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IMPROVEMENTS IN TREAT HODOSCOPE FUEL-MOTION CAPABILITIES*

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ABSTRACT

The fast-neutron detection system of the hodoscope has been a major ingredient in the success of the hodoscope as a fuel-motion monitoring device. While the original Hornyak-button detector system has met most of the current fuel-motion needs, the more stringent requirements of improved reactor-safety codes, and of new experimental test facilities necessitate improved detection capabilities. Development efforts have centered on three areas: the construction of an array of proton-recoil proportional counters to be used in conjunction with the Hornyak-button detectors, the upgrading of the Hornyak-button detectors to increase linearity and signal-to-background ratio, and the intercalibration of detectors using a modified horizontal and a new vertical scan system.

INTRODUCTION

As part of the U.S. fast-reactor safety program, experiments are being performed in the Transient Reactor Test Facility (TREAT) at Argonne-West. These experiments primarily investigate the various types of fuel motion that could occur in hypothetical core-disruptive accidents. A typical experiment involves one to seven fuel pins. These pins are encased in a steel containment and usually surrounded by sodium. The entire test apparatus is placed in the center of the TREAT core where it is subjected to a burst of reactor neutrons that produces fissions in the test fuel (a typical transient lasts from 2 to 20 s). The induced fission rate is sufficient to simulate the thermal environment of the fuel under both normal and abnormal reactor operating conditions.

Of particular interest in the transient tests is the quantitative determination of the timing and the magnitude of any fuel motion that occurs. From a detection point of view this task is complicated by (1) the large amount of steel surrounding the test pins (typically 12 to 50 mm), (2) the fact that the reactor power typically changes by three to four orders of magnitude during a burst, (3) the requirement that fuel motion be measured over time intervals as short as 1 ms for time periods of up to 20 s, and (4) the high-background radiation from neutrons and gamma rays that originate directly in the core or that are scattered by the steel test containment.

* Work perfomred under the auspices of the U.S. Department of Energy.

The *fast-neutron* hodoscope[1] is the principal fuel-motion detection device at the TREAT reactor. The layout of the imaging and detection components of the hodoscope, in relationship to the TREAT reactor, is shown in Fig. 1. The hodoscope views the fuel pins through an open slot in the north face of the TREAT reactor. Images of the pins are produced by a 360-slot cross-focused collimator. The image is detected by two independent detector arrays. Each array consists of 360 detectors (one detector behind each slot). Hornyak button detectors were used in the original array, and proton-recoil proportional counters are used in the new array just implemented. Also shown in Fig. 1 are two sections of lead filters (with variable thicknesses from 0 to 76 mm) that can be used to attenuate the count rate from the test section. A more detailed description of the hodoscope collimator and detector arrays is presented in Fig. 2.

The third component of the fast-neutron hodoscope, which is not shown in Fig. 1, is the data acquisition system[3]. It is located approximately 25 m from the detector array in the hodoscope control room. The acquisition system currently consists of a magnetic-disk, a tape unit, and a camera system. The disk system is capable of collecting a total of 8192 samples of data for sample times as short as 1 ms; each sample consists of 12 bits of scaler data for each of the 720 detectors.

A major reason for the success of the fast-neutron hodoscope is the use of Hornyak-buttons to detect fast neutrons that serve as a characteristic signature of the fuel. While the original Hornyak-button detector has met most of the current fuel-motion needs, new requirements will necessitate further gains in fuel sensitivity. At present, these improvements have centered on three areas: (1) efforts to improve the signal-to-background ratio, and the linearity of the Hornyak-button detector, (2) installation of a proportional-counter detector array, which should have improved linearity and stability, (3) mechanical improvements in the alignment of the detectors, and (4) new scanning capabilities for the determination of the detector efficiencies prior to a transient.

DETECTOR REQUIREMENTS - GENERAL

There are a wide range of physical requirements that a detector must meet to provide useful fuel-motion information. In general the actual detector parameters chosen will involve compromises. The following gives a brief description of some general detection requirements, and discuses their impact on the physical properties of a hodoscope detector.

Signal-to-Background Ratio

Probably the most important parameter in the choice of a fuel-motion detector is its signal-to-background, S/B, ratio. The bottom half of Fig. 3 shows the response of a single collimator slot and its associated detector as the slot is moved horizontally across a fuel pin. A cross section of the fuel pin and the surrounding steel and graphite containment is shown at the top. The data is for a Hornyak-button detector. The measured S/B ratio of 1.45 is typical of that found in single-pin tests at TREAT.

The best S/B ratio is obtained by choosing a signature from the fuel that is (1) not strongly attenuated by the surrounding steel, and (2) as different as possible from the background radiation that is scattered or created in the containment walls. Measurements[4] suggest that fast neutrons, in general, have a better S/B ratio than gamma rays of comparable energies, and that the S/B ratio slowly improves as the neutron energy is increased.

Thus the preferred fuel-motion detector is sensitive to high-energy neturons (energies greater than one MeV), and insensitive to both low- and high-energy gamma rays.

High Count-rate Capability

Since fuel motion must be detected over time intervals as short as one millisecond, the imaging detectors should be capable of generating sufficient counting statistics. This requirement implies counting rates of 300 to 500 kHz, and means that the detector pulse duration must be kept below 100 ns. In addition, the detector ought to have a large enough efficiency, after integration over a fission spectrum, to permit reaching these maximum count rates.

Linearity

Typically the reactor power varies over a range of three to four orders of magnitude during a reactor power burst. To allow normalization of data without introducing spurious fuel motion, the detector should respond linearly to changes in reactor power. A non-linear response can be tolerated provided it is known well enough to allow analytical correction of the measured response.

Stability

Because some fuel moves slowly in a transient, the detectors should not exhibit drifts due to count rate or power changes. Also the detector response should be stable over time periods of several months to minimize uncertainties in detector efficiencies, and to provide direct information on the fuel-pin calibration factor.

Size and Cost

The confined space behind the imaging collimator limits the size of a detector package to a diameter of 25 mm. Because 360 individual detectors and amplifier/discriminators are required for the array, the cost of the detector and the electronic package must be limited. In particular, complicated gamma-ray discrimination techniques are not feasible because of expense.

HORNYAK-BUTTON DETECTOR SYSTEM

A Hornyak-button[5] was used as the original detector in the fast-neutron hodoscope. This detector has the advantage of a good S/B ratio, a low gamma-ray sensitivity without complicated electronics, and a high count-rate capability. The main disadvantage is a non-linear response, which can usually be corrected analytically.

Description

A sketch of the Hornyak-button detector and its associated electronics is presented in Fig. 4. Light from the ZnS(Ag) in the scintillator section is amplified by the photomutiplier tube and the resulting current pulses are sent a distance of 23 m to an amplifier/discriminator board located in the hodoscope control room. After amplification, digital pulses from the disciminator are routed to individual scalers.

