

# Recent Results and Fabrication of Micro-Pocket Fission Detectors (MPFD)

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## ABSTRACT

Micro-Pocket Fission Detectors (MPFD) have been developed as real-time in-core neutron flux monitors. Tests have demonstrated linear operation with neutron flux varying through six orders of magnitude while surviving neutron fluences greater than  $10^{16}$  n/cm<sup>2</sup>. Their design is naturally background insensitive with high signal to noise pulses. Built from alumina ceramics, these devices are relatively simple to build and are inexpensive. They have been designed for fabrication into large arrays to facilitate 3-D mapping of a reactor core.

Keywords: Neutron detector, fission chamber, gas-filled detector, MPFD, power density mapping

## 1. INTRODUCTION

Reliable, real-time in-core neutron flux monitors are needed to map reactor transients and to increase reactor safety. Micro-Pocket Fission Detectors (MPFD) have been developed by incorporating the beneficial properties of existing detector designs for in-core neutron flux monitors. Fission and ionization chambers have the advantage of producing large signals with low background interference. Their main disadvantages are large size, high voltage requirements, and expense. Coated semiconductor detectors are inexpensive, have low voltage requirements, and can be miniaturized. However, they cannot survive the extreme environments found in a reactor core. Self-powered neutron detectors (SPND) have the advantages of no voltage requirement and small size but cannot follow reactor transients due to their slow response time. In addition, they are only useful in high neutron fluxes [1,2].

MPFDs have taken the gamma insensitivity and high signal to noise ratio of the fission and ionization chambers, the low voltage requirements and small size of SPND and semiconductor detectors, and the fabrication methods of semiconductor detectors to form a near ideal miniature real-time in-core neutron flux monitor. Variations of these detectors allow for the separation of thermal and fast neutron fluxes with the subtraction of background noise. In addition, a large array of these detectors is being deployed throughout the Kansas State University TRIGA Mark-II Nuclear Reactor in order to produce power density maps of the core during operation.

## 2. MPFD FABRICATION

MPFDs have been designed to take advantage of the positive design aspects of existing detection technologies. These technologies have shaped the basic operations of the detectors, the way in which they are built, and the extended usefulness of their design. Prototype testing of MPFDs has also led to improved methods for construction and have placed even higher expectations on the technology. An introduction into the basic design of MPFDs will give the background into the shaping of the constraints placed on their final design. Solutions to these constraints are then laid out for the substrates, the reactive coatings, their assembly, and the associated electronics. Critical results showing the potential of MPFD technology will then be presented.

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## 2.1 Design

An MPFD is very similar to a typical parallel plate type fission chamber (see Figure 1 and Figure 2). It contains two conductive plates on either side of a gas filled pocket. A thin coating of neutron reactive material is placed on one or both of the chamber walls. Neutrons interacting in the reactive coatings eject energetic ion reactions into the gas filled pocket. A neutron event is then recorded by observing an induced charge or voltage from the motion of electrons and ions produced through interactions between the reaction product and the fill gas. What makes an MPFD primarily different from typical fission chambers is its size. With gas pocket sizes of only 0.5 mm (0.02 in) width by 1 mm (0.04 in) diameter, with the largest part of the detectors being the 30 gauge lead wire. This micro size allows multiple MPFDs to be assembled into large arrays of detectors. The small size also permits point detector modeling with negligible errors in neutron flux or fluence calculations. The design of MPFDs is naturally gamma radiation insensitive while the neutron reactive materials can be tailored to be sensitive to specific neutron energy ranges.

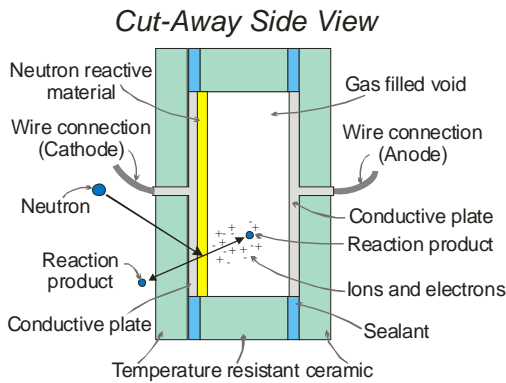


Figure 1: Cut-away side view of an MPFD chamber.

