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INTERIM REPORT

PRELIMINARY EVALUATION OF TECHNIQUES FOR PREDICTING THE SPECTRA OF
NEUTRONS TRANSMITTED BY GRID PLATE SHIELDS

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Abstract

This is an interim progress report on the status of the LMFBR shielding program in progress at Oak Ridge National Laboratory. The effort is mainly concerned with the evaluation and development of calculational techniques for predicting the fluence of neutrons that penetrate a sodium and stainless steel shield to reach the grid plate beneath the FFTF core. Experimental determinations of the spectra of neutrons transmitted through 12-in.- and 24-in.-thick shields of sodium, of iron, and iron pins plus sodium are compared with two-dimensional discrete ordinates calculations, and, in some cases, with Monte Carlo calculations of these spectra. Also presented are the results of a series of one-dimensional ANISN calculations made to evaluate the effect of material choice in an early FFTF configuration. On the basis of the studies completed to date, a number of conclusions are presented outlining the current situation regarding shielding design calculations of this nature.

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I. INTRODUCTION

The solution to a number of design problems pertinent to the LMFBR program and the FFTF reactor design requires the prediction of neutron energy fluence at a number of points external to the core. One such problem in the FFTF design is that of predicting and minimizing damage to the grid plate which supports the fuel elements. A proposed design incorporates shielding in the fuel elements so that the overall length is minimized while still limiting the total neutron fluence impinging on the grid plate to an acceptable level. The shielding material first considered was stainless steel in the form of small diameter rods which could be incorporated in the lower end of the fuel elements in an array similar to the cluster of fuel rods. This configuration allows the sodium coolant to pass through the system while at the same time provides additional neutron attenuation between the fuel and the grid plate.

The prediction of radiation transport in shields consisting of stainless steel and sodium and having such a complex configuration, i.e., a pin array of a large number of cylindrical rods, presents a severe challenge to our most sophisticated transport methods. Even neutron transport through single homogeneous elements such as iron or nickel where the cross section is highly structured over almost the entire neutron energy range, places a severe strain on either a discrete ordinates or Monte Carlo method. The discrete ordinates method would seem to require that the number of neutron groups be more nearly like 250 than the usual 25-40 to permit an adequate transport calculation. Since the techniques that have been developed for conducting the efficient Monte Carlo calculations require an importance function that is obtained from an adjoint discrete ordinates calculation, it is not readily apparent how the problem should best be solved with Monte Carlo, even though the Monte Carlo calculation does include an extremely large amount of detail in the cross-section data sets. In order to evaluate the degree of difficulty which might be encountered in predicting accurately the neutron transport in such heavy metal shields, a combined experimental and theoretical effort was developed at ORNL to study this shielding problem.

Because the FFTF design schedule requires that decisions concerning the grid plate shield be made at an early date, an interim report is being issued which presents the status of the program to date. This report also presents conclusions that have been reached based on a partially completed analysis of both the experimental data and the FFTF grid plate shielding problem. The calculations that have been completed are presented in tabular form along with tabulated experimental results. Although the hydrogen counter results are still undergoing detailed analysis and may change somewhat as a result of this analysis, the data presented here represent a considerable improvement over that reported earlier.

It should be noted that some of the data presented are different than previously reported.¹ The hydrogen counter data were obtained in the new series of experiments with improved energy calibration counters that contained no ^3He . All the NE-213 data have been multiplied by 0.85, which represents a calibration factor that is still subject to a possible 5% change. The streaming factors reported here are based on the actual angular and energy leakage spectra from the reactor; the previously reported values were for an isotropically incident flux.

Also discussed is a current evaluation of the state-of-the-art for calculating neutron transport in solid iron. The results of attempts to analyze a number of experiments both at the Tower Shielding Facility (TSF) and at other installations are presented.

II. DESCRIPTION OF EXPERIMENT

Measurements were made of the neutron spectra transmitted through shields of solid cast iron, shields containing steel pins immersed in sodium, and one shield consisting of sodium in a steel container. Figure 1 shows the general arrangement of equipment at the Tower Shielding Facility. The neutron source was provided by the TSF-SNAP reactor which is supported from above by a mechanism that makes possible changes in both position and elevation. The reactor may be readily moved away from the experiment so that changes can be made in the experimental geometry.

There was no attempt to "mock up" FFTF components except for the use of equivalent iron-to-sodium ratios. Thus, iron, rather than stainless steel, and sodium were the materials used and the pins-in-sodium sample shields utilized a square lattice. The sample shields were limited in diameter and total thickness in order to minimize the cost of the experiment. The diameters chosen, however, were shown by calculation to be sufficiently large so that the measurements were dominated by the radiation transported through the experimental shields rather than through the surrounding hydrogenous collar shield.

The sample shields were all cylindrical in configuration having a nominal diameter of 18 in. and those that included sodium were contained in a low carbon steel can that had a 1/4-in.-thick bottom and a 1/8-in.-thick cover. The iron pins sodium shields used were 8, 16, and 24 in. thick. The 3/8-in.-diameter pins were held in a square array by two carbon steel grid plates, the pitch being 0.519 in. The volume fraction of iron was approximately 38% and the sodium density was

Fig. 1. Experimental Configuration for FFTF Grid Plate Shield Measurements.

between 0.93 and 0.94 grams/cc. The lower grid plate was 1/8-in. thick while the upper one was 1/16-in. thick. Other sample shields used were a 16-in.-high can filled entirely with sodium and three 18-in.-diameter cast iron pieces with heights of 8, 16, and 24 in.

The collar shield was a steel tank filled with transformer oil (Sp. Gr. = 0.898) that was 2-ft high with a 3/8-in.-thick bottom and a 5/16-in. cover. A collar shield containing a typical sample is shown in Fig. 2. Shields less than 24-in. thick were supported by styrofoam having a density of 0.024 to 0.032 g/cc, and as can be seen in Fig. 2 the sample and styrofoam were surrounded by a thin plastic sheet in order to prevent oil from entering the styrofoam cells. One 24-in. shield of sealed styrofoam was used to evaluate the effect of this material on the transmission of neutron spectra.