The Hornyak button consists of a composite of lucite and ZnS(Ag) grains (five weight-percent ZnS(Ag) with a grain diameter of 40 microns). Neutrons interacting within the hydrogenous material produce recoil-protons that are detected as they pass through the ZnS(Ag) scintillator. Since electrons from gamma-ray interactions lose considerably less energy in the grains than do the recoil protons, gamma-ray discimination can be accomplished by pulse-height selection without complicated electronics.

The hodoscope electronics are designed to used the fastest decay component[6] (70 to 100 ns) of the ZnS(Ag) phosphor. Thus the detector can easily operate at count rates of several-hundred-thousand counts per second.

The measured efficiency of the Hornyak button is shown in Fig. 5. The calculated curve is from Reference 7. A fission spectrum is shown for reference. The discriminator threshold of the detector was set to exclude a majority of the gamma-rays produced in the detector. The efficiency of the Hornyak button in Fig. 5, after integration over a fission spectrum, is 0.15%.

The results from Fig. 5 show that the Hornyak button, at typical discriminator thresholds, is relatively insensitive to low-energy neutrons and that the efficiency above 3 MeV gradually increases with energy. Extrapolation of the data in Fig. 5 suggests that the Hornyak button would be a good choice for experiments that require detection of neutrons with energies of 5-15 MeV in areas with high backgrounds of gamma-rays and low-energy neutrons[8].

Improvements in the Hornyak Button

The main advantages of a Hornyak-button are the good S/B ratio (see Fig. 1) that is obtainable at reasonable detector efficiencies, the gamma-ray insensitivity, the high count-rate capability, and the low cost per detector.

There are two main disadvantages in the use of a Hornyak-button. The first is a non-linear count-rate response that increases faster than the reactor power. The second disadvantage is a count rate instability that is sometimes seen during a transient. Mathematical models have been developed to provide an analytical correction for both of these effects[1]. While these models appear to provide reasonable corrections to the data, their use does add uncertainty to the hodoscope fuel-motion results.

Work on increasing the effectiveness of a Hornyak button as a fuel-motion device has centered on improving the linearity of the detector and on increasing its S/B ratio. Studies performed during a transient suggest that the that supralinear response is due to a large current (10 to 50 nA) flowing through the photomultiplier. The major component of this current is probably due to the long-decay components of the ZnS(Ag) scintillator[9].

These large currents appear to cause an increase in the gain of the photomultiplier tube (and subsequently the count rate) in two distinct ways. The first effect occurs at the high end of the current range and is due to a redistribution of the bias voltage from the last few stages to earlier stages[10] that results in a net increase in photomultiplier gain.

The second increase in gain occurs at lower currents (5-20 na). The increase appears to be due to the use of low interstage voltages (60-80 V) between the dynodes. Experiments suggest that at these voltages small changes in the photomultiplier-tube current can result in gain changes, which vary from tube to tube. This effect can be reduced by increasing the interstage dynode voltages.

Attempts to limit these gain changes have centered on use of zener diodes on the last one or two stages and the investigation of photomultiplier tubes with a smaller number of stages to allow operation at higher interstage voltages. Investigations have also been made of a Hornyak button using a scintillator with a lower total light output than ZnS(Ag).

The second area of Hornyak-button improvement centers on increasing the S/B ratio without decreasing the detector efficiency. This increase is required for future fuel-motion tests in the TREAT upgrade reactor, in which the fuel pins will be surrounded by thicker capsule walls, and in which the calibration factors of the fuel will be considerably smaller.

The S/B ratio of a fuel-motion detector can be improved by increasing the average energy of the detected neutrons. Theoretical calculations[7] have been made on the effect of grain size, grain concentration, detector size, and light transparency on the neutron efficiency and gamma-ray sensitivity of a Hornyak button. These studies suggest the changes in the present Hornyak-button parameters can increase the sensitivity to neutrons with energies above 5 MeV without decreasing the absolute detector efficiency.

At the present time several new types of Hornyak-button detectors are being designed for tests at the TREAT reactor.

PROPORTIONAL-COUNTER ARRAY

There were two main goals behind the construction of a second detector array for use in fuel-motion studies. The first was the desire to have a completely redundant data-detection and data-collection system to reduce the possibility of data loss during expensive fuel-motion tests. The second was to provide a detector that had a linear and stable response, which would complement the Hornyak button.

The choice of a proton-recoil proportional counter was based on work done in Karlsruhe for the CABRI hodoscope[11]. This work had shown that a 0.1 MPa (1-atm) proton-recoil proportional counter was capable of operating linearly at high count rates and over a wide range of reactor powers. The key to this linear performance was the operation of the proportional counter in the current mode, and the use of a low-noise current amplifier, which would permit operation at gains as low as 10-15.

A major disadvantage of the 0.1 MPa proportional counter was the relatively poor S/B ratio at reasonable detector efficiencies. Experiments at the TREAT reactor indicated that both the S/B ratio and the efficiency of the proportional counter could be made comparable to that of the Hornyak button if the gas pressure of the counter was raised to 0.5 MPa. The use of this higher pressure, in turn, required that the proportional counter be operated at voltages of ~6000 V to minimize space-charge effects.

Description

A sketch of the proportional counter is shown in Fig. 6. The counter is filled with methane at a pressure of 0.5 MPa (5 atm). The anode wire is made of tungsten and is 0.0508 mm in diameter. The proportional counter has an active length of 200 mm, and a diameter of 25.4 mm. In Fig. 6, the neutrons from the collimator slot enter from the left and exit at the right.

Because of space limitations, the high-voltage connection is made at the front of the detector while the signal is taken off the back. This arrangement saves space, but does increase the chance that a high-voltage arc on the signal side of the counter could destroy the anode wire. High-voltage arcing is minimized by careful choice of components, by strategic placement of insulators in the high-voltage regions, and by placing the detectors in an enclosure filled with SF_6. The use of SF_6 also serves to reduce spurious noise pulses arising from corona discharge.

The current amplifier and discriminator are mounted directly behind the signal leads of the detector to minimize noise effects. The electronics are contained in a 12.7 mm wide by 102 mm long package that is mounted outside the beam. A sketch of the amplifier and discriminator circuit is shown in Fig. 7. The amplifier has a noise sensitivity of approximately 100 nA and a rise time of 50 ns. Signal cables are provided to allow control of the discriminator threshold voltage from the hodoscope control room.

In addition to a shielding enclosure for each amplifier and discriminator, the entire array of detectors and electronics is r/f shielded from reactor noise by the aluminum SF_6 enclosure. Only the high-level discriminator output signal is sent to the hodoscope control room from the proportional counter enclosure.

One of the design requirements for the detector array was a pulse-height versus discriminator response that was the same for all detectors to within 10%. This requirement was met by (1) matching the gains of each of the proportional counters, and (2) providing provisions in each electronic package for ajustment of the amplifier gain and the discriminator zero level.

