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NEET Micro-Pocket Fission Detector- FY 2012 Status Report

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EXECUTIVE SUMMARY

A new project, that is a collaboration between the Idaho National Laboratory (INL), the Kansas State University (KSU), and the French Atomic Energy Agency, Commissariat à l'Énergie Atomique et aux Energies Alternatives, (CEA), has been initiated by the Nuclear Energy Enabling Technologies (NEET) program for developing and testing 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 Materials Test Reactors (MTRs). Ultimately, evaluations may lead to a more compact, more accurate, and longer lifetime flux sensor for critical mock-ups, 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. The real-time, high accuracy data from a MPFD will significantly enhance various development and qualification efforts and new multi-physics code validation efforts.
- 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.
- New high-fidelity reactor physics codes will need a small, accurate, multipurpose in-core sensor to validate the codes without perturbing the validation experiment, MPFDs fill this requirement.
- 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 to accurately visualize the flux and temperature profiles in the reactor.

This report summarizes the research progress for year 1 of this three year project. Highlights from our research accomplishments include:

- A joint collaboration was initiated between INL, KSU, and CEA. Note that CEA is participating at their own expense because of interest in this unique new sensor.
- An updated conceptual MPFD design was developed.
- Materials and tools to support the new design were procured.
- Candidate construction methods to support the new design are being evaluated at INL.
- Electrical contact and fissile material plating methods are being explored at KSU.
- Updated detector electronics have been designed, built and tested at KSU.
- A project meeting was held at KSU to discuss the roles and responsibilities between INL and KSU for development of the MPFDs. In addition KSU demonstrated the performance of their newly designed electronics.
- An initial detector evaluation plan has been developed by INL and KSU.

As documented in this report, FY 12 funding has allowed the project to meet all planned accomplishments for developing this unique new, compact, multipurpose sensor for irradiation testing programs.

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TABLES

ACRONYMS

ATR	Advanced Test Reactor
ATRC	Advanced Test Reactor Critical facility
BWR	Boiling Water Reactor
CEA	Commissariat à l'Énergie Atomique et aux Energies Alternatives
DOE	Department of Energy
DOE-NE	Office of Nuclear Energy in the Department of Energy
EDL	Electronics Design Laboratory
FCRD	Fuel Cycle Research and Development
FNDS	Fast Neutron Detection System
FY	Fiscal Year
HFIR	High-Flux Isotope Reactor
HPIL	Health Physics Instrument Laboratory
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
MWt	MegaWatt thermal
NEET	Nuclear Energy Enabling Technology
NGNP	Next Generation Nuclear Plant
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 Annual Status Report

1. INTRODUCTION

Materials Test Reactor (MTR) irradiation testing, which is often performed at harsh conditions (e.g., high flux, high temperature, etc.), 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 material reactions during irradiation.

The following report summarizes annual progress toward developing Micro-Pocket Fission Detectors (MPFDs) capable of measuring thermal neutron flux, fast neutron flux and temperature all 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, and operational performance of such sensors in advanced testing environments.

MPFDs utilize the same operational concept of previous fission chamber designs, but with a geometry that uses 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 are 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 will provide improved and additional operational information of interest to DOE-NE programs. Deployment of several sensors throughout irradiation tests will provide additional information that will supplement developmental efforts that utilize high-fidelity reactor physics codes.

1.2. Objectives of NEET Funded 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] The NEET ASI has funded this MPFD project because it addresses this cross-cutting need by developing, fabricating, and evaluating the performance of robust prototypes of compact multipurpose 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 are compact to minimize their impact on the irradiation test data. Specific details related to current requirements for thermal, fast, and temperature sensors requested by DOE-NE programs for fuels and material irradiations are provided 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 prototyic 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[4,13,15 through 17] 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 Ref. 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: radiation-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

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	Desired 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
maximum 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.

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 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[4,13,17] 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 materials 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 -	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 detector sensors in typical irradiations that are currently of interest to DOE-NE programs. 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 irradiation, the neutron flux, or the integral exposure, 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 2, 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 MegaWatt thermal (MWt) ATR and the 100 MWt High Flux Isotope Reactor (HFIR).

Table 3. Summary of advantages and disadvantages of typical flux sensors.[18 through 26]

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 Flux 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 which is based on the principle that different elements (and different isotopes of the same element) when placed in a neutron field will interact selectively with respect to the energy of the incident neutron. A flux wire or foil is simply a material of known composition and purity that is placed in a neutron field. When the interaction product is radioactive, the resulting induced activity can be measured and correlated to the integral incident neutron exposure[18]. As indicated in Table 3, this measurement and correlation can only be performed after the irradiation is complete, and the flux wire or foil is removed from the reactor.

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

Deployment simply requires 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 to protect them. 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 time between 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.

2.1.2. Self Powered Neutron Detectors

Self Powered Neutron Detectors (SPNDs) are a commonly used active method for monitoring local neutron flux. SPNDs are built using materials that become radioactive in a neutron field and produce a small current that is measured which is correlated to the neutron flux (Figure 2). 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 for the signal. 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[18]. 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 current between the emitter and collector is measured via external circuitry.

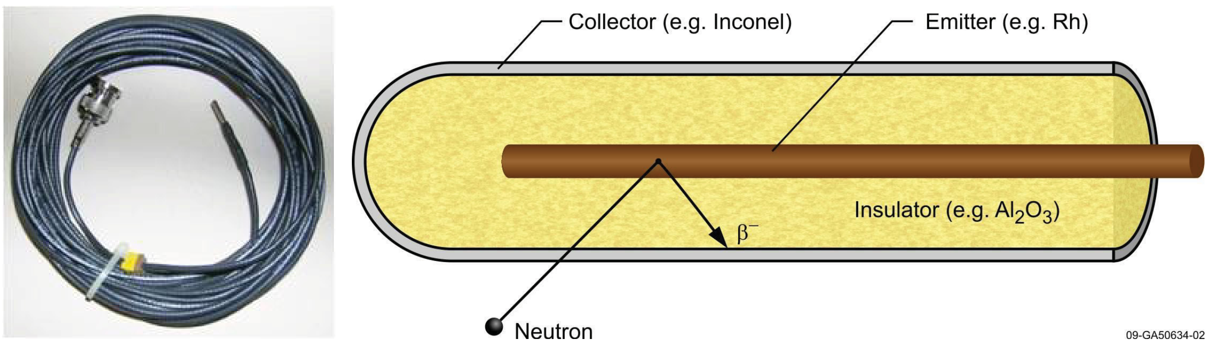

Figure 2. Representative Self-Powered Neutron Detector (SPND) and component sketch.

