Advances in the Development and Testing of Micro-Pocket Fission Detectors (MPFDs)

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Abstract A new method of fabricating micro-pocket fission detectors (MPFDs) has been developed. Deployable into iron-wire flux wells, MPFDs are neutron sensors capable of real-time, in-core flux measurements. A cyclic potential sweep method was used to deposit 0.1 ± 0.006 μg of natural U onto one 0.33-mm diameter Pt electrode on one face of the MPFD chamber. The MPFD was operated in the central thimble and IRIS flux wells of the KSU TRIGA Mk II nuclear reactor. The MPFD response was observed to be linear with respect to reactor power with no sign of dead time between 10 kWth and 700 kWth. The IRIS flux well was utilized to observe a $1.50 reactor pulse with a max power peak full width at half maximum of 12 ms.

1. Introduction

The need to monitor the neutron flux ($n \cdot cm^{-2} \cdot s^{-1}$) within the core of a nuclear reactor has driven research in numerous neutron detection methods. The neutron flux within the core of a nuclear reactor is indicative of its operational power level; an increase in the neutron flux indicates an increase in operational power level. In order to gain a complete understanding of the operation of a nuclear reactor, the neutron flux and power level must be accurately reported to operators. Presently, solutions exist to monitor the neutron flux via radiation monitors that are kept outside of the core. However, this method of flux measurement can is susceptible to errors due to neutron transport through the materials found between the core and the detector system. Moreover, information regarding minute variations in flux around the core, due to fuel burn up or control-rod insertion etc., is entirely lost at distances outside of the reactor core.

Development and deployment of small, accurate, and robust neutron flux measurement systems is an important enhancement for advancing nuclear fuel technology. A need exists to place neutron sensors within the reactor core to provide information on the neutron flux for both nuclear test reactors, and commercial power reactors [1]. The high-radiation and high-heat environment found within a nuclear reactor core are not conducive to the operation of many types of radiation detectors. First, the high neutron flux found within a reactor core, often on the order of 10^{14} $n \cdot cm^{-2} \cdot s^{-1}$ [1], will either burn up a detector's neutron conversion material too quickly, reducing the device's overall lifetime, or will induce a count rate so high that the detector becomes experiences significant dead time. Second, the high temperature present within most reactor cores, often exceeding 300°C [1], would either destroy many detector systems (such as scintillators) or render them entirely unusable (such as would be the case for most semiconductors). Furthermore, in-core sensors must typically be located within narrow channels within the reactor core (< 1 cm in diameter) [1]. The physical requirements

for in-core neutron sensors limit material selection and device geometry. Several technologies exist which are used to measure neutron flux for in-core and near-core environments. Ionization chambers and fission chambers are commonly used for near-core neutron measurements [1]. Typical ionization and fission chambers are necessarily large, and are only capable of monitoring neutrons which have escaped the reactor core. Such devices are impractical for in-core measurements because of their large size, fragile construction, and large flux perturbation. Miniature fission chambers are commonly used for in-core neutron measurements. Miniature fission chambers are typically lined with highly enriched uranium, and made in a cylindrical geometry [1]. Device dimensions for miniature fission chambers are usually in the mm to cm range. The burnup of fissile material, and buildup of fission fragments in sealed miniature fission chambers greatly limits the application of such devices for extended periods of time. A fission chamber using enriched ^{235}U will decrease in sensitivity by 10% after an integrated neutron fluence of 10^{20} n cm^2 in a typical power nuclear reactor [2]. In order to extend stable device lifetime, fertile isotopes can be added to the neutron-sensitive coating [2]. The buildup of fission fragments in the sealed gas chamber of typical miniature fission chambers also produces a 'memory effect', where the radioactive decay of fission fragments in the detection gas produces a residual current, reducing device accuracy [1]. Sub-miniature fission chambers utilize highly-enriched (97% ^{235}U) uranium coatings upon the cathode wall of small, sealed, proportional gas detectors [3]. Current-mode operation is required for in-core operation of sub-miniature fission chambers due to the high neutron sensitivity of the fissile coating. The stable device lifetime also suffers from the high sensitivity, limiting the effective use of such detectors to fluences $< 2 \times 10^{21}$ n cm^{-2} [3]. Such devices are impractical for use in critical mock-ups, high performance material test reactors (MTRs) and transient test reactors because of low-fluence design and large flux perturbation when installed in-core or near-core.

