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Micro-pocket fission detectors (MPFD) for in-core neutron flux monitoring

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Abstract

Micro-pocket fission detectors (MPFD) have been fabricated and tested as in-core flux monitors in the 250 kW TRIGA nuclear reactor at Kansas State University. The prototype devices have been coated with a natural uranyl-nitrate to provide a neutron reactive coating. The devices are composed of alumina substrates sealed together to form a miniature gas pocket 3 mm in diameter and 1 mm wide. The devices are radiation hard and can operate in pulse mode in a neutron flux exceeding $10^{12}\,cm^{-2}\,s^{-1}$. Placed in the central thimble of the reactor core, the MPFDs have shown count rate linearity from low to high power. Dead time losses become apparent at power levels exceeding 100 kW, yet are still low enough to allow for pulse mode operation.

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Keywords: Neutron detector; Reactor instrumentation; Fission chamber

1. Introduction

There is a need for neutron radiation detectors capable of withstanding intense radiation fields, capable of performing "in-core" reactor measurements, capable of pulse mode and current mode operation, capable of discriminating neutron signals from background gamma ray signals, and that are tiny enough to be inserted directly into a nuclear reactor without significantly perturbing the neutron flux. A device that has the above features is the subject of a Nuclear Engineering Research Initiative (NERI) research project, in which miniaturized fission chambers are being developed and deployed in the Kansas State University (K-State) TRIGA Mark-II research reactor. The unique miniaturized neutron detectors are to be used for three specific purposes:

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(1) as reactor power-level monitors, (2) power transient monitors, and (3) real-time monitoring of the thermal and fast neutron flux profiles in the core. The third application has the unique benefit of providing information that, with mathematical inversion techniques, can be used to infer the three-dimensional (3D) distribution of fission neutron production in the core [1].

Micro-pocket fission detectors (MPFD) are capable of performing near-core and in-core reactor power measurements. The basic design utilizes neutron reactive material confined within a micro-sized gas pocket, thus forming a miniature fission chamber. Active device dimensions presently range from 0.5 to 2 mm thick, and 1 to 3 mm in diameter, thereby allowing them to be inserted directly between fuel elements of a TRIGA reactor core. Fabricated from inexpensive ceramic materials, the detectors can be placed throughout the core to enable the 3D mapping of the neutron flux profile in "real-time". Initial tests have shown these devices to be radiation hard and potentially capable of operating in a neutron fluence exceeding $10^{19}\,cm^{-2}$ without noticeable degradation.

Materials presently under investigation for the fission chambers include enriched ^{235}U and ^{232}Th. The small dimensions permit faster time responses than those typically observed from gas-filled detectors. Further, the tiny gas chamber dimensions prevent significant energy deposition within the active gas volume from β particles, γ-rays, or even α particles. Fission fragments deposit 3 MeV of energy, or more, per event within a chamber only 0.5 mm wide, as calculated by TRIM, thereby establishing a very high neutron to background signal ratio [2,3]. Tests reveal that the miniature size of the detectors, along with the low atomic number materials composing the chambers, are practically insensitive to gamma rays in environments up to several hundred roentgen (R) per hour [3,4].

2. MPFD design considerations

Shown in Fig. 1 is a cutaway view of the basic detector concept. It consists of a small ceramic structure, within which is a miniature gas-filled

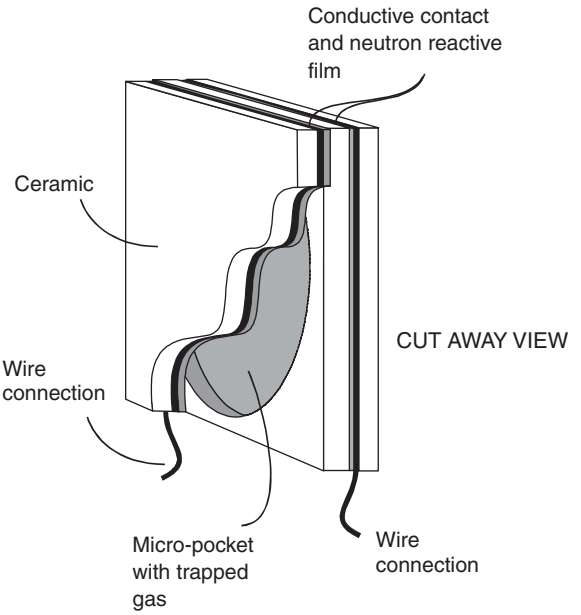

Fig. 1. The micro-pocket fission detector (MPFD) is formed from insulating materials, such as aluminum oxide or oxidized silicon wafers. The opposing sides of each pocket are coated with a conductor followed by a neutron reactive film, such as ^{10}B, ^{6}LiF, ^{235}U, or ^{232}Th.

