PROTON-RECOIL SPECTROMETER FOR FAST NEUTRON SPECTRA*

L. Harris, Jr., G. F. Knoll, and J. S. King

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Department of Nuclear Engineering
The University of Michigan
Ann Arbor, Michigan

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ABSTRACT

A proton-recoil spectrometer has been designed to measure fast neutron energy spectra in the energy range of 2 to 12 Mev. The principal feature of this spectrometer is its ability to operate reliably with the source end of its collimator in gamma fields of 10^7 to 10^8 r/hr. Such operation is made possible by the use of silicon semiconductor detectors and by the techniques used to reduce background. Reactor spectra which penetrated 0, 20, and 40 cm of H_2O were measured and are compared with calculated spectra.

INTRODUCTION

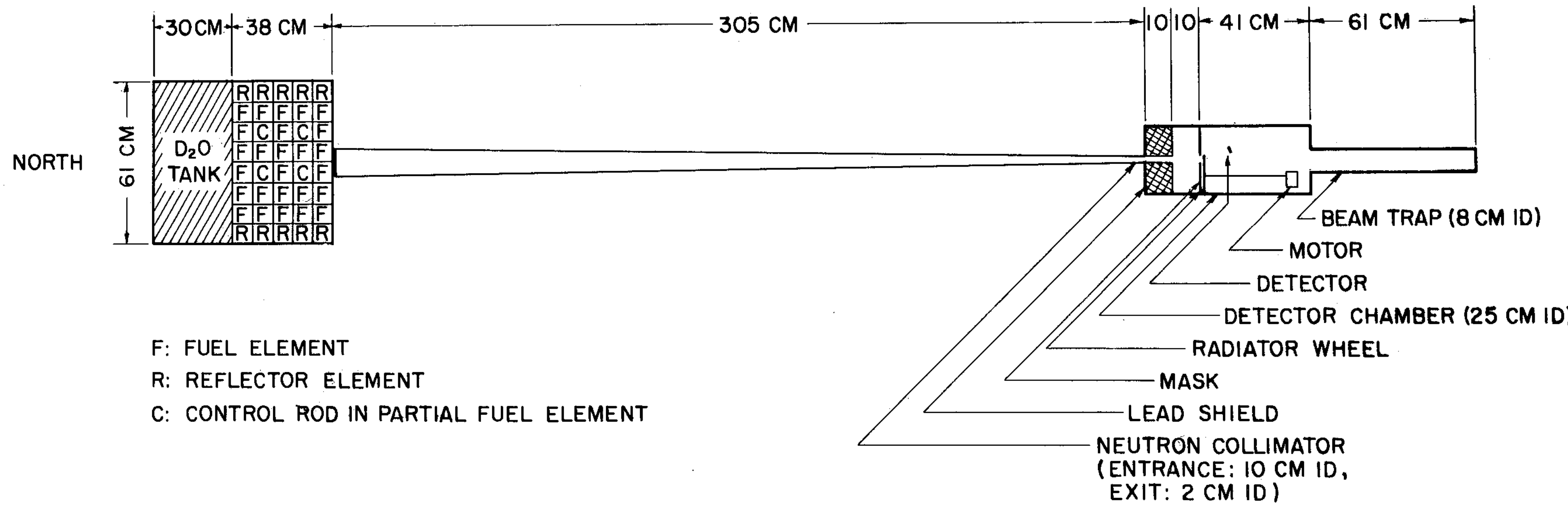
The measurement of the energy distribution of fast neutrons which have penetrated various thicknesses of materials provides data for comparison with calculated spectra. Such a comparison is useful to the development of the theory of fast neutron penetration in matter as well as being essential for making reliable shielding calculations. Most measurements of fast neutron penetration spectra have been made using a nuclear reactor as the fast neutron source. However, because of the high intensity gamma flux which is associated with a reactor, the background problems are such that only a few measured penetration spectra have been published.[1-3]

The fast neutron spectrometer which is described here is a proton-recoil device that was specifically designed to make reliable measurements in the presence of high gamma fields. It is presently being used which the source end of its collimator in gamma fields of 10^7 to 10^8 r/hr. The principal features of the instrument which permit such operation are the use of silicon semiconductor detectors and the several techniques used to reduce background.