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 experimental location to outside the reactor vessel for final measurement, hence SPNDs can only be deployed in specific experimental locations in the reactor. The outer electrode serves as a boundary between the reactor coolant and the emitter and insulator. 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 are that it is self powered, it provides near real time neutron flux measurement and is a robust sensor. The disadvantages are that it has delays associated with its response, it requires a high neutron flux to generate a large current, it requires a calibration, it is generally only used for thermal neutrons, and it requires the signal leads to go from the experiment to outside the reactor vessel[18].

Table 4. Typical emitters for SPNDs.[18]

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

2.1.3. Fission Chambers

Fission chambers are another commonly used active method for monitoring local neutron flux. As shown in Figure 3, fission chambers are built using two electrodes, one of which has a fissile material deposit that emits fission fragments when exposed to 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 has a fill gas to aid in detector operation. 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 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.[18]

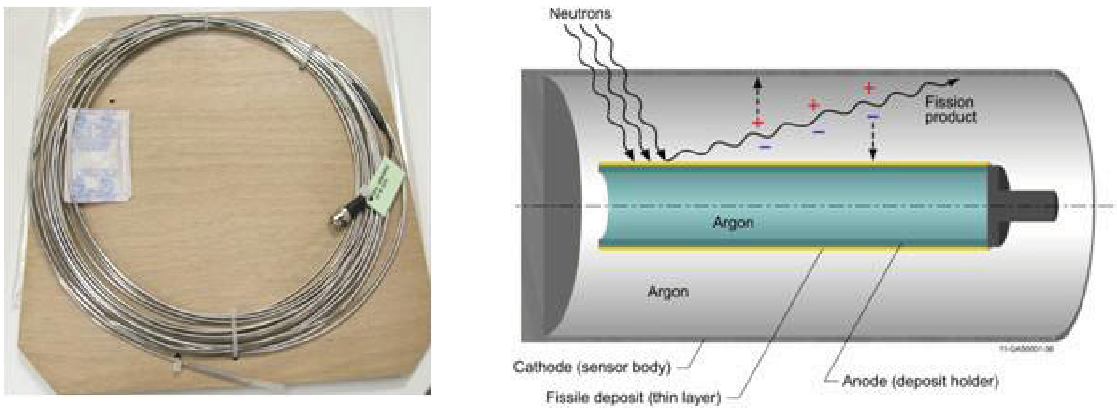

Figure 3. Representative fission chamber and component sketch.

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 experimental locations in the reactor and sometimes are deployed outside the reactor core. Like SPNDs, the outer electrode serves as a boundary between the reactor coolant and the inner materials. 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 are that it is real time, it can be used for high and low neutron fluxes, it can be designed for thermal and fast neutron flux measurements, and it is more accurate then SPNDs.[18] The disadvantages are that it is more delicate, it can require a larger space in the reactor, and it requires the signal leads to go from the experiment to outside the reactor vessel.

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 robust enough 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).[25,26] CEA-developed fission chambers are as small as 1.5mm dia. for sub-miniature fission chambers and 3mm dia. 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.[25,26] CEA has built these fission chambers to be sensitive to thermal and fast neutrons 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 high flux environments with high gamma ray rejection. Prior to the development of a new type of fission chamber CEA models the expected response with specially developed software.[25,26]

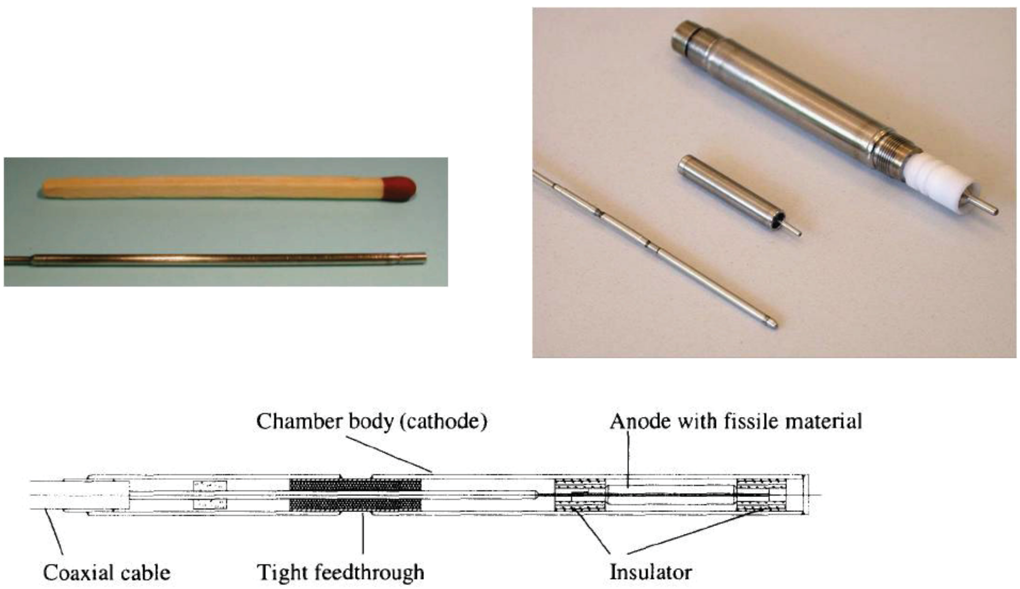

Figure 4. Representative CEA miniature fission chambers and component sketch.[25,26]

2.1.3.2. Micro-Pocket Fission Detectors

Within the last decade, efforts have been initiated by the Kansas State University (KSU) to develop Micro-Pocket Fission Detectors (MPFDs)[19 through 24] that have the potential to simultaneously detect thermal and fast flux along with temperature in a single miniature sensor. Initial evaluations to demonstrate the proof of concept have already been performed at the KSU TRIGA reactor. However, prior to deployment of these new MPFDs in a US MTR, it is recognized that a more robust sensor design is required. MPFDs for MTR applications are currently under development in this joint INL-KSU-CEA 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, but what sets the MPFD design apart from other fission chambers is that 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 then that of other types of background radiation interactions in the detector. Another benefit is that the small size allows them to have a faster response time, and thus, have the potential to achieve higher count rates then conventional fission chamber designs. The construction materials chosen for the MPFD are temperature and radiation resistant ceramics. All of these characteristics make MPFDs well-suited to survive the harsh conditions present in DOE-NE MTR experiments.[19 through 24]

3. ENHANCED MPFD INVESTIGATION

This section discusses the history of the KSU-designed MPFD, including the initial design and testing results. The scope for this NEET project is then presented with the status of the work completed in FY12.

