Fabrication and Testing of a Modular Micro-Pocket Fission Detector Instrumentation System for Test Nuclear Reactors

Michael A. Reichenberger, *Member, IEEE*, Daniel M. Nichols, *Member, IEEE*, Sarah R. Stevenson, Tanner M. Swope, Caden W. Hilger, Jeremy A. Roberts, Troy C. Unruh, and Douglas S. McGregor, *Member, IEEE*

***Abstract*— Advancements in nuclear reactor core modeling and computational capability have encouraged further development of in-core neutron sensors. Measurement of the neutron-flux distribution within the reactor core provides a more complete understanding of the operating conditions in the reactor than typical ex-core sensors. Micro-Pocket Fission Detectors have been developed and tested previously but have been limited to single-node operation and have utilized highly specialized designs. The development of a widely deployable, multi-node Micro-Pocket Fission Detector assembly will enhance nuclear research capabilities. A modular, four-node Micro-Pocket Fission Detector array was designed, fabricated, and tested at Kansas State University. The array was constructed from materials that do not significantly perturb the neutron flux in the reactor core. All four sensor nodes were equally spaced axially in the array to span the fuel-region of the reactor core. The array was filled with neon gas, serving as an ionization medium in the small cavities of the Micro-Pocket Fission Detectors. The modular design of the instrument facilitates the testing and deployment of numerous sensor arrays. The unified design drastically improved device ruggedness and simplified construction from previous designs. Five 8-mm penetrations in the upper grid plate of the Kansas State University TRIGA Mk. II research nuclear reactor were utilized to deploy the array between fuel elements in the core. The Micro-Pocket Fission Detector array was coupled to an electronic support system which has been specially developed to support pulse-mode operation. The Micro-Pocket Fission Detector array composed of four sensors was used to monitor local neutron flux at a constant reactor power of 100 kWth at different axial locations simultaneously. The array was positioned at five different radial locations within the core to emulate the deployment of multiple arrays and develop a 2-dimensional measurement of neutron flux in the reactor core.**

***Index Terms*— In-Core Instrumentation, MPFD, Micro-Pocket Fission Detector, Reactor Instrumentation, TRIGA.**

I. Introduction

Research nuclear reactors commonly utilize neutron-sensitive radiation detectors located external to the reactor core to monitor reactor power [1, 2]. Advancements in nuclear reactor core modeling and computational capability have encouraged further development of in-core neutron sensors. Measurement of the neutron-flux distribution within the reactor core provides a more complete understanding of the operating conditions in the reactor than ex-core sensors. Solutions presently exist to monitor the neutron fluence experienced during reactor experiments, however information regarding minute variations in flux due to local fuel burnup, control rod motion, and experimental effects are often not captured.

Small, accurate, and robust neutron-flux sensors are an important development for the enhancement of advanced nuclear fuel testing [3]. The environment within a nuclear reactor core is not ideal for the operation of many types of radiation detectors. The high-radiation environment, including intense fields of neutrons, gamma-rays, and beta-particles quickly overwhelm most conventional radiation detectors. Even specially developed neutron detectors (such as Self-Powered Neutron Detectors (SPNDs) and sub-miniature neutron detectors) must make corrections to the measured data to compensate for the high count rate and significant burnup induced by neutron-fluxes often on the order of 10^{14} n cm^{-2} s^{-1} [2, 4, 5]. Conventional in-core sensors often utilize neutron-sensitive coatings with large neutron-absorption cross sections, whose presence can also decrease the local neutron flux near the sensor.

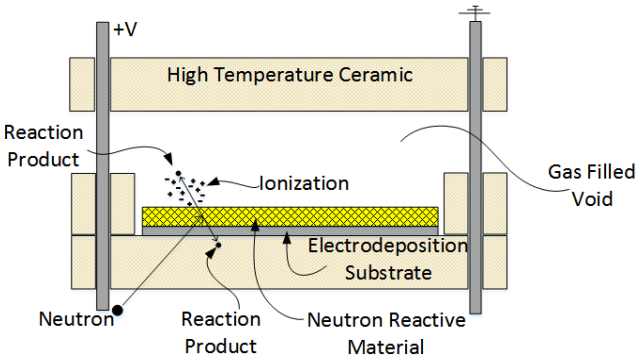

Fig. 1. Neutron-induced fission in the neutron reactive coating of an MPFD produces fission fragments which ionize the gas-filled pocket. The small size reduces ionization from non-fission fragments such as gamma-rays and beta-particles.