SPECTROMETER

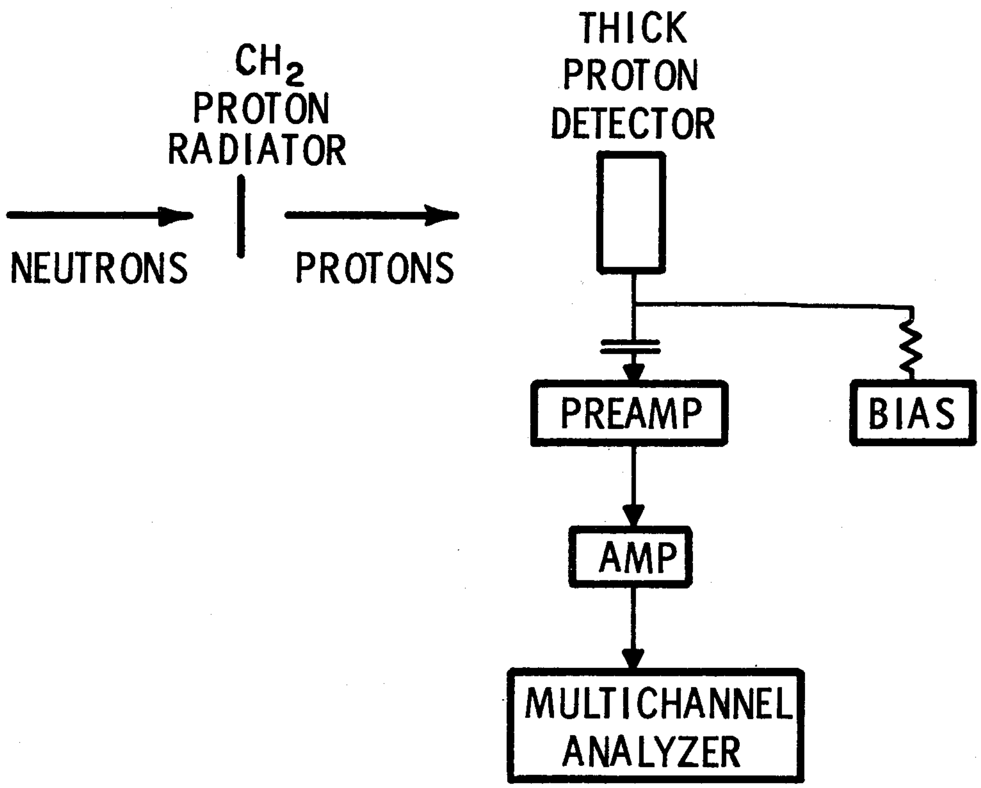
Figure 1 shows the core configuration of the Ford Nuclear Reactor and the principal features of the spectrometer. Both the core and spectrometer are suspended at a depth of about 6 meters in an open light water pool. The axis of the neutron collimator is positioned along the core centerline with the source end of the collimator against the south face of the core. The collimator, detector chamber and beam trap are evacuated. Fast neutrons from the core stream through the collimator to the proton radiator where about one out of every 10^6 neutrons scatters a proton from the radiator to the detector. The silicon surface barrier detector is positioned off the collimator axis at an angle of 24° so as to be out of the direct beam and to be shadow shielded by the lead. The mask is located in the chamber to shield the detector from charged particles which may originate in the throat of the collimator. The beam trap serves to reduce backscattering to the detector. The motor rotates the radiator wheel so that various thickness polyethylene radiators can be positioned on the collimator axis.

Figure 2 shows a block diagram of the electronics used with a thick silicon surface barrier detector. The fully depleted detector is 1000 microns thick which corresponds to the range of 12 Mev protons in silicon. The detector is connected to a vacuum-tube, charge-sensitive preamplifier. The



FORD NUCLEAR REACTOR CORE CONFIGURATION AND PRINCIPLE FEATURES OF PROTON-RECOIL FAST NEUTRON SPECTROMETER

Figure 1



ELECTRONICS USED WITH THICK (1000 MICRONS) PROTON DETECTOR

Figure 2

preamplifier output signal is amplified and then analyzed by a multichannel pulse height analyzer.