pocket. A conductive layer is deposited on opposing sides of the device, but not the perimeter. Neutron reactive material, such as ^{235}U, ^{232}Th, ^{10}B, or some material containing ^{6}Li, is applied over the conductive contact(s). Although both sides may be coated with neutron reactive material, only one side needs to be coated for the device to work. The ceramic pieces must be insulators and must not be composed of neutron-absorbing material. For instance, aluminum oxide or oxidized silicon may be used. Connecting wires must be sealed well so that no gas leaks out. Additionally, the ceramic pieces must be sealed with high-temperature cement such that the seal integrity is secure within the hostile environment of a reactor core.

Of greatest interest for the present generation of MPFDs is ^{235}U as a conversion material. Pure ^{235}U has microscopic and macroscopic 2200 m s^{-1} neutron fission cross-sections of 577 barns and $28\,cm^{-1}$, respectively [5,6]. Fission reactions in ^{235}U cause the emission of two fission fragments

per fission with energies predominantly ranging from 60 to 110 MeV, energies easily discernable from background γ-rays.

The device is operated with a voltage applied across the gas chamber. Neutron interactions in the reactive coating cause the ejection of energetic fission products. When these energetic ionizing particles enter the gas pocket, they produce ionization in the form of electron–ion pairs. The applied voltage causes the positive ions and the electrons to separate and drift apart; electrons to the anode and positive ions to the cathode. The motion of the charges produces an induced current that is recognized and measured by sensitive external electronics. The result is a measurable pulse indicating a neutron interaction in the detector.

Since the charge-detecting medium is a gas, it is improbable that γ-rays interact in the detecting medium; hence, the MPFD naturally discriminates out γ-ray background noise. The components comprising the mechanical structure of the device are low-Z materials such as aluminum oxide, silicon dioxide, or magnesium oxide. As a result, γ-ray interactions in the MPFD structure will most likely be Compton scattering events, which eject recoil electrons of only modest energy into the gas. Because the stopping power of electrons in a gas is substantially lower than the stopping power of fission fragments, the charge-induced signals are significantly larger for fission fragments than for recoil electrons. Furthermore, since the device is gas-filled, there is no detecting medium that radiation can actually destroy, a clear advantage over liquid or solid detectors. Hence, the device is much more radiation hardened than typical semiconductor and scintillation neutron detectors. The neutron detection efficiency can be modified for specific uses by two methods: (1) the device can be under- or over-pressurized with gas to change the ionization density in the detector (altering the output signal), or (2) the neutron reactive coatings can be made thin or thick to decrease or increase neutron interaction rates.

Shown in Figs. 2 and 3 are the ranges and energy deposition in P-10 gas at 1 atm pressure for 95-MeV bromine fission fragments and 60-MeV iodine fission fragments [2]. These fission

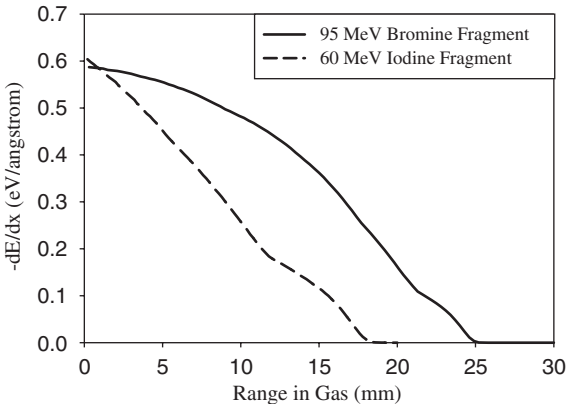

Fig. 2. Energy deposition and ranges for typical fission fragments in 1 atm of P-10 gas.

