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NEUTRON BEAM CHARACTERIZATION AT THE NEUTRON RADIOGRAPHY REACTOR (NRAD)

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ABSTRACT

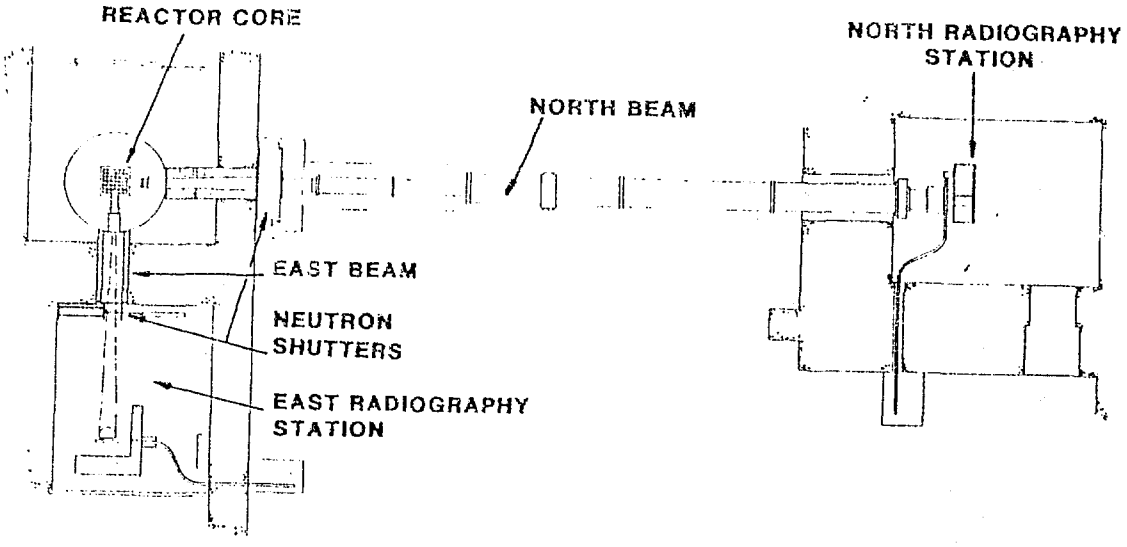
The Neutron Radiography Reactor (NRAD) is a 250-kW TRIGA Reactor operated by Argonne National Laboratory and is located near Idaho Falls, Idaho. The reactor and its facilities regarding radiography are detailed in another paper at this conference; this paper summarizes neutron flux measurements and calculations that have been performed to better understand and potentially improve the neutronics characteristics of the reactor.

FACILITY DESCRIPTION

NRAD was designed for the radiography of highly absorbing fuel elements or fuel assemblies; fuel from both fast reactors and thermal reactors have been successfully radiographed at NRAD. To achieve the necessary penetration of fuel, an indirect technique using the 1.4 eV resonance of an indium foil is utilized in most applications.

There are two beams of differing lengths in the NRAD facility, north and east. A plan view of the facility is shown in Figure 1. Much effort has been taken to minimize scattered neutrons in the beams through placement of neutron absorbing materials which allows sharp definition of the beams. Both beams have changeable apertures that allow selection of L/D ratios from 50 to 300 in the east and 185 to 700 in the north. Each aperture consists of a fixed block of boron nitride with a 90-mm hole, which yields the lowest L/D ratio for each beam. A movable block containing two smaller holes can be moved in front of the fixed block to obtain the larger L/D ratios.

The beam source tubes are located next to the core face, with less than 20 mm of water between the fuel and the beam tubes. The NRAD fuel consists of 8% (weight) uranium enriched to 70% ^{235}U, with 1.5% (weight) of erbium as a burnable poison. The fuel is actually a U/Zr-H mix, giving the TRIGA reactor its very strong prompt negative temperature coefficient. The U/Zr-H and the fact that the beams are extracted nearly directly from the fuel leads to some interesting differences between NRAD and most other radiography facilities.



