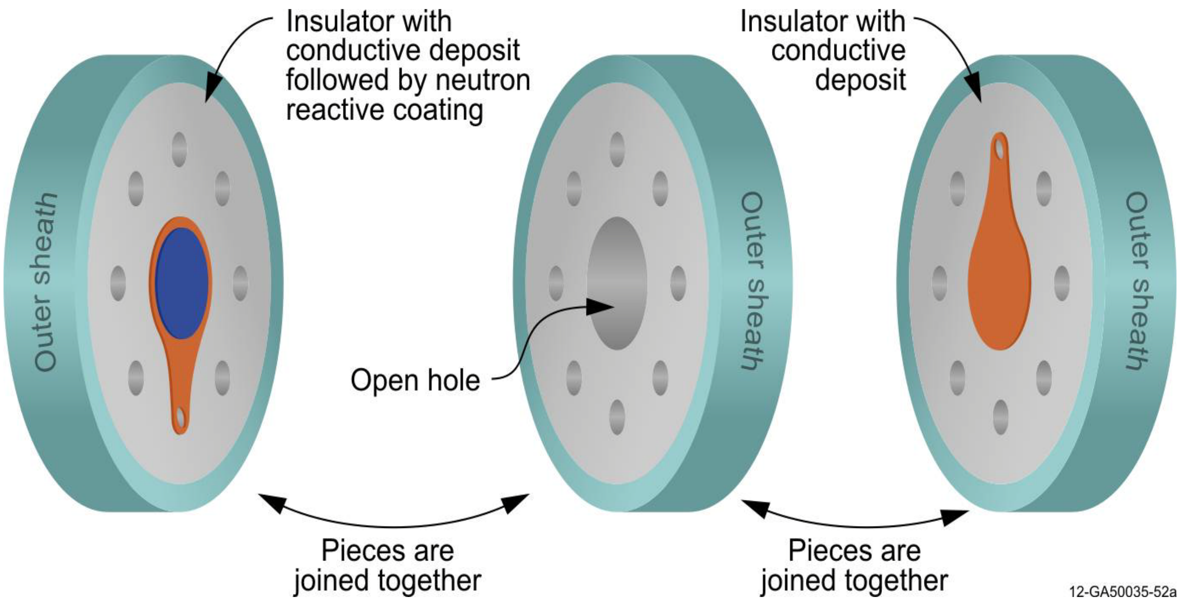

Figure 15. Round geometry MPFD design suitable for MTR irradiations.

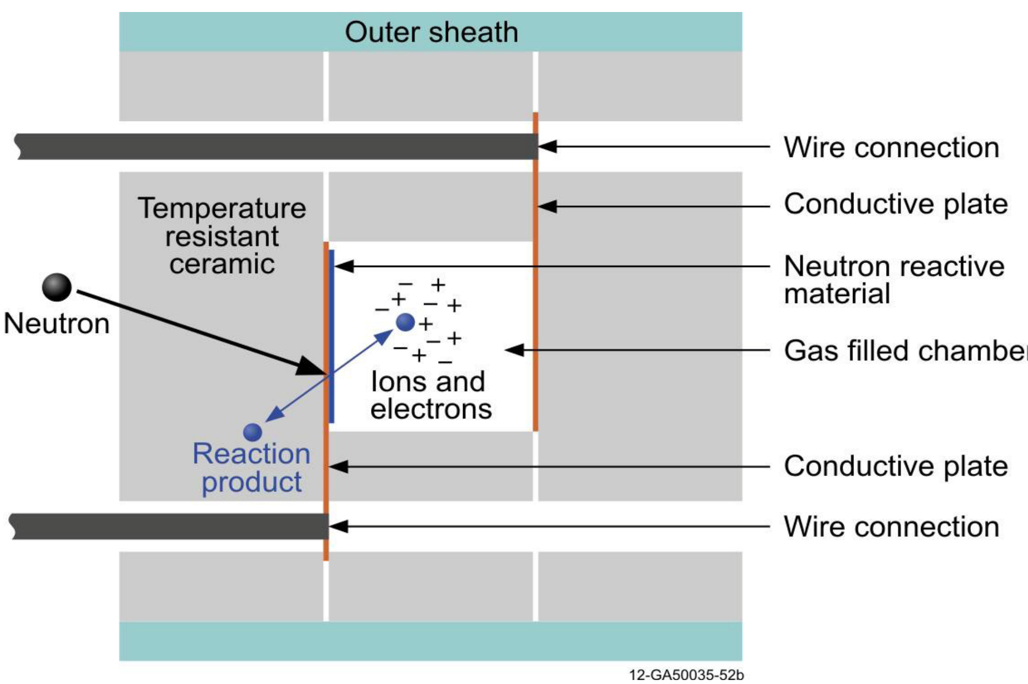

Figure 16. Component diagram of MPFD design showing wire locations.

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 17). This eliminates the additional wire bonding required in the KSU design, thus improving thermocouple performance and robustness.