The gamma-ray sensitivity of the detector was minimized to avoid degradation of the S/B ratio and to reduce the gamma-ray contribution to space-charge effects. The decrease in gamma-ray sensitivity was accomplished by off-setting the center of the counter from the collimator beam, by machining the entrance and exit plates of the detector to a thickness of 1.1 mm (in the collimator beam area), and by placing the electronics outside the beam.

Each proportional counter is wrapped in an insulating sleeve and mounted in a steel support tube that is aligned with the collimator slot. For ease of maintenance and repair, the array has been divided into four interchangable quarter-panels. The cost of each detector was approximately $225. The cost of the amplifier and discriminator module was $25.

Discussion

The three detector parameters of interest, in terms of fuel-motion detection, are the S/B ratio, the efficiency, and the linearity. Figure 8 shows the variation in S/B ratio and detector efficiency (in this figure the count rate is proportional to the efficiency) for three proportional counters with different gas pressures. The S/B ratio and the efficiency of the Hornyak button is shown for reference. The data clearly indicate that a 0.5 MPa detector is required if the S/B ratio and the efficiency of a proportional counter are to be comparable with that of a Hornyak buton.

The main problem with the use of a high gas pressure is the fact that space-charge effects are proportional to the square of the gas pressure[12]. Some of this increase sensitivity to space-charge effects can be offset, however, by raising the operating voltage of the proportional counter. Tests at TREAT suggested that using voltages of 5000 to 6000 V should decrease the space charge enough to allow linear operation of a 0.5 MPa proportional counter over the entire TREAT reactor power range.

The count-rate response of a proportional-counter detector to a reactor transient (peak power of 4000 MW) is shown in Fig. 9. The reactor power is indicated by the solid line. A total of 76 mm of lead was placed in front of the proportional-counter array to reduce the maximum count rate. The peak counting rate of the detector is 260,000 cps, and the deadtime of the detector and its associated electronics is 400 ns. The good agreement between the reactor power and the proportional counter indicates that space-charge effects were negligible in this test.

Status

A total of 250 proportional-counter detectors have been recently installed at the TREAT facility. The system is still in an initial testing and debugging stage, but preliminary examination of the transient data for fuel-motion test C02 indicates good agreement with the main features of the Hornyak-button data.

The detectors appear to be very stable (less than a +/- 2% variation in count rate over a period of two weeks). In addition, the pulse height response as a function of discriminator voltage is essentially the same for all of the detectors. This means that the efficiency of the entire array of detectors can be modified by simply changing the supply threshold-supply voltage rather than ajusting each individual detector threshold voltage.

MECHANICAL IMPROVEMENTS

In conjunction with the installation of the proportional-counter array, work was completed on an improved horizontal and a new vertical scan system. These new systems allow the hodoscope collimator to be scanned both vertically and horizontally under computer control. While the principal use of the new scanning system is in obtaining radiographic information (using fast-neutrons) on the fuel disposition prior to and after a test, the new scanning capabilities offer the possibility of determining both the relative efficiency of all of the detectors as well as the TREAT flux shape. The use of the reactor to calibrate the detectors should lead to considerable improvement in the uniformity of detector response during a transient.

CONCLUSIONS

The current and planned improvements in the hodoscope-detector systems coupled with the new mechanical features of the hodoscope collimator should provide increased sensitivity to fuel. With this increased fuel-motion sensitivity it is likely that most of the requirments imposed by the current reactor-safety codes and by the new test facilities can be met.

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Fig. 1. Sketch showing the relationship between the TREAT reactor and the hodoscope collimator and detection systems.

Fig. 2. Detailed elevated view of the TREAT cross-focused collimator.

Fig. 3. Hodoscope scan of a single fuel pin with a Hornyak-button detector.

Fig. 4. Sketch of a typical Hornyak-button detector and its associated electronics.

Fig. 5. Efficiency of the Hornyak button as a function of neutron energy.

Fig. 6. Sketch of a proton-recoil proportional counter.

Fig. 7. Schematic of a proportional-counter amplifier/discriminator circuit.

Fig. 8. Relationship between the signal-to-background ratio and detector efficiency as a function of neutron energy for three different proportional-counter pressures.

Fig. 9. The detector count rate divided by TREAT power for a typical proportional counter. Peak reactor power is 4000 MW.

