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BEAM CHARACTERIZATION AT THE NEUTRON RADIOGRAPHY FACILITY (NRAD)

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ABSTRACT

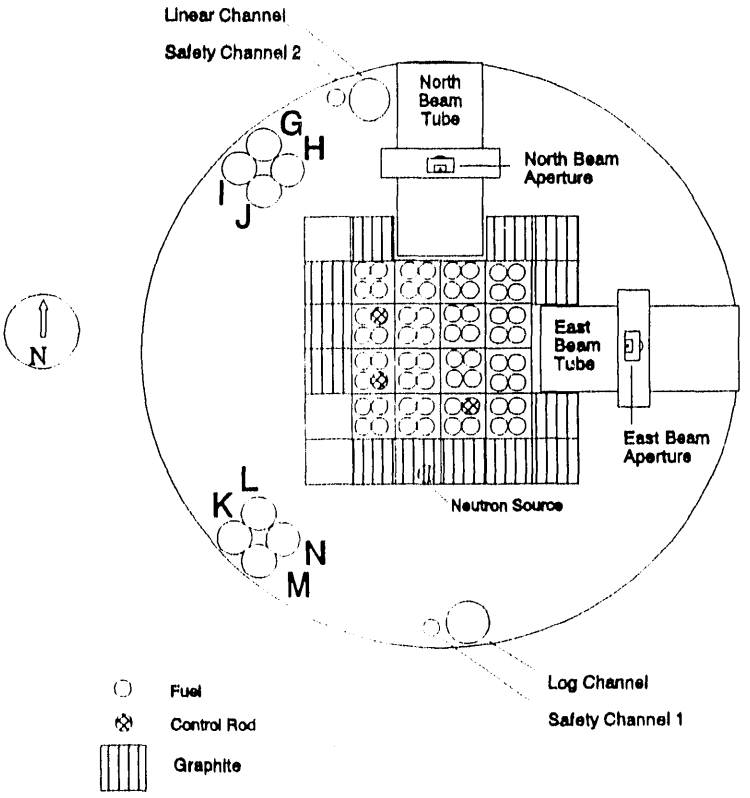
An ongoing project to characterize the neutron beams at the Neutron Radiography Reactor (NRAD) is described in this paper. The effort has consisted of computer modelling with three dimensional diffusion theory to obtain a trial spectrum, foil activation measurements, and the use of the SAND-II unfolding code. It was expected and found that diffusion theory will underpredict the fast flux. However, it is claimed that precise characterization of the entire spectrum is not necessary for comparisons among neutron radiography facilities; rather, the use of simple fast neutron indicators should be adequate. A specific example used at NRAD is the U-235/U-238 fission reaction rate ratio. A ratio such as this could be used in the same manner as the classic gold cadmium ratio for interfacility comparisons with regard to fast neutrons.

Introduction

The Neutron Radiography Reactor (NRAD) is located at Argonne National Laboratory - West near Idaho Falls, Idaho in the Hot Fuel Examination Facility (HFEF). HFEF is a large hot cell facility that was designed primarily for the post-irradiation examination of experimental nuclear reactor fuel. NRAD became operational in 1978; the original facility consisted of a TRIGA reactor obtained from the Puerto Rico Nuclear Science Center and a single radiography beam (east). A second beam (north) was added in 1982.

The NRAD reactor is normally operated at 250 kW for radiography. The present configuration consists of 60 TRIGA/FLIP fuel elements (70% enrichment) with three boron-carbide control rods. The reflector is water or graphite, depending on location. The reactor is located in a 2.0 m diameter by 3.5 m high aluminum tank. Because a large portion of the radiography performed at NRAD is that of highly neutron-absorbing reactor fuel, indirect radiography techniques (utilizing the indium resonance) are used.

To obtain the hard spectrum component, the beams are initiated using source tubes that extend from the core face (with less than 20 mm of water between the reactor fuel and the beam tubes) to the tank wall. Both beam tubes have adjustable apertures utilizing boron-nitride blocks with holes drilled in them. The reactor configuration and the location of the beam tubes within the tank is shown in Figure 1.