Two neutron spectrometer systems were used to measure neutron spectra penetrating the shields. One of these systems is the NE-213 proton-recoil neutron spectrometer developed by Burrus and Verbinski,² which has been used in a number of experiments at the TSF.^{3,4} The NE-213 detector was positioned approximately 26 ft below the shield sample in a lead and water shield which contained a collimator of the configuration shown in Fig. 1. The collimator dimensions were chosen so that the diameter of the area on the base of the shield viewed by the detector was 3 ft.

The second is the hydrogen recoil counter system also known as the Benjamin spectrometer.⁵ A brief description of the system and method of calibration is given in Appendix A.

Fig. 2. Collar Shield Containing Typical Sample.

III. RECENT CONCLUSIONS BASED ON COMPARISON OF CALCULATIONS WITH TSF EXPERIMENTS

The conclusions which have been reached as a result of the studies completed to this point are concerned with the evaluation of the available calculational methods for neutron transport in LMFBR shields and, in particular, neutron transport in shields consisting of iron pins immersed in sodium. In addition, some conclusions have been reached concerning the effectiveness of stainless steel or iron as a shield material. These conclusions are summarized as follows:

- 1) Based on the experimental measurements, the addition of steel rods to the 16-in. or 24-in. sodium shield reduced the total neutron flux at energies above 50 keV beneath the shield by a factor of 1.5 or less.
- 2) The calculated results from both the Monte Carlo and discrete ordinates codes for the experimental configuration indicate that the total number of neutrons leaving the shield are increased by a factor of about 1.5 due to streaming in the 24-in.-thick pin array. In this energy range the calculated results for the total flux from both the Monte Carlo and the discrete ordinates methods agree satisfactorily with the experiment. The "streaming factors" are defined as the ratio of the neutron flux being transported in the actual case to that calculated for an homogenized case.
- 3) A comparison of the discrete ordinates results with the NE-213 measurements for the 24-in. pin array shows that the discrete ordinates calculation underestimates the high-energy flux by almost a factor of 2 for all neutron energies, primarily because there was a strong uncollided flux component which was not adequately treated in the calculations; the angular quadrature, S_{100} , chosen was too coarse in the forward direction. The maximum streaming factor calculated for the 24-in. cell using the DOT code was about 10 for neutrons of energies near 5 MeV. This streaming factor is apparently too low; the maximum streaming factor seems to be about 20 for high-energy neutrons.
- 4) An evaluation of the calculated standard deviations indicates that the Monte Carlo calculations did not achieve good statistics for

the scattered flux. However, comparison of the average Monte Carlo calculations with results from the hydrogen counter for the 24-in. pin array did show agreement within 20%. Both the Monte Carlo and DOT techniques give agreement ($\sim 20\%$) within the accuracy of the measurements beneath the bare core and the sodium shield.

5) An ANISN calculation of the homogenized configuration similar to the FFTF indicates that the stainless steel in all the regions below the core increases the attenuation of the neutron flux at the grid plate by a factor of 12 relative to pure sodium. The effect of the stainless steel in the shield region alone is a factor of 3, which is much larger than the reduction observed in the experiment. Since the size of the sodium passage is much larger through the transition regions, streaming factors here would be worse; therefore, the overall attenuation could easily be off by a large factor if homogenized calculations are used.

6) The streaming effects depend on the neutron spectrum and angular distribution incident to the shield and will affect the attenuation characteristics of the material beyond the shield as well. The homogenized calculations also indicate that stainless steel is a relatively poor shielding material to be used for this application. The attenuation factors were increased by 20 when the stainless steel was replaced by tungsten carbide in the shield region alone, and by a factor of 40 when the boron-10 carbide replaced the stainless steel.

7) The comparisons of calculations and experiments for neutron transport in pure iron indicate that the calculational techniques must be further developed and that a definitive comparison with experiment has yet to be achieved. A technique must be developed for decreasing the machine time for the Monte Carlo problems such as this where the neutrons undergo a very large number of scatterings in penetrating the shield. For the discrete ordinates method, either a large number of energy groups appropriately spaced in the cross-section structure or a good *a priori* spectral weighting of the point cross-section data in forming few-group constants must be used. The comparisons of calculations and experiments for neutron transport

in iron are required in order to determine the adequacy of the cross-section data and the calculational techniques. The cross-section data have been improved with the recent high-resolution measurements of the total cross section. However, the angular distributions due to elastic scattering are not well known and are reported with very broad energy resolution. The comparisons with integral experiments which emphasize scattering will indicate whether these data are sufficient.

8) With respect to accurate radiation transport calculations in the reactor facility, including shield, support structure, pressure vessel, etc., it is our opinion that none of the present techniques are adequate. Diffusion theory is incapable of handling the streaming paths and the deep penetration in iron. The discrete ordinates method is useful for deep penetration in bulk media and for some streaming problems. However, the complex geometry of the numerous streaming paths prohibits a calculation of the whole facility with present techniques. A calculation of the entire system with Monte Carlo is theoretically possible; however, significant increases in computation speed must be made before such a calculation is practical. Consequently, a significant effort is required to develop a method which is capable of accurate radiation transport calculations for the full reactor system. Such calculations are necessary as benchmarks for the application of simpler, less accurate, design techniques.

9) It is concluded that a comparison of only the relative shapes of measured and calculated neutron spectra in a transport experiment provides little confidence in the calculational method.

IV. COMPARISON OF EXPERIMENTAL AND CALCULATED RESULTS

In order to facilitate comparison of calculated and measured results and to determine the effect of iron pins in the sodium shield, the data are presented in tabular form as ratios between various quantities for each neutron energy group corresponding to the 40-group structure used in the DOT calculations. In order to make these comparisons, the large number of groups that resulted from unfolding of the spectrometer data were "collapsed" to fit the DOT group structure. In addition, the absolute values of the measured fluxes are given.