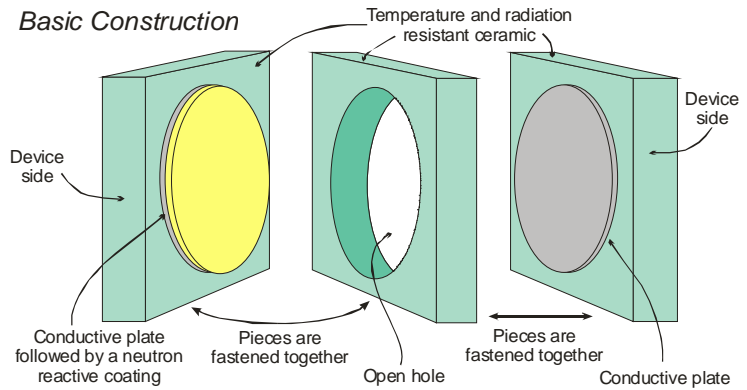


Figure 2: Basic construction of an MPFD chamber.

## 2.2 Design Constraints

The primary goal of the MPFD project is to develop an array of micro sized neutron detectors for dispersion throughout the Kansas State University TRIGA Mark-II Nuclear Reactor core. This alone imposes significant constraints on the design of the MPFDs. First and foremost, the detectors must be inserted into existing 8 mm (0.315 in) holes located in the upper grid plate of the reactor core (see Figure 3) [3]. Placing the detectors inside of an aluminum tube, for structural support and to isolate them from the cooling water, reduces the available space to only 6.2 mm (0.245 in) in diameter. An additional design constraint is that all of the materials must be capable of withstanding thermal and fast neutron fluences in excess of  $10^{21}$  n/cm<sup>2</sup> and gamma doses in excess of  $10^{12}$  rads.

Over the course of development, additional constraints have been added to the detector design. One such constraint is the ability to track thermal and fast neutrons separately while also monitoring background gamma radiation, signal noise and temperature. The formation of the thermal, fast, and background detectors require the substrates' design to minimize cross contamination of the fissile material. Construction of prototype devices identified the need for backfilling the detectors with argon after epoxies and substrates were cured. Placement and design of the contact points also became critical for good wire connections.

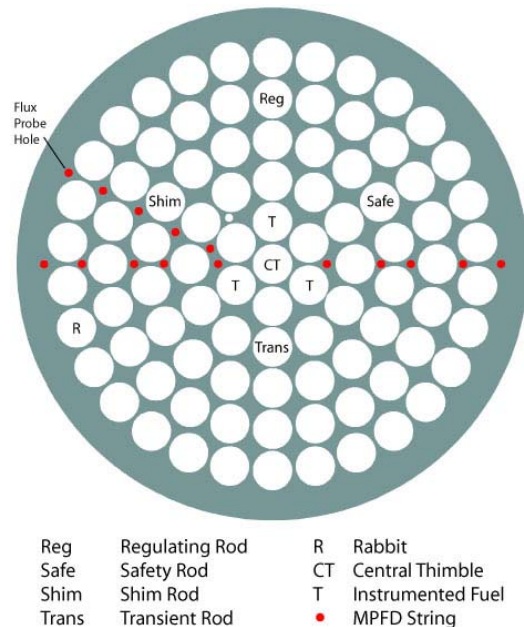


Figure 3: Grid configuration for the Kansas State University TRIGA Mark-II Nuclear Reactor after its upgrade to 500 kW.

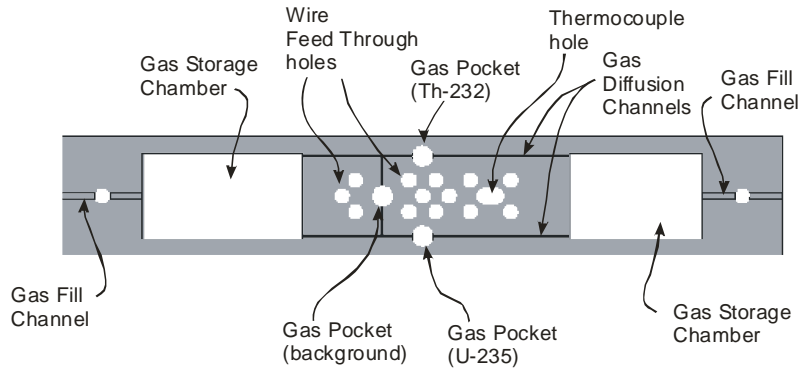


Figure 4: Design for the middle, or cavity, substrate for a triad MPFD with built-in thermocouple (MPFD<sup>3</sup>-T).

