4.0 FAST REACTORS

NEUTRON SPECTRUM STUDIES IN THE PCTR FAST NEUTRON CAVITY

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Introduction

Neutron spectrum measurements were made in the interior of the Fast Neutron Cavity assembled inside the central zone of the Physical Constants Testing Reactor (PCTR). An intercomparison between two experimental methods for determining the neutron spectrum was obtained using a proton-recoil spectrometer and a multiple foil activation method. The results of these neutron spectrum measurements provide a valuable check of both reactor theory and analytical technique for developing calculational methods applicable to fast-thermal coupled reactor cores.

Proton-Recoil Spectrometer Measurements

Proton-recoil counter measurements using both hydrogen-gas-filled and methane-gas-filled detectors were made in the center of the Fast Neutron Cavity, following the method of E. F. Bennett.[1] The neutron spectrum obtained from the proton-recoil counter data, shown in Figure 4.1, is the composite of several measurements at the same reactor flux level. Count rates during all measurements were kept below 920 counts per sec. The proton-recoil spectrum was observed in consecutive overlapping energy intervals, obtained by varying the gas multiplication in each proportional counter. The methane detector spanned energies between 1.4 MeV and 160 keV in three intervals. Neutron energies between 335 keV and 9.6 keV were observed in six intervals using the hydrogen detector. Corrections for systematic errors in the recoil-proton spectrum including wall-and-end effect, inhomogeneous electric field effect (tip effect), and heavy nuclei recoil distortion were made in the data analysis. The fast neutron flux spectrum was