The calculated results were obtained on an absolute basis. The leakage per watt of reactor power is dependent on calculations^{5a} which gave a value of 8.0×10^{10} neutrons per watt sec, and the calculations were checked against experimental results. The measurements are also obtained on an absolute basis. External foils which monitor the neutron leakage from the reflector have been related to the absolute fission rate within the core. This correlation was obtained during critical experiments on the reactor by utilizing fission foils placed within the core and also making gamma-ray scans of the fuel elements from the entire core.

Table 1 presents the experimental results for the bare core. Tables 2 and 3 present a comparison between both the Monte Carlo and DOT calculations and experiments for the bare core at the hydrogen counter and the NE-213 counter positions, respectively.

The statistical deviation in the hydrogen counter measurements is similar to the variation observed in the ratio between calculations and measurements; namely, 5-8%. The DOT calculations appear to be somewhat high for energies above 1 MeV at the hydrogen counter positions, whereas the Monte Carlo calculations appear to agree at 1 MeV and appear to be approximately 25% low near 0.25 MeV. The comparison of the calculations with the NE-213 results shows agreement within 20% over most of the energy range, and where the deviations become significant (above 10 MeV) the statistics of the measurements become quite poor.

Table 1

MEASURED NEUTRON FLUXES FOR THE UNSHIELDED BEAM

Upper Energy (MeV)	Flux, n/cm ² sec MeV Watt					Upper Energy (MeV)
	Hydrogen Counter ^a			NE-213 Counter ^b		
	1 atm.	3 atm.	10 atm.	Run 1	Run 2	
1.50			6.24+4 ^c		7.55-2	14.9
1.22			7.07+4	2.33-1	1.95-1	13.5
1.00			7.56+4	4.64-1	4.81-1	12.2
0.821			9.16+4	1.26+0	8.84-1	11.1
0.672			8.90+4	1.57+0	2.26+0	10.0
0.550		1.12+5	1.05+5	3.44+0	3.65+0	9.05
0.450		1.24+5		6.85+0	6.48+0	8.19
0.369		1.35+5		1.03+1	1.19+1	7.41
0.302		1.59+5		1.90+1	2.01+1	6.70
0.247	1.43+5	1.45+5		3.15+1	2.97+1	6.06
0.202	1.87+5	1.53+5		4.06+1	4.08+1	5.49
0.166	1.80+5	1.76+5		5.89+1	6.00+1	4.97
0.136	1.93+5	2.33+5		8.35+1	8.44+1	4.49
0.111	2.26+5			1.10+2	1.11+2	4.07
0.067				1.32+2	1.29+2	3.68
				1.84+2	1.77+2	3.33
				2.91+2	2.79+2	2.73
				3.84+2	3.74+2	2.23
				4.84+2	4.75+2	1.83
				5.97+2	5.72+2	1.50
				6.72+2	6.49+2	1.22
				8.26+2	7.93+2	1.00
						0.821

^a Located 77 cm below bottom of core.^b Located 888 cm below bottom of core.^c Read as 6.24 x 10⁴.

Table 2

COMPARISON OF MEASUREMENTS AND CALCULATIONS FOR THE UNSHIELDED
BEAM FOR NEUTRON ENERGIES LESS THAN 1.5 MeV

Ratio of Measured to Calculated Flux							
DOT Calculations				Monte Carlo Calculations ^b			
Upper Energy (MeV)	1 atm. ^a	3 atm.	10 atm.	Upper Energy (MeV)	1 atm.	3 atm.	10 atm.
1.50			0.850	1.00			1.02
1.22			0.838	0.512		0.863	
1.00			0.790	0.256	0.745	0.730	
0.821			0.923	0.128	1.20		
0.672			0.897	0.064			
0.550		0.988	0.929				
0.450		0.968					
0.369		1.05					
0.302		1.11					
0.247	0.894	0.910					
0.202	1.17	0.961					
0.166	0.975	0.954					
0.136	0.909	1.10					
0.111	1.07						
0.067							

^aPressure refers to hydrogen pressure in the counters. Distance of counter from the bottom of the core, 77 cm.

^bThe fractional standard deviation varied from 0.02 to 0.20.

Table 3

COMPARISON OF MEASUREMENTS AND CALCULATIONS FOR THE UNSHIELDED
BEAM FOR NEUTRON ENERGIES FROM 0.8 TO 15 MeV

Ratio of Measured ^a Flux to Calculated Flux					
DOT Calculations			Monte Carlo Calculations ^b		
Upper Energy (MeV)	Run 1	Run 2	Upper Energy (MeV)	Run 1	Run 2
14.9		1.39	14.9		0.595
13.5	1.56	1.31	8.0	1.03	1.03
12.2	1.24	1.29	4.0	1.23	1.20
11.1	1.44	1.01	2.0	1.03	1.00
10.0	0.824	1.19	1.0		
9.05	0.909	0.964			
8.18	1.01	0.957			
7.41	0.884	1.02			
6.70	1.05	1.11			
6.06	1.17	1.10			
5.49	1.05	1.05			
4.97	1.11	1.13			
4.49	1.18	1.19			
4.06	1.21	1.23			
3.68	1.18	1.16			
3.33	1.23	1.18			
2.73	1.25	1.20			
2.23	1.14	1.11			
1.83	1.07	1.05			
1.50	1.11	1.06			
1.22	1.10	1.06			
1.00	1.20	1.15			
0.821					

^aMeasurements made with a NE-213 counter. Distance of counter from bottom of core, 888 cm.

^bThe fractional standard deviation varied from 0.01 to 0.11.

The next series of tables presents the data for the 16-in.-thick shields for both pure sodium and the pin array.