3.1. Overall Plan and Schedule

This project consists of three tasks that will be completed, depending on funding availability, within three years. As indicated in Table 5, Task 1of this project will be devoted to enhancing the MPFD design to accommodate INL-developed HTIR-TCs and improve robustness for higher temperature, high flux, long-duration applications. Task 2 activities include selecting candidate materials and fabrication techniques will be considered and evaluated to develop an optimized design required for higher flux US MTR testing.Inital evaluations will also be performed. Results from these evaluations will be considered to develop, fabricate, and verify the performance of a final MPFD design. For Task 3, the 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. Reports, journal articles, and appropriate patent paperwork will be submitted accordingly.

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 reactors and commercial applications.

Table 5. MPFD development tasks.

MPFD Development tasks	Dates	
	Start	Finish
1.0 MPFD Design Enhancement and Evaluation		
MPFD redesign for HTIR-TC (KSU, INL, CEA)	3/1/2012	5/30/2012
Evaluate and enhance prototype design in HTTL (INL)	5/1/2012	12/31/2012
Develop detector evaluation plan (KSU, INL, CEA)	4/1/2012	12/31/2012
2.0 MPFD Construction/Evaluation		
Build prototype MPFDs (INL, KSU)	7/1/2012	5/31/2013
Initial evaluation of detectors at ATRC (INL, CEA, and KSU)	6/1/2012	6/30/2013
Results and recommendations documentation	7/1/2014	9/30/2014
3.0 MPFD Final Results		
Construct and Evaluate Final Design	8/30/2013	6/30/2014
Annual Report (INL, KSU)	9/30/2012	9/30/2014
Journal Articles and Patent Paperwork (INL, KSU)	9/30/2012	9/30/2014

3.2. Redesign of MPFD

Within the last decade, efforts were initiated by KSU to develop MPFDs. Initial evaluations to demonstrate the proof of concept have already been performed at the KSU TRIGA reactor. However, prior to deployment of these new MPFDs in a high pressure, high temperature and high flux environment, such as the ATR or the HFIR, it is recognized that a more robust sensor design should be developed. In this project, a new design will be developed and fabricated 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 with the expertise in miniature fission chamber design possessed by CEA.

3.2.1. KSU MPFD Design

Initial development of prototype MPFD designs began at KSU with large (~25 mm x 25 mm) alumina substrates with electrical contacts deposited on them (Figure 5).[19 through 24] The neutron reactive materials used for prototype evaluations where applied in a variety of methods, 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 reactors with successful results. However, it was recognized that the manufacturing process was not ideal to produce detectors for in-core applications.

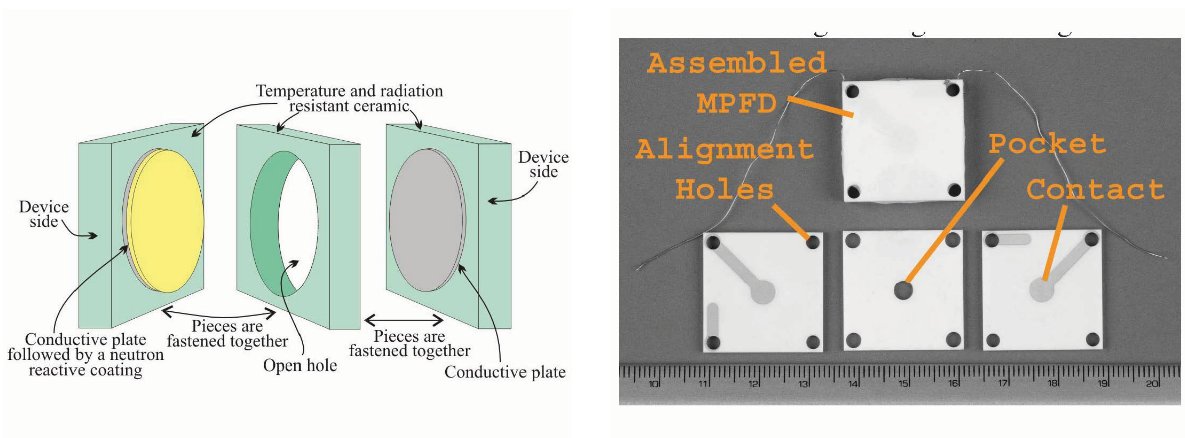

Figure 5. MPFD component sketch (left) and initial KSU prototype MPFD (right).[19 through 24]

Further refinements to the KSU MPFD design combined three chambers (one fast, one thermal, one background) and 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 (Figure 6).[19 through 24] Electroplating proved to be the most reliable method to deposit the neutron reactive materials, uranium for thermal neutron detection, and thorium 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 the final KSU design of MPFDs in their TRIGA reactor had limited success.[19 through 24] The testing demonstrated 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 detector output signal. The operational issues were a result of the water flooding into the probe tubes, wiring issues and electronics used with the MPFDs. The probe tubes were constructed

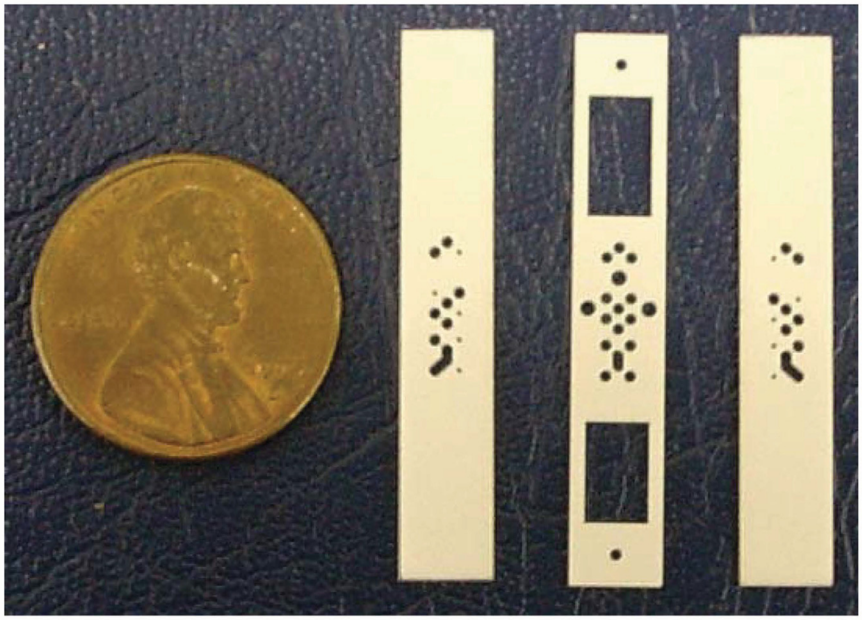

Figure 6. Final KSU MPFD design with thermal/fast fission chambers, background chamber and thermocouple.[19 through 24]

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 deployment in the reactor tank demonstrated that several tubes did not remain water tight.