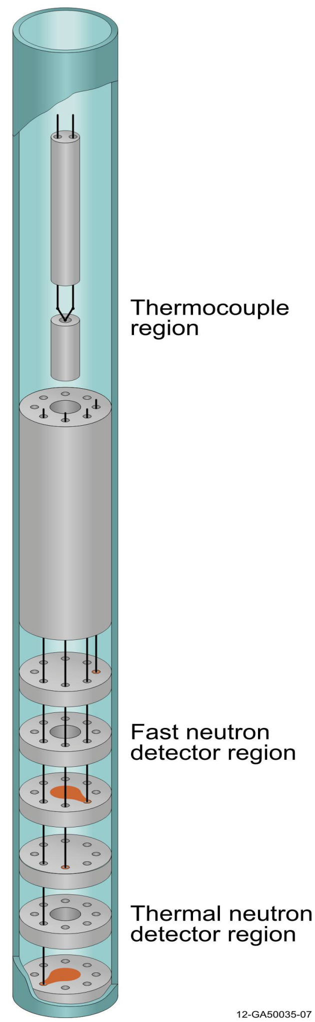

Figure 17. Enhanced MPFD assembly shown in tube with thermocouple above fission chambers.

3.3.2. 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 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 (Figure 18) and tested successfully with an older MPFD installed in the KSU TRIGA reactor (Figure 19). However, some component values on the amplifier board required minor adjustments to match the capacitance of the new MPFD design. These changes were made when the enhanced MPFDs were assembled and tested for capacitance.

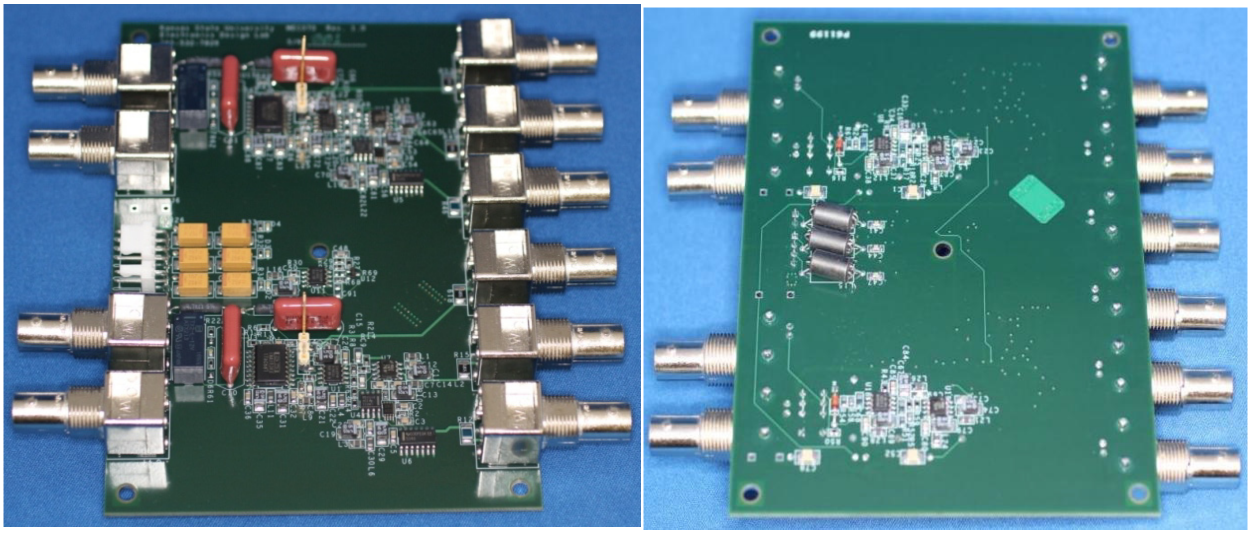

Figure 18. New MPFD amplifier

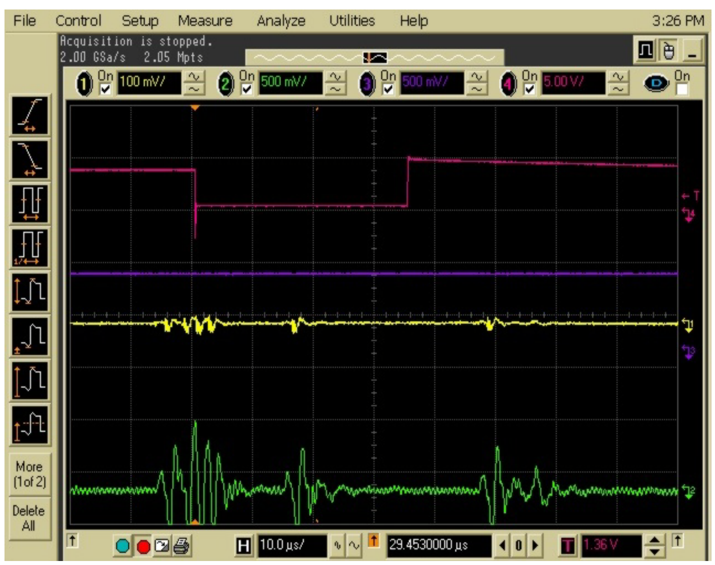

Figure 19. Analog and digital signals from MPFDs in KSU TRIGA reactor.

3.3.3. 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 7). 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 were explored as possible contact materials, and platinum provided the best contact.