This work, presented at the International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications, June 19-23, 2017, was supported in part by the U.S. Department of Energy under Grants DE-NE0008408 and NE0008305.

M. A. Reichenberger, D. M. Nichols, S. R. Stevenson, T. M. Swope, C. W. Hilger, J. A. Roberts, and D. S. McGregor are part of the S.M.A.R.T. Laboratory at Kansas State University, Manhattan, KS 66502 USA (e-mail: mar89@ksu.edu).

T. C. Unruh is part of the HTTL at the Idaho National Laboratory, Idaho Falls, ID 83415 (e-mail: troy.unruh@inl.gov).

Micro-Pocket Fission Detectors (MPFDs), illustrated in Fig. 1, have been constructed and tested previously [6, 7]. MPFDs exhibit exceptional gamma-ray discrimination due to their small chamber size and have successfully operated in neutron fluxes as high as 10^{15} n cm^{-2} s^{-1} [7]. The one-of-a-kind instruments developed for previous experiments have successfully demonstrated the ability of MPFDs to measure neutron flux in numerous test reactor conditions [7]. In-core testing at the Kansas State University TRIGA Mk. II research reactor included steady-state reactor operations from 10 kWth to 700 kWth reactor power, positive power transients with periods of 10 sec., 20 sec., and 40 sec., negative power transients from -$0.10 to -$0.80 [7].

Future deployment of MPFDs at numerous nuclear reactor research facilities will benefit from the development of a more standardized MPFD instrument package. In addition to the development of an integrated electronics package (which includes high-voltage supply, pre-amplification, shaping, and discrimination), a modular sensor array has been developed. The use of this sensor array will enable the deployment of a network of MPFDs into the core of various research nuclear reactors. The data provided by an array of MPFDs deployed through the core of a research reactor can then be used to enhance material experimentation and certification, or to benchmark nuclear reactor simulations.

II. Sensor Fabrication

The modular MPFD array utilized a fully encapsulated design which included an electronic plug and a vacuum/fill assembly for ionization gas. The MPFD sensors were located near the end of the array which was encapsulated by an approximately 183-cm long, 0.794-cm diameter stainless steel tube. The sensors were equally spaced within the bottom portion of the tube as shown in Fig. 2. The spacing within the MPFD array was designed to yield equal spacing of sensors throughout the fuel region of the TRIGA reactor core, as illustrated in Fig. 3.

Each MPFD node was fabricated using polished alumina disks separated by machined alumina spacers. A 1.5-mm diameter electrode was evaporated onto the bottom disk and electrodeposited with natural uranium [8]. X-ray fluorescence was used to confirm the presence of uranium on each sample. Then, alpha spectrometry was used to measure the activity of each sample and to determine the mass of uranium which was deposited, summarized in Table 1.

TABLE I
URANIUM MASS FOR EACH MPFD NODE

MPFD Node	Uranium Mass (μg)
0 (bottom of array)	0.619 ± 0.014
1	0.548 ± 0.025
2	0.630 ± 0.026
3 (top of array)	0.533 ± 0.023

The array was assembled by insulating 8 30-AWG alumel wires with silica insulation between the electrical plug and the sensor region. Each MPFD sensor required a single anode and cathode wire. The MPFDs were indexed such that each ionization chamber was exposed to one anode wire and one cathode wire on opposing sides of the sensor as illustrated in Fig. 1. Therefore, the sensors did not share any common anodes nor cathodes. The assembly was inserted into the encapsulation tube and heated to approximately 100 C during three 1-hr vacuum purges each followed by a backfill with ultra-high