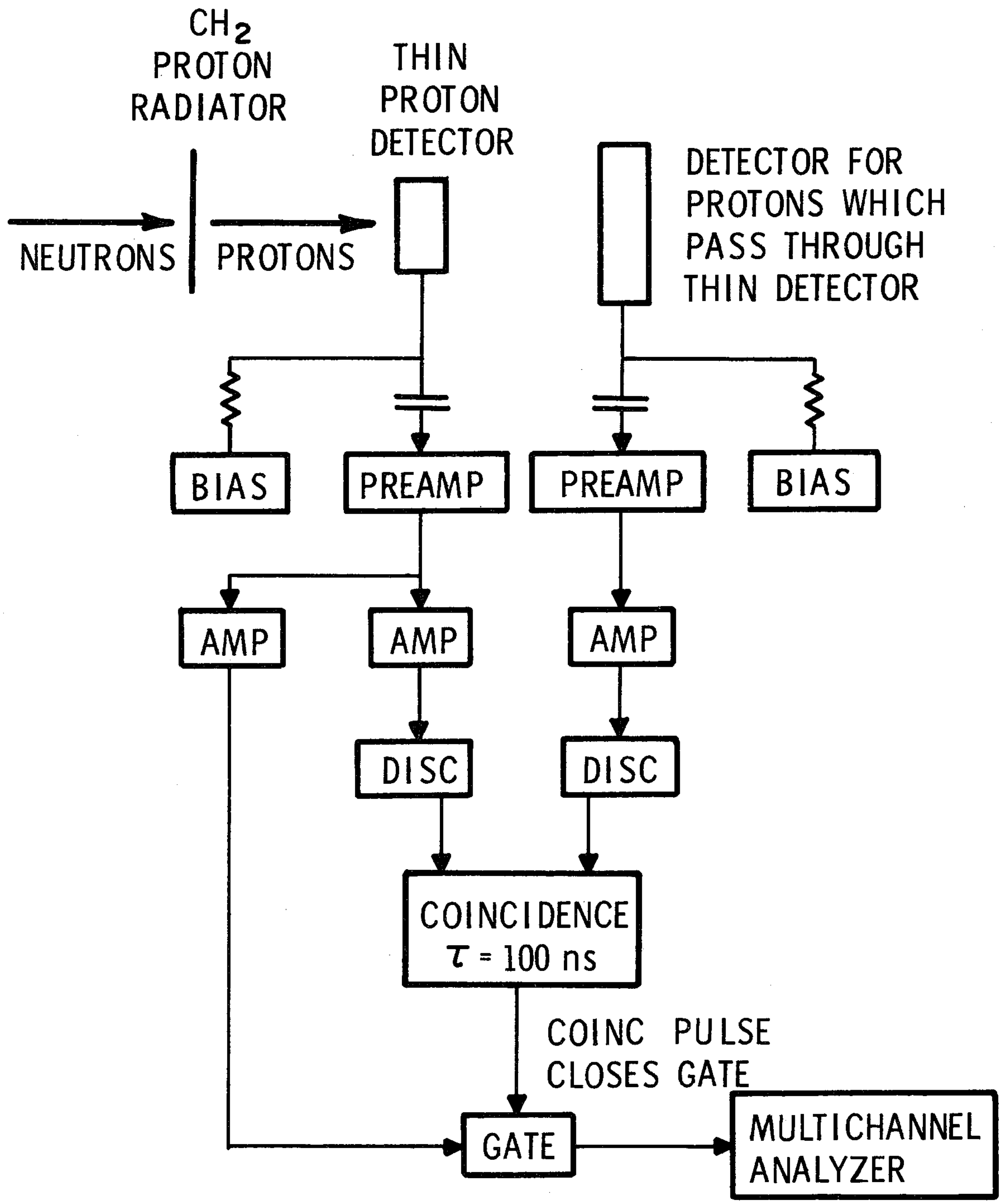
As has been indicated, the spectrometer is specifically designed to operate with the source end of its collimator in high gamma fields. Even so, the background always sets a lower limit on the neutron energy at which spectrum measurements can be made. A signal-to-background ratio of one was selected as a practical lower limit for reliable data. Here background refers to any counts which are not due to protons that have been scattered from the CH_2 radiator by fast neutrons. The obvious sources of background are carbon nuclei which have been scattered from the CH_2 radiator by fast neutrons, and Compton electrons from gamma interactions. Charged particles from neutron induced reactions may also be present. Except for the recoil carbon nuclei, these charged particles can originate within the detector itself and within the structural and shielding material that is in the vicinity of the detector. The effects of recoil carbon nuclei can by reduced by taking background measurements with thin carbon films replacing the CH_2 films on the radiator wheel.

The remaining background can be reduced by decreasing the detector thickness. However, if the detector is so thin that some of the higher energy protons are not stopped in the detector,then it is necessary to avoid counting them since their energy losses in the detector do not correspond to their full energy. A fully depleted detector with a thickness of 250 microns, which corresponds to the range of 5 Mev protons in silicon, was therefore used for spectrum measurements in the energy range 2 to 5 Mev.

Figure 3 shows the arrangement used to count only those protons which are stopped in the fully depleted thin detector. Signals from the thin detector pass through the preamplifier and amplifier to the gate which is normally open. However, if the second detector, which is positioned behind the thin detector, detects a proton simultaneously with the thin detector, a coincidence pulse closes the gate so that the signal from the thin detector does not reach the multichannel pulse height analyzer.