Neutron Radiography Facility

(PLAN SECTION)

FIGURE 1

INITIAL MEASUREMENTS

Initial gold foil measurements in the NRAD north and east beams revealed several points:

1. The thermal flux in both beams obeys $(L/D)^2$ scaling to within 5%, with L/D ranging from 26 to 300. However, the resonance flux (above the cadmium cutoff) predicted by $(L/D)^2$ scaling is lower than the measured resonance flux by 20-25% at the higher L/D ratios. This indicates that the aperture is not as effective for the higher energy neutrons.

2. The cadmium ratio in the east beam varies from 2.2 at an L/D of 50 to 1.9 at an L/D of 125. Cadmium ratios this low indicate a significant lack of thermalization of the beam. This is not surprising given the fact that the beams are taken almost directly from the reactor fuel (i.e., with very little moderator from source to beam other than the ZrH in the TRIGA fuel itself). It is also seen that a harder spectrum is obtained at the higher L/D ratios, which is probably due to the effect of the movable aperture block acting as a thermal neutron filter, and causing a slight shift in the spectrum.

3. Fifty millimeters of polyethylene attenuates the thermal neutron flux at the lower L/D ratios, but causes an enhancement at the higher L/D ratios, indicating that the thermalization of fast neutrons is greater than the attenuation of the thermal neutrons in the beam.

A perfect collimator/aperture combination will obey $(L/D)^2$ scaling, i.e., the flux at a plane (Φ) is related to the entrance aperture flux (Φ_o) by

$$\Phi \equiv \frac{\Phi_o}{16(L/D)^2}$$

This is merely the ratio of the area subtended by the aperture ($\pi D^2/4$) to the solid angle at a given distance L ($4\pi L^2$). Thus, the assumption is made that the aperture system totally blocks any neutrons not passing through the aperture itself. It would be expected that the aperture would be less effective at higher energies. Additionally, as more thermal absorber material is placed in the beam, it is expected that a hardening of the spectrum would result, which is consistent with observations #2 and #3 above.

Recently, the feasibility of using NRAD for NDA on unknown quantities of fissionable material has been investigated. Basically, the technique would consist of using the NRAD beam to interrogate samples, and measure fission neutrons emanating from the sample (90° from the beam axis). The geometry of the problem is shown in Figure 2. Initial scoping measurements were made of ^{235}U fission rates, both in the beam and off-axis (where the fission neutron detector would be located); the off-axis measurement is an indicator of the amount of room scatter, which will lead to a background signal.