Once the electrical contacts are in place, the second plating step will deposit the material (natural uranium for thermal neutron detection and thorium for fast neutron detection). Two methods for fissile material deposition were investigated. The first method is standard electroplating as was used with the initial MPFD design and some of the prototypes developed in this project. The small substrates and thin depositions utilize a specialized nA-current micro-electroplating system at KSU (Figure 20). The second method utilizes electroless plating that does not require an electric current to be applied to the plating solution. Both methods required 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 final depositions.

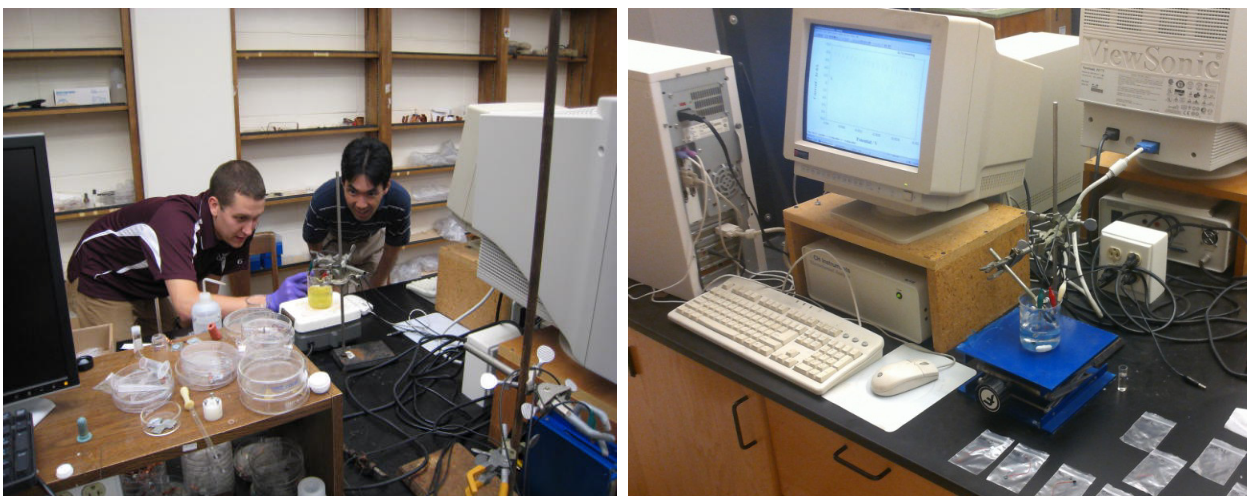

Figure 20. Micro-electroplating uranium at KSU.

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 FY14, an alternative vendor provided alumina substrates that had smoother surfaces without any cracks. Contact deposition quality has greatly improved as shown using an optical profilometer (Figure 21), x-ray fluorescence analyzer (Figure 22), and electrochemical analyzer. Investigations to develop and characterize a robust electrical contact with a fissile material deposition were completed in FY14.

3.3.4. Design and Material

For this NEET-funded project, the HTTL's expertise in robust sensors for MTR irradiations was used in the design, construction and evaluations of the MPFD prototypes. Using this expertise, the design was changed to a round, stackable geometry that was more suitable for installation in a leak-tight tube and that

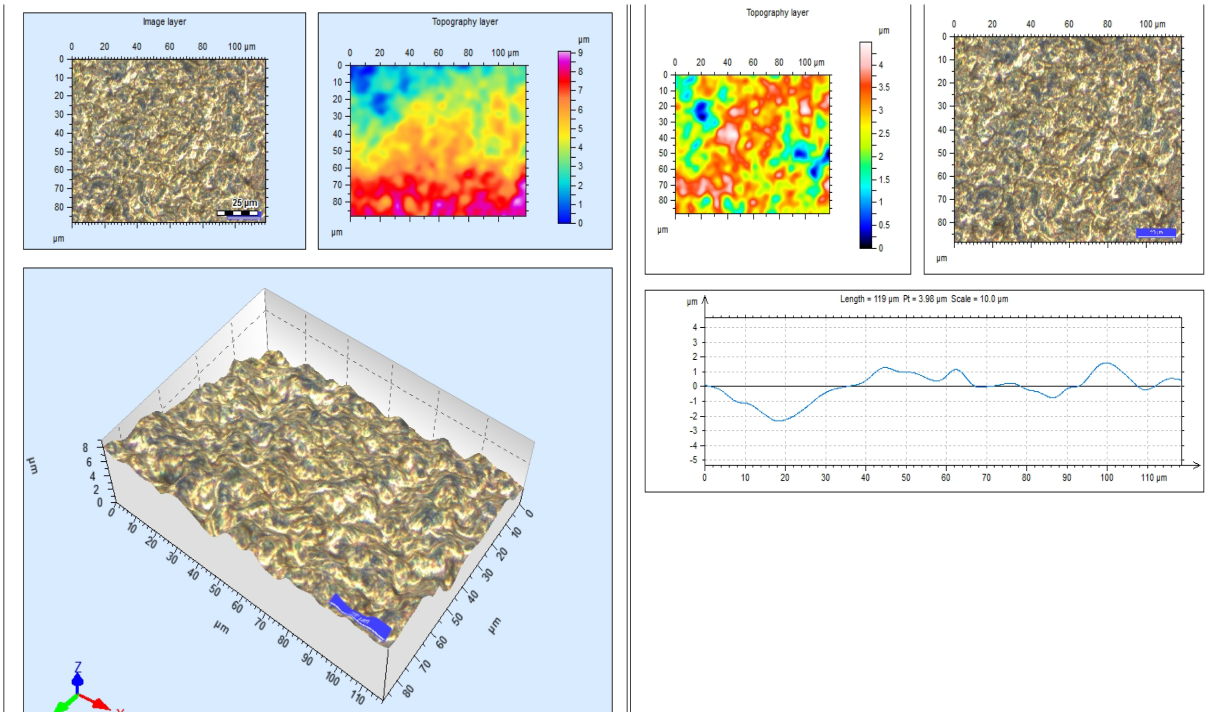

Figure 21. Electroplated sample of uranium under analysis with optical profilometer.