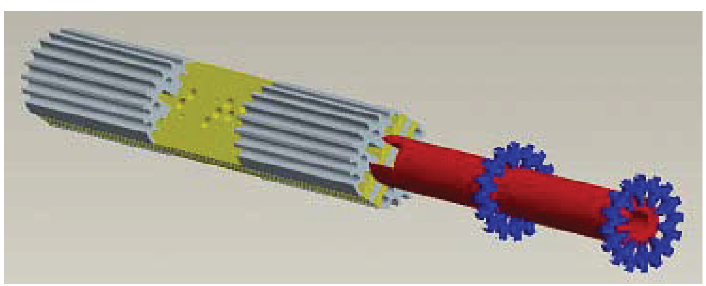

Figure 7. Wire guides for final design of KSU MPFDs.[19 through 24]

The wiring was required to exit the MPFD perpendicular to the substrate and immediately make a 90 degree bend to travel up inside a protective metal sheath. The wires were separated from each other using wire guides (Figure 7), 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 the detector unusable.

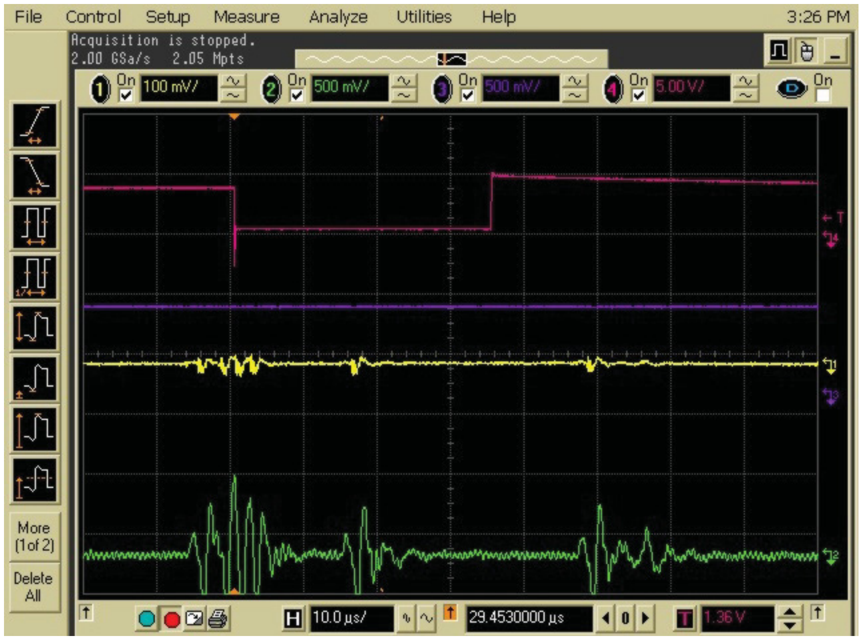

Figure 8. Noise pickup seen in the pre-shaped analog signal (yellow) and the post-shaped analog signal (green), large enough to generate a digital signal (red).

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 lead to multiple pulses (Figure 8) from a single detector that shared a power supply with other detectors.[19 through 24]

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. The KSU-designed MPFD did not meet these requirements so an enhanced version suitable for DOE-NE irradiation is under development 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 conceptual design is based on a round stackable geometry (Figure 9). 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, so water ingress is no longer a problem. Second, the round geometry will insulate the wires along their entire length from the reactor core to the data acquisition system, so the potential for wire-to-wire contact is eliminated. Third, the wire connections are made through the detector substrate, eliminating the 90 degree wire bend (Figure 10).

It was also determined that the third chamber used for detection of background radiation was unnecessary because it had been proven that 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 11) and does not require additional wire bonding as the KSU design did, thus improving thermocouple performance and

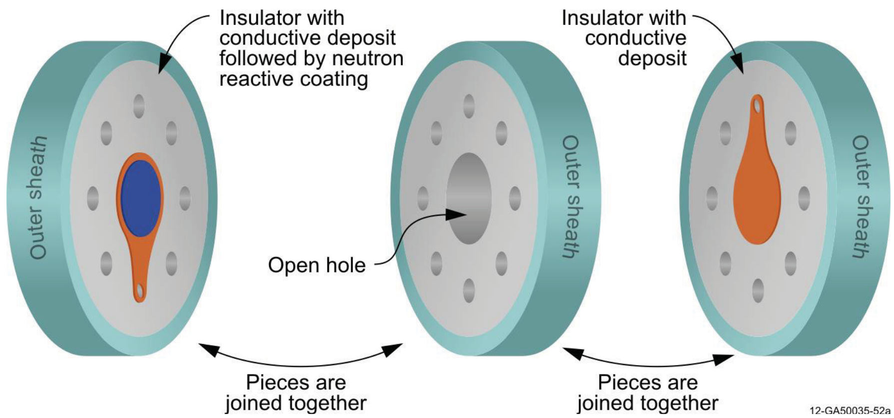

Figure 9. Round geometry MPFD conceptual design suitable for MTR irradiations.

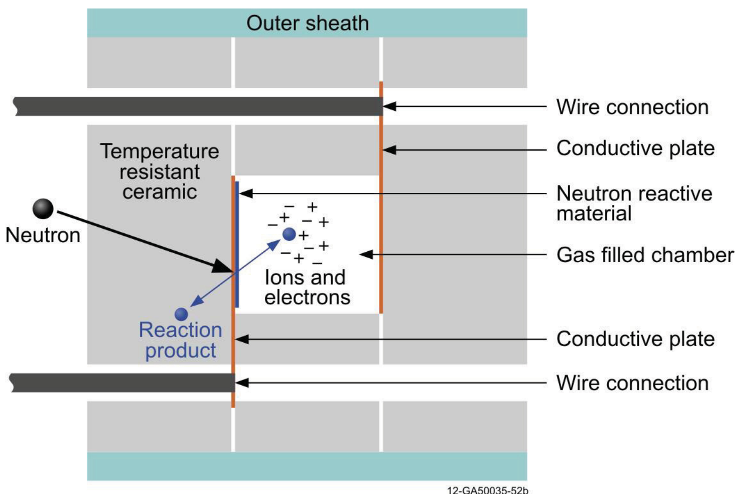

Figure 10. Component diagram of MPFD conceptual design showing wire locations.

robustness. It is recognized that details of the MPFD conceptual design given in this report will change as the design is further developed and tested..