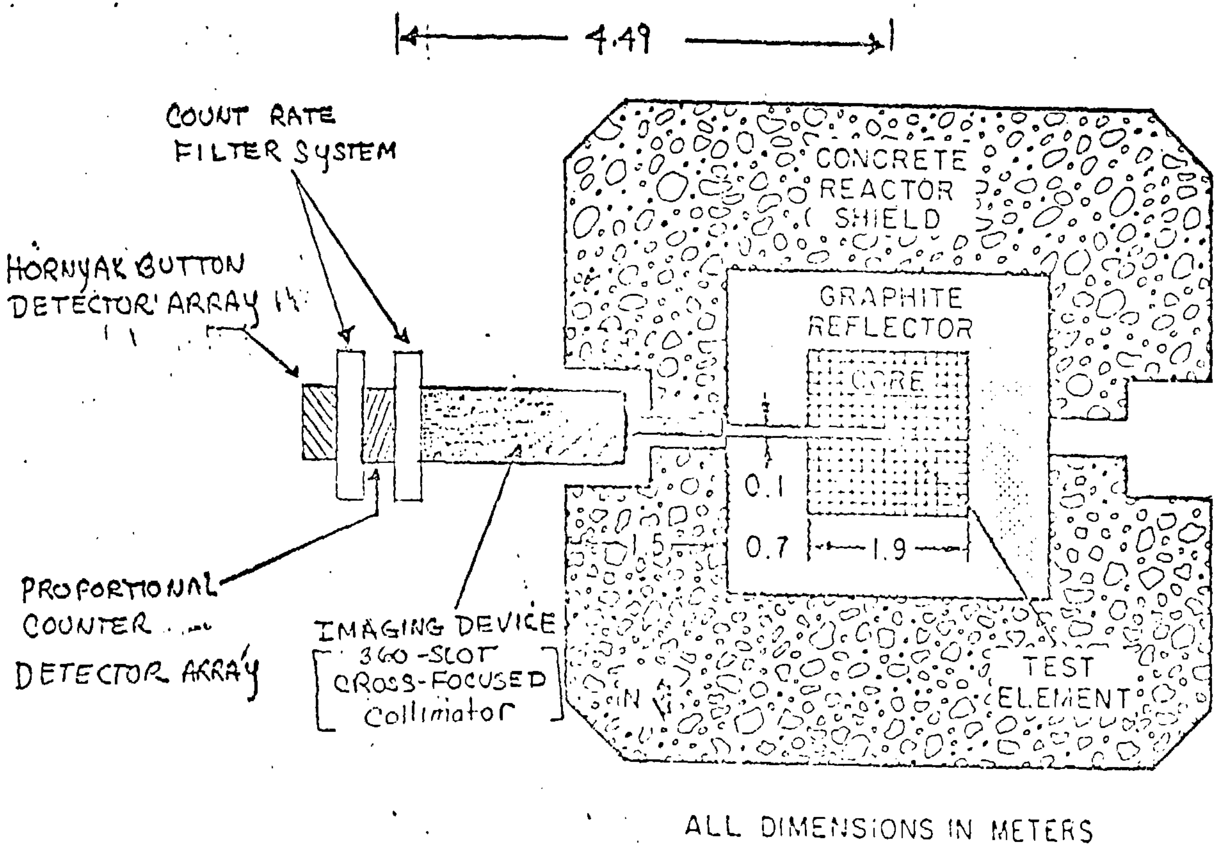

4.49
COUNT RATE FILTER SYSTEM
HORNYAK BUTTON DETECTOR ARRAY
CONCRETE REACTOR SHIELD
GRAPHITE REFLECTOR
CORE
0.1
0.7
1.9
1.5
TEST ELEMENT
PROPORTIONAL COUNTER DETECTOR ARRAY
IMAGING DEVICE
360-SLOT CROSS-FOCUSED Collimator
ALL DIMENSIONS IN METERS

Fig. 1

(1)

