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PROTON-RECOIL PROPORTIONAL COUNTER TESTS AT TREAT

by

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PROTON-RECOIL PROPORTIONAL COUNTER TESTS AT TREAT*

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Summary

A methane filled proton-recoil proportional counter will be used as a fission neutron detector in the fast-neutron hodoscope. To provide meaningful fuel-motion information the proportional counter should have: a linear response over a wide range of reactor powers (space charge effects are minimized); a good signal-to-background ratio (the number of high energy neutrons detected must be maximized relative to low energy neutrons, and ~~the~~ gamma ray sensitivity must be kept small); and a detector efficiency for fission neutrons above 1 MeV of approximately 1%. In addition, it is desirable that the detector and the associated amplifier/discriminator be capable of operating at counting rates in excess of 500 kHz. This paper reports on tests that were conducted on several proportional counters at the TREAT reactor. The goal of these tests was the determination of a set of counter parameters that would optimize fuel motion detection. The results show that a proton-recoil proportional counter with a methane gas pressure of 0.5 MPa, a counter diameter of 25.4 mm, an anode wire diameter of 0.0504 mm, and a length of 200 mm will be able to meet most of the hodoscope detector requirements.

Fuel Motion Detection

As part of the U.S. fast-reactor safety program, transient tests (1 to 30 s duration) are conducted on encapsulated fuel pins placed in the center of the Argonne-West Transient Reactor Test Facility (TREAT). A diagnostic requirement for these tests is the measurement of fuel motion before, during, and after failure of the tested fuel pins. Because the fuel pins are surrounded by flowing sodium, and containment walls with thicknesses varying between 10 and 25 mm, fuel motion is monitored by detecting fast-fission neutrons that are emitted by the fuel and that pass through the material surrounding the fuel pins. While fuel motion can also be monitored by detecting prompt fission gamma rays, the poor penetrability and low signal-to-background ratio of these gamma rays limits their usefulness in monitoring fuel motion.

The fast-neutron hodoscope[1,2] produces an image of the fuel pin through the use of a 360-slot steel collimator that is focused on the test fuel. Fission neutrons from each rectangular shaped slot are detected by individual neutron detectors and then converted into electronic signals that are counted and stored over time intervals as small as 0.6 ms.

The optimum hodoscope fuel motion detector should have a linear response over a TREAT power range of 0.8 to 15,000 MW, a signal-to-background S/B ratio that is greater than two, and an efficiency (approximately 1%) that is sufficient to ensure adequate counting statistics over the smallest data collection intervals (1 ms). The current neutron detector consists of a Hornyak button[3] mounted on a photomultiplier tube. While the Hornyak button has a high S/B ratio (due to good gamma rejection and high neutron energy threshold), it has a low efficiency and a non-linear response that increases with reactor power. While this non-linearity can be corrected analytically in most cases, this correction does increase the uncertainty in the measured fuel motion.

Recent work at Karlsruhe[4] has shown that a proton-recoil proportional counter can be operated linearly at high counting rates (approximately one megahertz) and at high reactor powers provided that space charge effects are minimized by keeping the detector gain low (10 to 20) and the gamma ray sensitivity small. The low gain requirement can be satisfied by the use of low-noise current amplifiers. The gamma sensitivity requirement is inherently satisfied in the collimated beam geometry of the hodoscope since by design the collimated beam interacts only with the material in the entrance and exit faces of the counters. Because the Karlsruhe work was limited to a pressure of 0.1 MPa and because they were unable to measure the S/B ratio, a series of tests on proportional counter performance were conducted at TREAT. The goal of these tests was to obtain an understanding of the impact of various counter parameters on the linearity, S/B ratio and efficiency.

Experimental

Two different series of tests were performed. The first series measured the linearity of the proportional counters in three transient tests with peak reactor powers of 3933, 3924, and 7232 MW. The gains of the detectors were changed between the 3933 and 3924 MW transients but were kept fixed between the 3924 and 7232 MW transients. A 12.7 mm sheet of lead was placed between the back of the collimator and the detectors for the 7232 MW transient.