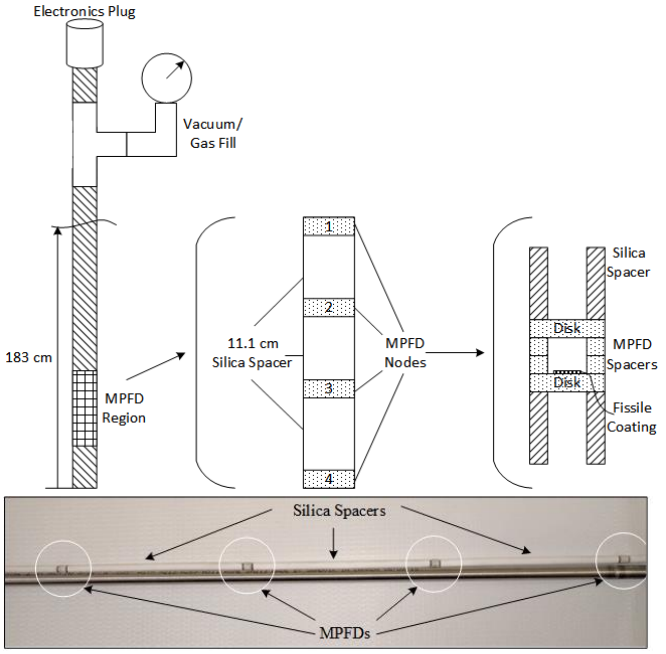

Fig. 2. The encapsulated MPFD array included an electronic feedthrough and vacuum/fill assembly. Silica spacers were used to separate four MPFD nodes at the bottom of the array by 11.1-cm, together spanning the full length of fuel in the TRIGA reactor core.

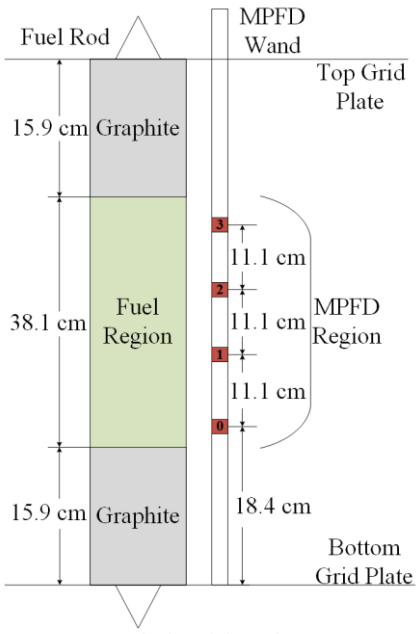

Fig. 3. The MPFD array was deployed through 8-mm penetrations in the fuel grid-plate. The distribution of sensors was centered on the same vertical axis as the reactor fuel in the TRIGA reactor core.

purity neon gas to 30 psig. Neon was of particular interest as an ionization gas because of its higher charge-carrier mobility and average ionization energy compared to argon [9]. Although not necessary for testing at the KSU TRIGA Mk. II research nuclear reactor, neon could be a useful alternative for higher flux applications.

III. Experimental Procedure

The MPFD array was first deployed into the grid-plate penetration between the B and C fuel rings at the KSU TRIGA Mk. II research nuclear reactor. The plug at the top of the MPFD array was connected to a 7.62 meter multi-conductor cable with additional tinned copper overbraid to reduce RF pickup from other electrical sources in the reactor pool. The MPFD-4 electronic support system was used to process the signal from all four MPFD sensors simultaneously and to interface with a PC. Custom LabView® software was developed to monitor the MPFD signals and to log the count rate for each channel in real-time. A 200 V bias was applied across each of the MPFD nodes and a 0.25 µs shaping time with a gain of 12 was used to shape the MPFD signals. Finally, a discrimination threshold of 800 mV was set to discriminate noise. The internal pulsar, designed to emulate a typical neutron-induced signal, registered a peak amplitude of 1.6 V.

The reactor was then brought to 1 kWth with cooling circulation pumps engaged and neutron-induced pulses were observed on all 4 MPFD channels. Then reactor power was increased to 100 kWth and sustained for at least 10 minutes during which time the count rate from the MPFDs were logged every 250 ms. The reactor was shut down and the MPFD array was moved to the C-ring flux port.