NRAD CORE PLAN VIEW

An ongoing effort to characterize the neutron beams at NRAD has been occurring for the past several years. The most recent efforts have consisted of computer modeling of the NRAD core to determine a trial neutron spectrum. The unfolding code, SAND-II (Ref. 1), was then used with foil measurements and the trial spectrum. This yields the best estimate of the beam spectrum obtained to date.

Computer Model

The ANL three-dimensional diffusion theory code DIF3D (Ref. 2) was used to model the NRAD core to obtain a trial spectrum. Unit cell cross-sections were generated using EPRICELL (Ref. 3) in a 43 group format. There are 14 groups above 100 eV, 17 groups between 1 eV and 100 eV, and 12 below 1 eV. The DIF3D model was run in XYZ geometry, with 12 zones in X and Y each and 10 zones in Z. The model includes hardware above and below the core (e.g., grid plate, control rod drive hardware) and terminates with a layer of 61.0 cm of water as the upper and lower axial reflector. The same thickness of water is used as the boundary layer in the X and Y directions. Each unit cell in the core area is 4.05 cm (X) by 3.85 cm (Y), and consists of homogenized fuel, clad, and water with the cell cross-sections generated by EPRI-CELL as noted above. The active portion of the core (38.1 cm in height) was modeled as 3 zones.

The beam tubes at NRAD are basically thin walled aluminum boxes that are filled with helium and are placed close to the active fuel region (see Figure 1). It is well known that diffusion theory is not able to treat the near vacuum condition that these beam tubes represent. The beam tube zone was modelled as a smeared region of water and aluminum with a reduced density; this is inadequate for predicting emerging currents as either transport theory or Monte Carlo calculations are required. However, the purpose of this model is to obtain a trial spectrum and it is assumed that the beam tube does not greatly perturb the spectrum, at least to the extent that the SAND-II unfolding process is able to compensate for the errors in the trial spectrum. It is to be expected that the trial spectrum will underpredict the fast energy region due to the greater directional dependence of the fast flux, which diffusion theory cannot model. This expectation was validated by the SAND-II unfolding process using activation rate data.

Foil Measurements

A series of activation foil measurements in the east beam was performed using a combination of thermal, resonance, and threshold foils, which are listed in Table 1. Additional measurements have been made with U-235 and U-238 fission foils. The reaction rates from these foils were used to obtain an independent "spectral indicator" to demonstrate consistency with the SAND-II results. The measurements were taken at a reactor power of 250 kw, with a beam aperture L/D=50.

TABLE 1. Activation

a) Fast Reaction Activation Rates (reactions/second/target atom)