The second series of tests measured the S/B ratio and detector efficiency for a single fuel pin surrounded by a steel containment that varied in thickness between 1.6, 12.7, and 25.4 mm. The signal in these tests corresponds to unscattered fission neutrons that are emitted by the fuel pin. The background is a combination of neutrons from the reactor fuel in back of the fuel pin and of neutrons from the reactor fuel that are scattered into the line-of-sight of the hodoscope by the test containment. In these tests the S/B ratio was measured by scanning the hodoscope across the fuel pin in small horizontal increments.

The physical characterestics of the proportional counters tested are given in Table 1. All of the counters were filled with methane gas and used a cylindrical field geometry. No attempt was made to minimize the amount of material in the entrance and exit windows.

TABLE 1. Physical charatteristics of the proportional counters tested.

Pressure (MPa)	Diameter (mm)	Anode Wire Diameter (mm)	Length (mm)	Manufacturer
0.5	25.4	0.0254	254	Reuter Stokes
0.2	25.4	0.051	102	LND
0.1	25.4	0.051	102	LND
0.1	25.4	0.102	102	LND

The gains of the detectors were calculated using the formula of Reference 5. The free parameters A and B in the gain curves were determined experimentally by a least-squares fit between the measured gains and the formula given in Reference 5. A value of 2.7/torr-mm was used for the constant A, and a value of 32.4 V/torr-mm for B.

Because of time limitations, the current-sensitive amplifier-discriminator system was the same as that used in a fission counter ionization chamber described in Reference 6. The noise level of this amplifier-discriminator system varied between 50 and 100 nA. This noise level corresponds to an approximate energy threshold of 120 to 240 keV for a counter gain of 10. The amplifier had an integration time constant of 60 ns and a differential time constant of 30 ns in the linearity tests. The pulse-pair resolution of the system was 800 ns.

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Linearity

Space charge is expected to be the major source of non-linearity in the count rate response of a proportional counter. At high reactor powers and high detector counting rates, the slow collection time of the positive ions (typical collection time for the tested counters varied between 0.6 and 2.5 ms) results in a reduction in the effective voltage of the counter. This in turn lowers the gain of the counter and produces a decrease in the observed counting rate.

The study of the counter linearity was broken into two parts. The first part experimentally measured the reactor power level at which a non-linear response was observed. The second part was concerned with finding a simple formula that would allow extrapolation of the experimental results to counters with different physical parameters.

Table 2 gives a summary of the proprotional counter parameters for the three transient tests. The power level at which a detector exhibited a non-linear response is shown in the sixth column of Table 2. The only detected non-linearity occurred in the 0.5 MPa detector during the 3924 and the 7232 MW transients. Figure 1 shows the TREAT power and the measured counting rate of the 0.2 and 0.5 MPa proportional counters for the 3924 MW transient. The Hornyak button response is shown for reference.

TABLE 2. Proportional counter parameters and results for the three transient tests. A dash in the sixth column indicates that the detector response was linear over the entire power range of the transient.

Peak Reactor Power	Pressure	Wire Radius	Voltage	Gain	Power of Non-Linear Response	
					Expt.	Theor.
(MW)	(MPa)	(mm)	(V)		(MW)	
3933	0.5	0.0127	3622	9	-	3100
	0.2	0.0254	2904	14	-	22600
	0.1	0.0254	1905	25	-	43500
	0.1	0.0504	2591	15	-	151000
3924	0.5	0.0127	3960	21	1800	1600
	0.2	0.0254	3250	50	-	8590
	0.1	0.0254	2200	155	-	9440
	0.1	0.0508	2918	62	-	46720
7232	0.5	0.0127	3960	21	1400	1600
	0.2	0.0254	3250	50	-	8590
	0.1	0.0254	2200	155	-	9400
	0.1	0.0254	2918	62	-	46720

It is possible, using a model of the space charge effect developed by Henricks[4] and some simplifying assumptions, to develop an equation that describes the relative behavior of space charge effects between proportional counters with different physical parameters. The use of the non-linearity data from Table 2 then allows the prediction of the reactor power levels at which other detectors will become non-linear.