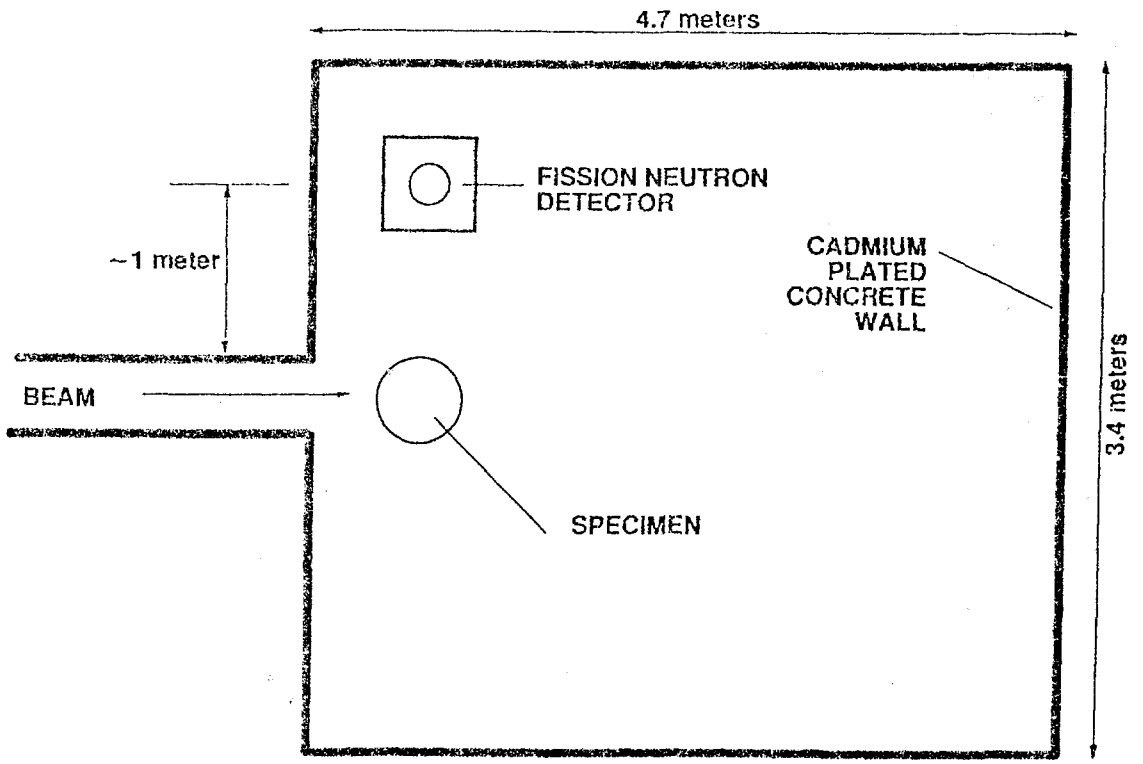


FIGURE 2 - NDA GEOMETRY

It was found that the off axis/on axis ratio of fission rate was 7.1×10^{-3} for a bare chamber, and 3.1×10^{-2} for a cadmium covered chamber. The on-axis cadmium ratio (for ^{235}U) was found to be 15.3, while the off-axis ratio was 3.5, indicating the room scatter is quite hard instead of more thermalized as might be first expected. The hardness of the spectrum of room scatter was further confirmed when it was discovered that a 100 mm annulus of 4% boric acid and water surrounding an off-axis fission counter actually increased the fission rate (but decreased it in the on-axis position). This has been explained by the fact that the back wall of the cell is plated with cadmium, acting as an effective thermal filter. These measurements have shown the need for a more carefully designed beam stop if it is desired to reduce off-axis fluxes. For the problem described above, the contribution to the signal from off-axis scattered neutrons can be reduced by collimating the fission neutron detector such that its main contribution comes from the unknown sample. Measurements are currently underway to determine the effectiveness of this.

NEUTRON SPECTRUM

As measurements with results described above were obtained at NRAD, it became clear that the neutron spectrum was not necessarily ideal for radiography utilizing the 1.4 eV indium resonance, and was certainly not optimum for thermal neutron radiography. It was thus desired to obtain a more accurate representation of the neutron spectrum; this will aid in determining if any improvements can be made using neutron filters.

A series of activation foil measurements was performed using a combination of thermal, resonance, and threshold foils, which are listed in Table 1. The spectrum was unfolded using the methodology described in Reference 1; the differential spectrum obtained is shown in Figure 3. The spectrum shows a strong thermal