An Am^{241} source which emits 5.48 Mev alphas is used for the energy calibration of the spectrometer. The alpha source is suitable because the detector response is the same for equal energy protons and alphas which are stopped in the detector. A pulse generator, whose output varies linearly, is connected to the preamplifier input to determine the zero energy channel and to check the linearity of the electronics.

The alpha source is also used to observe the effects of pulse pile-up. This is done by monitoring the width of the alpha pulse height spectrum as the count rate is increased. It is assumed that pulse pile-up effects are negligible as long as the alpha FWHM is unchanged. The maximum allowable reactor power for the experimental runs was chosen as that power at which the alpha FWHM was only slightly wider than that for zero power. This power level



ELECTRONICS USED WITH THIN (250 MICRONS) PROTON DETECTOR WITH ANTI-COINCIDENCE ARRANGEMENT WHICH ALLOWS ONLY PROTONS WHICH ARE STOPPED IN THE FIRST DETECTOR TO BE COUNTED

Figure 3

was 200 kilowatts using the thick detector with the collimator against the core. Using the thin detector with the collimator against the core, the reactor was operated at its maximum power of 2 megawatts.

The energy of the protons which are counted is equal to the energy of the neutrons incident on the radiator times the squared cosine of the n - p scattering angle minus the energy lost by the protons in the radiator. The two principal effects which determine the energy resolution of the spectrometer are the variations in the squared cosine of the n - p scattering angle due to the finite areas of the radiator and detector, and the variations in the proton energy losses in the radiator. These two variations are combined quadratically to give the spectrometer resolution function.

Figure 4 shows the spectrometer resolution or FWHM in percent as calculated for the two radiator thicknesses used in the spectrometer. The variation in the FWHM at the lower energies is due to the energy dependence of the proton energy losses in the radiator. For the higher energies, the FWHM is determined almost entirely by the variation in the squared cosine of the n - p scattering angle. This variation, when expressed as a percent, is independent of energy. It can be seen that the use of the thinner radiator for spectrum measurements from 2 to 5 Mev represents a substantial improvement in the resolution. Hence, the thinner radiator is used with the thin detector. The thicker radiator is used with the thick detector to increase the efficiency at higher energies. It is important to note that the limiting resolution of 13 percent is determined by the radiator-detector geometry and can be modified substantially. Of course, changing the radiator-detector geometry to modify the resolution will also modify the efficiency in the opposite manner.

The efficiency can be defined either in terms of the neutron flux which is incident on the radiator or in terms of the neutron angular flux which is incident on the source end of the collimator and is directed about the collimator axis. Figure 5 shows the efficiency given in terms of the number of neutrons counted per unit time per unit neutron flux normally incident on the radiator. The energy dependence is that of the n - p scattering cross section. This efficiency is multiplied by the collimator efficiency to get the total efficiency. The collimator efficiency is just the solid angle subtended by the source end of the collimator and is 0.88×10^{-3} steradian for this collimator.

Figure 6 shows the total efficiency which is the number of neutrons counted per unit time per unit neutron angular flux incident on the source end of the collimator and directed about the collimator axis. The angular flux is a directed quantity which is the number of neutrons per sec per cm^2 per steradian moving in some $\delta\Omega$ about $\bar{\Omega}$. For this spectrometer, the $\bar{\Omega}$ of the measured angular flux is directed about the collimator axis toward the radiator.