In Henricks' model the percent change in the proportional counter voltage is given as

$$\Delta \frac{V}{V} \propto \frac{ITG}{VL} , \qquad (1)$$

where I is the total current, T is the transit time of the positive ions, G is the gain, V is the voltage, and L is the length of the counter. The change in voltage produces a decrease in the count rate because it effectively reduces the gain. Rather than try to determine the exact relationship between the percent voltage change and the percent count rate change it will be assumed in the following that the percent voltage change is proportional to the percent count rate change for the class of detectors being investigated.

The current I of the counter is proportional to the efficiency, the TREAT power W, and the total energy lost by the incident beam. The efficiency of the counter is in turn proportional to the gas pressure P and the length L. Because most of the incident particles are not stopped in the counter (the range of a 1 MeV proton in a 0.5 MPa detector is 16 mm), it is reasonable to assume that the total energy loss is also proportional to the gas pressure. Thus

$$I \propto PLWP . \qquad (2)$$

Substituting *Equation* 2 *into* Equation 1 then gives

$$\Delta \frac{V}{V} \propto \frac{WTGP^2}{V} . \qquad (3)$$

The observation that the 0.5 MPa detector exhibited a non-linear response at a power level of 1400 to 1800 MW can now be used along with Equation 3 to predict at what power levels other detectors with different parameters will become non-linear. The last column in Table 2 gives these predicted values assuming that the 0.5 MPa detector became non-linear at 1600 MW. A positive ion mobility of 2.75 cm/s per v/cm was used to calculate the transit times. In general, Equation 3 appears to qualitatively take into account changes in counter pressure, gain, anode radius, and length in predicting space charge effects.

Equation 3 indicates that the pressure of a proportional counter must be kept as low as possible if space charge effects are to be minimized. The data show that the 0.1 and 0.2 MPa detectors will easily meet the linearity requirements of the hodoscope detector system provided that the counter gain is kept near 10. The tested 0.5 MPa detector will not have a linear response over the required TREAT power range. However, by reducing the gain by 40% and by increasing the tube voltage, the linear response of the 0.5 MPa detector can be extended to a TREAT power of 10,000 MW.

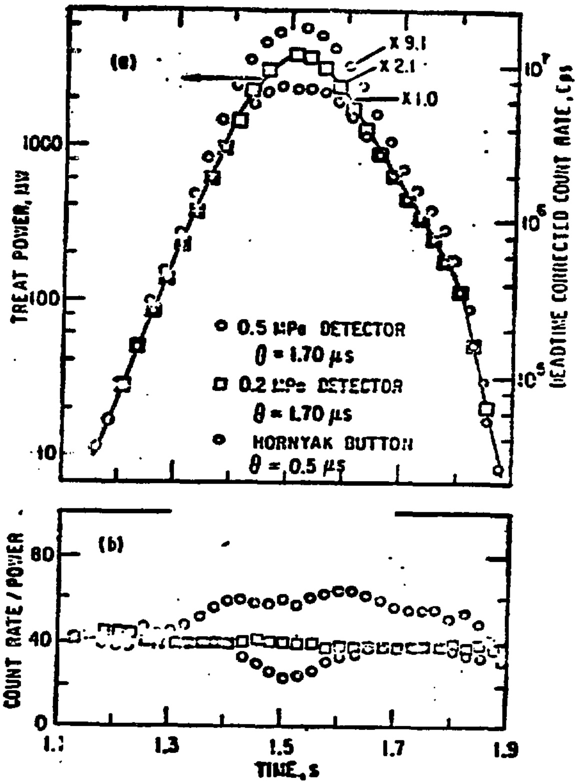

Fig. 1a. Reactor power and detector response as a function of time. The numbers associated with each curve show the amount by which data was multiplied.

1b. The detector count rate divided by the reactor power.

Signal-to-Background Ratio

The signal in the hodoscope consists of unscattered fission neutrons from the fuel pin. Since the energy spectrum of these neutrons will be harder than the energy spectrum of the background neutrons that have been scattered one or more times, the S/B ratio will increase as the energy of the detected neutron increases[8]. Thus optimization of the S/B ratio for a hodoscope detector consists in varying the counter parameters and discriminator threshold to maximize the number of high energy neutrons detected while minimizing the number of low energy neutrons.