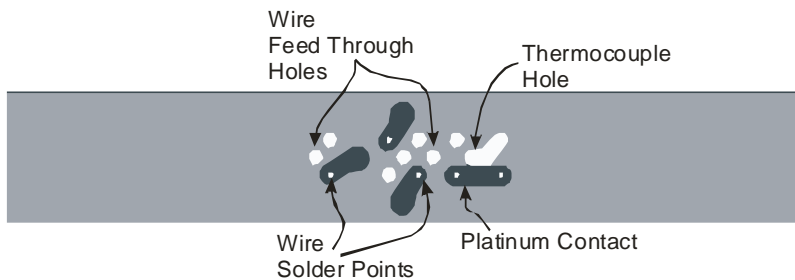


Figure 5: Design for the base substrate piece. Two of these and a cavity form the triad MPFD with built-in thermocouple (MPFD<sup>3</sup>-T).

The conductive traces must be continuous on a single substrate. Minimal distance and maximum width of these traces is also desired in order to ensure low resistive paths [6,7]. With these new constraints, and the design constraints mentioned in section 2.2, the substrate configurations shown in Figure 4 and Figure 5 were developed.

The design shown in Figure 4 and 5 is centered around a triad of detectors: a fast neutron (Th-232) detector, a thermal neutron (U-235) detector, and a background detector. A location is also provided for an integrated thermocouple, thus designating this design as an MPFD<sup>3</sup>-T (MPFD triad with thermocouple). The base substrate (Figure 5) is designed so that it can be used on both sides of the cavity substrate (Figure 4). The cavity substrate also includes two large chambers for gas storage. Channels are milled into the cavity substrates in order to connect the detector chambers, or gas pockets, to these gas storage chambers. A larger channel is milled into either side so the device can be evacuated and backfilled after the three substrates have been epoxied together. An epoxy plug is injected into these gas fill channels while inside the argon glove box (Figure 8) in order to trap the backfilled gas. Small holes in the middle of these channels help secure the epoxy plug in place.

The hole pattern for the wire feed-throughs match up, as shown in Figure 6, to make small solder pockets. A wire will stick through the smaller opening extending from the pocket. A conductive epoxy is injected into the pocket in order

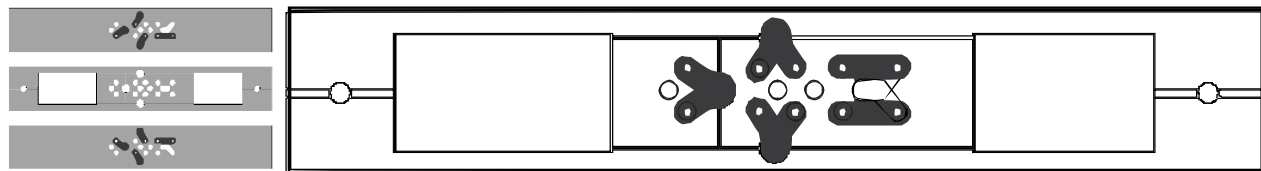


Figure 6: Transparent view showing how the holes line up when the substrates are stacked to form a triad MPFD with built-in thermocouple (MPFD<sup>3</sup>-T).

These constraints were expanded to include the high temperature and pressure environments found in commercial and naval reactors. It is from all of these constraints that the design of the MPFDs has been shaped beyond the “basic parallel plate fission chamber.”

### 2.3 Substrate Design

Several materials were analyzed for the substrate material. Some of these included Green Tape® [4], green pure alumina, zircalloy, silicon, and alumina. Alumina was chosen for its known high melting point, structural integrity, radiation hardness, availability, and cost. Silicon is still under study as a lower temperature device and green pure alumina holds potential for mass production of customizable MPFDs [5]. Prototype detectors have been constructed using “scrap” alumina substrates from our laboratory. Through the construction of several prototypes, it has been determined that the routing of conductive traces and wire connections are critical to a successful detector.



Figure 7: Contacts are evaporated onto the base substrates through photomasks using physical vapor deposition (PVD).



Figure 8: Custom glove box designed for backfilling the detectors with argon fill gas.

to make a secure, positive, and non-protruding connection to the platinum conductive trace. This platinum trace (Figure 5) is evaporated onto the base substrates through a photomask using physical vapor deposition (PVD) (Figure 7). A 1.0  $\mu\text{m}$  thick layer of platinum is deposited on top of a 0.1  $\mu\text{m}$  thick layer of titanium. The substrates are then heat treated in an argon atmosphere to 900°C (ramped at 100°C·h<sup>-1</sup>) in order to decrease the film's resistivity through vacancy coalescence [6,7].

A third hole in the pattern is provided so that one of the wires may be threaded back through the device for producing a twisted pair for noise reduction [8]. The oval center hole for the 5-hole thermocouple pattern is used to house the thermocouple, keeping it from protruding beyond the plane of the substrates. This also allows for a variety of thermocouple, or other 2 wire sensors, to be installed in the device, even after fabrication is complete.