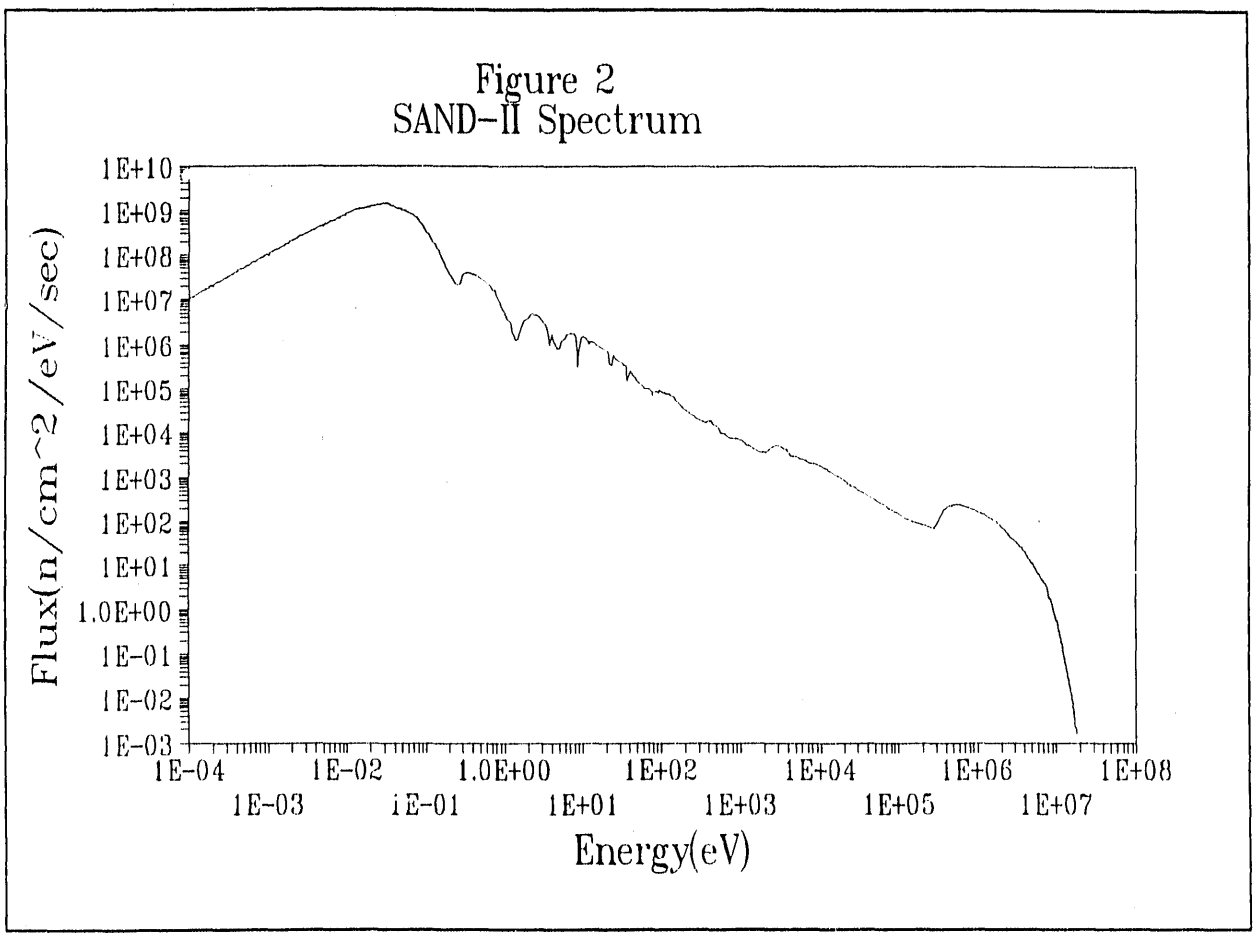
Reaction	Reaction Rate	Nominal Threshold, MeV
$^{115}In(n,n')\ ^{115m}In$	6.12155×10^{-17}	1.2
$^{47}Ti(n,p)\ ^{47}Sc$	5.318×10^{-18}	2.2
$^{58}Ti(n,p)\ ^{58}Co$	3.4685×10^{-17}	2.8
$^{64}Zr(n,p)\ ^{54}Cu$	1.09×10^{-17}	2.8
$^{54}Fe(n,p)\ ^{54}Mn$	2.5055×10^{-17}	3.1
$^{46}Ti(n,p)\ ^{46}Sc$	4.2235×10^{-18}	3.9
$^{56}Fe(n,p)\ ^{56}Mn$	4.823×10^{-19}	6.0
$^{59}Co(n,\alpha)\ ^{56}Mn$	8.7715×10^{-20}	6.8
$^{48}Ti(n,p)\ Sc^{48}$	1.3055×10^{-19}	7.6

b) Resonance and Thermal Reaction Activation Rates (reaction/second/target atom)

Reaction	Reaction Rate	Cadmium
$^{59}Co(n,\gamma)\ ^{60}Co$	3.746×10^{-15}	bare
	7.1295×10^{-16}	Cd covered
$^{197}Au(n,\gamma)\ ^{198}Au$	1.5875×10^{-14}	bare
	7.978×10^{-15}	Cd covered
$^{115}In(n,\gamma)\ ^{116m}In$	2.3365×10^{-14}	bare
	7.828×10^{-15}	Cd covered
$^{98}Mo(n,\gamma)\ ^{99}Mo$	1.0135×10^{-16}	bare
	9.31×10^{-17}	Cd covered
$^{45}Sc(n,\gamma)\ ^{46}Sc$	2.328×10^{-15}	bare
	1.2115×10^{-16}	Cd covered

Spectrum Unfolding

The unfolding code SAND-II was used with the trial spectrum obtained from DIF3D and the activation rate data, presented in Table 1, as input. The results of this unfolding are presented in Figure 2. Because of the limited amount of data available, the SAND-II spectrum is not very complete. However, it is felt that the basic shape and magnitude is valid.