Some typical hodoscope scans of a single fuel pin are shown in Fig. 2. The containment thickness is 12.7 mm. Data from the 0.2 MPa, 0.5 MPa, and the Hornyak button detector are presented. The reactor power during the tests was 80 kW.

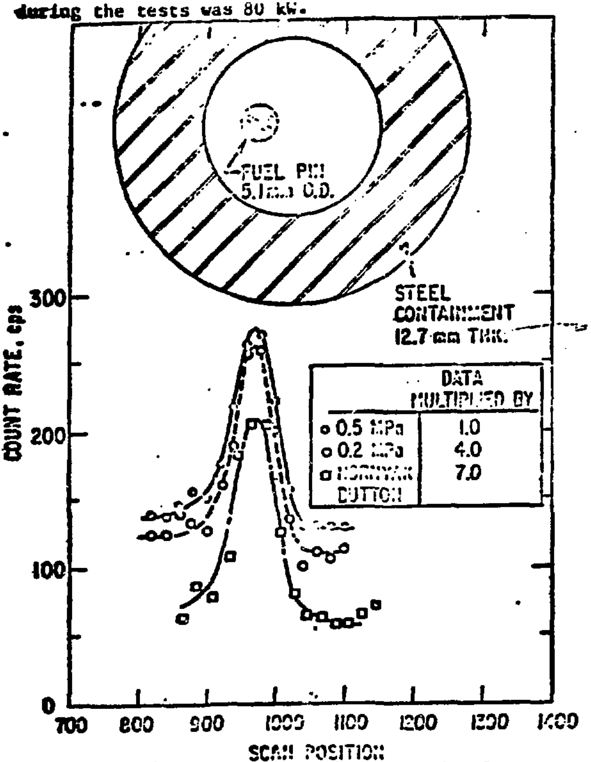

Fig. 2. Hodoscope scan with proportional counters and Hornyak button of a single fuel pin. The reactor power was 80 kW.

The S/B ratio as a function of discriminator threshold is shown in Fig. 3. The counting rate as a function of threshold is also shown for reference. The increase in the counting rate at low discriminator thresholds is due to the presence of gamma rays. The decrease in counting rate at high thresholds is due to a rapid decrease in the detection efficiency of the proportional counter for high energy neutrons. The decrease occurs because the average energy loss by recoil protons from high energy neutrons is smaller than the discriminator threshold energy. This also explains why the rapid decrease in detector efficiency for the 0.5 MPa detector occurs at a higher energy threshold than that of the 0.1 MPa detector.

Figure 3 shows that the S/B ratio of the 0.5 MPa detector is closest to that of the the Hornyak button. The data also indicate that the S/B ratio improves as the neutron threshold is increased. A limitation on how much the S/B can be improved is set by the change in the detector efficiency. In going from a threshold of 0.3 MeV to 1.5 MeV the S/B ratio of the 0.5 MPa detector improves by a factor of 2.5 while the efficiency decreases by 3.5. However, in going from 1 .5 MeV to 3.0 MeV the S/B ratio improves by a factor of 1.7 while the efficiency decreases by a factor of 100. Results