3.3. KSU Research

KSU experience in producing the initial MPFD prototypes is beneficial for producing an updated version of MPFDs. KSU's tasks for year one include building, testing and optimizing detector amplifier boards for the new design as well as upgrading the fissile deposition system and purchasing the required raw materials for detector substrate fabrication. KSU has provided input for monthly reports documenting their progress.

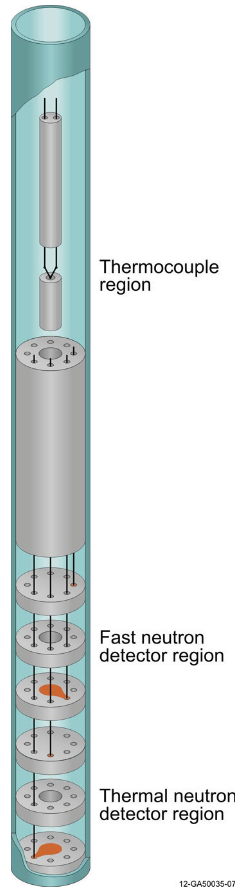

Figure 11. Enhanced MPFD conceptual assembly shown in tube with thermocouple above fission chambers.

3.3.1. KSU Facilities

KSU has several specialized laboratories to aid in the construction and testing of MPFDs.[27 through 29] 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, an ion mill, a vacuum annealing chamber, microscopes, ovens, grinders, an assortment of various 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 (Figure 12) that has been fully operational as of March 2012.[27]

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.[27]

The TRIGA Mark II research reactor at KSU supports education, research, training, and regional industries (Figure 13). The reactor is used extensively by the SMART Laboratory for testing of radiation senors and irradiation of materials. The KSU TRIGA has a 1.25MW 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 [28].

Figure 12. New 1000 square foot class 100 clean room facility at the KSU SMART Laboratory.[27]

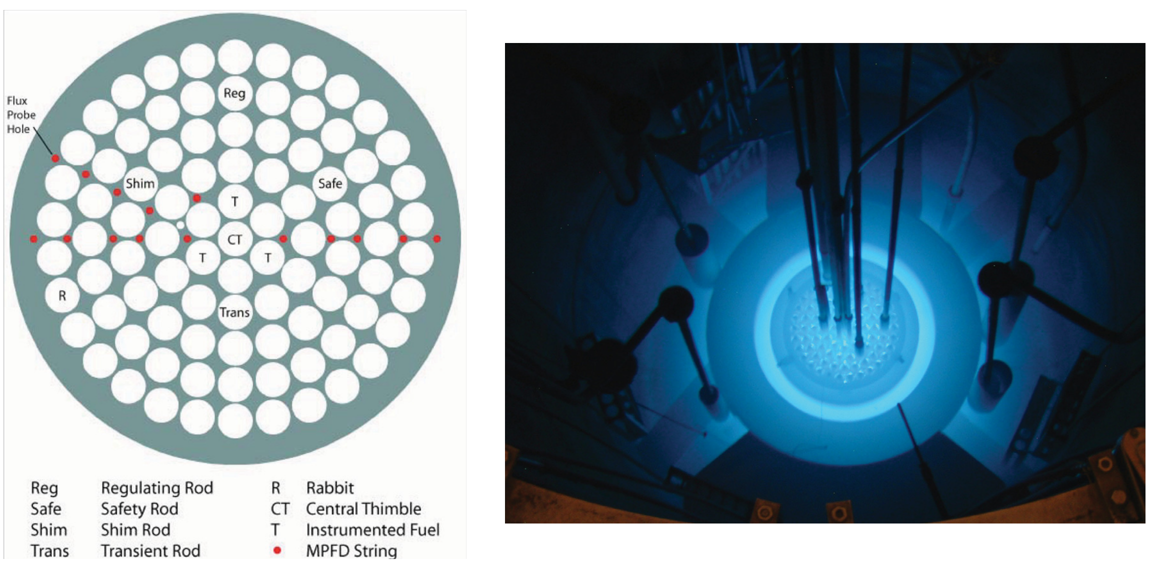

Figure 13. KSU reactor core diagram with MPFDs installed (left) and in operation (right).[28]

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.[29]

3.3.2. Electronics for Enhanced MPFD

Previous MPFD electronics 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 and redesigned with low-pass filters between each other. 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, all with 50 Ohm impedance. A prototype amplifier (Figure 14) has been assembled at the KSU EDL and tested successfully with an older MPFD installed in the KSU TRIGA reactor. It is expected that some component values on the amplifier board will 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.

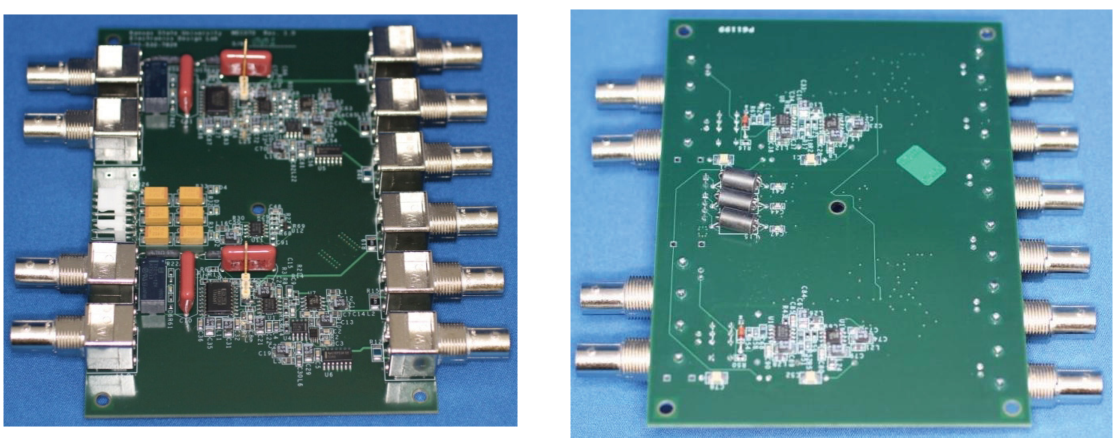

Figure 14. KSU designed amplifier board: front (left) and back (right).

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. 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 are being explored as possible contact materials.