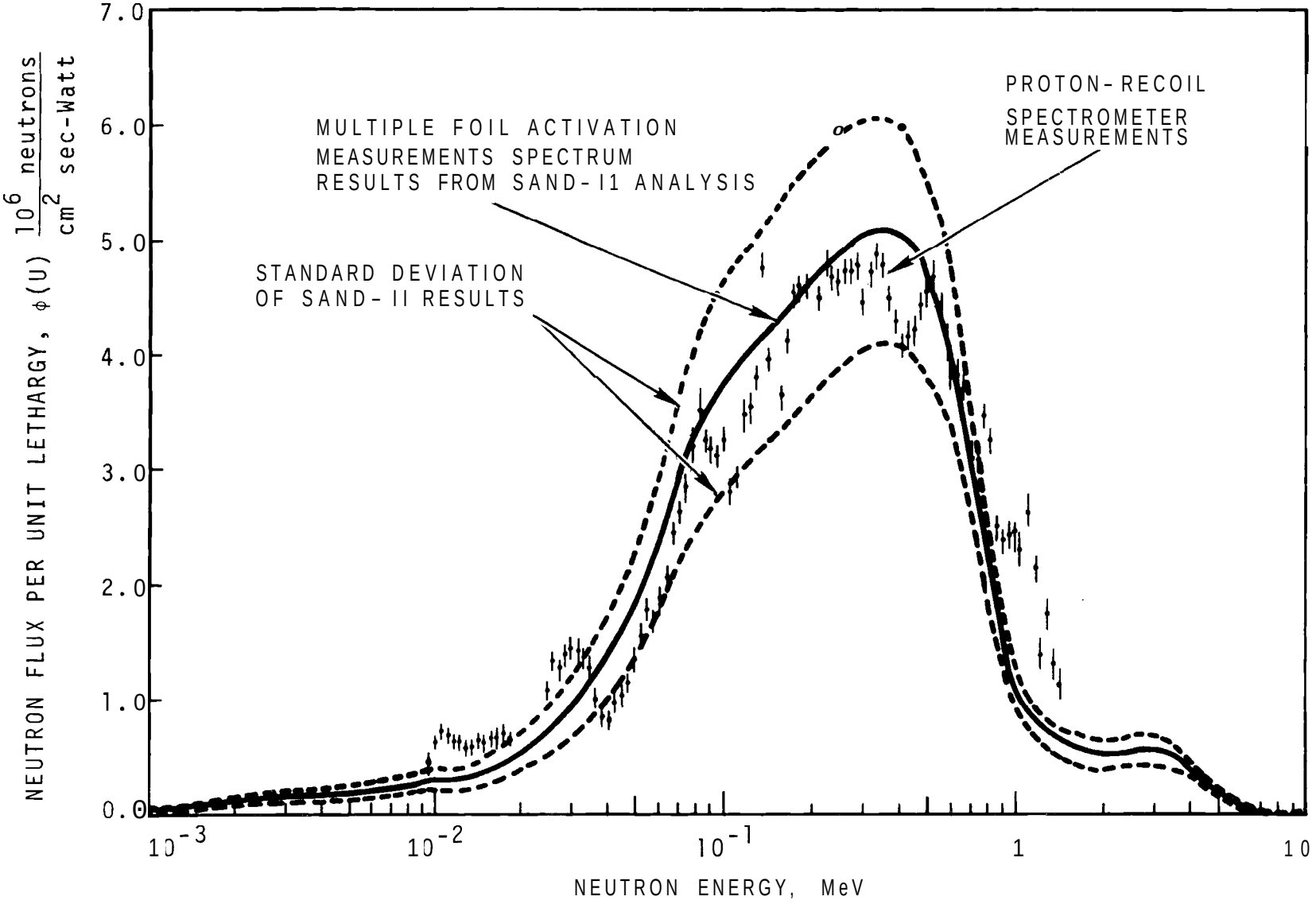

FIGURE 4.1. Comparison of Proton-Recoil Spectrometer and Multiple Foil Activation Results

unfolded by differentiating the proton recoil-spectrum using computer program PSNS.[2] The spectrometer was calibrated using the $^{14}N(n,p)^{14}C$ reaction which releases ionization equivalent to a proton with energy of 615 keV when thermal neutrons are incident. Both detectors, containing 4.0% nitrogen, were calibrated in the PCTR thermal column[3] with the reactor at a 10 watt power level. The averaged composite neutron spectral results from the proton-recoil measurements, shown in Figure 4.1, consist of inverse variance weighted data from the individual measurements within the neutron energy interval 1.4 MeV to 9.6 keV. Neutron energy resolution was narrower than 15% (full-width at half-maximum) over the energy interval 1 MeV to 40 keV and increased to about 23% at 10 keV.

Multiple Foil Activation Measurements

Analysis of multiple foil activation measurements in the empty Fast Neutron Cavity (FNC) was made to obtain a set of saturated activities for 26 foil reactions. Six of these reactions are threshold reactions that respond only to neutrons with energies in the fast range. The remaining twenty reactions were obtained from bare foils, foils covered by 0.1 cm thick cadmium filters, and foils covered by 1.0 cm thick ^{10}B filters. Neutron filters altered the energy responses of the foils such that activation data spanning three different neutron energy ranges were obtained.

Activation shelf-shielding corrections were measured by irradiating several foil thicknesses of the same material simultaneously and extrapolating the specific activities to zero thickness. The absolute counter efficiency calibration for a NaI(Tℓ) gamma-ray scintillation spectrometer was measured with a set of IAEA standard sources of known activity. The sources included: ^{241}Am (60 keV), ^{57}Co (122 keV), ^{203}Hg (279 keV), ^{22}Na (511, 1275 keV), ^{137}Cs (622 keV), ^{54}Mn (835 keV), ^{88}Y (898, 1836 keV), and ^{60}Co (1173, 1332 keV). Infinitely

