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POSITION-SENSITIVE FISSION COUNTER FOR
IN-CORE FLUX PROFILE MONITORING*

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Oak Ridge, Tennessee 37831, USA**MASTER**Abstract

A prototype model of a position-sensitive fission counter (PSFC) was developed for power-range flux profile monitoring in light-water reactor cores. The flux profile is measured by delay-line position encoding and time interval decoding of individual fission pulses from 11 small fission counters incorporated along a coaxial transmission line. Significant improvements over currently used flux profile monitors are the 33-cm spatial resolution of the 3.5-m-long PSFC and the requirement for only one cable penetration into the reactor pressure vessel.

Introduction

Continuing research on advanced methods of thermal neutron detection¹ resulted in the development of a prototypic position-sensitive fission counter (PSFC) for in-core monitoring of axial flux profiles in light-water reactors. The inherently better spatial resolution capabilities and the requirement for only one coaxial cable penetrating the pressure vessel are the main advantages of this PSFC concept over currently used flux profile monitors.²

The main purpose of this research was to obtain data for the design of an engineering model of a PSFC and thereby enable the commercialization of this concept. We wanted to prove (a) that a spatial resolution better than 1 pixel per 90 cm is attainable, and (b) that fission counters are still operable in the pulse counting mode in the high gamma radiation fields ($>10^9$ R/h) present inside the core of light-water reactors operating at full power.

Description and Characteristics of the Test
Counters and Instrumentation

A prototypic PSFC was developed to measure the spatial resolution capabilities for fission-counter

pulses. Because this PSFC was not designed for in-core operation, a low-sensitivity fission counter was developed to model the pulse-counting capabilities of the PSFC in high gamma radiation field intensities of up to 3×10^9 R/h.

PSFC Prototype

The PSFC prototype is a 3.5-m-long coaxial transmission line (Fig. 1) with 11 small fission counters incorporated into the dielectric at 33-cm intervals. The outer diameter of the line is 1 cm, its impedance is $Z_0 = 50 \Omega$, and its propagation velocity is $v = 12.2$ cm/ns.

The neutron sensitivity of each of the 11 small fission counters is 10^{-6} cps/nv (nv = unit of neutron flux in neutrons per square centimeter per second). This sensitivity was selected to enable testing of the PSFC concept in the relatively low neutron flux (10^8 nv) at the beam holes of the ORNL High-Flux Isotope Reactor. (The sensitivity of these fission counters for an engineering model must be reduced to

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Fig. 1. The prototypic neutron flux monitor resolves 11 pixels over its 3.5-m length and requires only one coaxial cable penetration into the reactor pressure vessel.

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Fig. 1

achieve a count rate of 10^5 cps per counter at typical power-range flux levels.) The fissionable material is electroplated onto two metal rings per counter in the form of UO_2 . The inside cathode diameter of each fission chamber is 3 mm and the anode diameter (center electrode of the transmission line) is 1 mm, so that the resulting impedance of the fission counter is approximately equal to the line impedance of 50 Ω . Collimation of the fission fragments confines their trajectories to an annulus near the cathode, thereby maximizing the electron drift distance and thus the output pulse amplitude.³ The coating thickness is 2 mg/cm², the ^{235}U inventory per fission counter (2 rings) is 0.2 mg, and the collimator transmission efficiency is $\sim 1\%$.

The signal output end of the PSFC is sealed with a BNC coaxial connector for connection to the single 50- Ω coaxial cable required between the PSFC and electronic circuits for bias and pulse transmission. At the other end of the PSFC the transmission line is connected to an unterminated 5-cm-long, lumped-element delay line (50- Ω impedance, 10-ns delay). The PSFC was filled with 80% Ar + 20% CF_4 at 10^5 Pa for high electron drift velocity and short collection time.¹

The PSFC operates as follows: a current pulse is generated at the location of a neutron-induced fission in the $^{235}UO_2$ coating whenever the resulting fission fragment ionizes the counter gas volume and free electrons drift toward the anode in the applied electric field. One half of this current pulse propagates toward each end of the coaxial transmission line with a propagation velocity v . The pulse propagating toward the output connector arrives at the PSFC output at a time $t_1 = t_0 + x/v$, where t_0 is the time of fission and x is its location in relation to the connector output. The other pulse is reflected at the open circuit end of the lumped-element delay line and arrives at the PSFC output at $t_2 = t_0 + (2L - x)/v + 2D$, where L is the length of the coaxial line and D the total delay time of the lumped-element delay line. Thus, the time interval between the arrival times of the two halves of any current pulse at the PSFC output—a measure of the position of the fission event—is $T = t_2 - t_1 = 2[(L - x)/v + D]$. For values of $L = 3.5$ m, $v = 12.2$ cm/ns, and $D = 10$ ns, the range of this time interval is $77 \text{ ns} > T > 20 \text{ ns}$ for $0 < x < L$.