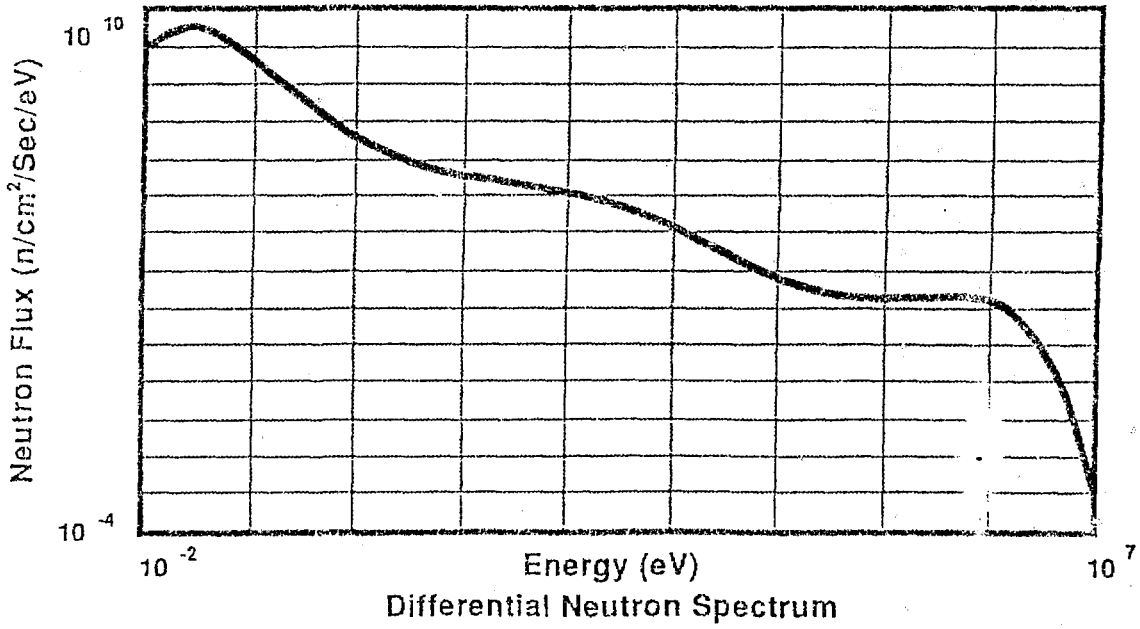


FIGURE 3

TABLE 1: ACTIVATION FOILS

Energy (eV)	Reaction
Thermal	$^{197}Au\ (n,\gamma)\ ^{198}Au$
Thermal	$^{235}U\ (n,f)$
Thermal	$^{115}In\ (n,\gamma)\ ^{116m}In$
1.46	$^{115}In\ (n,\gamma)\ ^{116m}In$
4.9	$^{197}Au\ (n,\gamma)\ ^{198}Au$
132	$^{59}Co\ (n,\gamma)\ ^{60}Co$
480	$^{98}Mo\ (n,\gamma)\ ^{90}Mo$
5000	$^{45}Sc\ (n,\gamma)\ ^{46}Sc$
1.2×10^6	$^{115}In\ (n,n')\ ^{115m}In$
2.2×10^6	$^{47}Ti\ (n,p)\ ^{47}Sc$
2.8×10^6	$^{58}Ni\ (n,p)\ ^{58}Co$
2.8×10^6	$^{64}Zr\ (n,p)\ ^{64}Co$
3.1×10^6	$^{54}Fe\ (n,p)\ ^{54}Mn$
3.9×10^6	$^{46}Ti\ (n,p)\ ^{46}Sc$
6.0×10^6	$^{56}Fe\ (n,p)\ ^{56}Mn$
6.8×10^6	$^{59}Co\ (n,\alpha)\ ^{56}Mn$
7.6×10^6	$^{48}Ti\ (n,p)\ ^{48}Sc$

component coupled with a fast component which is very close to a fission spectrum. It should be noted that the results shown in Fig. 3 are very preliminary; more work is planned in the near future to refine the neutron spectrum. However, calculations of the beam spectra using computer codes have confirmed the overall shape of the spectrum shown in Fig. 3; the shape is also consistent with the cadmium ratio, L/D behavior, and relative attenuation or shielding of hydrogenous specimens.

Currently, an effort is being made to obtain a better calculation of the NRAD beam utilizing 24 fast and 19 slow neutron groups. EPRI-CELL is being used to determine cell averaged cross-sections, and DIF-3D (an Argonne Reactor Physics Code) is being used to determine a best estimate of the spectrum. This estimate plus the results of the activation foils will be used with SAND-II to unfold the spectrum.

OTHER CALCULATIONS

The indirect radiography technique is ideally suited to a simple one-dimensional fixed source adjoint calculation, yielding the relative importance of a source neutron to a detector response.[2] An ideal neutron radiograph is a problem of simple transmission; any contribution to a foil response due to neutrons scattered down in energy will degrade the resolution.

It can be shown that the adjoint flux for a fixed source is

$$\Phi^{+} = \int \Sigma_{d} \Phi,$$

where the integration is taken over all parameters of interest, Φ is the regular "forward" flux, and Σ_d is the "detector's" macroscopic cross section, which is actually used as the fixed source for the adjoint calculation.

It is immediately seen from the above equation that the indium foil radiography technique used at NRAD is amenable to the adjoint calculation, as the foil can be considered to first order as a dirac delta function in space, energy, and angle (with a collimated beam) in plane geometry. The adjoint flux, as calculated by a discrete ordinates code such as ANISN, yields a quite direct measure of neutron importance for those source neutrons in the beam impinging on the sample of interest with regard to absorptions in the foil.