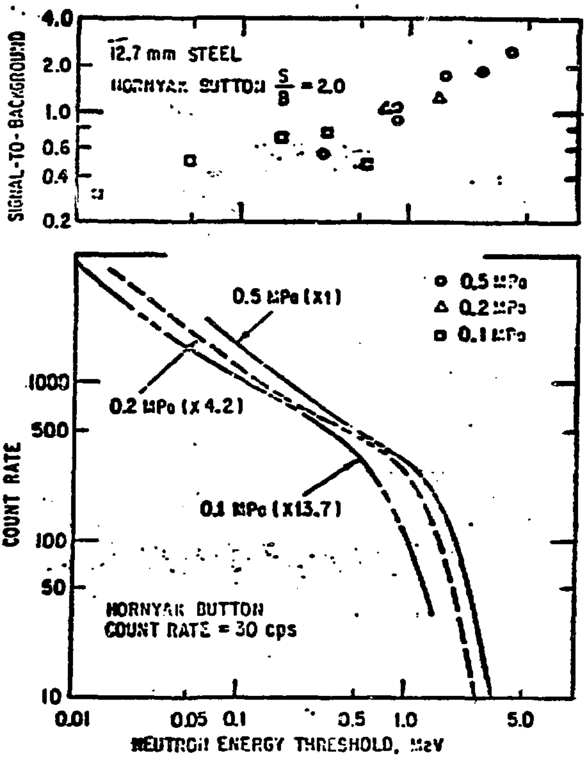

Fig. 3. The measured S/B ratio and the detector count rate as a function of neutron energy threshold. Because the detector current is not a simple function of the neutron energy, the energy scale is only approximate.

similar to Figure 3 were obtained for a containment thickness of 25.4 mm.

The TREAT experiments indicate that it is necessary to operate the proprotional counters at a high pressure in order to obtain a S/B ratio similar to that of the Hornyak button detector. For a 0.5 MPa detector with a neutron energy threshold of 1.5 MeV the S/B ratio of the proportional counter will be within 15 to 25% of the Hornyak button. The data also suggest that the S/B ratio of a proportional counter could be improved by increasing the counter radius since this would allow higher energy neutrons to lose more energy in the counter.

Detector Efficiency

The detector efficiency results are summarized in Table 3. They were taken from the data presented in Fig. 3 and were normalized to a tube length of 200 mm. The Table shows that the 0.5 MPa detector has an efficiency that is an order of magnitude better than the Hornyak button detector, even at a threshold of 1.5 MeV. The absolute efficiency at this threshold is approximately 1% which is in aggreement with the 0.15% measured efficiency of the Hornyak button.

Table 3. Efficiencies of the proportional counters relative to the Hornyak button.

Threshold (MeV)	Pressure (MPa)	Length (mm)	Count Rate Ratio PC/HB
0.3	0.1	200	2.8
0.3	0.2	200	9.6
0.3	0.5	200	19.
1.5	0.1	200	0.18
1.5	0.2	200	1.8
1.5	0.5	200	11.

Maximum System Counting Rate

In the transient tests the electronic system had a pulse pair resolution of 800 ns. As shown in Fig. 1, however, the measured deadtimes were considerably larger. (These deadtimes correspond to a maximum counting rate of approximately 550 kHz.) The exact reason for this discrepancy between the measured dead times and the pulse-pair measurements is not clearly understood. While it is possible that this discrepancy is due to space charge effects, a more likely explanation is pulse pile-up on the negative portion of the differentiated counter pulse as described in Reference 9. This suggests that some type of baseline restoration will be required in the final electronic design if counting rates of 1 MHz are to be achieved.

Final Proportional Counter Design

The final design of the proportional counter fuel motion detector involves a tradeoff between the range of reactor powers over which the counter will be linear, and the S/B ratio of the detector. In the final design we have chosen to emphasize the S/B ratio and limit the linear range of the detector.

The S/B ratio is maximized by operating the counter at high gas pressures and by using large tube diameters. The tube diameter of 25.4 mm is fixed by space limitations behind the collimator. The gas pressure of 0.5 MPa was chosen because it gave a S/B ratio only slightly worse than the Hornyak button while still allowing the detector to cover a reasonable range of TREAT powers.

Space charge effects can be minimized by raising the operating voltage of the counter. By increasing the anode radius from 0.0127 mm to 0.0254 mm, the operating voltage will increase to approximately 6000 volts. The higher voltage should extend the TREAT power at which the detector response becomes non-linear by a factor of two. A further increase will be obtained by designing the amplifier-discriminator system to operate at gains as low as six. In addition, the gamma sensitivity of the counters is also being reduced by offsetting the collimator beam from the electrical insulators in the center of the tube. a sketch of the final proportional counter design. It is expected that this counter will have a linear response up to TREAT powers of 10,000 MW

The choice of the above counter parameters has had some impact on the desgin of the mechanical components of the detector array. In particular the need to minimize high voltage breakdown in the detector components over the projected 10 year lifetime of the system has resulted in the entire array being enclosed in a [illegible] that will be filled with sulfur hexaflouride at atmospheric pressure. Since operating experience may suggest a slightly different gas pressure, provision has been made through the use of a long pump-out tube to allow the gas pressure to be changed at least three times.