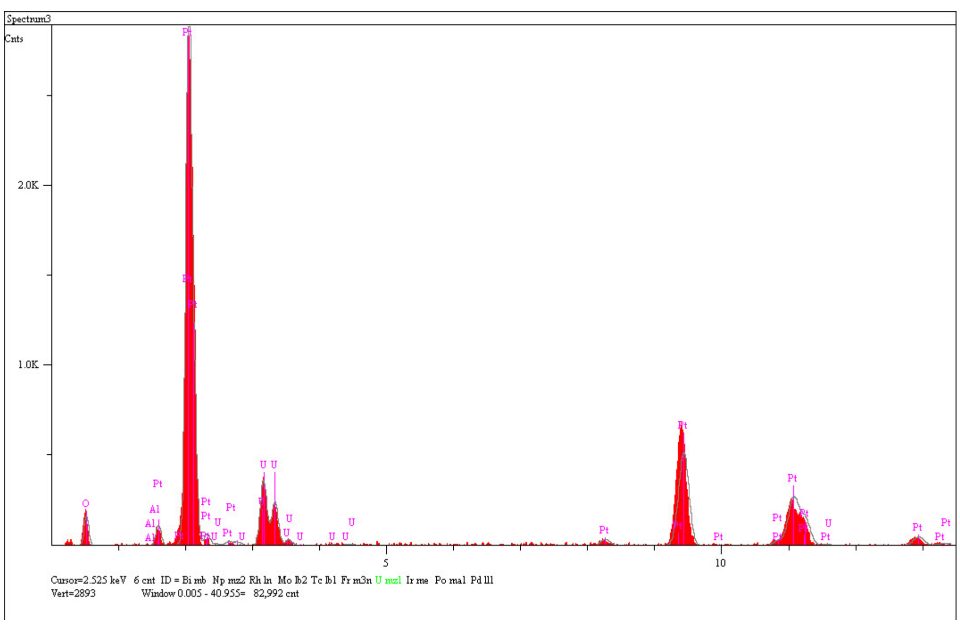

Figure 22. X-ray fluorescence spectrum of uranium coated sample.

has improved thermocouple connections and wiring transitions compared to prior designs. Research focused on building a robust prototype using less expensive, commercially-available materials capable of operating at temperatures up to 500 °C. For higher temperature applications in high flux MTRs, high temperature and radiation resistant materials suitable for the harsh environment will be utilized. In addition, it is anticipated that the design could be further enhanced and miniaturized in future projects.

The main components of the initial MPFD detector and extension cable are specially manufactured hard-fired alumina substrates and crushable alumina insulators (Figure 23), respectively, all housed within leak-tight stainless steel tubing. A “loose assembly construction” is used with a rigid stainless steel tube. This tube contains hard-fired alumina substrates for the fission chamber electrodes and the fissile depositions (Figure 7), a thermocouple, and wire contacts. The crushable alumina insulators serve as an insulator for the six wire extension cable with a stainless steel outer sheath (Figure 24). The extension assembly is drawn to the desired length and diameter to provide flexibility for installation in the reactor tank.

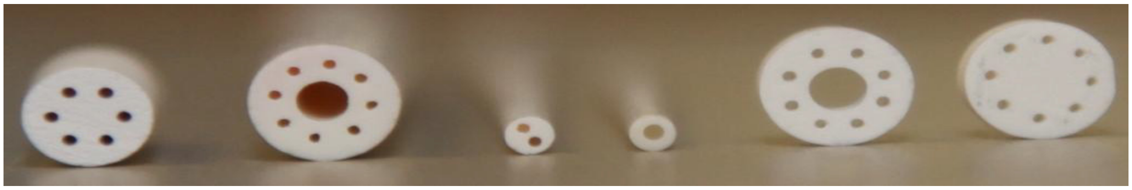

Figure 23. MPFD alumina substrates and insulators.

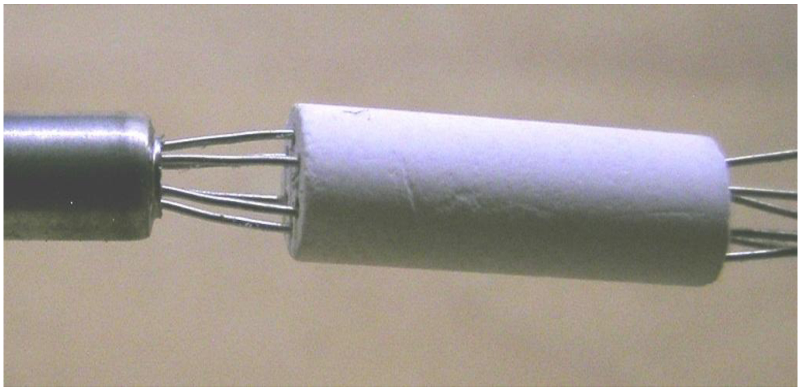

Figure 24. Extension cable with six wires threaded through insulation.