Low-Sensitivity Fission Counter

The low-sensitivity fission counter is made of stainless steel and is welded to the end-seal of an

MgO-insulated coaxial cable (Fig. 2). The active electrode gap between the flat faces of the coaxial anode-cathode cylinders is 1 mm. A 4-mm-diam centric portion of the anode face is coated with a thin layer of UO_2 . The total ^{235}U inventory is 20 ng, resulting in a neutron sensitivity of 2×10^{-8} cps/nv. The counter is filled with 95% Ar + 5% N_2 at 2×10^5 Pa pressure. The measured gamma sensitivity of the fission counter operating in the ionization current mode in a calibrated gamma field of 400 R/h is $0.25 \text{ pA} \cdot (\text{R/h})^{-1}$. The dimensions and sensitivity of this fission counter were chosen to simulate the design and performance characteristics of one of the eleven PSFC elements.

Fig. 2. The low-sensitivity fission counter simulates the performance characteristics of the PSFC components in high gamma fields ($>10^9$ R/h).

Counter Instrumentation

The PSFC instrumentation is composed of several units which are interconnected for the purpose of decoding the position coordinate of individual, neutron-induced fission events (Fig. 3).

An adjustable voltage supply is used to establish the electric field in the fission counters. The PSFC anode signals are amplified by a low-noise preamplifier having a gain of 100, a bandwidth of 400 MHz, input and output impedances of 50 Ω , and $<20 \text{ pA} \cdot \text{Hz}^{-1/2}$ noise referred to the input. The mercury-relay pulse generator sends test signals to the preamplifier input for amplitude and time calibration. The preamplifier output signals are processed by a filter amplifier, which uses a three-stage passive filter⁴ connected between four wideband gain stages (350-MHz bandwidth and 4.5 gain). The filter impulse response is a 20-ns-wide, unipolar output signal. The logic unit, connected to

Fig. 2

measured by an electrometer of 1 pA sensitivity, connected between the bias supply and the fission counter.

Experimental Results

PSFC Test

The spatial resolution capability of the prototype PSFC was tested with thermal neutrons from a beam hole (HB1) of the ORNL High-Flux Isotope Reactor. The estimated thermal neutron flux was 10^8 nv.

Because limited beam size did not allow full-length exposure of the PSFC, we sequentially accumulated the data of the position spectrum (Fig. 4) by moving the PSFC lengthwise across the neutron beam in incremental steps of 33 cm. Thus, at each step one of the 11 fission counters was centered in the neutron beam while position data was integrated for a 100-s time period.

The measured spatial uncertainty caused by timing error was <10 cm (fwhm) for all fission counters of the PSFC. The amplifier noise contribution, measured with reference signals from the pulse generator, was 3.6 cm (fwhm). Signals from fission counter positions 10 and 11 (closest to the lumped-element delay line) were not detected because the logic unit was unable to resolve pulse pairs separated by time intervals <30 ns.

Low-Sensitivity Fission Counter Test

The count-rate capability of the low-sensitivity fission counter was tested at two distances from the

Fig. 3. The position of a neutron-induced fission is decoded by measuring and recording the time interval ($T = t_2 - t_1$) between the components of the corresponding current-pulse pair from the PSFC encoder.

the filter amplifier output, responds to pulse pairs from the PSFC by generating two logic outputs ("start" and "stop"), separated by the time interval $T = t_2 - t_1$ between the arrival time of the two halves of a neutron-induced current pulse. The conditions for valid outputs are that both components of a pulse pair occur within the range $30 \text{ ns} < T < 100 \text{ ns}$, and cross a preset amplitude discriminator threshold. The time-interval spectrum of output pulse pairs from the logic unit is converted into a pulse-height spectrum in the time-to-amplitude converter (TAC) and stored and displayed in the pulse-height analyzer (PHA). The total conversion gain of these two units is 2.5 PHA channels per nanosecond.