An example of a specimen radiographed at NRAD is one of the severe fuel damage test loops from the Power Burst Facility (PBF). These loops were nominally 140 mm in diameter, containing the equivalent of 77 mm of 5.76% enriched UO_2 from 28 light water reactor fuel pins as well as assorted structural material. After being subjected to overpower or undercooling tests at PBF, the fuel pins are generally melted at least at certain axial locations, yielding a homogenized problem. The most recent loop contained control rod material, which led to another problem that will be described later. A concern of the radiography of a sample such as the above with a mixed spectrum of beam neutrons is the relative contribution to the foil response from neutrons scattered down in energy through the sample and also fission neutrons produced in the sample itself. The ideal radiograph is produced from simple transmission, and any foil response caused by scattered or fission neutrons will lead to a loss of resolution. A simple multigroup adjoint calculation demonstrated immediately that 49% of the foil response was due to neutrons of energy 1.308 to 1.595 eV, 45% from 1.595 to 1.855 eV, and the rest from 1.855 to 3.928 eV. As there was no importance for a thermal neutron, one can conclude that fissions in the sample contribute nothing to the foil response. There is some contribution from downscattered neutrons, but one can conclude that it is due to small angle scattering and should lead to minimal loss of resolution.

It was mentioned above that the last loop contained control rod material, which replaced four fuel pins. The control rod material was 80% silver, 15% indium, and 5% cadmium. In the post-test radiographs, it became apparent that the control rod material had melted, and in certain locations the image was essentially black. Again a simple adjoint calculation demonstrated immediately

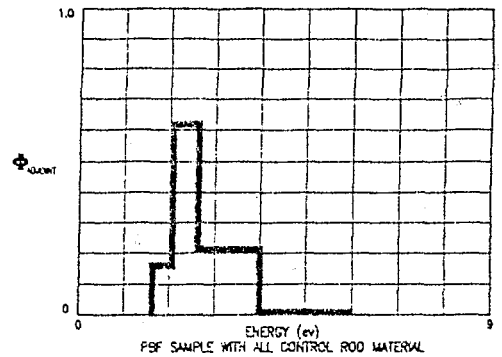
that even a small amount of indium makes a radiograph using indium foils extremely difficult to obtain. The calculation performed with the control rod material smeared throughout the UO_2 shows that there is no foil response due to the indium resonance neutrons, which obviously makes the radiograph not a simple transmission problem. The majority of the importance function was in the 2.0- to 4.0-eV range, indicating that downscattering is required to get any foil response from neutrons penetrating that sample. To confirm the logical postulate that the indium in the control rod material was the major factor in the change in the importance function for this case, a calculation was performed in which just the indium was removed. The result was essentially identical to the case with no control rod material, showing that highly absorbent silver and cadmium have no effect. The results of the three adjoint calculation are shown in Figure 4. It should be mentioned that another foil material would possibly have yielded acceptable results for this problem (e.g., gold, although there would be some interference between the gold and silver resonances).

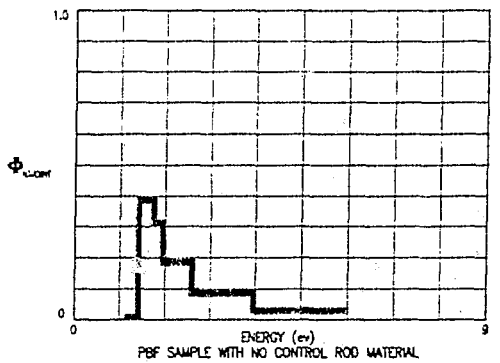
The previous calculations demonstrated that radiography performed on a typical fuel bundle can be interpreted as simple transmission, except for cases where the sample contains smeared material identical to the foil material. This would not be the case for a sample containing large amounts of light nuclei, especially hydrogenous material. An importance function was calculated for a 10-cm slab of polyethylene, and the results shown in Figure 5. In this case, the bulk of the importance function for an indium foil is above 87 keV, indicating that the great majority of the foil response would be due to neutrons downscattered greatly in energy. This would indicate that the neutron spectrum of the NRAD beams would not be well suited to the radiography of hydrogenous material; for that case, a well-thermalized beam, using a foil with strong thermal neutron response, would be required. This conclusion has led to the plans to install a removable neutron filter at the beam aperture to maximize the beam's thermal flux. To experimentally verify the conclusions drawn above, a plate of steel and a block of polyethylene of the same thickness (in mean free path) were radiographed, and the results scaned with a microdensitometer. The microdensitometer profiles are shown in Figures 6 and 7; it is immediately seen that the radiograph of the uniform polyethylene sample is extremely nonuniform, vividly demonstrating what the adjoint calculation predicted.