Once the electrical contacts are in place, the second plating step will deposit the fissile material, Uranium-235 for thermal neutron detection and Thorium-232 for fast neutron detection. Two methods for fissile material deposition are under investigation. The first method is standard electroplating as was used with previous designs of MPFDs. The small substrates and thin depositions utilize a specialized nA-current 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.

Initial electrical contact depositions were successful, however it was discovered that many of the alumina substrates where cracked between the outer wiring holes (Figure 15) 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. Investigations to develop a robust electrical contact are ongoing with fissile material deposition to follow.

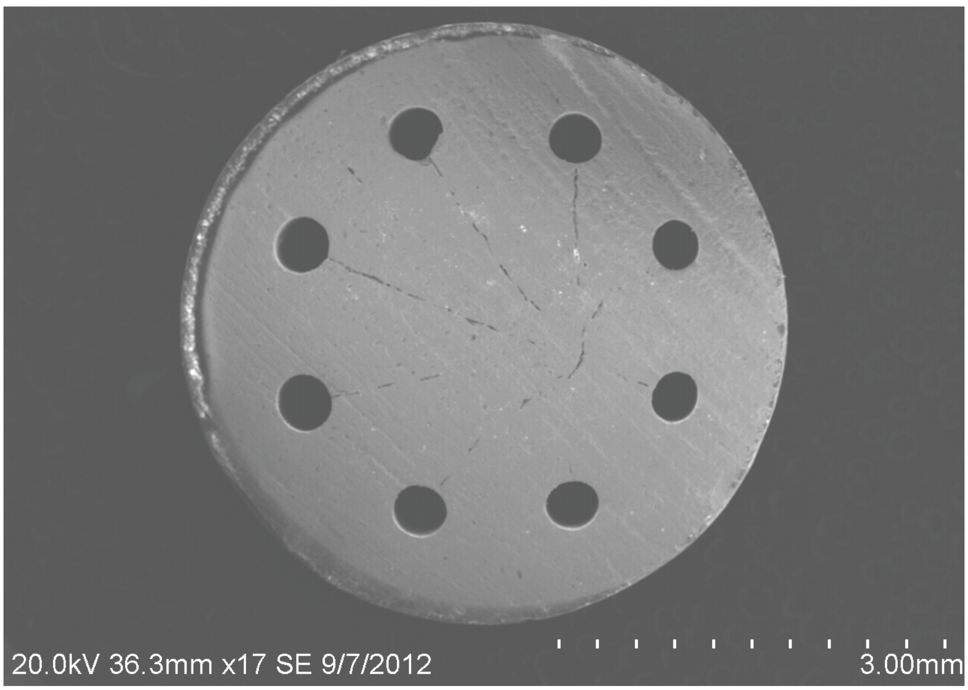

Figure 15. Alumina substrate showing cracks between outer wiring holes.

3.3.4. Project Meeting at KSU

As part of the FY12 activities, a project meeting was held at KSU on May 11 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. Analog and digital signals were obtained during TRIGA reactor operation at 100 kW, using one of the previous-generation detectors remaining in the reactor core. Two oscilloscope screen captures are shown in Figure 16. The yellow trace is the preamplifier output, and the green trace is the amplified output, and the red trace is the digital output. 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.

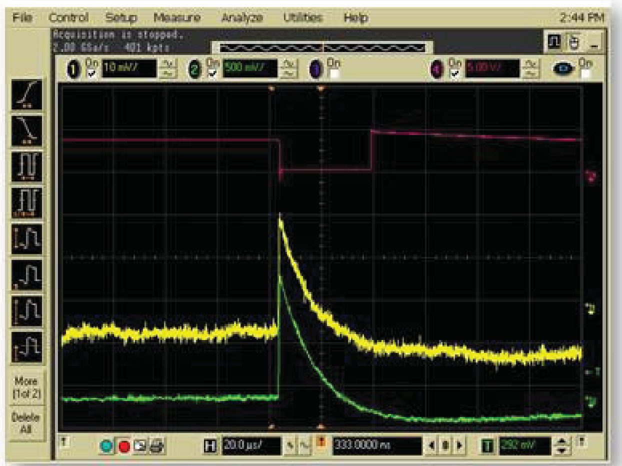

Figure 16. Oscilloscope traces from testing amplifier board in KSU TRIGA reactor.

3.4. 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 in completing this developmental effort.

3.4.1. INL Facilities

INL has several specialized facilities to constructed 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, and deformation in nuclear materials and test reactors. HTTL houses specialized equipment to support that 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, 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 NSUF, NGNP, AFC, and LWRS programs.[30]

In 2013, the HTTL will be relocated to a new state-of-the-art facility at INL, the Research Education Laboratory (REL), which is currently under construction. As indicated in Figure 17, the inclusion of a clean room and additional new state-of-the-art equipment will make the HTTL a world-class in-pile instrumentation development and testing facility.[31]

INL capabilities include two unique facilities for testing in neutron and gamma fields, the ATRC and the HPIL. A brief description of each of these facilities is provided below.

Figure 17. Research Education Laboratory (REL), currently under construction.[31]

The ATRC Facility core (Figure 21) is a near-identical nuclear mock-up of the ATR core and can provide valuable insight into the use of advances 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. In addition an ATR NSUF project has recently developed and installed Experiment Guide Tubes (EGTs) into N-16 dummy tube positions for comparison evaluations of real-time neutron flux detectors (Figure 21).[32]

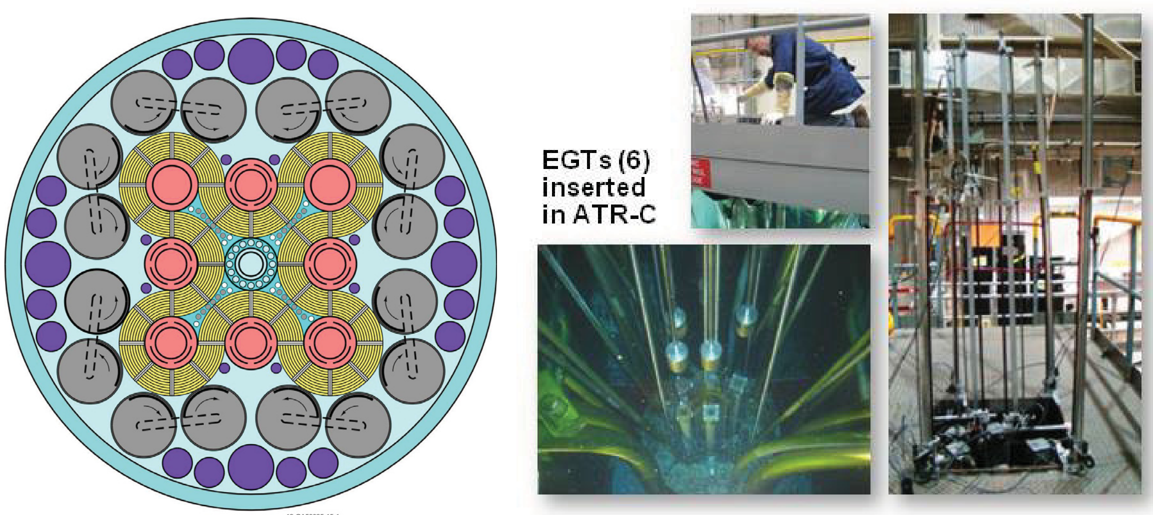

Figure 18. ATRC core (left) and Experiment Guide Tubes (EGTs) installed in the 6 N-16 positions (right).[32]