3.3.4.1. Construction Methods

MPFD construction was completed using equipment and techniques perfected by INL's HTTL staff.[3] 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 25 shows some of the specialized HTTL equipment used in MPFD fabrication. After the parts are assembled (Figure 26), it is inserted into the outer sheath, and welded together (Figure 27). 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 laser weld.

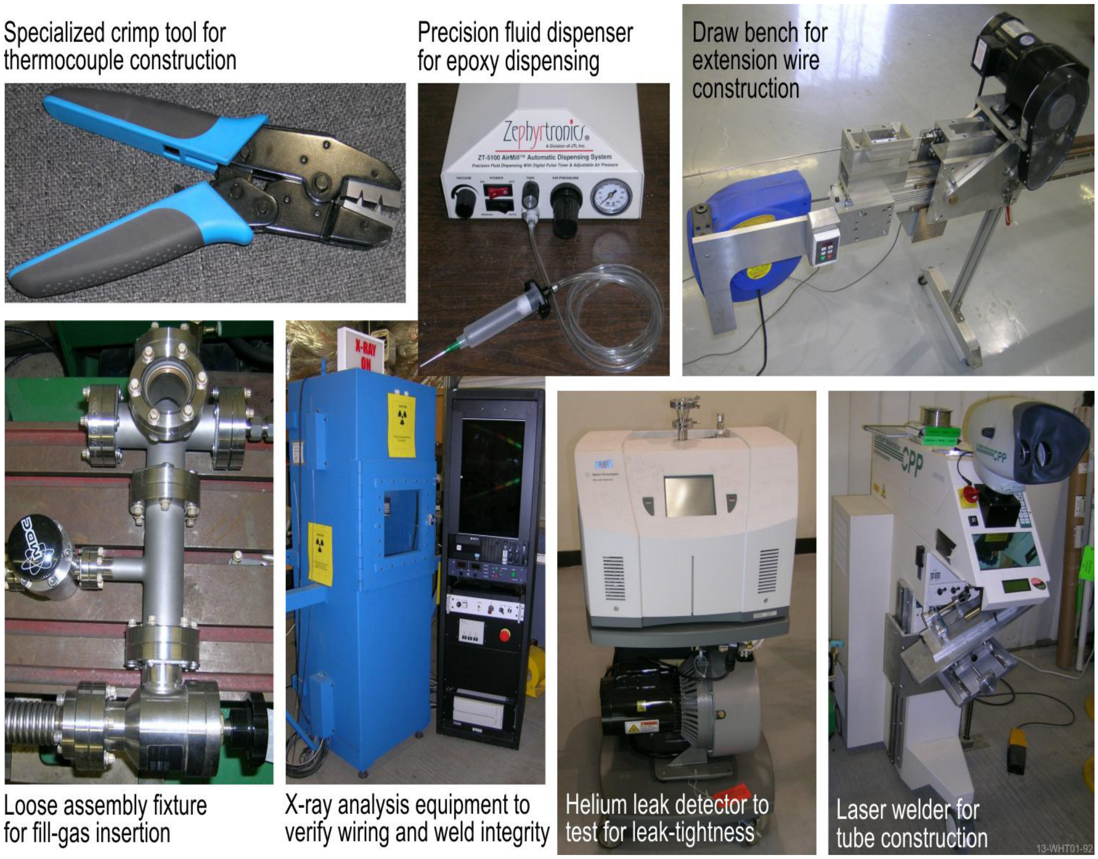

Figure 25. Various HTTL equipment for MPFD fabrication.

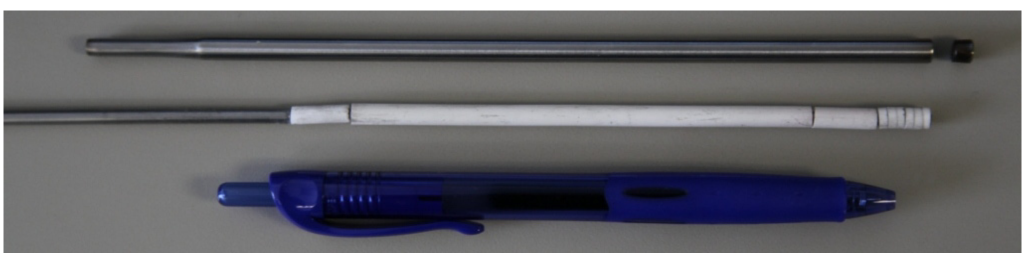

Figure 26. Exploded view of prototype MPFD compared to a standard ballpoint pen.

3.3.4.2. *Enhanced MPFD*

The final evolution of MPFD was achieved by making minor adjustments to proven construction methods. The amount of material used in the loose assembly section of the MPFD reduced the overall length of the MPFD for improved installation in a test. The electroplating and fissile deposition were greatly improved by procuring ultra smooth alumina substrates. This allowed for a more uniform fissile coating that was more easily deposited using updated material deposition methods. In addition, the improvement in the fissile coating aided fissile deposit characterization using a specialized 2π solid angle gas detector.