Table 4 presents the most recent hydrogen counter results for the 16-in. sodium sample and also the ratio of the measured neutron spectra for the iron-pin sodium shield to that for the sodium shield. Over most of the energy range the effect of the iron is to reduce the flux by only ~ 20 -40%. At the lowest energy range the counter with a hydrogen pressure of one atmosphere shows an increase in flux; however, this increase is probably not statistically significant in view of the measurements with the 3-atmosphere counter.

Table 5 demonstrates the effect of the iron pins on the downward-directed high energy flux. It gives a comparison of the NE-213 spectrometer measurements for the 16-in. sodium and the 16-in. pin array and their ratios. The iron pins appear to cause a reduction in neutron flux of about a factor of 3 for neutron energies greater than 2 MeV.

Table 6 presents the ratios of the measured results to the calculated results for the 16-in. sodium shield for both the Monte Carlo and DOT calculations. The maximum deviation between the measurements and the calculations is only about 30% for the DOT calculations, and the average deviation is less than 20%. There appears to be no correlation in the disagreement between calculation and experiment and the neutron energy. The large disagreement between the Monte Carlo calculations and experiments for neutrons below 100 keV can probably be attributed to bad statistics since the standard deviation was 33% for this energy group. It would appear that Monte Carlo results are good to within 10-20% for energies above 0.128 MeV, that the DOT calculations predicted neutron flux at all energy ranges within an accuracy of $\sim 20\%$.

Table 7 presents a comparison of both the DOT and Monte Carlo calculations with the neutron spectra transmitted by the 16-in. sodium sample as determined by the NE-213 neutron spectrometer. The Monte Carlo results show better agreement at high energies because the comparison is for a wide energy band (8-14.9 MeV), and the number integral over this wide energy band eliminates the statistical deviation from the NE-213 measurements.

Table 4

EXPERIMENTAL DETERMINATION OF THE EFFECT OF IRON PINS IN THE
16-IN. SODIUM SHIELD FOR NEUTRON ENERGIES LESS THAN 1.5 MeV

Upper Energy (MeV)	Flux through 16 in. Na, n/cm ² sec MeV watt			Flux ratio, 16 in. Na-Fe pins/16 in. Na		
	1 atm. ^a	3 atm. ^b	10 atm.	1 atm.	3 atm. ^b	10 atm.
1.50			1.06+4 ^c			0.306
1.22			1.04+4			0.411
1.00			1.14+4			0.551
0.821			1.11+4			0.725
0.672			1.43+4		0.559	0.603
0.550		2.63+4	2.26+4		0.670	
0.450		2.43+4			0.728	
0.368		3.24+4			0.732	
0.302		3.81+4		0.815	0.796	
0.247	3.30+4	2.97+4		1.14	0.740	
0.202	2.97+4	3.84+4		1.12	0.754	
0.166	3.43+4	4.29+4		1.30	0.589	
0.136	3.64+4	5.26+4		1.00		
0.111	4.12+4					
0.067						

^aRefers to pressure in hydrogen counters. Distance of counter from bottom of core, 77 cm.

^bThese columns represent an average of two runs.

^cRead as 1.06×10^4 .

Table 5

THE EFFECT OF IRON PINS IN THE 16-IN. SODIUM SHIELD
FOR NEUTRON ENERGIES FROM 0.8 TO 15 MeV

Upper Energy (MeV)	Measured Flux, ^a n/cm ² sec MeV watt			Flux ^b Ratio, Na-Fe Pins/ Na
	Na		Na-Fe Pins	
	Run 1	Run 2		
14.9	1.58-2 ^c	1.35-2	4.17-3	0.285
13.5	3.65-2	2.81-2	1.35-2	0.419
12.2	5.87-2	7.68-2	2.75-2	0.406
11.1	1.53-1	1.81-1	5.43-2	0.325
10.0	2.89-1	2.83-1	1.01-1	0.352
9.05	5.20-1	4.90-1	1.86-1	0.373
8.19	8.96-1	9.16-1	2.96-1	0.327
7.41	1.47+0	1.56+0	4.71-1	0.310
6.70	2.22+0	2.39+0	7.21-1	0.313
6.07	3.07+0	3.26+0	9.63-1	0.304
5.49	4.17+0	4.26+0	1.26+0	0.298
4.97	5.61+0	5.80+0	1.73+0	0.303
4.49	7.53+0	7.65+0	2.29+0	0.302
4.07	9.17+0	9.25+0	2.68+0	0.290
3.68	9.92+0	1.01+1	3.01+0	0.300
3.33	1.29+1	1.32+1	4.09+0	0.313
2.73	1.65+1	1.68+1	4.93+0	0.296
2.23	2.06+1	2.09+1	7.24+0	0.348
1.83	2.98+1	3.03+1	1.17+1	0.390
1.50	3.36+1	3.40+1	1.45+1	0.430
1.22	3.04+1	3.16+1	1.59+1	0.511
1.00	3.08+1	3.34+1	1.79+1	0.558
0.821				

^aMeasurements made with NE-213 counter. Distance of counter below bottom of the core, 888 cm.

^bBased on average of the two sodium shield runs.

^cRead as 1.58×10^{-2} .

Table 6

COMPARISON OF MEASUREMENTS AND CALCULATIONS FOR THE 16-IN.
SODIUM SHIELD FOR NEUTRON ENERGIES LESS THAN 1.5 MeV

Ratio of Measured to Calculated Flux									
DOT Calculations					Monte Carlo Calculations ^b				
Upper Energy (MeV)	1 atm. ^a	3 atm.		10 atm.	Upper Energy (MeV)	1 atm.	3 atm.		10 atm.
		Run 1	Run 2				Run 1	Run 2	
1.50				1.00	1.00				1.10
1.22				0.998	0.512		0.807	0.802	
1.00				0.979	0.256	0.902	1.02	1.01	
0.821				1.31	0.128	1.76			
0.672				1.09	0.064				
0.550		1.07	1.07	0.917					
0.450		1.22	1.18						
0.369		1.02	1.04						
0.302		1.13	1.12						
0.247	1.32	1.20	1.19						
0.202	0.788	1.01	1.03						
0.166	0.882	1.13	1.08						
0.136	0.855	1.25	1.22						
0.111	0.853								
0.067									

^aRefers to hydrogen pressure in the counters. Distance of counter from the bottom of the core, 77 cm.