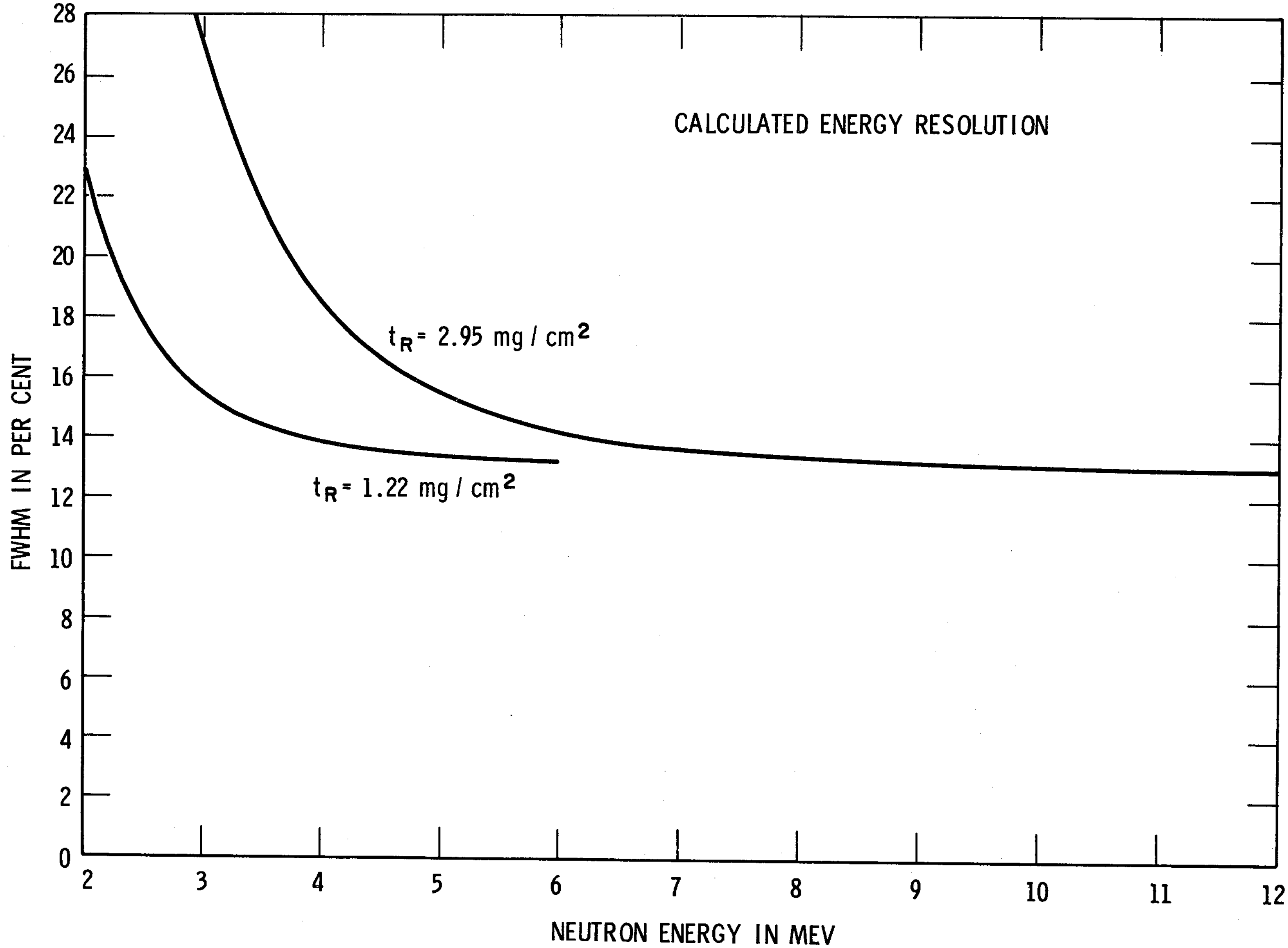

CALCULATED ENERGY RESOLUTION
t_R = 2.95 mg / cm^2
t_R = 1.22 mg / cm^2
FWHM IN PER CENT
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
2
3
4
5
6
7
8
9
10
11
12
NEUTRON ENERGY IN MEV