## 2.4 Neutron reactive coatings

Several materials may be used for the detection of neutrons through the fill gas ionization produced by their reaction products. Figure 9 shows the rates at which the reaction products from <sup>10</sup>B, <sup>6</sup>Li, <sup>235</sup>U, and <sup>232</sup>Th deposit energy through ionization of argon fill gas. The <sup>10</sup>B reaction follows two different branches. The first, which occurs 94% of the time, yields an 840 keV <sup>7</sup>Li ion, a 1.47 MeV  $\alpha$ -particle, and a 480 keV  $\gamma$ -ray. The second branch yields a 1.02 MeV <sup>7</sup>Li ion and a 1.78 MeV  $\alpha$ -particle. Interactions with <sup>6</sup>Li yield a 2.05 MeV  $\alpha$ -particle and a 2.73 MeV triton (<sup>3</sup>H) [9]. Heavy elements that undergo fission reactions, such as <sup>235</sup>U and <sup>232</sup>Th, yield a broad distribution of reaction products with a wide range of energy. Two common products are a 60 MeV Iodine fragment and a 95 MeV Bromine fragment [10]. When comparing the deposition rate of energy between all of the reaction products in an argon fill gas, one can

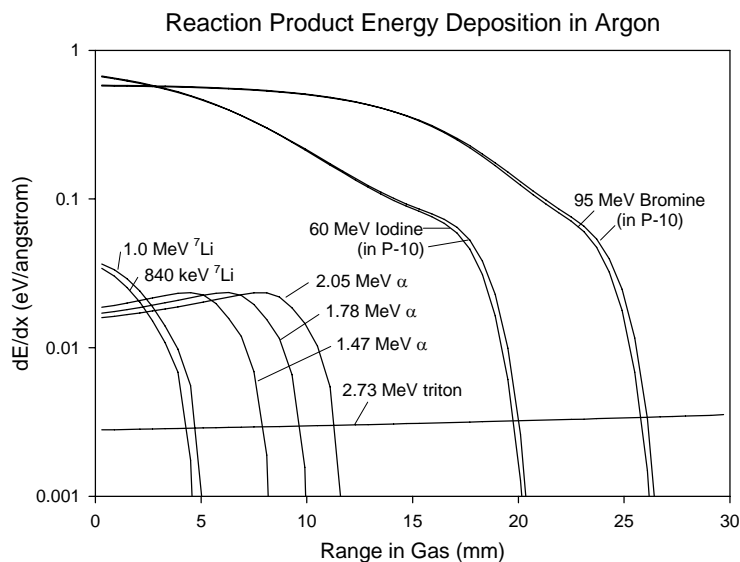


Figure 9: Energy deposition and ranges for typical neutron reaction products in 1 atm of Argon gas (unless noted, then P-10 gas) [11].

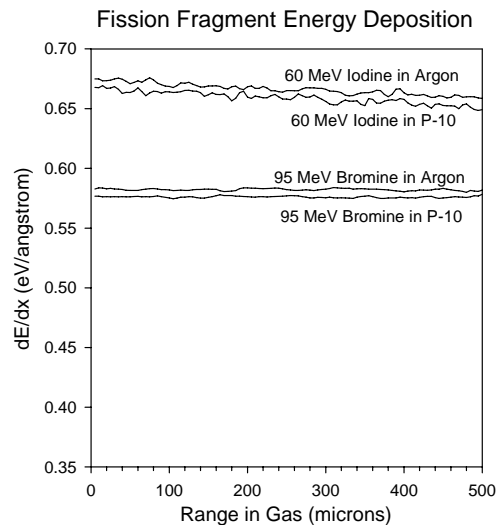


Figure 10: Energy deposition of typical fission fragments in an MPFD only 500 microns wide with 1 atm fill gas [11].

Table 1: Integrated energy deposition in 500  $\mu\text{m}$  of argon fill gas (unless specified).

Reaction Product	Energy (keV)
60 MeV Iodine	3332
(in P-10 fill gas)	3295
95 MeV Bromine	2911
(in P-10 fill gas)	2880
1.0 MeV $^7\text{Li}$ ion	180
840 keV $^7\text{Li}$ ion	168
1.47 MeV $\alpha$ -particle	94
1.78 MeV $\alpha$ -particle	86
2.05 MeV $\alpha$ -particle	80
2.73 MeV triton ( $^3\text{H}$ )	14
1 keV Gamma*	0.658

\*Largest energy deposited from curve fit in Figure 11.