^bThe fractional standard deviation varied from 0.05 to 0.33.

Table 7

COMPARISON OF CALCULATIONS AND MEASUREMENTS FOR THE 16-IN.
SODIUM SHIELD FOR NEUTRON ENERGIES FROM 0.8 TO 15 MeV

Ratio of Measured ^a to Calculated Flux					
DOT Calculations			Monte Carlo Calculations ^b		
Upper Energy (MeV)	Run 1	Run 2	Upper Energy (MeV)	Run 1	Run 2
14.9	2.22	1.90	14.9	0.697	0.699
13.5	1.79	1.38	8.0	1.21	1.25
12.2	1.14	1.49	4.0	1.26	1.29
11.1	1.31	1.55	2.0	1.08	1.10
10.0	1.17	1.15	1.0		
9.05	1.07	1.01			
8.19	1.12	1.15			
7.41	1.06	1.13			
6.70	1.23	1.33			
6.06	1.17	1.25			
5.49	1.20	1.22			
4.97	1.26	1.30			
4.49	1.42	1.44			
4.07	1.39	1.41			
3.68	1.24	1.26			
3.33	1.05	1.09			
2.73	1.25	1.27			
2.23	0.989	1.00			
1.83	1.02	1.04			
1.50	1.01	1.03			
1.22	1.08	1.12			
1.00	0.990	1.07			
0.821					

^aMeasurements made with NE-213 counter. Distance below core, 888 cm.

^bThe fractional standard deviation varied from 0.02 to 0.11.

The Monte Carlo energy bins are necessarily chosen to be coarse in order to achieve better statistics. Even so, it would appear that the results are in disagreement to the extent of 20-30% for energies above 1 MeV. This difference is considerably larger than would be expected from the quoted standard deviation of the Monte Carlo calculations. The DOT results also show 20-50% disagreements in the energy region from 3.7 to 5 MeV. However, at energies below 3.7 the agreement is very good.

Table 8 gives a ratio between measurements of the neutron spectra through 16 in. of sodium obtained with and without ^3He in the hydrogen counters. The rather significant change in the experimentally determined spectra was obtained with the hydrogen counters which did not contain ^3He . This change results both from the elimination of the count rate due to neutron interaction with ^3He and from a change in the energy calibration as determined by measurement of the counter response functions at the Oak Ridge Van de Graaff facility. As can be seen by looking at the ratio of the spectra as a function of energy, the perturbation introduced by the ^3He counting rate changed the unfolded results at all energies rather than at energies only near the ^3He peak.

Comparisons of the neutron flux measurements and the DOT calculations for the 16-in. sodium pin shield are presented in Table 9. The agreement between the measurements and calculations varies between 10 and 40% for the hydrogen counter with the largest disagreement being at the lowest neutron energies, as might be expected. The DOT calculations appear to be $\sim 35\%$ low over most of the neutron energy spectra measured by the NE-213 spectrometer. Much of the disagreement is consistent with that for the pure sodium and may not be related to the iron pins.

No comparisons have been made for the 16-in. experimental results with Monte Carlo calculations at this date since the effort has been directed toward obtaining Monte Carlo results with 24-in. samples only.

Table 10 presents the results of the measured neutron spectra transmitted by the 24-in.-thick pin array. Both the hydrogen counter results and the NE-213 results are presented in this table. Table 11 presents the ratio of the measured and calculated results at

Table 8

COMPARISON OF MEASUREMENTS MADE WITH HYDROGEN COUNTERS
CONTAINING ^3He TO THOSE MADE WITH COUNTERS WITHOUT
 ^3He FOR 16-IN. SODIUM SHIELD

Ratio of Fluxes Measured with ^3He in Counter to Those Without ^3He			
Upper Energy (MeV)	1 atm. ^a	3 atm. ^b	10 atm.
1.2			0.635
1.1			0.680
1.0			0.687
0.90			0.712
0.78			0.318
0.72			85.8
0.67			1.23
0.61			0.751
0.57			0.768
0.52			0.808
0.48			0.740
0.44		1.02	0.670
0.41		0.897	0.680
0.37		1.10	
0.31		0.878	
0.26		0.944	
0.22	0.614	0.962	
0.19	0.575	0.786	
0.16	0.572	0.738	
0.14	0.545	0.698	
0.12	0.428	0.753	
0.10	0.485		
0.083	0.511		
0.071	0.477		
0.060	0.332		

^aRefers to hydrogen pressure in the counters.

^bAverage of two runs used for the new measurements.

Table 9

COMPARISON OF NEUTRON FLUX MEASUREMENTS AND CALCULATIONS FOR THE
16-IN. PIN ARRAY

Ratio of Experimental to Calculated ^a Flux						
NE-213 Counter ^b		Hydrogen Counter ^c				
Upper Energy (MeV)	DOT Calc.	DOT Calculations				
		Upper Energy (MeV)	1 atm. ^d	3 atm.		10 atm.
				Run 1	Run 2	
14.9	1.65	1.50				0.997
13.5	1.82	1.22				1.07
12.2	1.43	1.00				1.01
11.1	1.23	0.821				1.10
10.0	1.08	0.672				1.22
9.05	1.51	0.550		1.09	1.05	0.989
8.19	1.02	0.450		1.14	1.04	
7.41	0.961	0.369		1.13	1.13	
6.70	1.26	0.302		1.29	1.19	
6.07	1.17	0.247	1.25	1.23	1.37	
5.49	1.18	0.202	1.27	1.12	1.03	
4.97	1.31	0.166	1.30	1.12	1.07	
4.49	1.55	0.136	1.46	1.11	0.810	
4.07	1.46	0.111	1.18			
3.68	1.33	0.067				
3.33	1.15					
2.73	1.41					
2.23	1.21					
1.83	1.36					
1.50	1.34					
1.22	1.36					
1.09	1.09					
0.821						

^aDOT calculations for homogeneous mixture multiplied by calculated streaming factor.^bDistance of counter from bottom of core, 888 cm.^cDistance of counter from bottom of core, 77 cm.^dRefers to hydrogen pressure in the counters. Distance of counter from the bottom of the core, 77 cm.