MODIFIED 1.2 m (48 in) HODOSCOPE

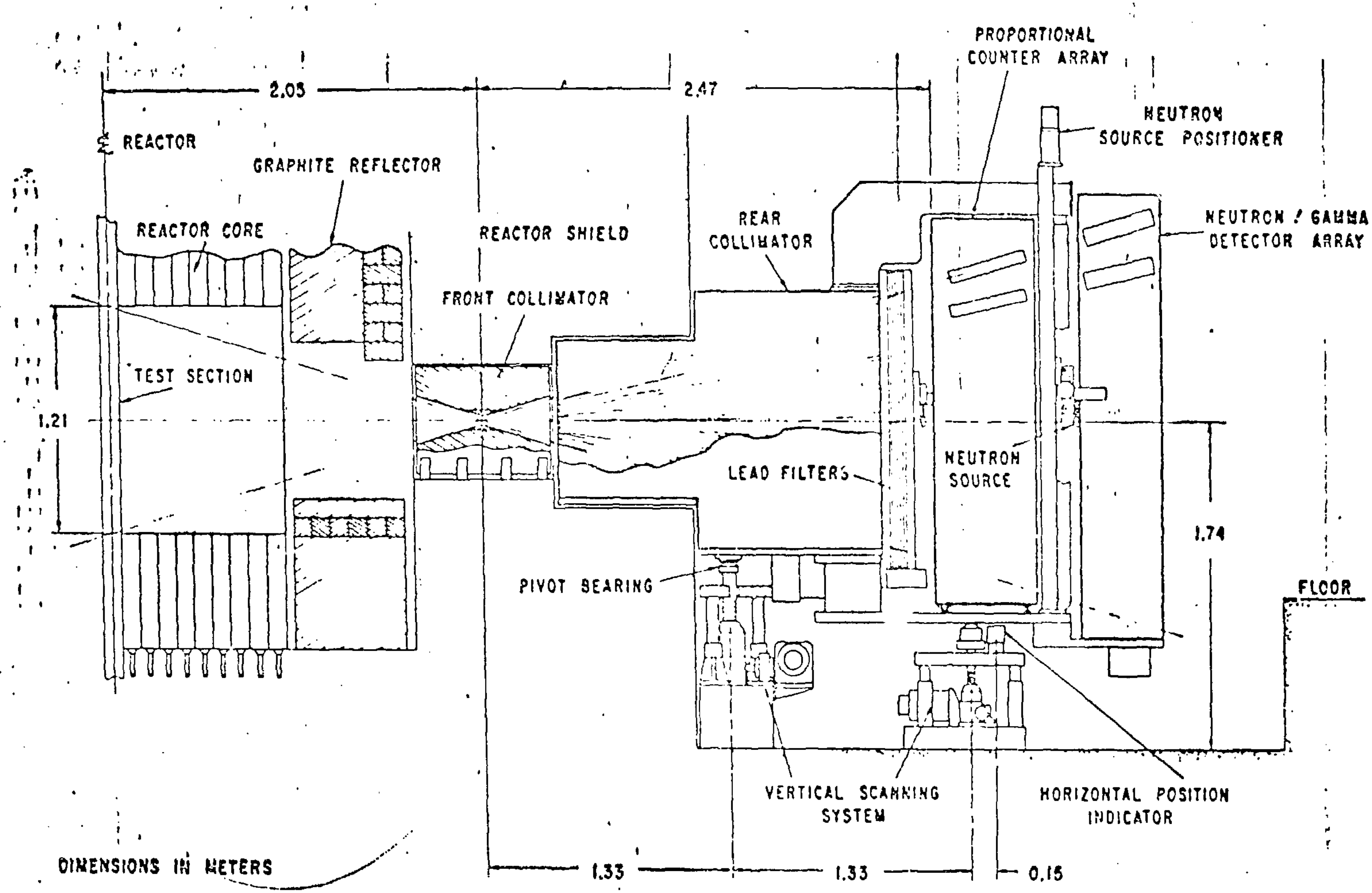


Fig. 2

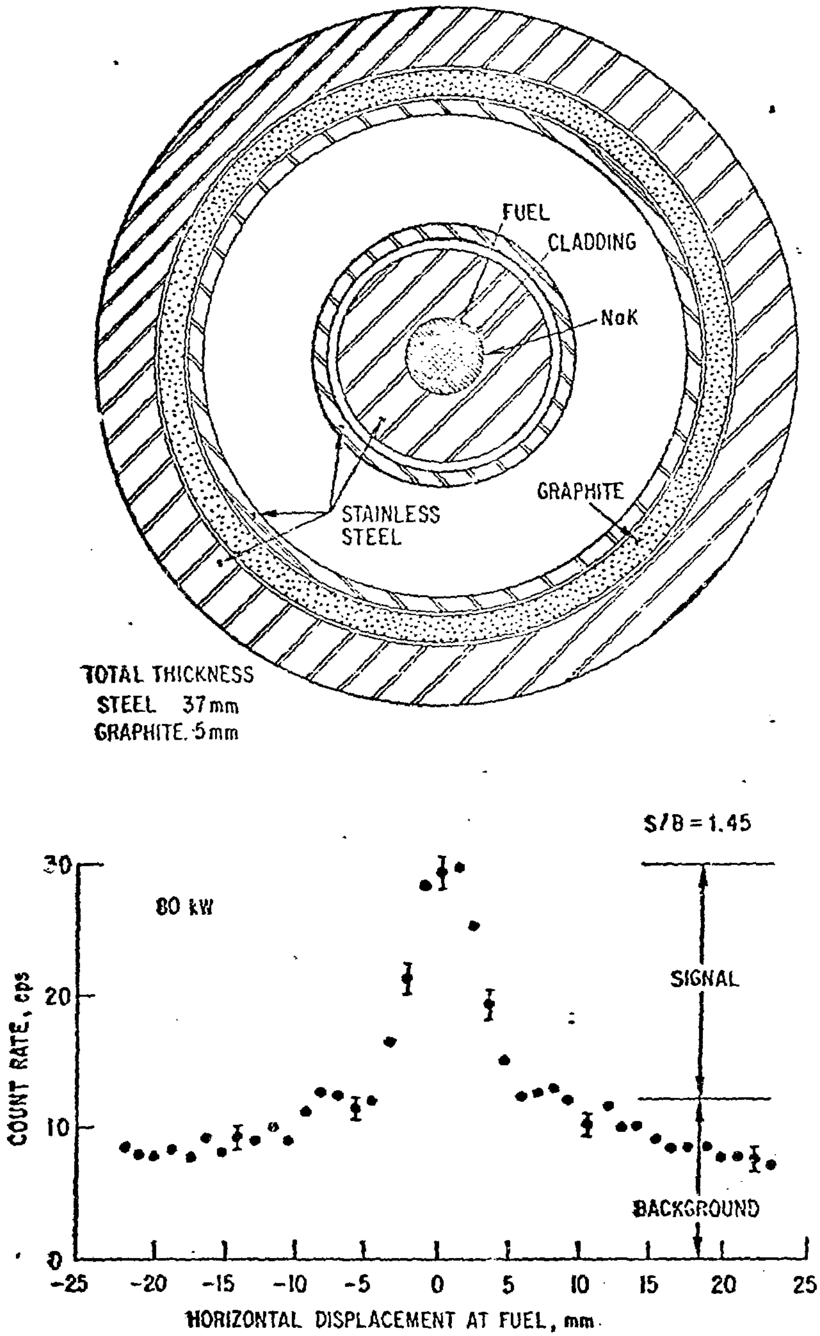

FUEL
CLADDING
NaK
STAINLESS
STEEL
GRAPHITE
TOTAL THICKNESS
STEEL 37 mm
GRAPHITE 5 mm
S/B = 1.45
80 kW