see from Figure 9 that the heavy element fission products significantly deposit more energy than all of the other reactions. When compressing the chamber size to a mere 500  $\mu\text{m}$ , the total deposited energy may be calculated by integrating the energy deposition rate (eV/angstrom) by the size of the chamber. Table 1 gives the resulting energy deposition of a 500  $\mu\text{m}$  wide chamber. MCNP4C [12] has also been used to find the approximate energy deposition of a gamma ray into atmospheric argon gas 500  $\mu\text{m}$  wide. For gamma ray energies below 1 keV, the minimum energy for MCNP4C, an estimate was included to show an approximation of the energy roll off. This estimate is based on the assumption that a gamma ray can only deposit as much energy as it has itself. From this, one can observe how insensitive MPFDs are to gamma ray background radiation. Although any of the neutron reactive coatings should produce signals beyond the background,  $^{235}\text{U}$  and  $^{232}\text{Th}$  have been chosen. Ninety-three percent enriched  $^{235}\text{U}$  has been shown [5] to produce a signal principally from thermal neutrons, whereas  $^{232}\text{Th}$  produce a signal from fast neutrons exceeding 1 MeV.

The application of the  $^{235}\text{U}$  and  $^{232}\text{Th}$  neutron reactive materials is done using ASCEFI, or the Automated System for the Consistent Electroplating of Fissionable Isotopes. This system is being constructed in order to produce these coatings to a calibrated thickness through electrolysis. In order to accomplish this, the system automatically cycles all fluids, holds constant fluid temperatures, controls rate of electrolysis, and total coating thickness. In addition, the system has the ability to coat five substrates for each of the two isotopes, totaling 10 in all.

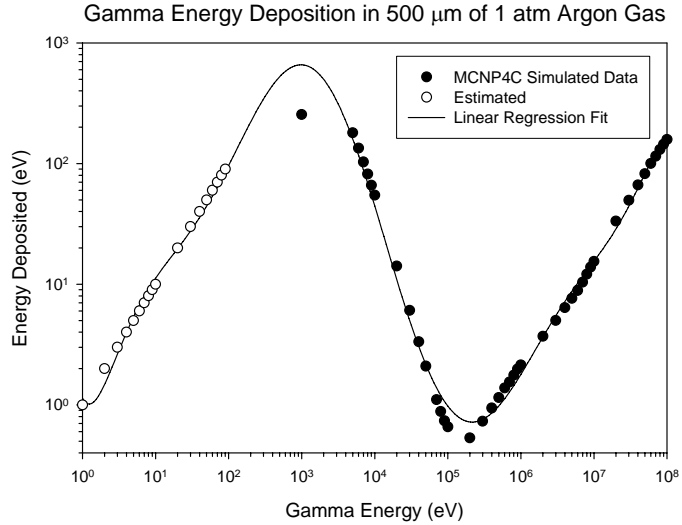


Figure 11: MCNP4C simulated energy deposition of gamma rays in 500  $\mu\text{m}$  of 1 atm argon gas [12].

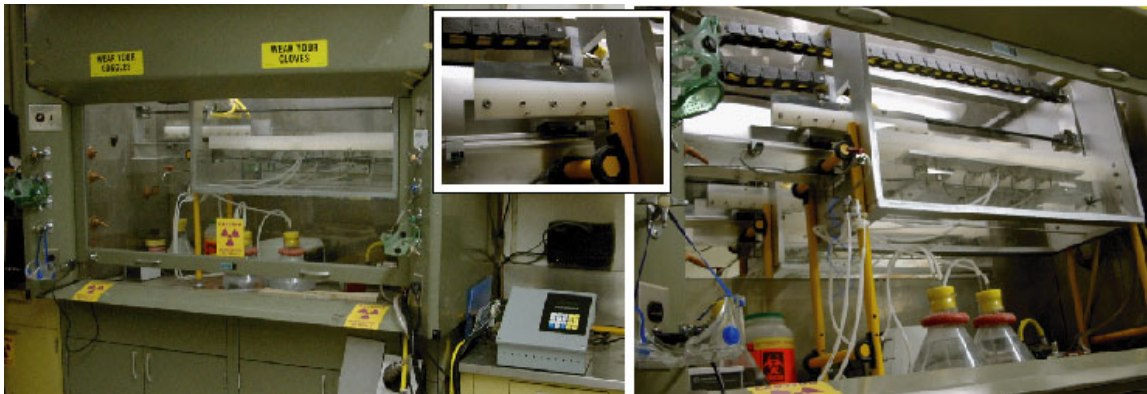


Figure 12: ASCEFI (automated system for the consistent electroplating of fissionable isotopes) is being constructed to apply a precise layer of U-235 and Th-232 to the detectors.