As shown, simple adjoint calculations were used to help interpret neutron radiography results at NRAD. Since most of the radiography performed at NRAD is of large test bundles containing fuel, the adjoint calculation has shown that efforts should be made to optimize the epithermal flux (near 1.4 eV). The adjoint calculation helped to interpret the effect of control rod material in a test loop and led to the search for another foil. Finally, the calculation of a hydrogenous sample shows that not all radiography can be treated as simple transmission, at least where there are higher energy neutrons available as there are at NRAD.

SUMMARY

In summary, an ongoing beam characterization program at NRAD has further enhanced the understanding of the beams. Calculations and measurements have been used; the ultimate goal is improvement of radiography through tailoring of the beams via filters.





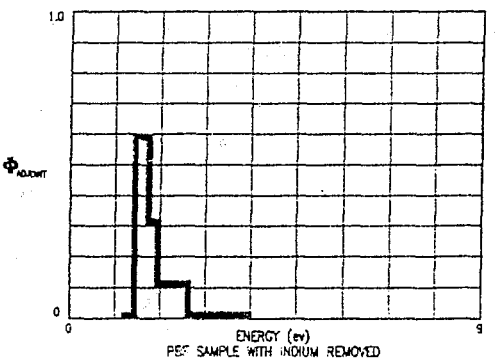
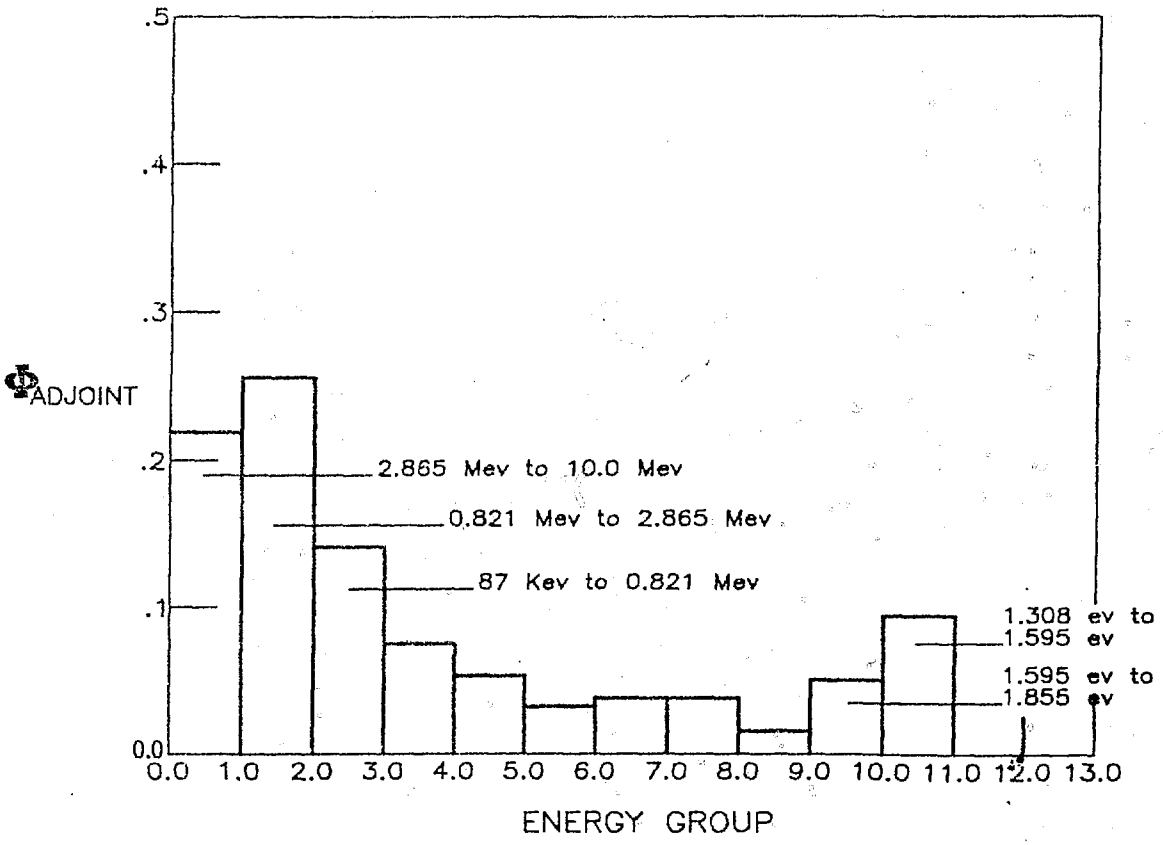