dilute saturated activities for the $^{115}In(n,\gamma)$, $^{197}Au(n,\gamma)$, and $^{63}Cu(n,\gamma)$ reactions were determined from foils irradiated in the PCTR thermal column. Non-l/v correction factors for the 2200 m/sec cross sections were calculated for the thermal column with THERMOS.[4] The thermal flux in the PCTR thermal column at 100 Watts was determined to be 1.07×10^8 neutrons per cm^2-sec (±2.6%). This flux level and the THERMOS calculated non-l/v factors for the thermal column were used to determine saturated activities of other reactions in the FNC from activity measurements relative to the thermal column. Saturated activities for the $^{235}U(n,f)$, $^{239}Pu(n,f)$, $^{232}Th(n,\gamma)$, and $^{238}U(n,\gamma)$ reactions were determined by this method. Infinitely dilute saturated activities for 26 foil reactions measured in the FNC are listed in Table 4.1. The average uncertainty in all the saturated activity measurements was less than 3%.

The infinitely dilute saturated activities obtained from foil measurements were analyzed using the SAND-I1 computer code[5] to unfold the neutron spectrum. Initial trial functions for the neutron spectrum in the SAND-I1 analysis included: a transport theory calculation[6] from DTF-IV,[7] a constant $\phi(u)$, a Gaussian function centered at 100 keV, and a Gaussian function centered at 1 MeV. The best SAND-I1 representation for the neutron spectrum, shown in Figures 4.1 and 4.2, was obtained from a weighted average of the iterative neutron spectrum solutions resulting from different initial trial functions. A weighting factor proportional to the inverse variance in the measured-to-calculated activity ratios was used in the averaging procedure. The standard deviation in the multiple foil activation neutron spectrum was inferred from the width, $\Delta\phi(E)_{Max}/\phi(E)_{Ave}$, of the envelope of all SAND-I1 solutions obtained from measured activities using different initial trial functions.

TABLE 4.1. Infinitely Dilute Saturated Activities

Reaction	Filter	Infinitely Dilute Saturated Activity, disintegrations/sec-nucleus	Nominal 90% Activity Limits, MeV	
			Lower Energy	Upper Energy
$^{27}Al(n,\alpha)^{24}Na$	Bare	5.62×10^{-20} (±3.3%)	6.600	12.500
$^{27}Al(n,p)^{27}Mg$	Bare	3.06×10^{-19} (±2.8%)	3.300	9.400
$^{58}Ni(n,p)^{58}Co$	Bare	1.65×10^{-17} (±3.9%)	2.200	6.900
$^{115}In(n,n')^{115m}In$	Bare	2.45×10^{-17} (±2.3%)	0.720	4.900
$^{103}Rh(n,n')^{103m}Rh$	Bare	4.73×10^{-16} (±3.9%)	0.300	3.800
$^{238}U(n,f)F.P.$	Bare	3.48×10^{-17}* (±3.4%)	1.500	5.500
$^{235}U(n,f)F.P.$	Bare	5.52×10^{-15}* (±2.8%)	6.00×10^{-8}	0.475
	Cadmium	4.03×10^{-15}* (±2.9%)	9.20×10^{-7}	0.600
	Boron-10	1.27×10^{-15}* (±2.7%)	0.012	1.400
$^{239}Pu(n,f)F.P.$	Bare	1.06×10^{-14}* (±2.9%)	9.20×10^{-8}	0.320
	Cadmium	4.44×10^{-15}* (±2.7%)	8.00×10^{-7}	0.690
	Boron-10	2.42×10^{-15}* (±3.7%)	0.023	2.100
$^{238}U(n,\gamma)\xrightarrow{\beta-}{}^{239}Np$	Bare	5.36×10^{-16} (±3.8%)	1.80×10^{-6}	0.400
	Cadmium	5.36×10^{-16} (±3.8%)	4.00×10^{-3}	0.400
	Boron-10	1.56×10^{-16} (±4.2%)	5.75×10^{-3}	0.760
$^{232}Th(n,\gamma)\xrightarrow{\beta-}{}^{233}Pa$	Bare	1.60×10^{-15} (±2.6%)	5.75×10^{-7}	0.400
	Cadmium	1.59×10^{-15} (±2.6%)	1.80×10^{-6}	0.425
	Boron-10	9.05×10^{-16} (±2.6%)	1.35×10^{-2}	0.660
$^{63}Cu(n,\gamma)^{64}Cu$	Bare	1.22×10^{-16} (±2.2%)	1.60×10^{-7}	0.280
	Cadmium	1.13×10^{-16} (±2.2%)	1.35×10^{-6}	0.300
	Boron-10	0.41×10^{-16} (±2.2%)	2.00×10^{-2}	0.500
$^{197}Au(n,\gamma)^{198}Au$	Bare	6.31×10^{-15} (±2.2%)	6.30×10^{-7}	5.75×10^{-2}
	Cadmium	6.18×10^{-15} (±2.2%)	2.20×10^{-6}	0.063
	Boron-10	3.47×10^{-16} (±2.2%)	8.80×10^{-4}	0.475
$^{115}In(n,\gamma)^{116m}In$	Bare	2.78×10^{-14} (±2.8%)	9.20×10^{-7}	2.00×10^{-6}
	Cadmium	2.71×10^{-14} (±2.8%)	1.05×10^{-6}	2.10×10^{-6}