## 2.5 Electronics

Since the development of MPFDs is for monitoring neutron events, and not spectroscopy, the system may use a simplified pulse counting system in pulse mode and a current monitor for current mode. Figure 13 shows the basic configuration of the system's circuitry. Pulse mode operations are monitored through a capacitively coupled common-mode differential (instrumentation) amplifier followed by a bandpass filter. The instrumentation amplifier helps minimize transmitted noise and decouples ground loops. The bandpass filter allows only those signals to pass which have a rise time of  $5 \mu\text{s}$ , which is the approximate rise time of neutron induced pulses in the detector. A simple Schmitt Triggered discriminator is then used to pass pulses above a specific threshold to a counter and register system as a logic pulse. The counter and register system allows the asynchronous neutron induced pulses to enter the central microcontroller synchronous system. Current mode operation is monitored through an instrumentation amplifier which reads the voltage across the bias resistor. The amplified voltage signal, which is proportional to the current, is converted using an analog-to-digital converter (ADC). This digital signal is then collected by the same central microcontroller system used by the pulse mode system. Additional circuitry is used to combine the pulse and current mode data from all 225 detectors into a data stream which may be read and interpreted by an off-site computer through a LAN (local area network) interface.

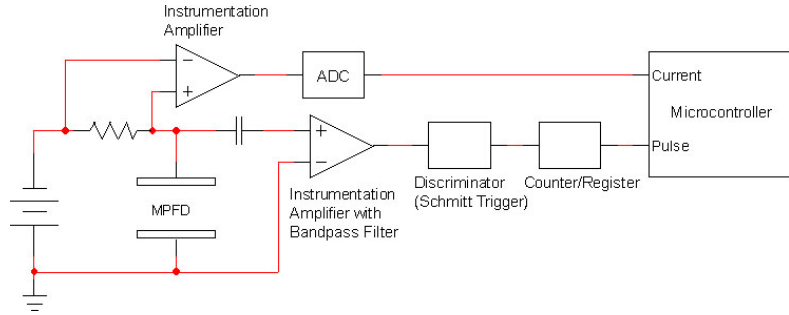


Figure 13: Circuitry to monitor an MPFD in both pulse mode and current mode operation.

One of the most significant challenges of the electronics has been the routing of the signals from the detectors out of the core. To remedy the difficulties imposed by the space restrictions (0.245 inch diameter), the high radiation fields, and the large number of signal wires, a specially designed system of alumina wire guides have been developed. These guides keep the wires separated to minimize short circuits due to radiation induced insulation failures. They also assist in holding the detector string together and keep all of the detectors aligned to the same plane. Two different guides have been designed in order to not only carry the wires down the tube, but also to guide them past the other MPFD<sup>3</sup>-T. Illustrations of these guides are shown in Figure 14 through Figure 16.



Figure 14: Wire guide to route wires around the detectors.



Figure 15: Disks used to keep wires separated as they leave the reactor core.

## 3. TESTING AND RESULTS

While the detector design discussed above is still under construction, several prototypes that led to its design have been tested at the K-State TRIGA Mark-II Nuclear Reactor Facility. Initial tests were performed using the tangential beam port which provides a thermal neutron flux of  $1.6 \times 10^6 \text{ n-cm}^{-2}\text{-s}^{-1}$  and gamma dose of approximately  $500 \text{ R-h}^{-1}$  [3]. This facility allows us to test the detectors in a dry environment prior to inserting them into the

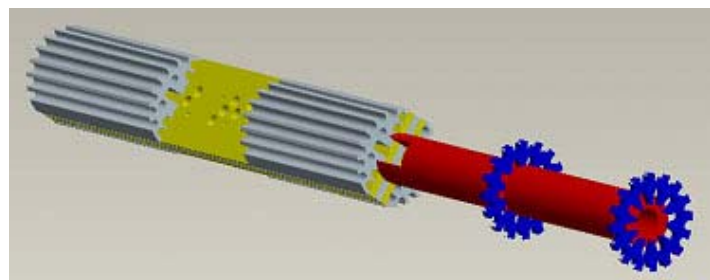


Figure 16: Assembly showing an MPFD3-T with the alumina wire guides and alumina tubes.

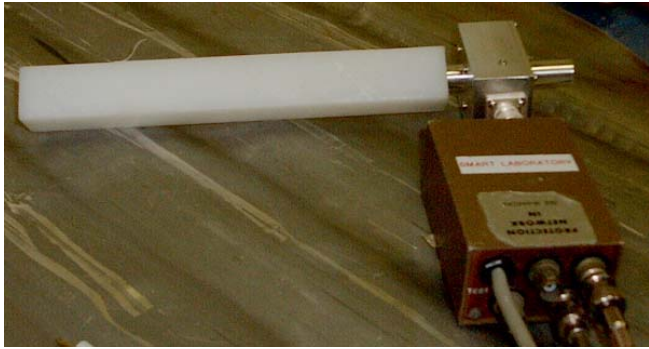


Figure 17: Prototype detector assembly which was plugged into a collimator for testing in a beam port.