Figure 4

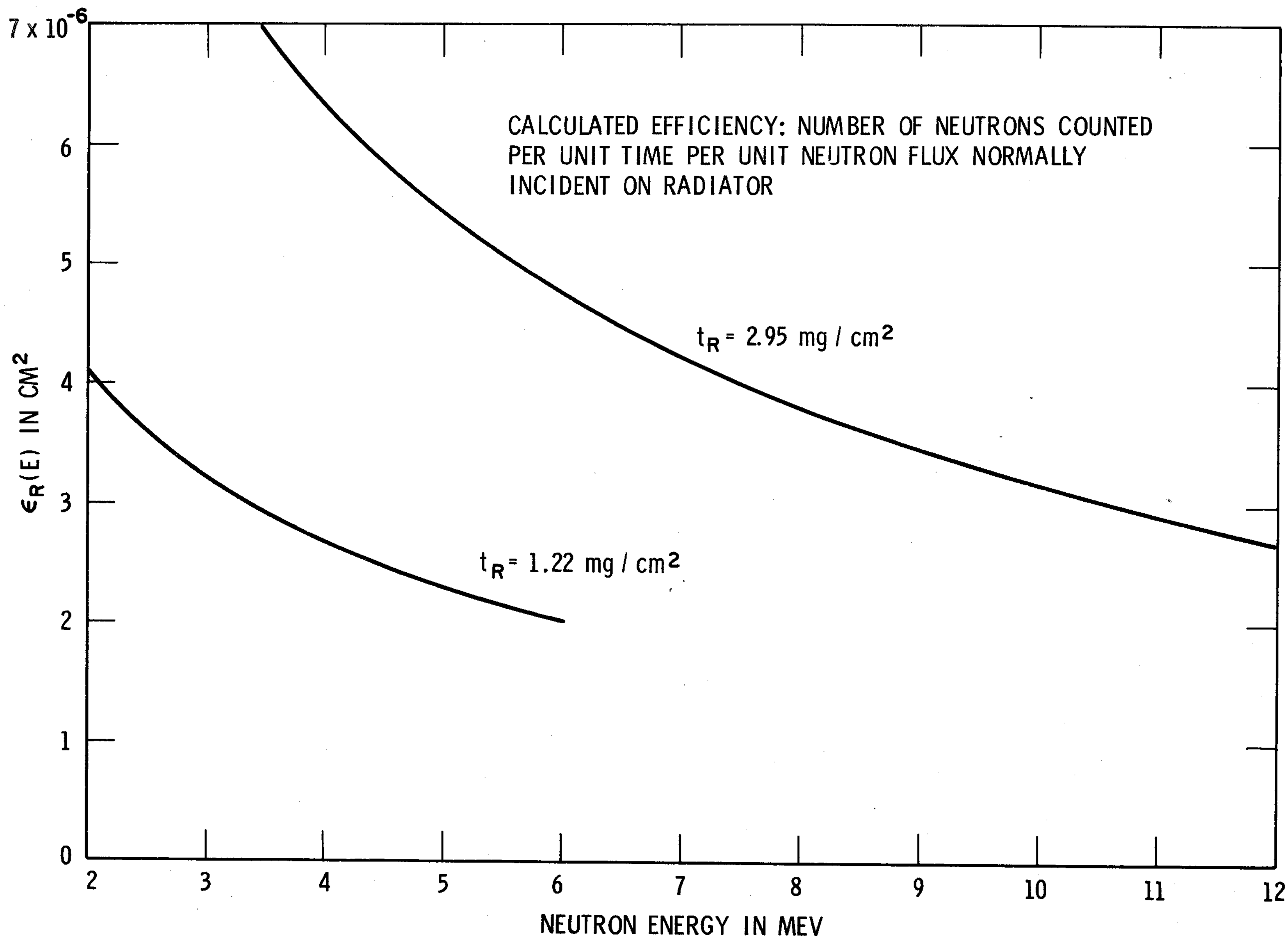

7 x 10^-6
6
5
4
3
2
1
0
$\epsilon_R(E)$ IN CM^2
CALCULATED EFFICIENCY: NUMBER OF NEUTRONS COUNTED PER UNIT TIME PER UNIT NEUTRON FLUX NORMALLY INCIDENT ON RADIATOR
t_R = 2.95 mg / cm^2
t_R = 1.22 mg / cm^2
2
3
4
5
6
7
8
9
10
11
12
NEUTRON ENERGY IN MEV