Alternatively, iron or gold activation analysis can be used to determine the neutron fluence within a reactor core during an operational period. However the neutron fluence is not as useful for experiments in high-performance reactors, transient test reactors, and critical mock-ups, which distinctly benefit from real-time flux measurement. Finally, self-powered neutron detectors (SPND) incorporate neutron-sensitive materials that decay by beta or gamma-ray emission. The simplest versions of SPNDs rely on the direct measurement of the beta decay current following a neutron absorption [1]. In contrast to typical fission chambers, SPN detectors are very small, and require no applied bias. However, the output current from SPN detectors is very small and suffers a time delay due to the nuclear decay [1].

2. Theory and Prior Research

Previous simulations have shown that a power density profile of a research reactor can be reconstructed using in-core neutron flux measurements [4]. Large prototypes (3-mm diameter electrode) using ^{235}U coatings were successfully tested in the neutron beam port of the KSU TRIGA Mk II research reactor [4]. The small size of MPFDs present advantages for in-core neutron monitoring [5]. The high specific ionization of fission fragments within the small (< 1 mm thick) gas pocket compared to gamma rays, high-energy electrons, and beta particles yields low background gamma ray sensitivity [5]. Pulse height discrimination can therefore be used when operating in pulse mode to separate the signal from non-neutron interactions. The small mass of neutron-conversion material present in the gas pocket results in an effective neutron sensitivity as low as 10^{-8} interactions per flux unit (depending on the energy-dependent flux profile). This low sensitivity results in minimal flux perturbation in the

detector region, producing an accurate flux measurement. Limiting flux perturbation due to the measurement device is particularly important for research and test reactors, where spatial flux profiles may be less understood than in large reactors [6].

Prototype MPFDs have been constructed and tested [4, 5, 7]. All of the prototype devices have demonstrated exceptional gamma-ray discrimination and have been used to detect neutrons in fluxes varying from 1.6×10^{6} $n \cdot cm^{-2} \cdot s^{-1}$ [4] to 2.4×10^{13} $n \cdot cm^{-2} \cdot s^{-1}$ [7]. Large prototypes (3-mm diameter) using enriched ^{235}U neutron-conversion material coatings suffered from significant dead time at elevated fluxes [5]. Enhancements to the detector chamber design and fabrication process were necessary to reliably produce MPFDs capable of deployment into test nuclear reactors [7]. Furthermore, recent progress electrodepositing natural U and Th onto small, circular Pt electrodes has advanced the capability to produce MPFDs with very thin neutron-sensitive coatings [8]. The cyclic potential sweep method described elsewhere [8] was used to fabricate the MPFD tested in previous iterations [7], and was improved as part of the present work.

3. Advances in MPFD Design and Fabrication

The present work was initiated with four primary objectives: Multi-nodal, in-core deployment via iron-wire flux well, neutron flux measurement, extended sensor operational lifetime, and reliable reproducibility. Multi-nodal measurement of the neutron flux is necessary to reconstruct the spatially varying power profile for the research reactor primarily through the measurement of the thermal-neutron flux. Large prototypes have been previously built and tested in specialized flux wells at the KSU TRIGA Mk II research reactor [4, 5, 7]. However,

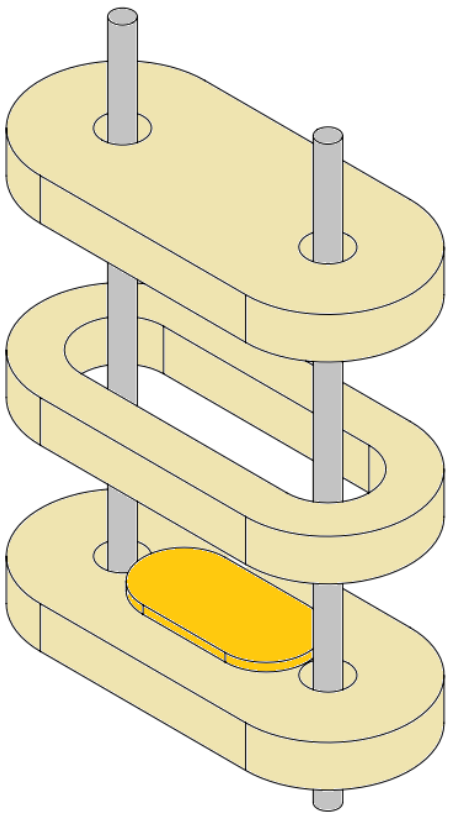

FIG. 1. Multi-wire MPFD assembly (patent pending)