To obtain the best analytical representation of the spectrum with these limited data, a fit to three energy regions was performed using classical approximations:

(1) *A thermal region using a Maxwellian*

$$\phi_t(E) = C\,Ee^{E/kT}$$

where kT = 0.03 eV (350K)
C = Constant
from 0 - 0.2 eV
from 0.2 eV - 100 keV
from 100 keV to 10 MeV

(2) *A 1/E scattering region*

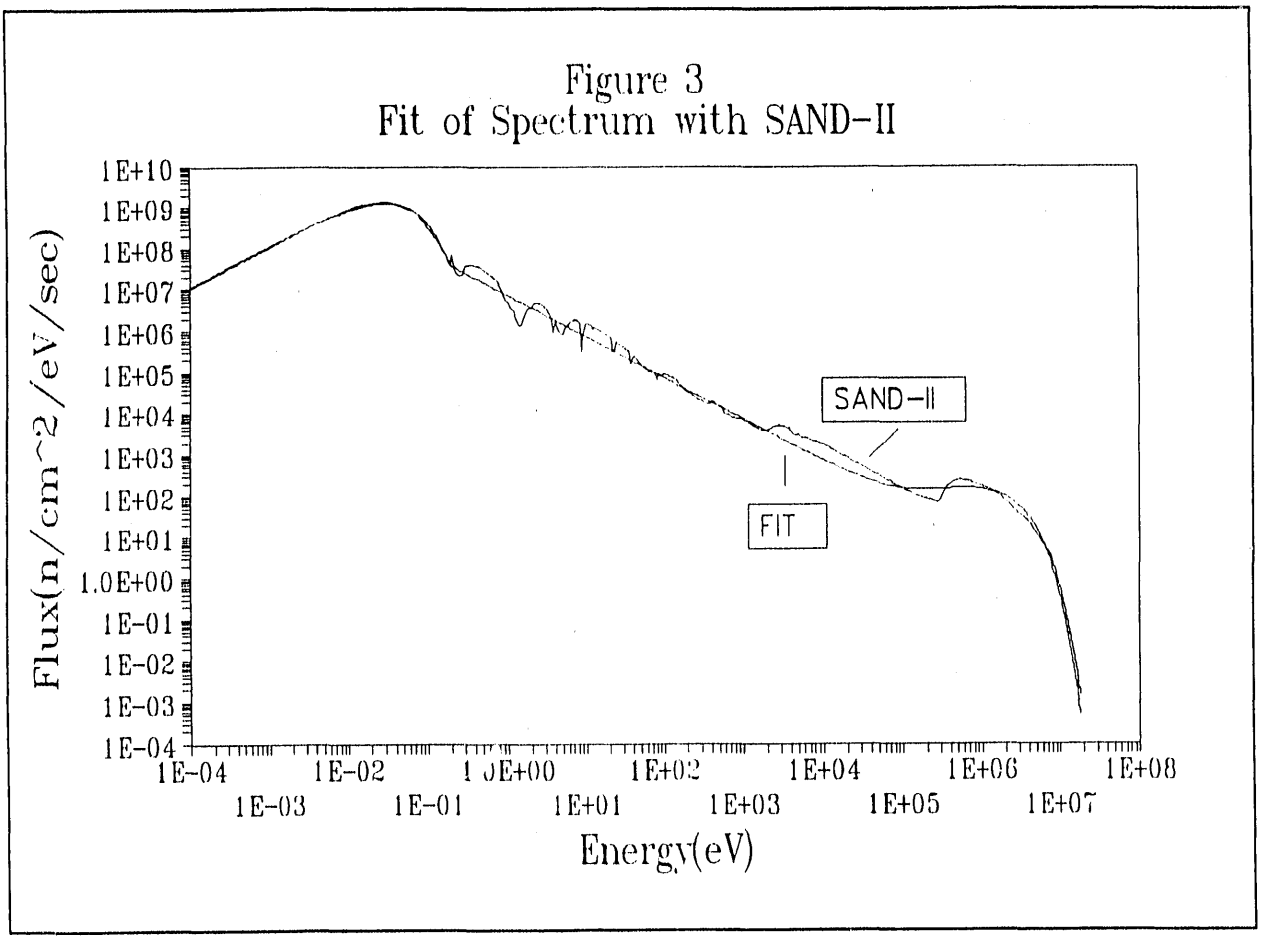
$$\phi_s(E) = C/E$$

(3) *a fission spectrum region*