Table 10

MEASURED NEUTRON FLUXES FOR THE 24-IN.-
THICK PIN ARRAY

Upper Energy (MeV)	Flux, n/cm ² sec MeV Watt				Upper Energy (MeV)
	Hydrogen Counter ^a			NE-213 Counter ^b	
	1 atm.	3 atm.	10 atm.		
1.50			1.25+3	1.70-2 ^c	14.9
1.22			1.79+3	4.88-2	13.5
1.00			2.67+3	1.06-2	12.2
0.821			2.94+3	2.15-2	11.1
0.672			5.73+3	4.97-2	10.0
0.550		8.82+3	8.50+3	7.13-2	9.05
0.450		9.55+3		1.16-1	8.19
0.369		1.81+4		1.83-1	7.41
0.302		2.32+4		2.70-1	6.70
0.247	1.54+4	1.61+4		3.43-1	6.06
0.202	2.51+4	2.32+4		4.32-1	5.49
0.166	2.88+4	2.66+4		5.90-1	4.97
0.136	3.53+4	3.227+4		7.60-1	4.49
0.111	6.76+4			8.93-1	4.07
0.067				9.10-1	3.68
				1.17+0	3.33
				1.30+0	2.73
				1.80+0	2.23
				3.12+0	1.83
				3.67+0	1.50
				4.92+0	1.22
				4.28+0	1.00
					0.821

^aLocated 77 cm below bottom of core.

^bLocated 888 cm below bottom of core.

^cRead as 1.70×10^{-2} .

Table 11

COMPARISON OF MEASUREMENTS AND CALCULATIONS FOR THE 24-IN.-THICK
PIN ARRAY FOR NEUTRON ENERGIES LESS THAN 1.5 MeV

Ratio of Measured Flux to Calculated Flux							
Upper Energy (MeV)	DOT Calculations			Upper Energy (MeV)	Monte Carlo Calculation ^b		
	1 atm. ^a	3 atm.	10 atm.		1 atm.	3 atm.	10 atm.
1.5			0.918	1.0			0.911
1.22			1.01	0.512		0.988	
1.00			0.767	0.256	0.891	0.855	
0.821			1.31	0.128	1.49		
0.672			1.07	0.064			
0.550		0.933	0.900				
0.450		1.07					
0.309		1.21					
0.302		1.22					
0.247	1.18	1.24					
0.202	1.08	1.00					
0.166	1.30	1.21					
0.136	1.34	1.21					
0.111	1.96						
0.067							

^aRefers to hydrogen pressure in counters. Distance of counter from the bottom of the core, 77 cm.

^bThe fractional standard deviation varied between 0.23 and 0.31.

the hydrogen counter position for the 24-in.-thick shield for both the DOT and the Monte Carlo calculations. The fractional standard deviations for the Monte Carlo results are between 0.23 and 0.31. These values are considered to be too large for the results to be reliable; therefore, it seems somewhat fortuitous that such generally good agreement occurred between the Monte Carlo calculations and the measured results. The DOT calculations generally appear to be in agreement with measurements to within 20%, except for the 1-atmosphere counter at the lower energies. It would appear that the end points in the calculated spectrum of the hydrogen counters are more subject to statistical deviation. Since the lowest pressure counter (1 atmosphere) has the pulse-height distribution generated for the high-energy neutrons subtracted from it during the course of the analysis, the results from this counter tend to exhibit the largest statistical fluctuations. Normally this agreement would be considered to be excellent for the purpose of comparing shield transmission calculations. However, we are attempting to predict the effect of the addition of the iron pins to the sodium shield, and as is shown in Table 12 the effect of the iron pins is relatively small at the hydrogen counter position, even for the 24-in.-thick sample. The magnitude of the effect is demonstrated by comparing the ratio of the measured neutron fluxes below the 24-in.-thick pin array with calculated fluxes below 24 in. of sodium alone. For neutron energies below 0.5 MeV the iron depresses the neutron flux by factors of 0.95 to 0.50. For energies above 1.50 MeV the effect of the iron is to reduce the transmitted flux by factors of between 0.20 to 0.35 over most of the energy range at the hydrogen counter position.

As can be seen in Table 13 the effect of the iron pin is somewhat larger on the high-energy neutrons as detected at the NE-213 counter position. Table 14 shows that the DOT calculation apparently overestimates the attenuation of the iron pins by approximately a factor of 2. The Monte Carlo predictions for the effect of the iron pins appear to be closer than the DOT results to the value obtained by dividing the experimental results for the sodium-iron pin shield by calculated sodium transmission results.

Neutron streaming factors were calculated by dividing the flux transmission results of a DOT cell calculation by the fluxes obtained with an

Table 12

EFFECT OF IRON PINS IN THE 24-IN.-THICK SHIELD
AT THE HYDROGEN COUNTER POSITION

Ratio of Neutron Flux with Iron Pins in Shield To That With Sodium Only						
Upper Energy (MeV)	Calc. Na-Fe/ Calc. Na	Upper Energy (MeV)	Calc. Na-Fe/ Calc. Na	Exp. Na-Fe/Calc. Na		
	DOT Calc.		DOT Calc.	1 atm. ^a	3 atm. ^b	10 atm.
14.9	0.225	1.50	0.208			0.160
13.5	0.282	1.22	0.271			0.254
12.2	0.289	1.00	0.604			0.377
11.1	0.351	0.821	0.364			0.462
10.0	0.307	0.672	0.629			0.646
9.05	0.311	0.550	0.540		0.470	0.453
8.19	0.343	0.450	0.556		0.574	
7.41	0.374	0.368	0.636		0.737	
6.70	0.317	0.302	0.707		0.826	
6.07	0.250	0.247	0.752	0.847	0.889	
5.49	0.257	0.202	0.705	0.734	0.680	
4.97	0.259	0.166	0.680	0.855	0.792	
4.49	0.231	0.136	0.723	0.944	0.862	
4.07	0.194	0.111	0.903	1.79		
3.68	0.207	0.067	0.873			
3.33	0.222	0.0409	0.614			
2.73	0.205	0.0318	1.18			
2.23	0.226	0.0248	0.990			
1.83	0.2856	0.0193	0.972			
1.50	0.208	0.0150	0.629			
		0.00912				

^aRefers to pressure in hydrogen counters. Distance of counter from bottom of core, 77 cm.