The instrumentation for the low-sensitivity fission counter measures (a) the integral pulse-height spectrum of the fission-counter output signals, and (b) the ionization current as a function of gamma dose rate and applied bias. For the pulse-height spectrum measurement, the preamplifier, filter amplifier, bias supply, and test pulser are the same as for the PSFC tests. The filter amplifier impulse response is a 40-ns-wide, unipolar signal; its output is connected to a discriminator input. The discriminator, capable of responding to fast (20-ns-wide) pulses, generates a logic output signal for each pulse that crosses the discriminator threshold level. The logic output pulses trigger the scaler unit, which measures the count rate of pulses larger than the threshold level as a function of this level setting. The ionization current is

Fig. 4. The position spectra indicate that (a) the spatial error is <10 cm (fwhm) in all PSFC elements (the amplifier noise is <3.6 cm), and (b) the fractional variation in fission counter sensitivity for pixels -8 is $\sigma = 0.2$ relative to the mean sensitivity.

Fig. 3

Fig. 4
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core window in the Oak Ridge Research Reactor (ORR) at ORNL: (1) at 50 cm, and (2) as close as possible (<5 cm). At both positions we measured the ionization current of the fission counter as a function of bias voltage to establish its saturation characteristics (Fig. 5) and to calculate the gamma dose rate. The measured values of ionization current at 400-V bias for positions 1 and 2 were 9.6 μ A and 0.3 mA respectively. Using the measured gamma sensitivity of $0.25 \text{ pA}(\text{R/h})^{-1}$, the corresponding values of gamma dose rate were 3.8×10^7 and $>1.2 \times 10^9 \text{ R/h}$. (The true value of gamma dose rate at position 2 is larger than indicated because the ionization current was not fully saturated at 400 V.) Also, at both counter positions we measured the integral pulse-height spectrum in pulse-mode operation (Fig. 6). The neutron count rate, measured at the plateau of the pulse height distribution, was 600 cps at position 1, which corresponds to a neutron flux of $3 \times 10^{10} \text{ nv}$, based on a fission-counter sensitivity of $2 \times 10^{-8} \text{ cps/nv}$.

The neutron flux at position 2 was $8 \times 10^{13} \text{ nv}$ which would generate a neutron count rate of $1.6 \times 10^6 \text{ cps}$. The plotted data were corrected for discriminator dead time; however, for count rates $>10^6 \text{ cps}$, level-crossing saturation in the filter amplifier caused appreciable error in the pulse-height spectrum. On the other hand, for count rates $<10^6 \text{ cps}$, the measured values are consistent with the neutron flux at position 2. The values for the gamma pile-up distribution at position 2 (γ_2) were estimated from the extrapolated values of the gamma pile-up distribution at position 1 (γ_1) by using the ionization current data (Fig. 5) and a Gaussian pile-up model.⁵ The measured pulse-height distribution at position 2 also contains a small contribution from pileup of protons from the $\text{N}^{14}(\text{n,p})\text{C}^{14}$ reaction in the counter gas which has a positive Q value of 0.6 MeV.

Fig. 5. The ionization current of the low-sensitivity fission counter is not fully saturated because of low electric field regions outside the electrode gap.

Fig. 6. The fission counter is operable in the pulse counting mode in a $1.2 \times 10^9 \text{ R/h}$ gamma field and $8 \times 10^{13} \text{ nv}$ neutron flux (position 2).

Discussion

Preliminary data obtained from measurements with the prototype models of a PSFC and a low-sensitivity fission counter provide an adequate basis for the design of an engineering model of the PSFC concept for in-core flux profile monitoring in light-water reactors. An evaluation of these preliminary data indicates four modifications of the counter and instrumentation that should be incorporated into the design of the engineering model PSFC: (a) the dead time of the logic unit should be shortened to $<20 \text{ ns}$ or the delay time of the lumped-element delay line of the PSFC should be increased to $D = 20 \text{ ns}$ to enable the detection and position measurement of neutron-induced fission pulses from locations close to the open end of the PSFC transmission line; (b) variations in the relative detection efficiency of the 11 fission counter elements (Fig. 4) should be minimized by reducing variations in the UO_2 coating and collimator construction; (c) the fill gas of the PSFC should be changed

Fig. 5

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Fig. 6
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from Ar + CF₄ to 95% Ar + 5% N₂, because the latter has been successfully used in high-level gamma radiation fields² whereas a recent irradiation study with Ar + CF₄ shows⁶ that this gas mixture probably would dissociate, thus limiting the useful lifetime of the PSFC; and (d) the interelectrode gap should be decreased to compensate for the lower electron drift velocity of the Ar + N₂ gas mixture.

With these modifications a PSFC design is feasible for operation in a >10⁹ R/h gamma field as an in-core flux profile monitor for light-water reactors. The present work proves that fission counters are still operable in the pulse-counting mode in such gamma fields and that a spatial resolution of 10 cm (fwhm) over the 3.5-m active length of the PSFC is attainable.

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