$$\phi_f(E) = Ce^{-1.036E}\sinh\sqrt{2.29E}$$

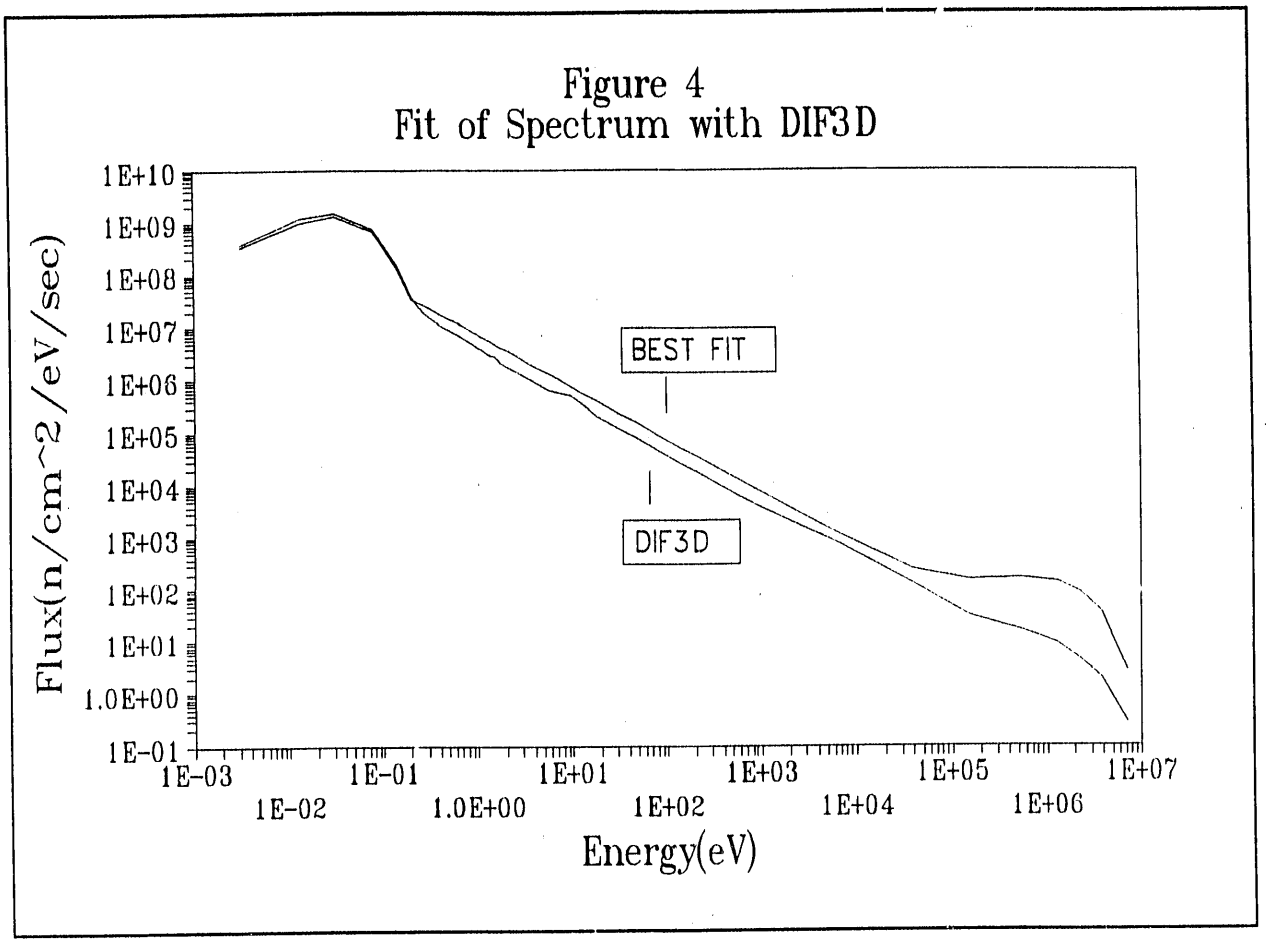
Normalization was accomplished in each of these three regions by forcing the integrals of the SAND-II spectrum to be equal to that of the analytical model; the results of this fit overlayed on the SAND-II spectrum of Figure 2 are shown in Figure 3. This fitted spectrum is considered to be an adequate representation of the beam spectrum in NRAD as of now.