The Health Physics Instrument Laboratory (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 NIST traceable Cf-252 neutron source that provides a 10 rem/hr neutron dose rate (Figure 19). The second irradiator, the Gamma Beam Irradiator houses NIST traceable Cs-137 and Co-60 of 800 R/hr and 400 R/hr does rates, respectively. These irradiators will be useful to test the neutron sensitivity of the MPFDs and the gamma-ray insensitivity.[33]

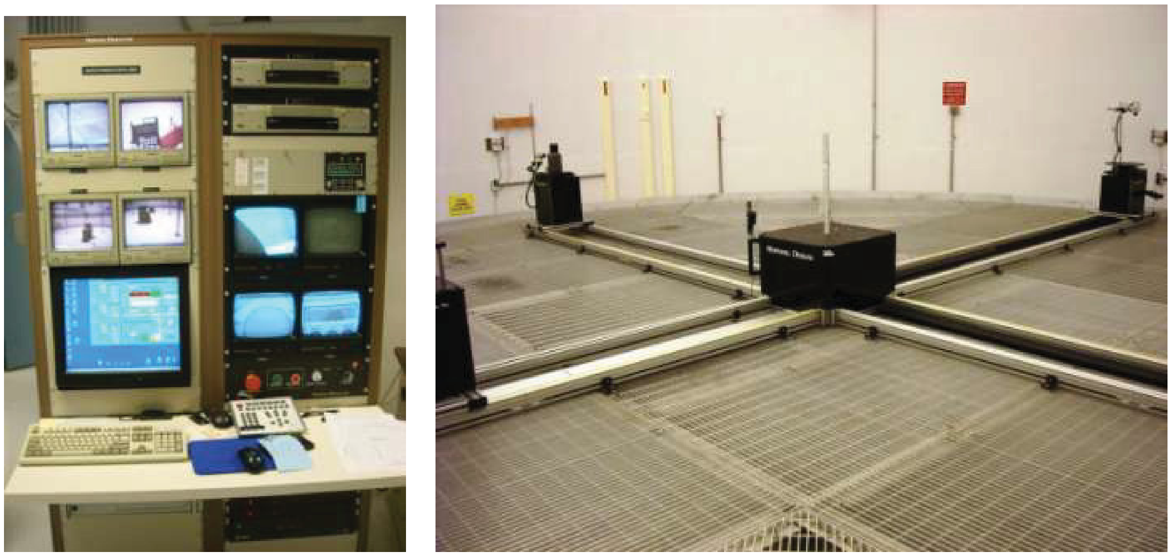

Figure 19. Health Physics Instrument Laboratory (HPIL) Low Scatter Facility equipment.[33]

3.4.2. Materials

During FY12, INL procured the materials needed for construction of the MPFD prototypes. Initial evaluations are focusing on building a robust prototype using less expensive, commercially-available materials. It is recognized that prior to deployment in a MTR experiment that other, more exotic, materials suitable for the harsh environment will 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 MPFD detector and extension cable (Figure 20) are specially manufactured hard-fired alumina substrates and crushable alumina insulators, respectively, all housed within leak-tight stainless steel tubing. Detailed specifications are given in Table 6. The hard-fired alumina substrates are the base for a "loose assembly construction" that have the fission chamber electrodes and fissile depositions, thermocouple junction and wire contacts all within a rigid stainless steel tube. The crushable alumina insulators serve as an insulator for the 6 wire extension cable with a stainless steel outer sheath. The extension assembly is drawn to the desired length and diameter to provide flexibility for exiting the reactor tank.

Table 6. Alumina parts for MPFD construction.

Description	Use
Crushable Al_2O_3 6 -hole insulator	Extension cable insulator
Hard-Fired Al_2O_3 9 hole insulator	Loose assembly insulator
Hard-Fired Al_2O_3 2 hole insulator	Thermocouple insulator
Hard-Fired Al_2O_3 1 hole insulator	Thermocouple junction insulator
Hard-Fired Al_2O_3 9 hole spacer	Fission chamber gas chamber
Hard-Fired Al_2O_3 8 hole substrate	Fission chamber electrode substrate

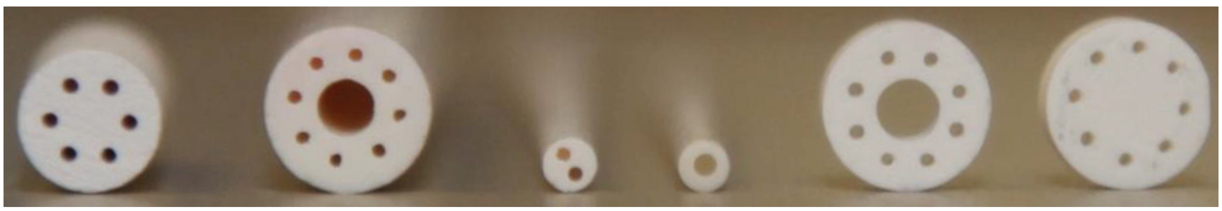

Figure 20. Alumina parts for enhanced MPFD construction.

3.4.3. Construction Methods

MPFD construction is under development using equipment and techniques perfected by INL's HTTL staff during development of other high temperature in-pile sensors.[1] The unique design of the MPFD requires several construction steps to be performed opposite of conventional in-pile sensor fabrications. It is also desirable to limit or eliminate wire splices during construction so a new method has been developed to draw the extension cable with open ends.

After the extension cable is constructed, the active region of the detector is assembled on the end using loose assembly construction methods. The parts are slid over the wires and oriented as shown in the exploded view in Figure 25. The thermocouple junction is made using standard HTTL methods, and the other wire connections are made using a high temperature conductive epoxy. After the parts are assembled, it is inserted into the outer sheath, and welded together. 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.