Figure 5

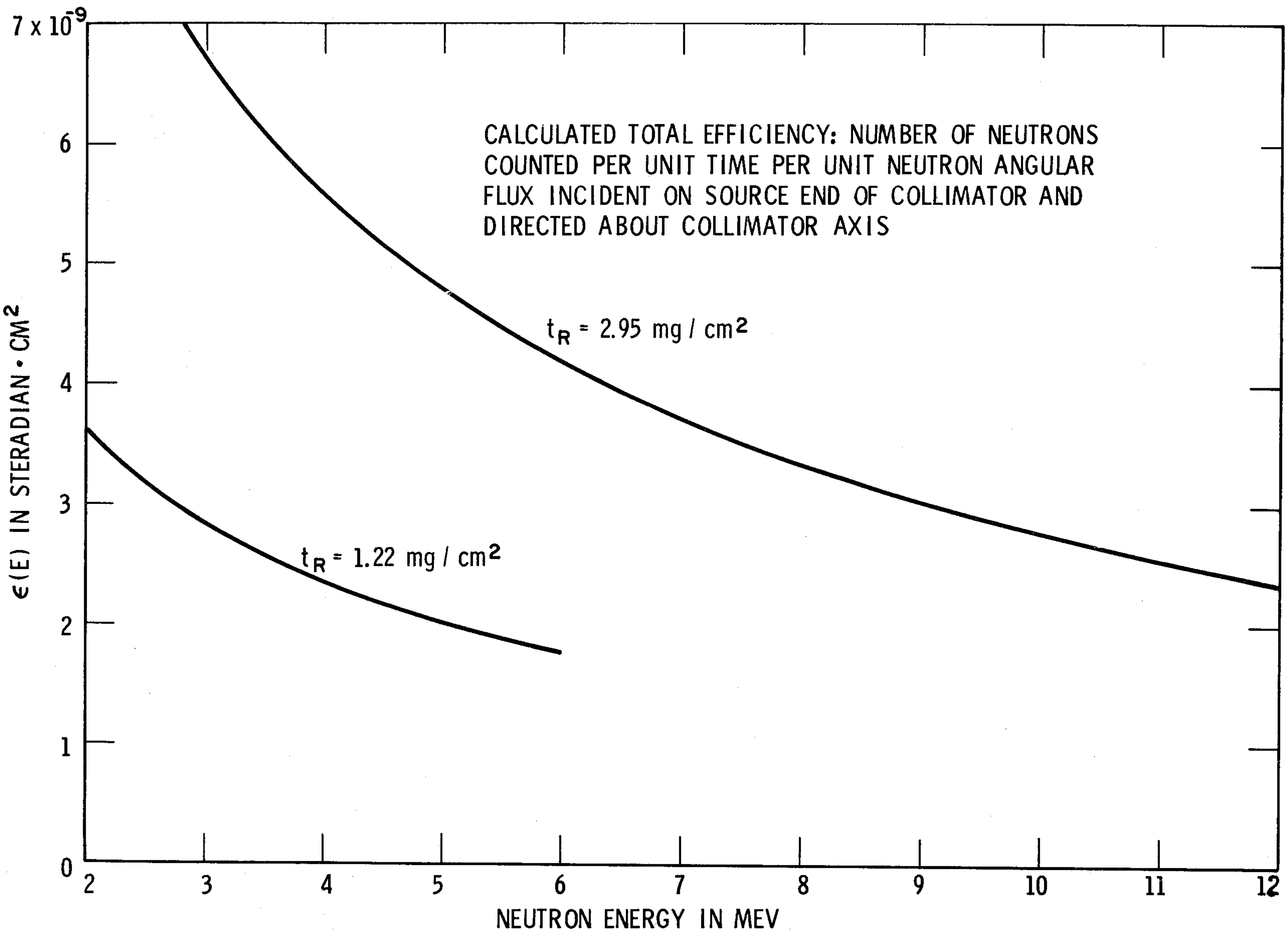

7 x 10^-9
6
5
4
3
2
1
0
2
3
4
5
6
7
8
9
10
11
12
NEUTRON ENERGY IN MEV
ϵ(E) IN STERADIAN • CM²
CALCULATED TOTAL EFFICIENCY: NUMBER OF NEUTRONS COUNTED PER UNIT TIME PER UNIT NEUTRON ANGULAR FLUX INCIDENT ON SOURCE END OF COLLIMATOR AND DIRECTED ABOUT COLLIMATOR AXIS
t_R = 2.95 mg / cm²
t_R = 1.22 mg / cm²

Figure 6

DATA

Figure 7 shows trial spectra in light water that were measured with the collimator against the south face of the core and with it moved back 20 cm and 40 cm from the core. All of the data are normalized to reactor power which was measured by a calorimetric method.[4] The signal-to-background ratio was greater than one for every point that is plotted.

The solid curves are spectra which were calculated with the NIOBE code[1] for a BSR-I core which was similar to the FNR core. It is noted that the only normalization between the measured and calculated spectra is to reactor power. Thin radiator-thin detector data and thick radiator-thick detector data are shown for each of the three penetration distances. It is believed that the reason the data points do not exactly overlap is due to an inadequate reactor power normalization procedure. It was inadequate in the sense that flux shifts in the core, due for instance to control rod withdrawal during xenon buildup, could change the fast neutron leakage flux on the south face of the core without changing the average reactor power. An independent measurement of this leakage flux is needed to normalize the data.

CONCLUSIONS

The limiting features of this spectrometer are (1) low efficiency, (2) moderate resolution, and (3) a signal-to-background ratio which becomes fractional at low energies. As has been mentioned, the resolution can be improved at the expense of efficiency and probably at the expense of the signal-to-background ratio.

Despite these limitations, the spectrometer will give reproducible measurements of neutron spectra in the energy range from 2 to 10 Mev in the presence of very high gamma fields. Also there is general agreement between the measured spectra and the spectra calculated with the NIOBE code. The conversion of proton pulse height spectra to differential neutron energy spectra depends only on the n - p scattering cross section, the proton energy losses in polyethylene, and the geometry. The straightforward nature of the conversion leads one to believe that absolute neutron fluxes can be measured with excellent reliability.