SIGNAL
BACKGROUND
COUNT RATE, cps
30
20
10
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
HORIZONTAL DISPLACEMENT AT FUEL, mm

Fig. 3

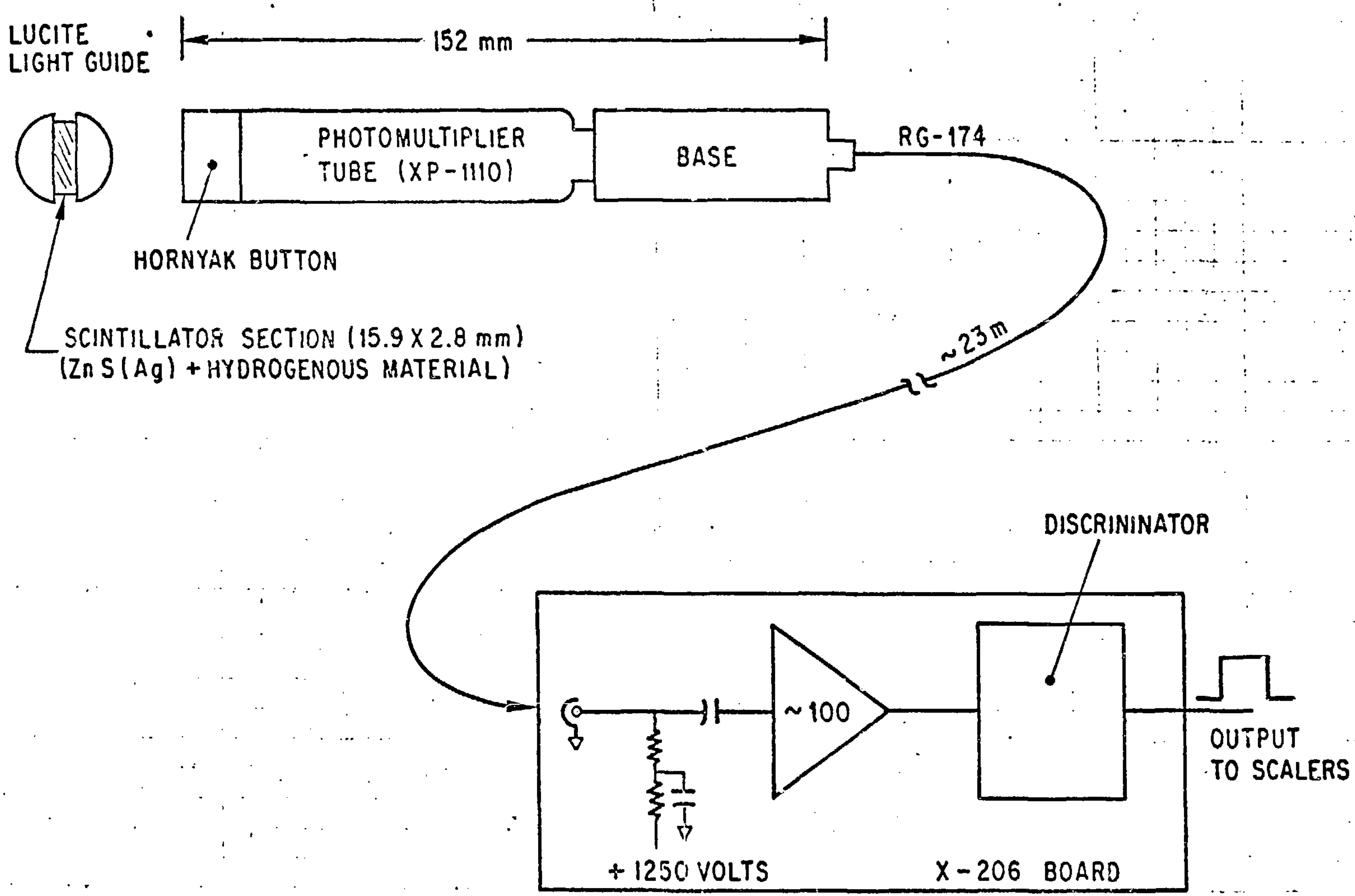
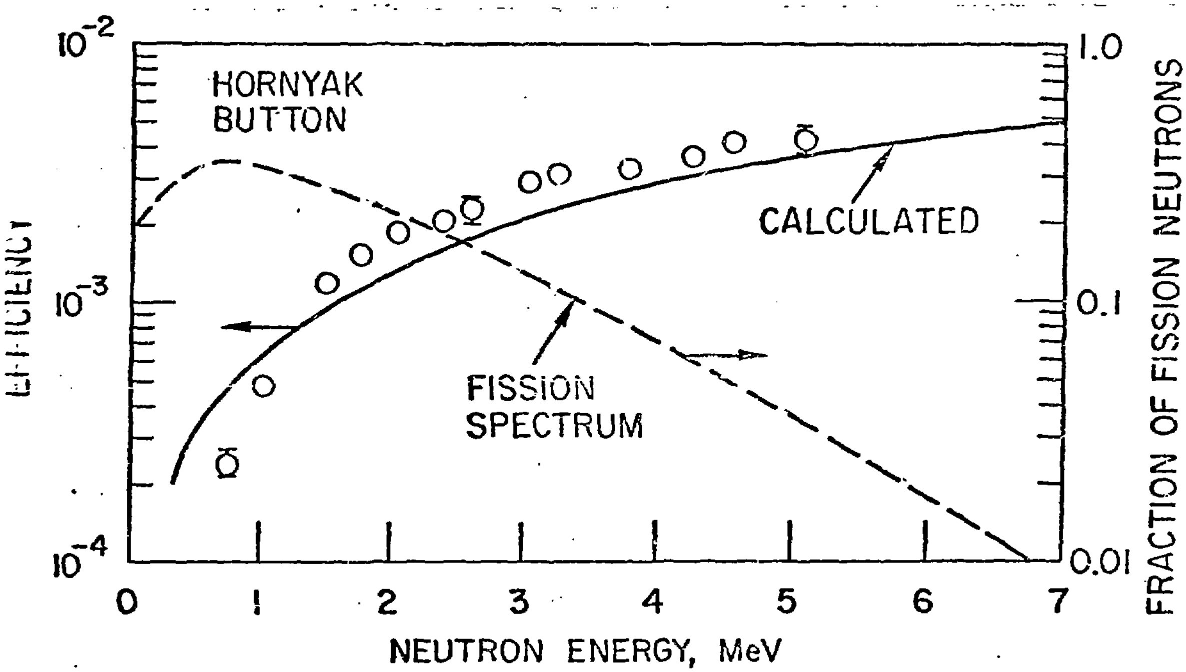