The wiring and tube-to-tube transitions were improved with specially machined stainless steel adapters that position the tubes uniformly for welding repeatedly. These adapters allowed the tubes to remain concentric while welding. In addition, a tube cap was specially machined for the loose assembly tube that fit better then previously hand-fabricated tube caps. These improvements are included in the MPFD shown in Figure 27.

Figure 27. Final enhanced MPFD assembly compared to a penny.

3.3.5. MPFD Evaluations

Laboratory testing of the new MPFD design was completed to evaluate the robustness of the epoxy wire connections, thermocouple performance, and the weld integrity. Sensor performance was assessed in the HTTL by considering thermocouple response, x-ray observations, helium leak checks, and resistance and continuity measurements. Sheath and weld integrity was evaluated using the HTTL helium leak testing equipment to verify that the assembly meets requirements for the ASTM leak rate of sheathed thermocouples.[41]

Leak testing revealed that MFPDs prototype leak rates were well below ASTM thermocouple leak rate limits. Both non-fissile and fissile MPFDs were evaluated using a specialized helium leak testing system at the HTTL as shown in Figure 28.

Figure 28. Leak testing an enhanced MPFD in specialized HTTL leak detection system.

After an acceptable leak rate was verified, external wiring was added to allow the enhanced MPFDs to be connected to a data acquisition system (Figure 29) for long duration tests in a high temperature furnace. These evaluations were performed in HTTL furnaces to verify the internal wiring connections and thermocouple performance would survive at 500 °C for 1000 continuous hours. The evaluations indicated the wiring connections and thermocouple performance could survive at these elevated temperature for more than 1000 hours. As shown in Figure 30, the MPFD thermocouple continued to provide a temperature reading consistent with the Type K reference thermocouple included in this test. Likewise, connections to flux detector components survive (as indicated by their continuous and consistent voltage signal) throughout the test.

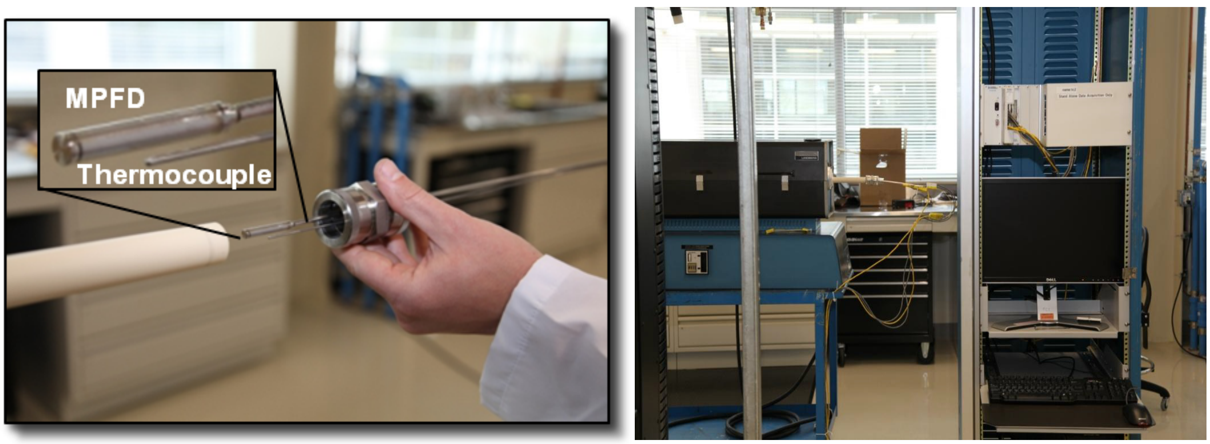

Figure 29. MPFD installation into furnace and data acquisition system.