deployment into an iron-wire flux well is intended to enable sensor deployment and calibration at many other research reactor facilities in the future, leading to the reduction of overall device dimensions. While previous prototypes and other in-core flux sensors utilize enriched ^{235}U, the present work sought to develop an in-core sensor with an extended operational lifetime in an active research reactor. Finally, the electrodeposition process was enhanced to improve reliability of the neutron-reactive coating process and enable the reproduction of sensors with similar characteristics.

The design parameters were set such that the detector chamber would fit within an iron wire flux well, thus modifications to previous designs were necessary. In order to facilitate a much smaller detector chamber (total volume < 1 mm^3), a multi-wire electrode configuration was chosen over the parallel-plate electrodes used in previous iterations [6]. The parallel wires run through an ionization chamber which is created by placing an Al_2O_3 spacer between two Al_2O_3 disks (Fig. 1). The present MPFD chamber measured 2 mm × 1 mm × 1.5 mm with an active chamber measuring 0.33 mm (diameter) × 0.5 mm. The anode and cathode wires were then run to an electronic feedthrough at the top of the flux-wire well and into the charge-sensitive preamplifier. The entire flux-wire well was back-filled with Ar ionization gas which is allowed to flow into the ionization chamber by the loose-stacked fabrication of the chamber [7]. A benefit of the design is that multiple pieces can be stacked to build multiple fission chambers, or several longer fission chambers composed of longer elements, upon a single string of wire electrodes. One or more surfaces of the disks and spacer can be coated with neutron-reactive material.

The improved electrodeposition techniques described in [8], were used to deposit 0.1 ± 0.006 µg of natural U onto one 0.33-mm diameter Pt electrode which was evaporated onto the MPFD disk face, as shown in Fig. 2. The mass of U was then measured using alpha-particle spectroscopy [7]. After the MPFD node was constructed, the insulated anode and bare cathode wires were held together using PTFE heat shrink and inserted into the central-thimble flux well at the KSU TRIGA Mk II nuclear reactor.

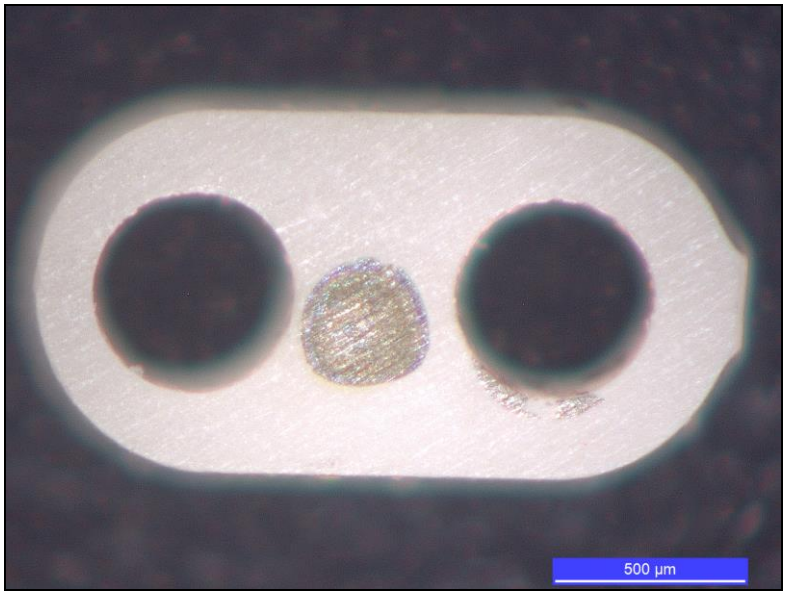

FIG. 2. Uranium electrodeposited MPFD disk.