^bThis column represents an average of two runs.

Table 13

EFFECT OF IRON PINS IN THE 24-IN.-THICK SODIUM SHIELD AT THE NE-213 COUNTER POSITION

Ratio of Flux With Fe Pins to Flux with Sodium Only							
Upper Energy (MeV)	Calc. Na-Fe/ Calc. Na	Exp. Na-Fe/ Calc. Na	Upper Energy (MeV)	Calc. Na-Fe/ Calc. Na	Exp. Na-Fe/ Calc. Na	Upper Energy (MeV)	Calc. Na-Fe/ Calc. Na
	DOT Calc.			DOT Calc.			Monte Carlo Calc.
14.9	0.273	0.421	1.22	0.247	0.568	14.9	0.411
13.5	0.239	0.425	1.00	0.351	0.460	8.00	0.342
12.2	0.212	0.372	0.821	0.393		4.00	0.314
11.05	0.260	0.335	0.672	0.512		2.00	0.299
10.0	0.184	0.480	0.550	0.274		1.00	0.463
9.05	0.181	0.259	0.450	0.338		0.512	0.454
8.19	0.153	0.258	0.369	0.452		0.256	0.905
7.41	0.156	0.235	0.302	0.441		0.128	0.600
6.70	0.140	0.282	0.247	0.620		0.064	
6.07	0.137	0.246	0.202	0.380			
5.49	0.129	0.250	0.166	0.361			
4.97	0.129	0.271	0.136	0.416			
4.49	0.120	0.305	0.111	0.466			
4.07	0.115	0.292	0.0674	0.605			
3.68	0.119	0.265	0.0409	0.346			
3.33	0.122	0.218	0.0318	1.03			
2.73	0.114	0.267	0.0248	1.30			
2.22	0.130	0.231	0.0193	0.69			
1.83	0.138	0.286	0.015	0.469			
1.50	0.168	0.308	0.00912				

Table 14

COMPARISON OF CALCULATIONS AND MEASUREMENTS FOR
THE 24-IN.-THICK PIN ARRAY FOR NEUTRON
ENERGIES FROM 0.8 TO 15 MeV

Measured Flux n/cm ² sec. MeV Watt	Ratio of Measured ^a to Calculated Flux			
	DOT Calculations		Monte Carlo Calculations ^c	
	Upper Energy (MeV)	Ratio	Upper Energy (MeV)	Ratio
1.70-3 ^b	14.9	1.54	14.9	0.702
4.88-3	13.5	1.78	8.0	1.21
1.06-2	12.2	1.75	4.0	1.37
2.15-2	11.1	1.64	2.0	1.63
6.64-2	10.0	2.80	1.0	
7.14-2	9.05	1.43		
1.16-1	8.19	1.69		
1.83-1	7.41	1.51		
2.70-1	6.70	2.02		
3.43-1	6.06	1.80		
4.32-1	5.49	1.94		
5.89-1	4.97	2.18		
7.60-1	4.49	2.99		
8.94-1	4.07	2.55		
9.10-1	3.68	2.23		
1.17+0	3.33	1.78		
1.30+0	2.73	2.34		
1.79+0	2.23	1.78		
3.12+0	1.83	2.06		
3.67+0	1.50	1.84		
4.92+0	1.22	2.30		
4.28+0	1.00	1.31		
	0.821			

^aMeasurements made with NE-213 counter. Distance below core, 888 cm.

^bRead as 1.70×10^{-3} .

^cThe fractional standard deviation varied from 0.04 to 0.18.

ANISN slab calculation for a homogeneous mixture of iron and sodium in the same proportion as in the cell. The streaming factors which were calculated for the total neutron flux (integral over energy) using the DOT results were 1.42 at the hydrogen counter position and 1.49 at the NE-213 detector position. The corresponding factors given by the Monte Carlo calculation were 1.36 and 1.85, respectively; however, the Monte Carlo results excluded neutrons below 1 keV in energy. In the DOT/ANISN analysis the cell contained one steel pin immersed in an annular ring of sodium, the area of the sodium annular ring being the same as the area in one cell of the rectangular matrix used in the experimental shield configuration. The results of the calculation are presented in Table 15 and are compared with the experimental results for the 24-in. shield. The calculated streaming factors are based on the actual reactor angular and energy leakage spectra.