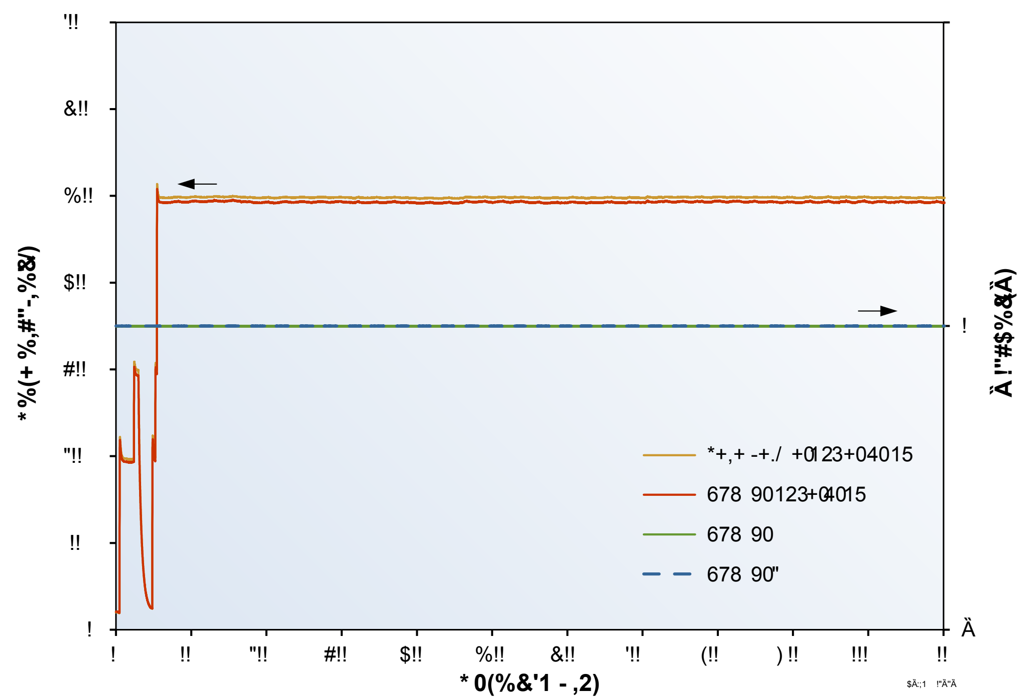

Figure 30. MPFD long duration high temperature test results.

Radiation sensitivity testing was performed at the KSU TRIGA reactor by installing the MPFDs in the central thimble of the reactor core (see Figure 31). The MPFDs were tested in-core at thermal and fast fluxes of 2.00 x 10^{13} n/cm^2-s and 2.00 x10^{14} n/cm^2-s, respectively. Initial measurements contained a noise component on the pulse shape that was determined to be caused by the primary coolant pump of the reactor. A filter was added to the amplifier electronics and the detector pulse signal improved. Additional evaluations were also performed in a TRIGA beamport to demonstrate the MPFD sensitivity to lower fluxes of 2.85 x 10^5 n/cm^2-s thermal and 1.3 x10^4 n/cm^2-s fast. Typical detector pulses before and after noise filtering are shown in Figure 32.

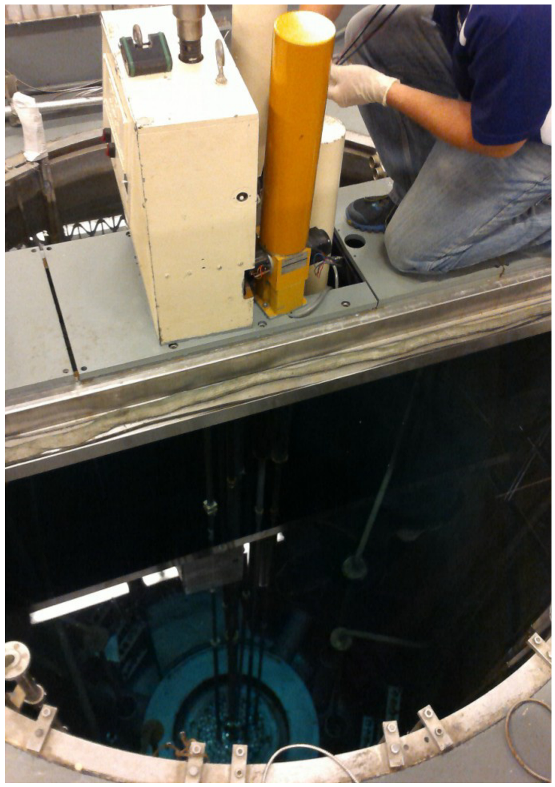

Figure 31. MPFD installation in the central thimble at KSU TRIGA reactor.

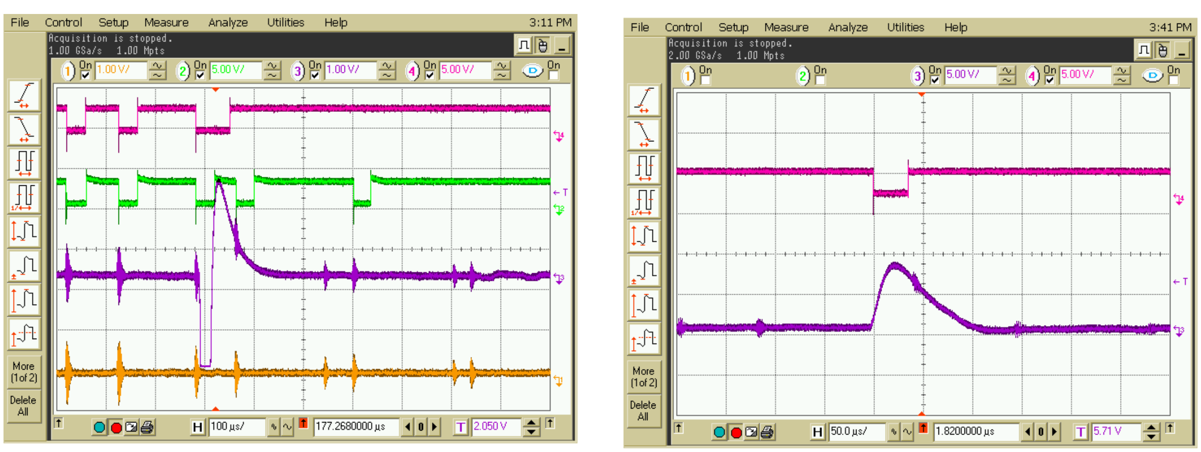

Figure 32. MPFD pulses before and after noise filtering during KSU TRIGA reactor testing.