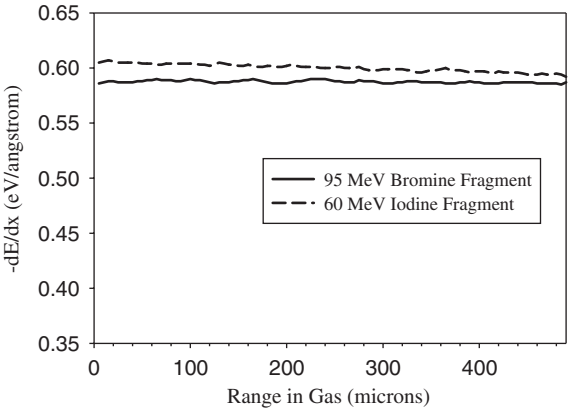

Fig. 3. Energy deposition for typical fission fragments in a MPFD only 500 μm wide.

fragments deposit only a small portion of their energy within the small dimensions of a MPFD, and yet, as seen from Fig. 3, the total integrated energies deposited within the micro-pocket is approximately 2.9 MeV for the bromine fragment and 3 MeV for the iodine fragment, all within a cavity *only* 500 μm *wide*. Such large energies are easily distinguished from background γ-rays. Finally, because the gas chamber is so thin, the MPFD can operate with only a 25 to 50 V bias, although higher biases are typically used to ensure operational stability.

Prototype MPFDs have been manufactured from machined aluminum oxide (alumina) pieces.

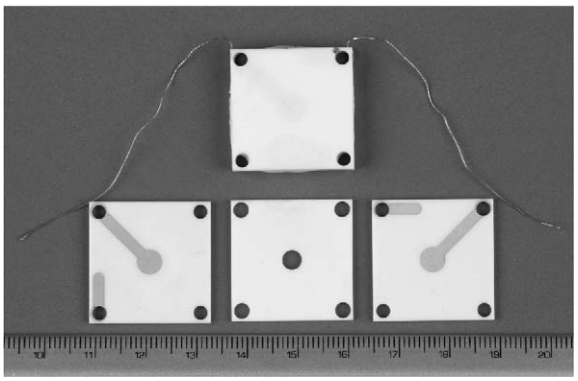

Fig. 4. A first generation MPFD, showing the main parts and an assembled device. The center piece forms the gas pocket, and the electrode patterns on the outer pieces form the cathode and anode. The major units on the scale shown are cm.

Each detector is composed of three different alumina pieces, the bottom cathode plate, the center plate, and the anode plate. Each center plate had a pocket 3 mm in diameter and 1 mm thick, thereby defining the gas pocket volume. Ti/Au compound metal contacts were evaporated upon the alumina cathode and anode pieces. The cathode pieces were aligned and fastened to center pocket plates with epoxy. A dilute solution of uranyl-nitrate was applied to the pocket bottom (upon the cathode contact) and baked with an infrared lamp. Afterwards, the pieces were inserted into a glove box, which was backfilled with P-10 gas. After waiting for the gas to displace any residual air in the chamber, the anode plates were fastened to the assembly with epoxy, thereby trapping the detecting gas inside. The final devices were cured in a baking oven at 90 °C. Cu wire leads were fastened to the test device cathode and anode plates with Ag epoxy. An assembled first generation MPFD, along with the basic components, is shown in Fig. 4.

3. Experimental procedure

Prototype MPFDs were first tested in a thermal neutron beam port tangential to the TRIGA core to observe the spectral characteristics and γ-ray insensitivity. The devices were each tested within an aluminum tube long enough to position them into the center of the K-State TRIGA reactor. Wiring from the detectors was over 7 m long, which is long enough to extend from the K-State TRIGA reactor core center to above the top of the reactor pool. A commercial Ortec 142A preamplifier was used to couple the detectors to common NIM electronics.

The detectors, biased at 200 V to ensure stability, were first tested at a tangential beam port with the reactor at full power, which provides a thermal neutron flux of $1.6 \times 10^6\,\mathrm{cm^{-2}\,s^{-1}}$. The gamma ray component is approximately 100 R/h. Spectra were accumulated with and without a 2-mm-thick Cd shutter, in which the Cd shutter served to block the thermal neutron component, thereby leaving only the gamma ray contributions to the signal. It should be noted that, with the Cd shutter blocking the neutron beam, the actual gamma ray background *increases* because of $^{113}\mathrm{Cd(n,\gamma)}^{114}\mathrm{Cd}$ prompt γ-ray emissions.