A single 10-minute measurement was conducted at 100 kWth

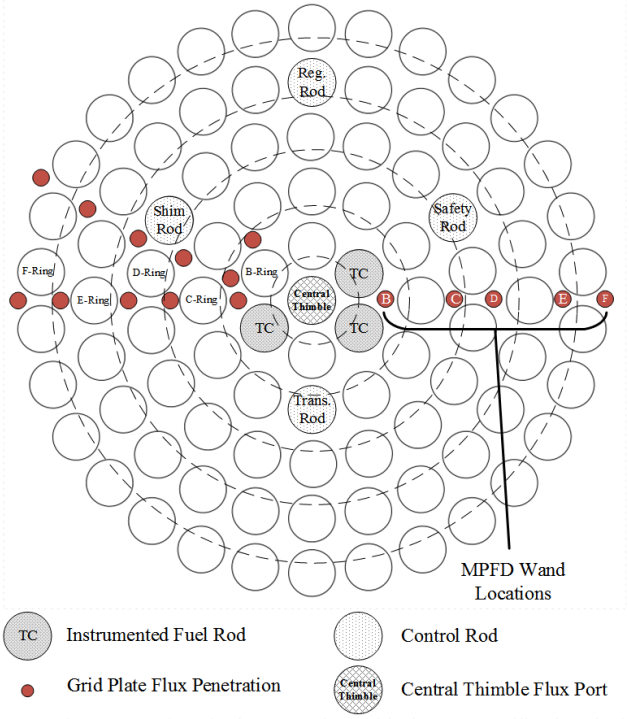

Fig. 4. Flux penetrations in the upper fuel grid-plate were utilized to deploy the MPFD array at three different radial locations in the TRIGA reactor core, outside the B-ring, D-ring, and F-ring of fuel.

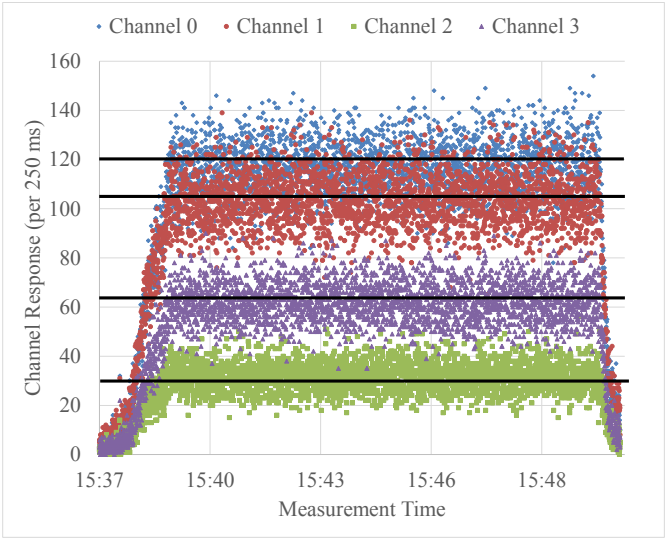

Fig. 5. Each of the four MPFDs were monitored in real-time as the reactor power was increased to 100 kWth and maintained for 10 minutes. The sensor response increased with reactor power and was stable at constant power.

reactor power for each of the 5 flux ports depicted in Fig. 4. Detector response was logged every 250 ms during each operation and integrated to determine an average count rate over the entire measurement period.

IV. Experimental Results

The real-time MPFD response rate was logged in 250 ms intervals, shown in Fig. 5. Data logging was initiated as reactor power was increasing and continued until after the 10 minute measurement interval when the reactor was shut down. An increasing count rate was observed as the reactor power approached 100 kWth. The sensor response remained stable throughout the duration of the measurement until the reactor was shut down. The real-time data was integrated over the 10-minute measurement to determine the average count rate for each sensor, summarized in Table II, and highlighted in Fig. 5. The average count rate for each channel was also divided by the mass of uranium deposited within each node to determine the mass-normalized count rate, summarized in Table II.

The average count rate for each channel was determined for each of five flux penetrations in the upper fuel grid plate of the KSU TRIGA Mk. II research nuclear reactor. The detector response for each MPFD decreased as the array was moved radially outward, shown in Fig. 6. Although reactor cooling was on for the duration of the measurements the in-core moderator temperature increased from 33 C to 36 C in the B-ring between the first and final measurement.

TABLE II
Average MPFD Count Rate at 100 kWth in the B-Ring of the KSU TRIGA Mk. II Research Nuclear Reactor
(Averaged over 10-Minute Measurement)

MPFD Node	Raw Count Rate (CPS)	Mass Normalized Count Rate (CPS/µg)
0 (bottom of array)	482 ± 0.9	779 ± 17.7
1	429 ± 0.9	782 ± 35.7
2	130 ± 0.5	207 ± 8.6
3 (top of array)	257 ± 0.7	483 ± 20.9

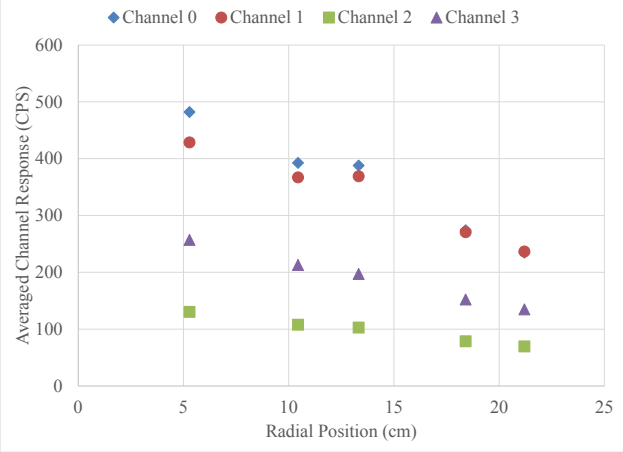

Fig. 6. The sensor response for each MPFD in the array decreased as the array was moved radially outward from the center of the reactor core.