Figure 3
Fit of Spectrum with SAND-II



A final comparison of the trial spectrum generated by DIF3D and the fitted spectrum obtained above is presented in Figure 4. As can be seen, the DIF3D spectrum underestimates the fitted spectrum in all regions above thermal, and in the region above 1 MeV, the difference is an order of magnitude.

Other measurements have been taken in the NRAD beam using direct fission product counting in 2π geometry. Special fission counters have been built for this purpose. The



counters are constructed of two hemispherical chambers, in which two separate fission foils can be placed (Ref. 4). Thus the ratio of reaction rates (e.g., U-238 vs. U-235) can be precisely measured using NIST calibrated foils. The U-238 reaction rate was measured with a foil containing 136.28 μ gram of uranium, depleted to 0.01393 w/o of U-235. The U-235 reaction rate was obtained with a foil of 121.7 μ gram of uranium with a U-235 abundance of 98.44%. The results of these measurements yield a ratio of U-235/U-238 reaction rates (fissions/second/gram) of 530 in the NRAD beam. By contrast, a metal fueled fast reactor ratio could be about 50 (Re.f 2). The fast flux (greater than 1.5 MeV) was estimated using the cross-section given in ASTM E-261 ("Standard Practice for Determining Neutron Fluence Rate, Fluence, and Spectrum by Radioactivation Techniques"). The result is a fast component of the flux predicted by the measured U-238 fission rate of 2.35 x 10^8 n/cm^2/sec, while the fit of SAND-II output (curve of Figure 3) yields a flux of 2.2 x 10^8 n/cm^2/sec; the difference is less than 10%. This is a good indicator that the fit of Figure 3 represents the fast flux, since the U-238 reaction rate was measured independently, and was not incorporated in the SAND-II unfolding process. It is felt that 10% consistency is adequate for these purposes, as there is no claim that these measurements will yield a truly accurate spectrum (e.g., adequate for benchmarking precise activation rates).

Practical Considerations

As stated earlier, it was recognized that diffusion theory is inadequate to predict the fast component of the flux. Unfortunately, the total transport problem is sufficiently

complicated that it will require an extensive effort to develop a better prediction. The geometry of the core and beam tubes does not lead to symmetry in any single coordinate system. Further complicating the analysis is the fact that the beam tube and aperture provide an imperfect collimator, especially for fast neutrons. It would be possible to develop X-Y or R-Z transport models to obtain an angular flux emergent from the core. This could then be coupled to an R-Θ model of the collimator and shield wall. A full Monte-Carlo model could model the geometry correctly; however to obtain a better estimate of the spectrum using Monte-Carlo would require a very large number of histories.

Summary

An attempt has been made to characterize the beam spectrum in NRAD using foil activation measurements and SAND-II, given the known limitations of a diffusion theory prediction of beam tube flux would be inadequate for the fast flux. This was borne out by the results of the SAND-II unfolding process, and also by an independent U-238 fission rate measurement.

In practice, it is not necessary that radiography facility characterize their beam spectra to great detail or accuracy. Foil or converter responses are usually thermal or epithermal. Simple measures of gold activation rates and cadmium ratios typically provide the degree of characterization adequate for inter-facility comparison. The only caveat to that simplistic view comes from radiography of light scattering materials (e.g., hydrogenous), where foil (or converter) response due to downscattered neutrons can greatly distort the image resolution. For these cases, it would be useful to have a simple measure of the fast flux. It is proposed that one of the existing ASTM standards for measuring fast neutron reaction rates could be adopted as fast neutron "spectral indicators". Candidates are E-263 (Iron - response above 2.2 Mev), E-264 (Nickel - response above 2.1 mev), and E-704 (U-238 - response above 1.5 Mev). U-238 fission rates have traditionally provided useful indicators in a fast spectrum. (It should be noted that in a thermal reactor the contribution from U-235 fission requires a substantial correction factor).

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