After the beam port tests, a MPFD was placed directly in the center of the K-State TRIGA Mark-II nuclear reactor. Cables extending from the reactor core, up through an aluminum tube, were used to connect the device to the Ortec 142A preamplifier above the water line, thereby ensuring that the electronics would not be damaged from water leaks or the radiation field. Detector measurements of 15-min duration were taken with the reactor power incrementally changed in power from 1 mW up to 225 kW, so that the thermal neutron flux at the detector location ranged from 10^3 to over $10^{12}\,\mathrm{cm^{-2}\,s^{-1}}$. The MPFD was operated in *pulse mode* for the entire experiment.

4. Results

The miniature gas pocket, as previously described, absorbs only a portion of the fission fragment energy. A Monte Carlo code was written to model the expected pulse height distribution from a MPFD. Shown in Fig. 5 are the expected spectral features for MPFDs with a 3-mm diameter and 1-mm wide micro-pocket and with a 4-mm diameter and 2-mm wide micro-pocket. The most salient spectral features are the large

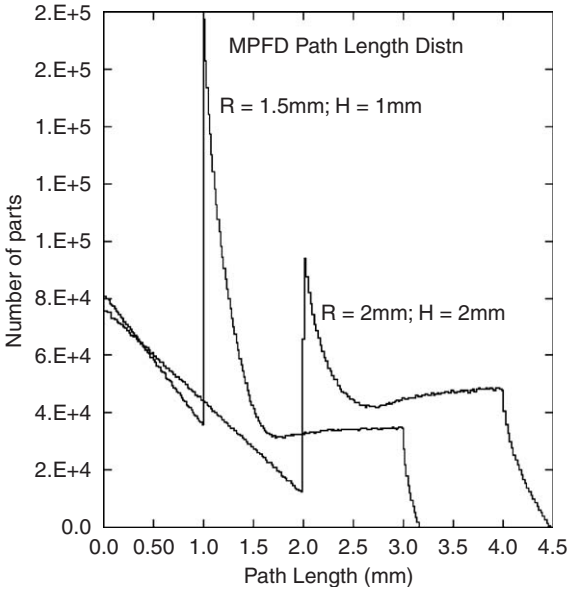

Fig. 5. Expected spectral features for a 3-mm diameter, 1-mm wide MPFD and a 4-mm diameter, 2-mm wide MPFD.

energy peaks at the lower energy portion of the spectra. The peaks comprise the average energy deposition in the tiny detectors (trajectories approximately perpendicular to the contacts), whereas the continua are from other possible angular trajectories of the fission fragments.

Shown in Fig. 6 is a spectrum with an MPFD located at the workspace of the K-State TRIGA reactor tangential beam port. The reactor power for this spectrum was 225 kW, which yielded an average thermal neutron flux of $1.6 \times 10^6\,\mathrm{cm^{-2}\,s^{-1}}$ and 10^2 R/h gamma ray background. A salient lower energy peak in Fig. 6 is clearly observed, as predicated by the modeled results of Fig. 5. Further, tests with cadmium shielding pieces in front of the MPFD show almost no pulses from γ-rays, demonstrating its excellent n/γ detection discrimination [3]. No spectra for the Cd shielded cases are shown because absolutely *no counts were recorded*.

Shown in Fig. 7 are the results from the MPFD tested within the center of the TRIGA reactor core. From these results it can be seen that the device demonstrated excellent count-rate linearity with reactor power. Further, the small size and

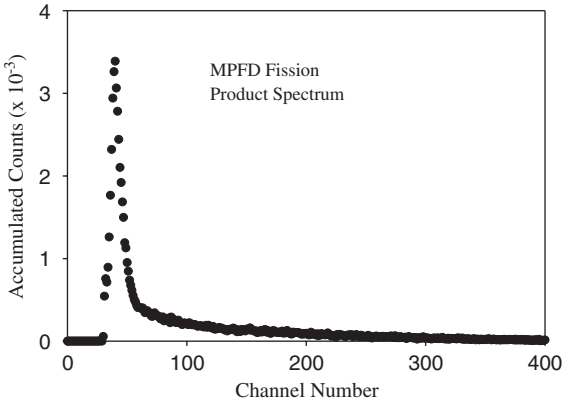

Fig. 6. Thermal neutron-induced spectrum from a prototype MPFD.