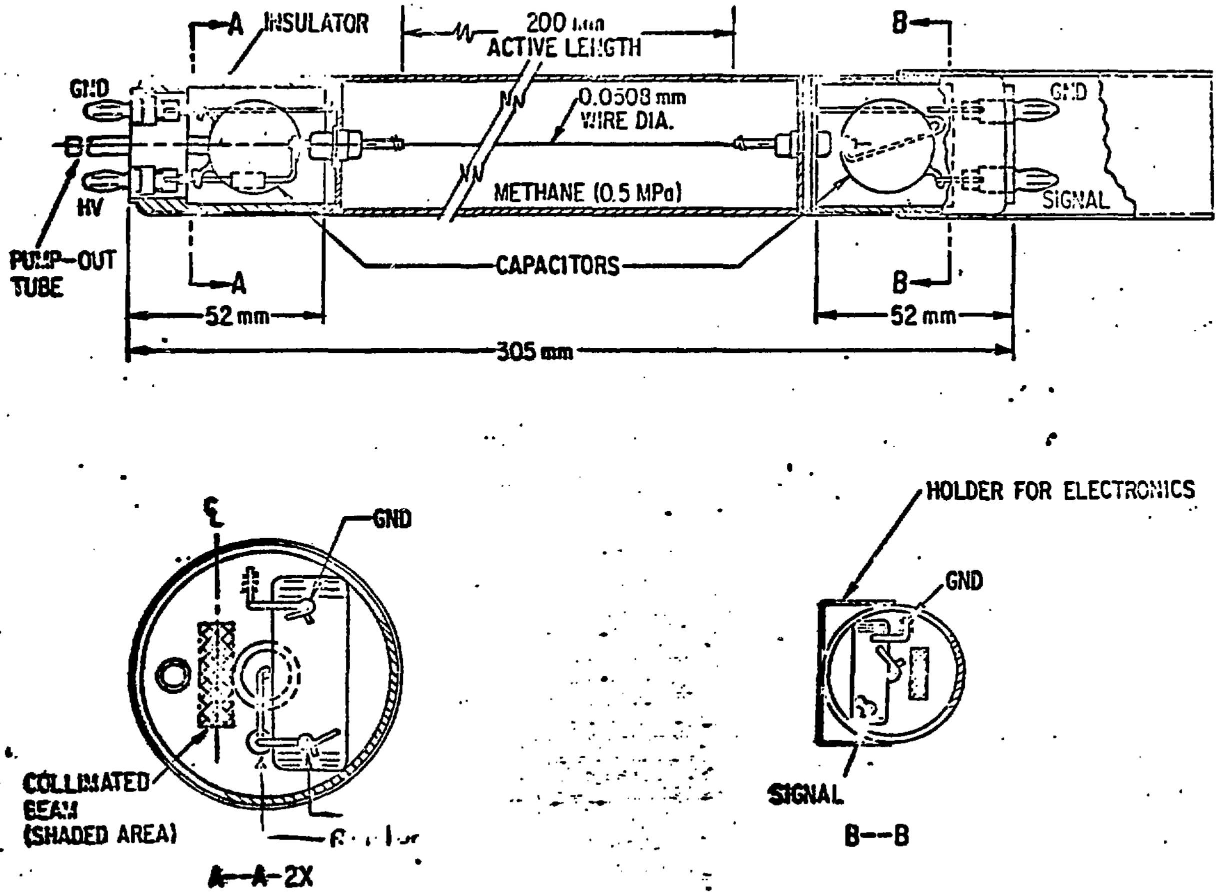

Fig. 4. Sketch of the proposed proton-recoil proportional counter.

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