LUCITE
LIGHT GUIDE
152 mm
PHOTOMULTIPLIER
TUBE (XP-1110)
BASE
RG-174
HORNYAK BUTTON
SCINTILLATOR SECTION (15.9 X 2.8 mm)
(Zn S (Ag) + HYDROGENOUS MATERIAL)
~23 m
DISCRININATOR
~100
OUTPUT
TO SCALERS
+ 1250 VOLTS
X - 206 BOARD

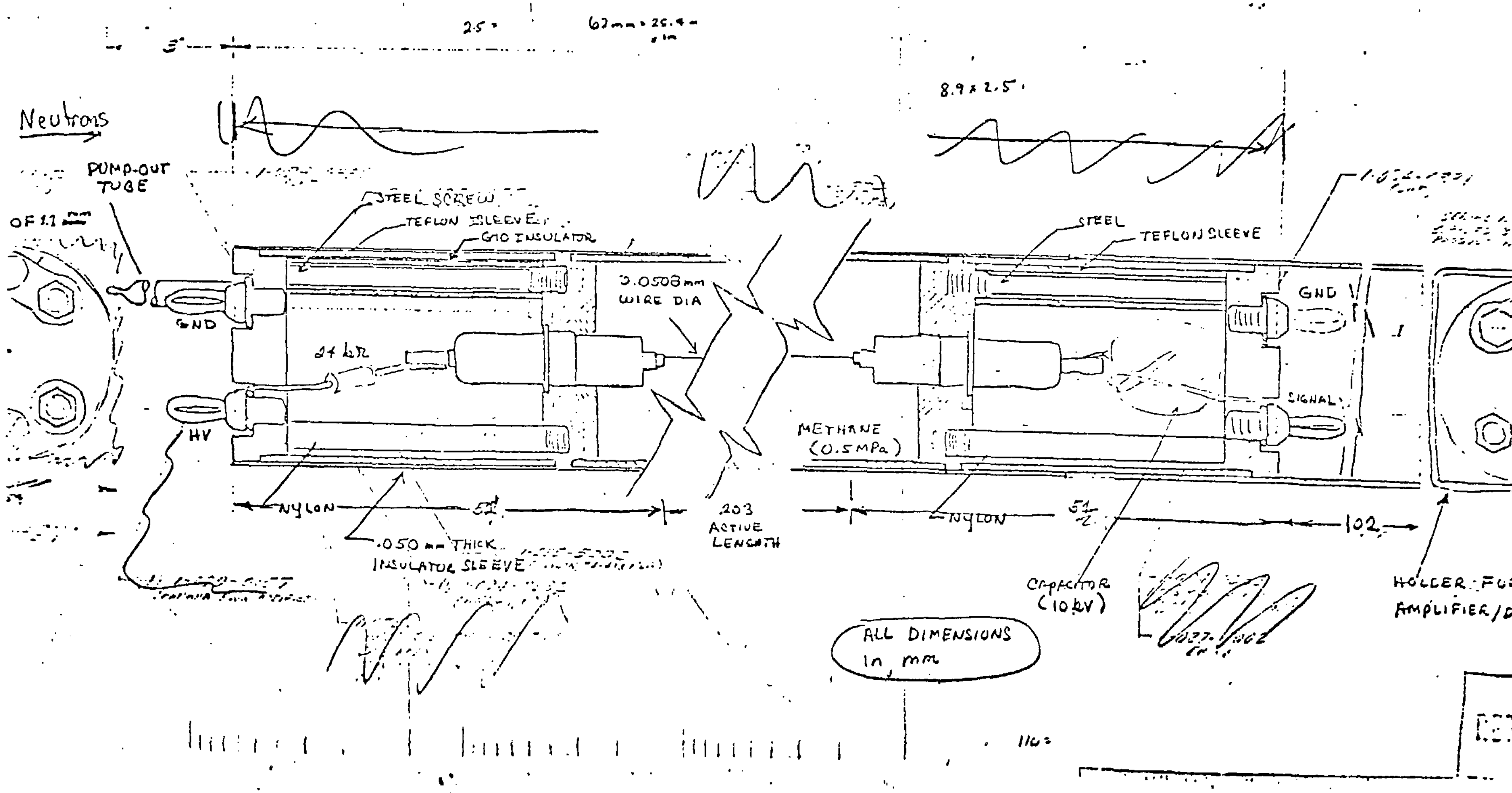
Fig. 4



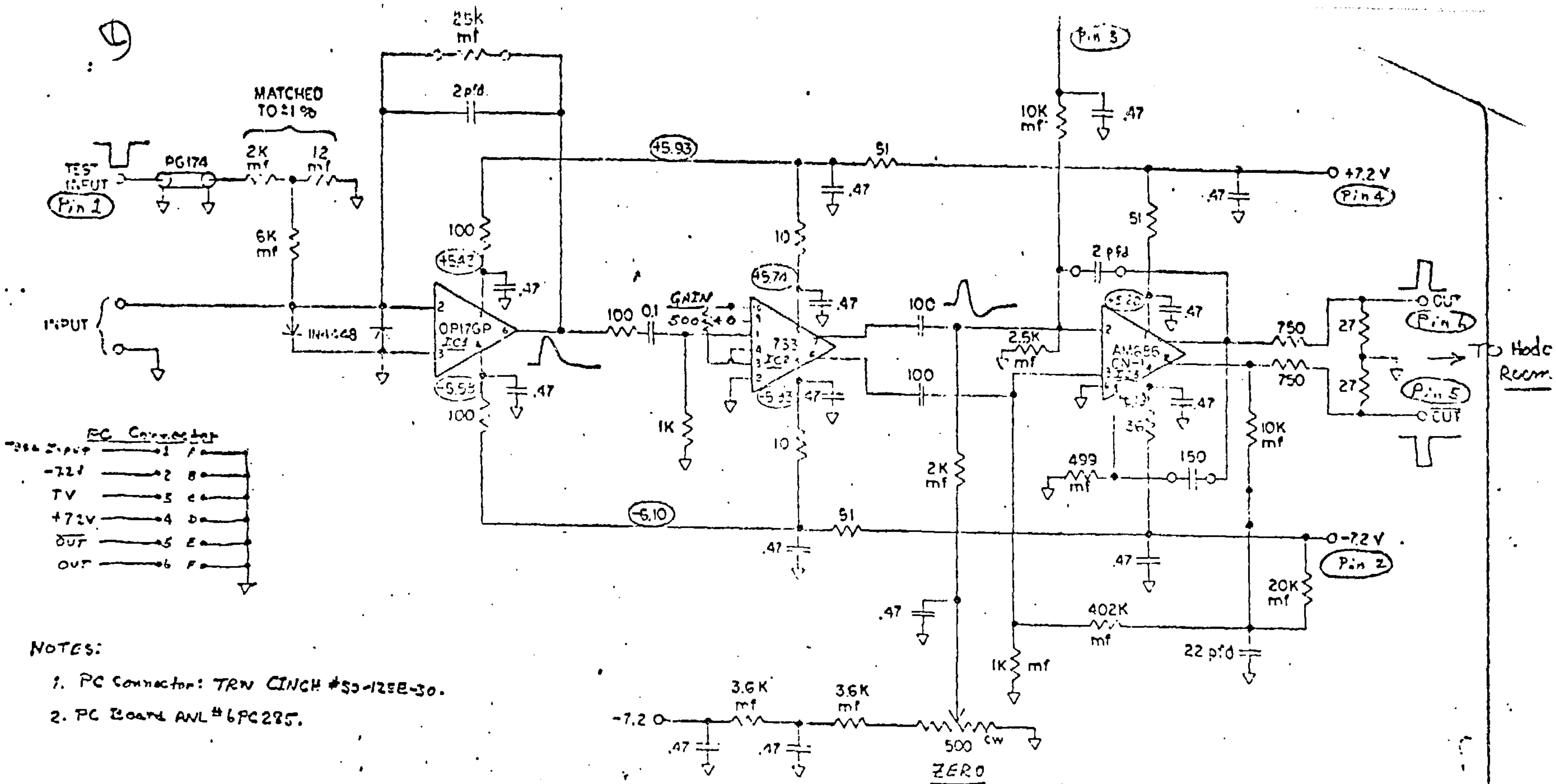
HORNYAK
BUTTON
CALCULATED
FISSION
SPECTRUM
EFFICIENCY
FRACTION OF FISSION NEUTRONS
NEUTRON ENERGY, MeV

Fig. 5

Fig. 6



Neutrons
PUMP-OUT TUBE
OF 1.1
GND
HV
24 kΩ
STEEL SCREW
TEFLON SLEEVE
G10 INSULATOR
0.0508 mm WIRE DIA
NYLON
51
.050 mm THICK INSULATOR SLEEVE
203 ACTIVE LENGTH
METHANE (0.5 MPa)
STEEL
TEFLON SLEEVE
GND
SIGNAL
NYLON
51
102
CAPACITOR (10 kV)
HOLDER FOR AMPLIFIER
ALL DIMENSIONS In mm
25
62 mm = 25.4
8.9 x 2.5



NOTES:

1. PC Connector: TRW CINCH #50-12EE-30.
2. PC Board ANL #6PC285.

01	NOTES, WAVEFORMS, NOMENCLATURE	7-6-?	
REVISION NO	REVISIONS	DATE	CHANGED BY

ELECTRONICS DIVISION

ARGONNE NATIONAL LABORATORY

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TITLE AMP-DISCRIMINATOR FOR TREAT HODOSCOPE PCA

DRAWING NO L5870-8101-DB-01

SHEET 1 OF 1

DESIGN BY J.J. SCHLUETZ — BUILT FOR C. FINK — DRN BY HAS

Fig. 7

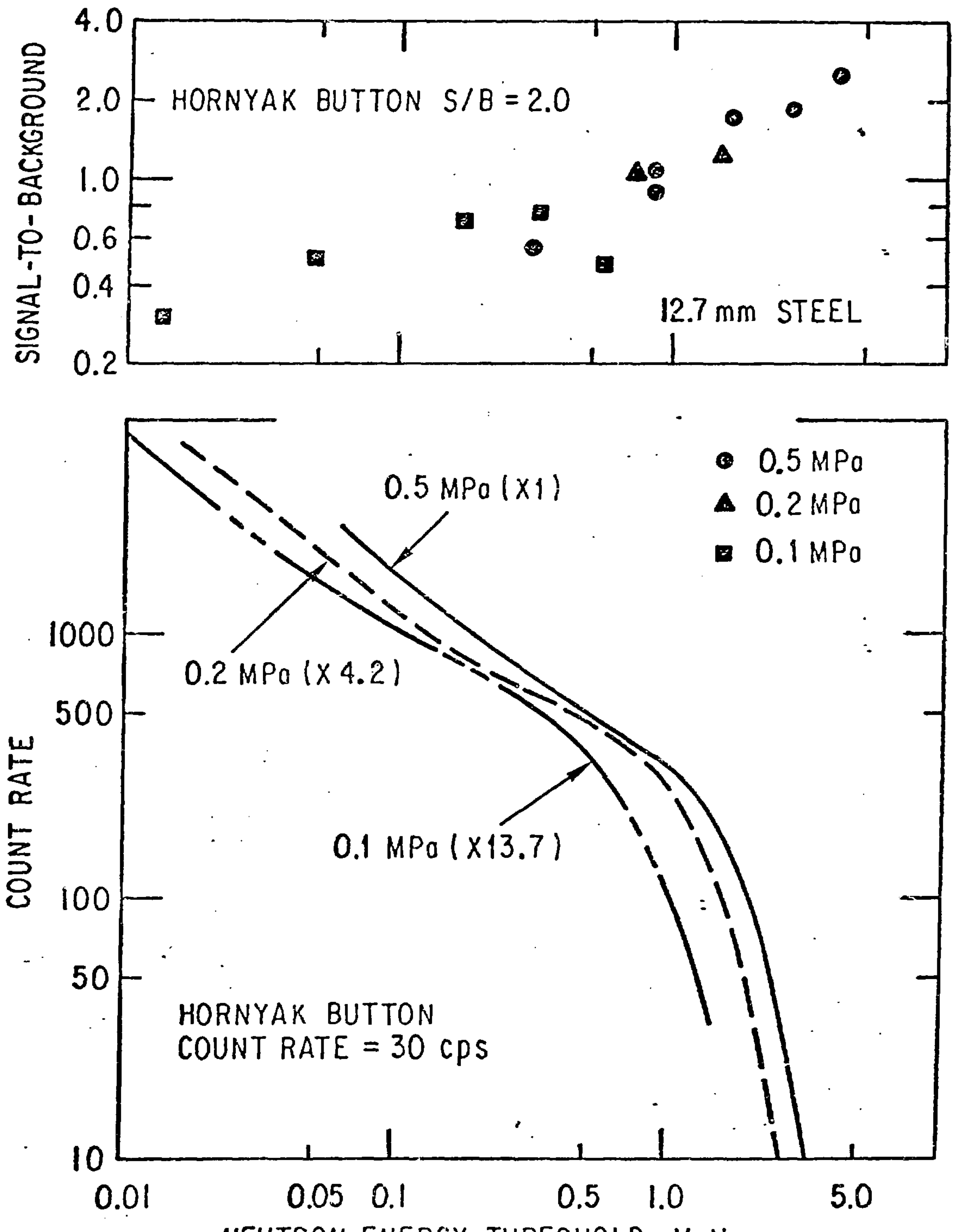
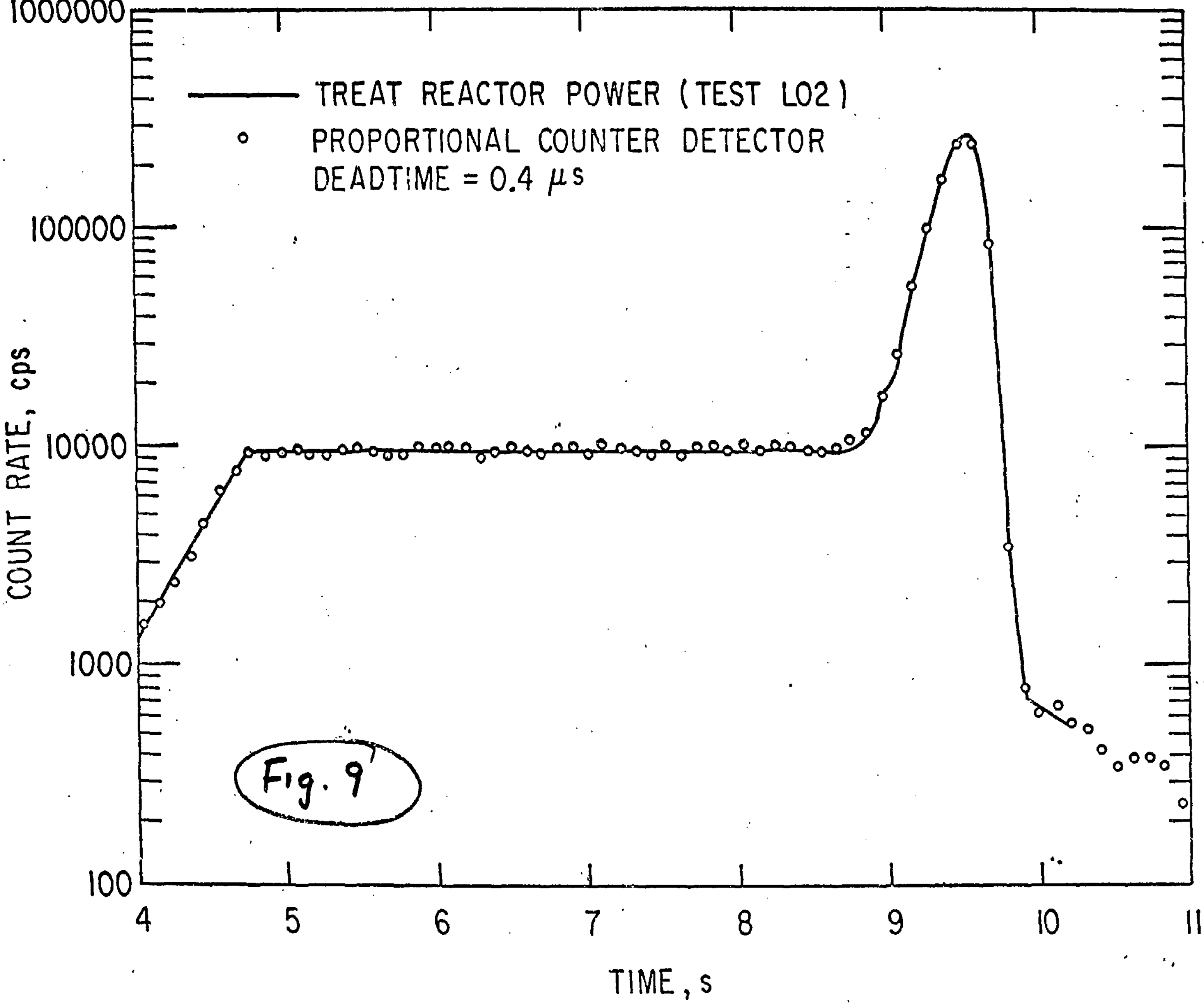

SIGNAL-TO-BACKGROUND
4.0
2.0
1.0
0.6
0.4
0.2
HORNYAK BUTTON S/B = 2.0
12.7 mm STEEL
COUNT RATE
1000
500
100
50
10
0.5 MPa (X1)
0.2 MPa (X 4.2)
0.1 MPa (X13.7)
0.5 MPa
0.2 MPa
0.1 MPa
HORNYAK BUTTON
COUNT RATE = 30 cps
0.01
0.05
0.1
0.5
1.0
5.0
NEUTRON ENERGY THRESHOLD, MeV

Fig. 8



TREAT REACTOR POWER (TEST L02)
PROPORTIONAL COUNTER DETECTOR
DEADTIME = 0.4 μs
COUNT RATE, cps
1000000
100000
10000
1000
100
4
5
6
7
8
9
10
11
TIME, s

Fig. 9