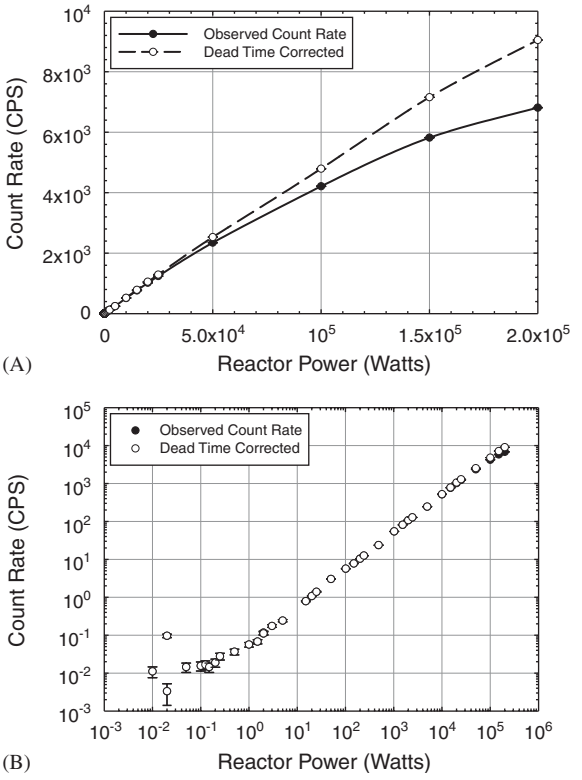

Fig. 7. The above figures show the response of a 3-mm diameter, 1-mm wide MPFD as a function of reactor power as inserted into the center of a 250 kW TRIGA Mark II nuclear reactor, where (A) is a linear plot and (B) is a log–log plot. The most recent devices are only 1 mm in diameter, and are expected to perform with no appreciable deadtime losses with the TRIGA reactor at full power ($\phi_{th} > 10^{13}$ neutrons $\mathrm{cm^{-2}\,s^{-1}}$).

minute amount of uranium used permitted pulse mode operation without appreciable deadtime distortions or problems. Deadtime losses became noticeable at neutron fluxes above $10^{12}\,cm^{-2}\,s^{-1}$, reaching a maximum dead time loss of only 24% at a neutron flux near $5 \times 10^{12}\,cm^{-2}\,s^{-1}$. Thus far, the MPFDs have withstood neutron fluences exceeding $10^{19}\,cm^{-2}$ without noticeable performance degradation.

5. Conclusions and future work

MPFDs have, thus far, shown exceptional radiation hardness to neutrons, gamma rays, and charged-particle reaction products, while showing no performance degradation for devices exposed to neutron fluences exceeding $10^{19}\,cm^{-2}$. Further, pulse mode operated devices have shown a linear relation to reactor power for neutron fluxes up to $10^{12}\,cm^{-2}\,s^{-1}$, and smaller MPFDs are expected to operate in pulse mode in even higher neutron fluxes. The next generation of MPFDs will be composed of a triad of detectors on a single substrate, one with a ^{232}Th coating, one with a ^{235}U coating, and one with no coating [3].

Such a triad permits monitoring of the fast neutron flux, the thermal neutron flux, and the gamma ray background, all at the same time. Further, the devices behave as point detectors, which greatly simplifies data interpretation. Strips of triads have been designed for insertion into the axial probe holes of the K-State TRIGA Mark-II reactor core, each strip having five triad sets distributed equidistantly along the length of the core fuel. Overall, 75 triad sets are to be inserted in a segment of the core. The devices can be operated in either pulse mode or current mode.

Data from such a MPFD array can be converted into a power density map of the reactor core for real-time analysis. Mathematical models are under development that can relate the power density profiles in the reactor's fuel rods to the flux densities at the detector locations. Key to this formulation is the construction of an appropriate response function that gives the flux at any position in the core to the fast neutrons born at an arbitrary axial depth in any of the core fuel rods. Response functions have been derived and used to illustrate the analysis methods [1,3]. Thus far, modeled results using predicted sensitivities of the MPFDs indicated that the power density in the fuel can be determined provided that appropriate boundary conditions regarding device placement are met. Good matching to power density profiles can be achieved with as few as five detector triads per detector string [3,4].

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