3.4.4. 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 7. High temperature evaluations are performed in HTTL furnaces (Figure 22) and evaluated by device response in the case of the thermocouple performance or by observation using X-rays or resistivity measurements for

Figure 21. Laser welder for assembling MPFDs.[1]

the wiring connections. The weld integrity is evaluated by using the HTTL helium leak testing equipment to verify the assembly exceeds the requirement for the ASTM leak rate of sheathed thermocouples.[1]

Table 7. MPFD Evaluation schedule.

Evaluation Type	Comments	Dates	
		Start	Finish
Leak Rate	Meet or exceed ASTM standard	9/1/2012	11/1/2012
High Temperature 1	Test limits of materials and construction methods with non-fissile samples	9/1/2012	3/1/2013
Gamma Response (HPIL)	Verify gamma insensitivity	3/1/2013	4/1/2013
Neutron Response (HPIL)	Verify neutron response	3/1/2013	4/1/2013
High Temperature 2	Test temperature limits with fissile samples	4/1/2013	6/1/2013
Reactor Testing (ATRC)	Low power in-core testing	10/1/2013	12/31/2013
Reactor Testing (TRIGA)	Transient testing (reactor pulse)	12/31/2013	2/1/2014

Figure 22. Tube furnaces for high temperature evaluation.[1]

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.

3.5. Summary for FY12 Work

Initial work to develop an enhanced MPFD for MTR irradiations is underway. The joint work between INL and KSU has produced an updated design with supporting materials, equipment, and electronics. KSU efforts have focused on updating their 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 to 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. In addition, initial evaluations are underway to test the high temperature robustness and leak-tightness of the new construction methods.

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 that will lead to this goal.

During FY13, 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. More complex evaluations will utilize the INL's ATRC using specialized fixturing installed at the ATRC. This fixturing is used to characterize and cross-calibrate a wide range of flux detectors, including SPNDs, CEA-developed fission chambers, and specially-developed BTB fission chambers. CEA will model the detector response and compare to actual results. This data will be used to develop a smaller, improved design of MPFD that will be constructed and evaluated in FY14.

Table 8. MPFD FY13/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. Construction

Construction of a MPFD prototype is expected to be completed in the first half of FY13. 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 3.4.3. Special focus will be given to alternative wire connections and tube-to-tube welds and end-cap integrities.

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

4.2. Future Evaluations

Testing will begin in the second half of FY13 and continue into FY14, pending funding availability. The testing will demonstrate that the MPFDs can survive the high temperatures and respond as expected to neutron irradiations. Comparison will be made between other thermocouples and real-time flux sensors.

4.2.1. HTTL

Initial 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 complete, high temperature evaluations will be completed using the available high temperature furnaces at the HTTL. The epoxy wire connections will be tested by observation using X-rays 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 follow-on 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 23) 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 response testing is complete, the MPFD will be moved back to the HTTL for a serious of high temperature evaluations in the tube furnaces (Figure 23) to test 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, 33]

Figure 23. Tube furnaces (left) and neutron irradiator (right) for MPFD response testing.[1, 33]

4.2.3. Reactor

The next step in evaluations will characterize the detector response in-core, pending funding availability. 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 completed Experiment Guide Tubes (EGTs) that place the MPFDs in several different locations and elevations throughout the ATRC core (Figure 24). The data will be compared to integral flux measurements from previously completed reactor flux profile characterizations. It is anticipated that the data from the MPFDs can be used to reconstruct a 3-D flux map of the ATRC core. In addition, evaluations will be performed in the North West Large In-Pile Tube (NW LIPT) using specialized fixturing (Figure 30) to cross-calibration the MPFDs with SPNDs, CEA-developed fission chambers and specially developed Back-to-Back (BTB) fission chambers, pending funding availability.[32]

Should ATRC availability limit in-core testing at INL, the KSU TRIGA reactor (Figure 25) has the ability to perform in-core testing of the MPFDs in the central thimble irradiation housing. The measurement campaign would 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.[28]

Figure 24. Equipment for reactor testing in the ATRC: NW LIPT chamber fixturing (left) and Experiment Guide Tubes (left).[32]

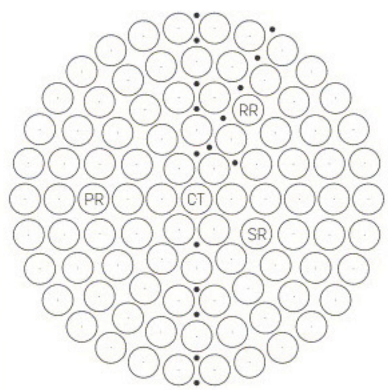

Figure 25. Potential testing in the central thimble (CT) of the KSU TRIGA reactor.[28]

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 40+ years 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 will be required to the geometry definitions in the CEA computer codes.[25, 26]

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

One of the many DOE-NE programs evaluating new fuels and materials requesting an enhanced flux/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

A research program has been initiated by the NEET 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 in typical high performance MTR irradiation tests.
- New high-fidelity reactor physics codes will need a small, accurate, multipurpose in-core sensor to validate the codes without perturbing the validation experiment; MPFDs fill this requirement.
- 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 simultaneously deployed; obtaining data required to visualize the reactor flux and temperature profiles.

As part of this effort to develop a new sensor a joint collaboration has been initiated between INL, KSU, and CEA to produce MPFDs capable of surviving the harsh environment of DOE-NE MTR irradiations. Highlights for FY12 efforts include:

- An updated design of MPFD has been developed. Previous INL HTTL experience developing robust in-pile sensors for high flux and high temperatures applications was utilized to redesign the MPFDs.
- Materials and tools to support the new design have been procured. Stainless steel tubes and custom alumina substrates and insulators have arrived in support of new construction methods.
- Construction methods to support the new design have been initiated at INL's HTTL. Modified methods for cable construction and final assembly are under evaluation.
- Two electrical contact and fissile material plating methods are being explored at KSU to determine which method will provide the most 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 design of MPFD fission chamber 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 initiated between INL and KSU. The detector evaluation plan includes a combination of 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 1 of a 3 year project. Initial work is underway with future work scheduled to finish prototype development and evaluate the MPFD in a variety of testing conditions, pending funding availability. Once NEET program evaluations are completed, the final MPFD will be deployed in MTR irradiations, enabling DOE-NE programs evaluating the performance of candidate new fuels and materials to better characterize irradiation test conditions.

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