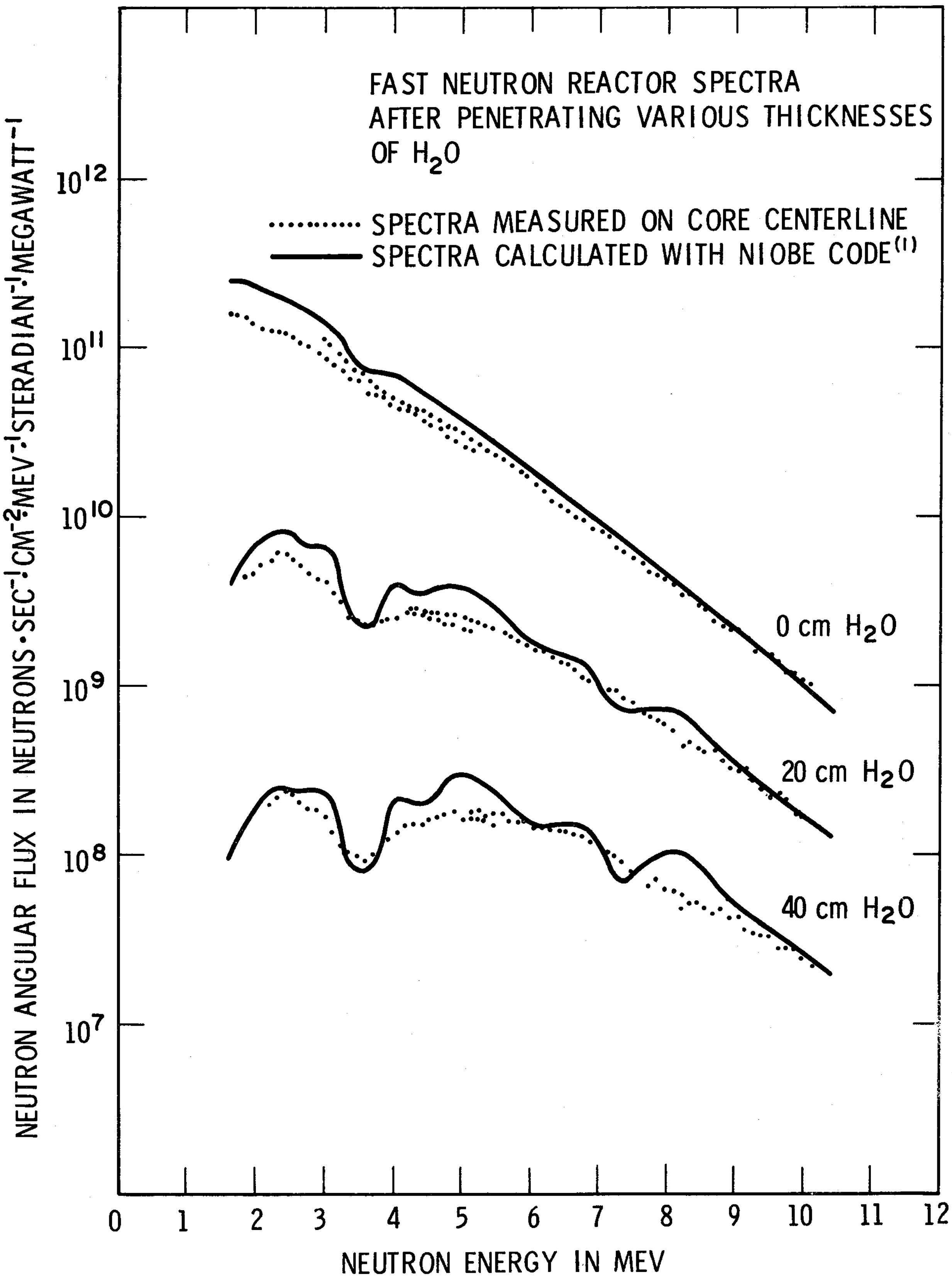

FAST NEUTRON REACTOR SPECTRA
AFTER PENETRATING VARIOUS THICKNESSES
OF H_2O
SPECTRA MEASURED ON CORE CENTERLINE
SPECTRA CALCULATED WITH NIOBE CODE[1]
0 cm H_2O
20 cm H_2O
40 cm H_2O
NEUTRON ANGULAR FLUX IN NEUTRONS·SEC^{-1}·CM^{-2}·MEV^{-1}·$STERADIAN^{-1}$·$MEGAWATT^{-1}$
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
0 1 2 3 4 5 6 7 8 9 10 11 12
NEUTRON ENERGY IN MEV

Figure 7

ACKNOWLEDGMENTS

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