FIGURE 4 - PBF ADJOINT FLUX



ADJOINT FLUX FOR 10 CM OF POLY

FIGURE 5

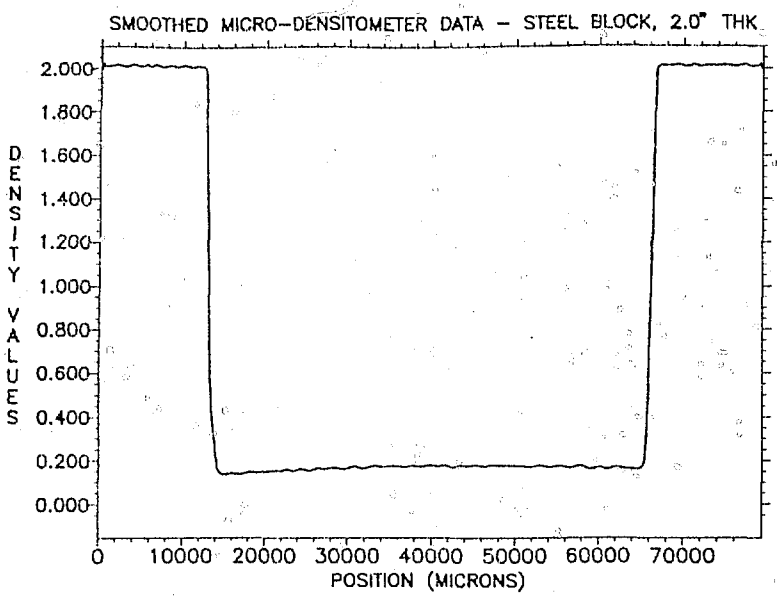


FIGURE 6

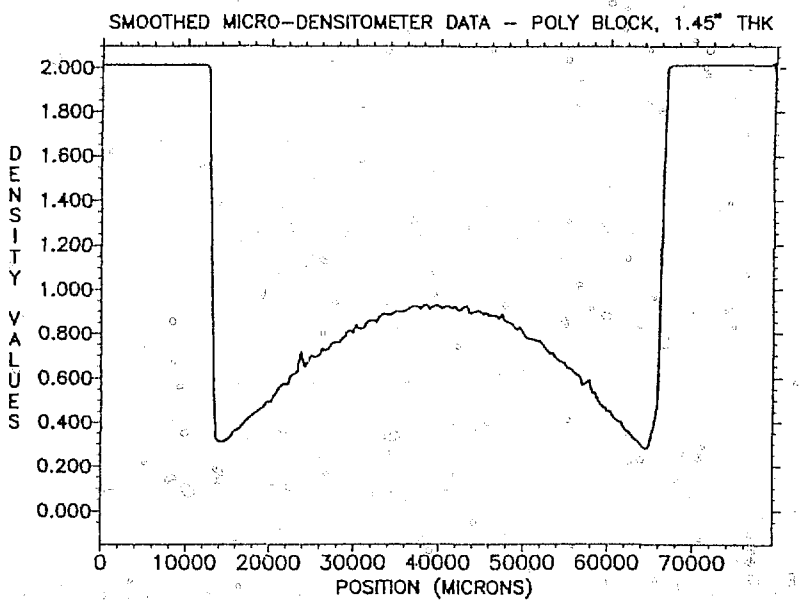


FIGURE 7

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