V. Conclusions

Each of the four MPFDs responded to changes in the neutron flux in the reactor core and maintained a stable response with constant reactor power. Previous testing of MPFDs has only been conducted using ultra-high purity argon as an ionization gas. The successful use of neon as an ionizing gas for MPFDs has been demonstrated. The response of each sensor also decreased as the array was moved radially outward. However, the mass-normalized response for each sensor did not produce the expected results.

Although a different raw count rate was expected for each sensor due to the axial distribution of MPFDs in the reactor and the different amount of fissile material present in each detector, the mass normalized response was expected to be very similar for opposing nodes. Nodes 0 and 3, and nodes 1 and 2 were positioned within the array to be equidistant from the central axis of the fuel region in the core. Therefore it was expected that the mass-normalized response for the opposing sensors would reflect the relative symmetry of the neutron flux within the core. Re-assessment of the fissile mass present in each MPFD node will help to determine the source of error in determining the mass-normalized sensor response.

Work continues to develop a method of calibrating MPFDs in order to extract neutron flux magnitude from the count rate reported by the sensors. Improvements to the fabrication process have made possible the assembly and deployment of multiple MPFD arrays. Future studies will expand on the results of this preliminary work, measuring the neutron flux in the reactor core with axial and radial spacing simultaneously.

Acknowledgments

This paper presents work supported by the US Department of Energy Office of Nuclear Energy Contracts DE-NE0008408 and NE 0008305. MPFDs were fabricated at the Kansas State University Semiconductor Materials and Radiological Technologies laboratory (Manhattan, KS). Sensor testing was conducted at the Kansas State University TRIGA Mk. II research nuclear reactor facility (Manhattan, KS).

References

[1] J. J. Duderstadt and L. J. Hamilton, Nuclear Reactor Analysis, Wiley & Sons, Inc., 1976.

[2] G. F. Knoll, Radiation Detection and Measurement, Hoboken, N.J.: John Wiley, 2010.

[3] T. Unruh, J. Rempe, D. McGregor, P. Ugorowski and M. Reichenberger, "NEET Micro-Pocket Fission Detector - FY 2013 Status Report," Idaho national Laboratory, Idaho Falls, ID, 2013.

[4] G. Imel, "Performance of Hafnium and Gadolinium Self Powered Neutron Detectors in the TREAT Reactor," *Nucl. Inst. and Meth. Res. B,* no. 111, pp. 325-336, 1996.

[5] C. Blandin, S. Breaud, L. Vermeeren, M. Webber, "Development of New Sub-Miniature Fission Chambers: Modeling and Experimental Tests," *Prog. in Nucl. Energy,* vol. 43, pp. 349-355, 2003.

[6] D. S. McGregor, M. F. Ohmes, R. E. Ortiz, A. S. M. S. Ahmed, J. K. Shultis, "Micro-Pocket Fission Detectors (MPFD) for In-Core Neutron Flux Monitoring," *Nucl. Inst. and Meth.,* no. A554, pp. 494 - 499, 2005.

[7] M. A. Reichenberger, T. D. F. George, R. G. Fronk, P. B. Ugorowski, J. A. Geuther, J. A. Roberts, T. Ito, H. B. Vo-Le, S. R. Stevenson, D. M. Nichols, D. S. McGregor, "Advances in the Development and Testing of Micro-Pocket Fission Detectors (MPFDs)," in *International Conference on Research Reactors: Safe Management and Effective Utilization*, Vienna, Austria, Nov. 16-20, 2015.

[8] M. Reichenberger, T. Ito, P. B. Ugorowski, B. W. Montag, S. R. Stevenson, D. M. Nichols and D. S. McGregor, "Electrodeposition of Uranium and Thorium onto Small Platinum Electrodes," *Nucl. Instrum. and Meth.,* no. A812, pp. 12-16, 2016.

[9] N. Tsoulfanidis, "Measurement and Detection of Radiation," Taylor and Francis, Washington, 1995.