* $\frac{Fissions}{sec\text{-}nucZeus}$

$$\text{Average Error} = \frac{\sqrt{\sum_{i=1}^{N} \sigma_i^2}}{N} = 2.977\%$$

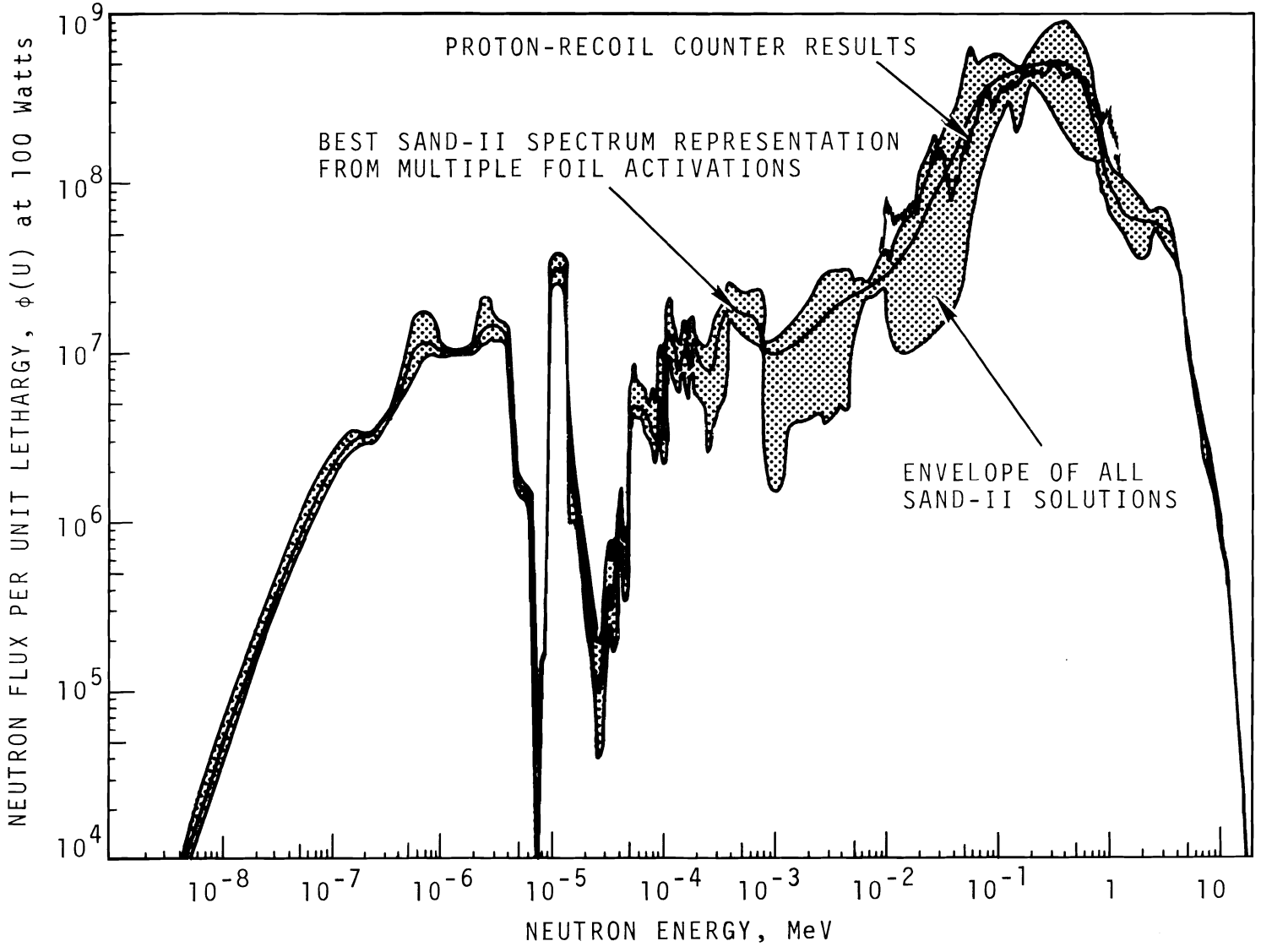

FIGURE 4.2 *Neutron Flux Spectrum in the PCTR Fast Neutron Cavity*

Discussion and Comparison of Results

The integral flux in the neutron energy interval 9.32 keV to 1.17 MeV was obtained from the SAND-I1 analysis of multiple foil activations within +3% uncertainty from all iterative spectrum solutions. This permitted normalization of proton-recoil spectrometer results to multiple foil activation results, as shown in Figures 4.1 and 4.2. In addition to permitting direct comparison between the two experimental methods, this normalization was used as an absolute flux level calibration for the proton-recoil spectrometer. The envelope of all SAND-I1 solutions exhibited poor resolution in the interval where the proton-recoil counter results were obtained. The activation cross sections were small and similar in shape over this neutron energy interval. Activation integrals were relatively insensitive to the shape of the neutron spectrum in the region of the flux peak. Agreement of the results from the two methods was encouraging. Large flux depressions at about 7 eV and between 20 and 40 eV, shown in Figure 4.2, were the result of ^{238}U resonance absorption in the FNC buffer. The apparent depression in the SAND-I1 spectrum at approximately 2 MeV is believed to be due to errors in the cross sections and the activation measurements for the $^{115}In(n,n')^{116m}In$ and $^{58}Ni(n,p)^{58}Co$ reactions.

Energy degradation of fission spectrum neutrons into the few hundred keV energy region, as shown both by experimental results and calculations,[6] was the result of ^{238}U inelastic scattering in a uranium buffer zone. This 5.4-in. uranium buffer zone completely surrounded a 1/2-in. thick stainless steel box (29.0 in. by 29.0 in. by 24.7 in. inner dimensions) forming the large Fast Neutron Cavity.[8] The uranium fuel in the FNC absorbed incident thermal neutrons and produced fast neutrons by the fissioning process such that a flux of predominantly fast neutrons entered the central cavity.

Neutron spectrum results from multiple foil activation measurements were obtained over the entire energy spectrum, 10^{-10} to 18 MeV. Detailed neutron spectrum structure was measured by proton-recoil spectrometer methods in the energy interval, 9.6 keV to 1.4 MeV, comprising 80% of the integrated neutron flux. Thus, each of these two experimental methods supplemented and confirmed the information obtained from the other. Using both methods permitted the absolute value of the neutron flux spectrum to be obtained in the center of the FNC with the PCTR operating at a 100 Watt power level.

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