4. SUMMARY

All project objectives were met and all planned project activities were completed. The joint work between INL, KSU, and CEA produced an updated MPFD design with supporting materials, equipment, and electronics.

The testing and analysis completed in this project has provided the necessary 'proof-of-concept' data to demonstrate the viability of MPFDs for higher fluence irradiations. This new sensor offers ATR and HFIR users enhanced capabilities for real-time measurement of the thermal and fast flux and of temperature with a single, miniature detector. This section summarizes the objectives, accomplishments, importance, and future work of this NEET project.

4.1. Project Objectives

The project objectives were carefully chosen to develop a sensor that would significantly advance flux detection capabilities for irradiation tests in US MTRs. These objectives, which were all successfully completed within this three year project, include:

- Redesign MPFDs to ensure survivability in US MTR irradiations for measurement of fast flux, thermal flux, and temperature.
- Select and procure new high temperature compatible materials for MPFD construction.
- Design and construct a new amplifier compatible with the MPFD.
- Develop deposition tools and methods for MPFD electrode deposition.
- Develop a fissile material deposition system and methods for MPFD fissile deposition.
- Develop construction methods for the new geometry of the MPFD.
- Assemble a non-fissile prototype MPFD.
- Perform leak rate evaluations of non-fissile prototype MPFD.
- Perform high temperature evaluations of non-fissile prototype MPFDs.
- Refine and improve prototype MPFD design as needed to develop an enhanced MPFD design.
- Characterize fissile deposition system for enhanced MPFD design.
- Select and procure new materials for enhanced MPFD design.
- Refine construction methods for enhanced MPFD design.
- Assemble enhanced MPFD with fissile deposit.
- Perform laboratory and radiation evaluations of enhanced MPFD.
- Submit final project report and publications on MPFD development and evaluations.

4.2. Accomplishments

The development, testing and analysis completed in this project has provided the necessary 'proof-of-concept' data to demonstrate the viability of MPFDs for higher fluence irradiations. Highlights from our research accomplishments include:

- Redesigned MPFDs to fit inside a round geometry that is more suitable for installation in US MTR irradiation tests.
- Designed, built, and tested a new signal amplifier compatible with the MPFD.
- Designed and constructed specialized shadow masks in electron-beam evaporator for MPFD electrode deposition.
- Assembled electroplating system and characterized electroplating methods for MPFD fissile deposition.

- Developed unique construction methods to reduce the amount of welding and wiring connections for the round geometry MPFD.
- Assembled a non-fissile prototype MPFD to evaluate wiring connections and construction methods.
- Verified leak rate exceeded minimum acceptable requirements for MPFD prototypes.
- Successfully performed a high temperature evaluation of 1000 hours at 500 °C of non-fissile prototype MPFD.
- Developed a fissile material characterization system for enhanced MPFD design.
- Improved electroplating, welding and wire connections methods for enhanced MPFD design.
- Designed and assembled enhanced MPFD prototype using new construction methods with characterized fissile deposits.
- Performed neutron evaluations of enhanced MPFD prototype in-core at the KSU TRIGA reactor.

In summary, this project developed a new sensor that offers US MTR users enhanced capabilities for real-time measurement of the thermal and fast flux and of temperature with a single, miniature detector.

4.3. Importance of Superior Flux Detector

When implemented, these sensors will significantly advance flux detection capabilities for irradiation tests in US MTRs. 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 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 flux and temperature profiles in the reactor.

4.4. Future Work

The accomplishments of this project have attracted funding to support several DOE-NE projects for additional MPFD applications. This future work will build on current activities completed in this initial project, but the MPFD will be specifically tailored to survive higher temperature irradiations and transient testing irradiations.

As needed, the basic MPFD design will be upgraded with higher temperature materials and optimized for the recently awarded NEET proposal, *Enhanced Micro-Pocket Fission Detector (MPFD) for High Temperature Reactors*.[42] High temperature construction for this new project will focus on refining the construction methods for new materials needed to construct high temperature capable MPFDs. INL construction methods are not expected to deviate significantly from what has been outlined in Section 3.3.4.1. Special focus will be given to alternative materials, wire connections, tube-to-tube welds and end-cap weld integrities. KSU construction will focus on providing repeatable electrode and fissile material deposition procedures that can survive higher temperatures. In particular, the fissile material deposition and wire connections must survive to 800 °C. Continued characterization of the fissile material deposition will also be performed so that detector response can be accurately modeled.

In addition, the MPFD will be optimized and evaluated for transient reactor operation under the recently awarded Integrated Research Project (IRP) proposal, *Advanced Instrumentation for Transient Reactor Testing* that includes the MPFD for use as an in-core sensor along with a suite of other advanced instrumentation.[42] This effort will focus on developing a robust, fast response MPFD that will survive testing in a transient reactor. Higher temperature, long duration HTTL furnace testing and transient testing at the KSU TRIGA reactor is expected to be completed as part of this project. Results will provide valuable insight into the use of a MPFD at high power transients encountered during transient reactor operation.

The NGNP program has expressed interest in instrumenting the graphite in the top capsule in an upcoming fuel irradiation AGR-5/6/7 with an MPFD. This evaluation will further demonstrate the usefulness of the MPFD to simultaneously measure fast flux, thermal flux and temperature in an typical ATR long duration irradiation test.

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