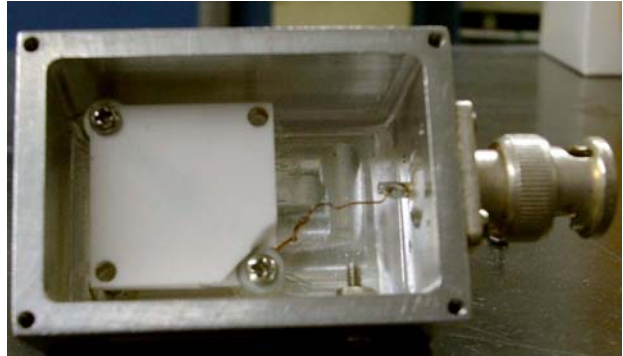


Figure 18: An alumina prototype detector mounted in a box for beam port testing.

reactor tank. The detector assembly shown in Figure 17 allowed the detector to be plugged directly into the beam port's collimator. The actual detector was mounted in an aluminum box as shown in Figure 18. The MPFD was built using spare alumina pieces and had a pocket diameter of 3 mm and width of 1 mm. Natural uranium was deposited onto one of the conductive plates using a paintbrush dipped into a uranyl-nitrate and deionized water solution. This detector design was operated between 100 and 200 volts dc bias. The resulting spectrum shown in Figure 19 was collected. In order to verify the detector's operation an MCNP simulation was completed (Figure 20). Comparisons between the two figures show good agreement between the theoretical and observed spectra. A one inch thick cadmium filter was placed between the beam and the detector to filter out the neutrons. The high gamma field (100 R) did not record a single count even with the LLD set at channel 4, thus showing how insensitive MPFDs are to background gamma radiation [5].

Another testing device has been constructed for implementing in-core tests. This device is approximately 22 feet long and has two 45 degree bends in order to prevent neutron streaming. An MPFD was loaded into the tube attached to a 20 foot twisted pair cable. This cable was then connected to a 142A Ortec preamp. After making sure the detector was operational in the beam port (Figure 21) it was inserted into the central thimble of the reactor. The reactor was operated from 10 mW up to 200 kW (thermal power), which produces a neutron flux of  $1.2 \times 10^{13}$  n-cm<sup>-2</sup>-s<sup>-1</sup> at 250 kW [3]. After collecting data for 15 minutes at each of the 46 different power levels, it was found that the

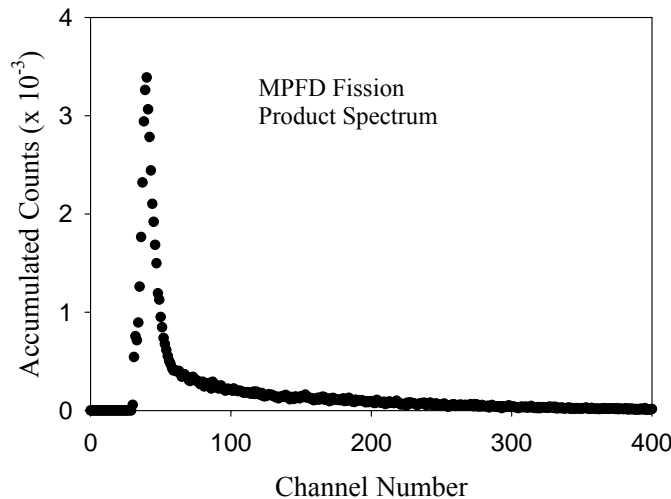


Figure 19: Spectrum from natural uranium coated fission detector placed in a neutron beam with a large gamma background [5].

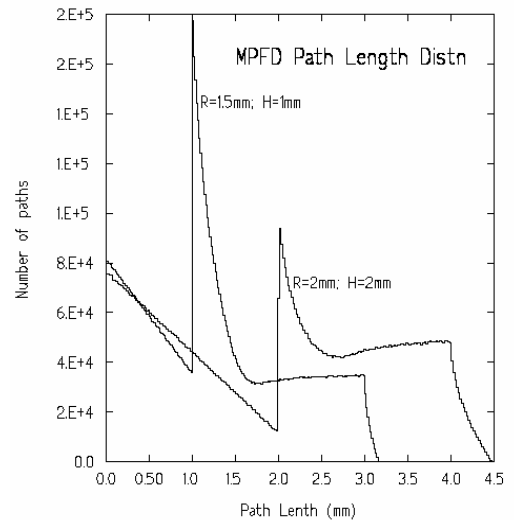


Figure 20: Theoretical fission product pulse height spectrum calculated in MCNP for different sized detectors.



Figure 21: Tube for in-core testing of an MPFD. Here it is being tested in the beam port prior to insertion into the reactor.

detector was linear in its response (Figure 22), with an  $R^2$  value for a linear fit of 0.9986. This test was done with the detector operating in pulse mode only. The variations in the response at low power levels are due to the difficulty in controlling the reactor and the calibration of the reactor's instrumentation. This test is conclusive evidence of the capabilities of MPFD technology.

## CONCLUSION

Prototype tests have demonstrated that MPFD technology will be radiation hard, capable of operating at low and high flux levels, provide high signal-to-noise outputs, be easily customizable, and inexpensive to manufacture. Soon these devices will be assembled into a large array of detectors spread throughout our reactor's core, providing a three dimensional map of the neutron densities. This data will then be plugged into a mathematical model to find a 3-D core power map in real-time. Information from these detectors will provide additional insight into a reactor's dynamics allowing for more robust core designs with optimizations in fuel burn up.

Their ability to be manufactured inexpensively will allow new fuel bundles to be built with these detectors as imbedded devices. Future tests are slated for design optimizations for use in Gen IV reactor systems. We look forward to the continued development of the next generation of in-core radiation monitoring systems.

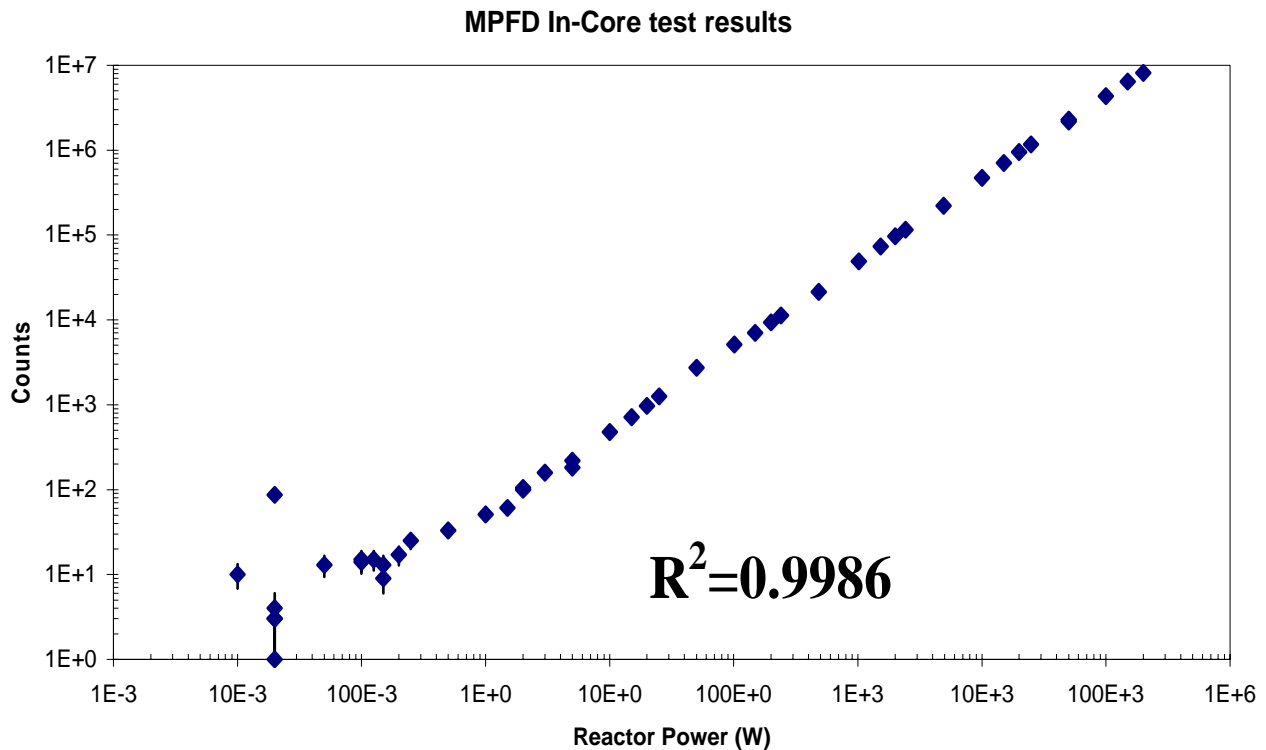


Figure 22: In-core results from 10 mW up to 200 kW thermal power with the detector operating in pulse mode.

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