Table 15

NEUTRON STREAMING FACTORS AS A FUNCTION OF
ENERGY FOR PIN ARRAYS

Upper Energy (MeV)	Cell Calculation ^a		Exp./Calc. ^b	Upper Energy (MeV)	Cell Calculation		Exp./Calc.
	16-in.	24-in.			16 in.	24-in.	
14.9	4.70	8.76	13.5	1.22	1.23	1.36	3.13
13.5	3.91	6.59	11.7	1.00	1.12	1.18	1.55
12.2	3.29	5.06	8.87	0.821	1.06	1.14	
11.1	3.46	5.32	8.72	0.672	1.05	1.10	
10.1	3.90	6.06	15.8	0.550	1.25	1.37	
9.05	2.82	6.64	9.51	0.450	1.22	1.34	
8.19	4.27	6.69	11.3	0.368	1.09	1.16	
7.41	4.58	7.32	11.0	0.302	1.10	1.16	
6.70	5.18	8.86	17.9	0.247	1.04	1.09	
6.07	5.49	9.76	17.6	0.202	1.22	1.34	
5.49	4.57	7.48	14.5	0.166	1.37	1.53	
4.97	4.86	8.35	18.2	0.136	1.17	1.28	
4.49	5.21	9.49	24.1	0.111	1.26	1.41	
4.07	4.95	8.86	22.6	0.067	1.10	1.20	
3.68	3.30	5.08	11.3	0.0409	1.72	1.93	
3.33	2.82	4.01	7.16	0.0318	2.19	2.34	
2.73	2.52	3.37	7.88	0.0248	0.957	1.01	
2.23	2.12	2.73	4.85	0.0193	1.02	1.10	
1.83	1.87	2.33	4.81	0.0150	1.14	1.24	
1.50	1.55	1.85	3.40	0.00912			

^aRatio of a DOT Fe-Na cell calculation to a homogeneous Fe and Na shield ANISN calculation.

^bRatio of measured transmitted neutron flux to a DOT calculated flux transmitted through a homogeneous sodium iron-pin array.

V. NEUTRON TRANSPORT IN IRON

The requirement for the ability to perform accurate neutron transport calculations in iron and iron alloys is common to both the AEC (LMFBR) and DASA shielding programs at ORNL. This requirement is still unfulfilled since no clear demonstration of this ability has been achieved.

The ORNL "broomstick"⁵ experiment demonstrated that the total neutron cross-section data for iron were insufficiently known above 1 MeV.⁶ The results of this experiment led to the recent GGA measurement of the iron total cross sections.⁷ The ORNL-evaluated iron cross-section set which uses the new GGA data now gives good agreement with the "broomstick" experiment in which the uncollided flux through 12 in. of iron was measured at the TSF. It now becomes necessary to compare transport calculations using the full cross-section set with integral experiments which include scattering.

Calculations of neutron transport in iron are exceptionally difficult because of the numerous high-energy scattering resonances in the neutron cross sections. Only the most explicit transport calculations using point cross-section data have a possibility for high accuracy in a detailed calculation of the neutron spectra. The angular distributions for elastic scattering are not now known to a resolution that is within an order of magnitude of that of the total cross section, and therefore much of the physics is left out even when the transport calculations are done using the current set of point cross sections. It is also necessary to know the degree of accuracy and range of applicability of multigroup theory because of the increasing use of discrete ordinates codes and also the use of multigroup cross sections in Monte Carlo codes.

The relatively simple problem of a point fission source in a 1.5-meter radius sphere of iron was used for the comparison of Monte Carlo calculations using point cross sections and discrete ordinates multigroup calculations. In order to exhibit gross differences, comparisons have been made of integral quantities such as the fluence above 10 keV and the fast dose, both as a function of radius. Figure 1 shows the results of several calculations for the fast dose (a Henderson single-collision

Fig. 3. Radial Distribution of Fast Neutron Dose From a Point Fission Source in a 1.5-Meter Radius Sphere of Iron.

dose), and Figure 4 shows the corresponding results for the flux above 10 keV. Monte Carlo (06R) calculations are shown using cross-section data from the ENDF/B library and from the new ORNL evaluation. The disagreements between the Monte Carlo calculations are as large as a factor of 1.8.

Also shown in Figs. 3 and 4 are the results of multigroup calculations using ANISN. In these calculations only 1/E weighting was used in the cross-section preparation. Good multigroup results may be obtained by *a priori* weighting of the point cross sections using suitable spectra or by choosing a group structure such that the simple 1/E weighting is adequate. The latter course was chosen as the more straightforward because the use of arbitrary weighting spectra gives results which are unbounded above and below, while the use of unweighted cross sections in a variable number of groups with variable spacing gives results which are bounded above by the true answer. The fluxes generated by calculations using an appropriate fine group structure may be used as the weighting function for the calculation of broad group constants or as a standard for selection of a scheme for producing weighting spectra.

The first ANISN calculation used ENDF/B data reduced to 39 groups above 10 keV. The results from this calculation are high at small depths and more than an order of magnitude low at large depths compared with the Monte Carlo calculations. The 266-, 260-, and 296-group ANISN calculations used the point data from the recent ORNL evaluation. Results from the 266-group calculation, although considerably improved over the 39-group results, are still quite low at deep penetration. In an effort to improve the set, a cross-section edit program was written to plot the point form and multigroup form of the total cross sections simultaneously. These plots showed that the group boundaries of the 266-group set were not properly aligned. A new 260-group structure was selected, and calculations were made which showed considerable improvement over the previous 266-group results.

At this point in the study, the fluence was separated into six energy bins -- 4-6 MeV, 2-4 MeV, 1-2 MeV, 0.1-1.0 MeV, 0.03-0.1 MeV,

Fig. 4. Radial Distribution of Fluence ($E \geq 10$ keV) From a Point Fission Source in a 1.5-Meter Radius Sphere of Iron.

and 0.01-0.03 MeV. The fluence in these bins was plotted as a function of radius. Comparison of these results with Monte Carlo calculations showed that more detail was needed in the cross section in the 0.01- to 0.1-MeV energy range. A revised 296-group structure was selected and the results of the ANISN calculation with the 296-group structure are fairly good. The fast-neutron dose and fluence ($E \geq 10$ keV) are only 20 to 25% low at one-meter radius. Such close agreement is probably the best that can be achieved using less than 300 groups and $1/E$ weighting in the cross-section set.

Figures 5 through 8 show comparisons of results for the 06R Monte Carlo and the 296-group ANISN calculations for the six energy bins. The unexpected disagreement in the 2- to 6-MeV energy range is, at present, unexplained; however, it might result from differences in the treatment of the inelastic cross sections in the Monte Carlo and discrete ordinates calculations.

Future work will include further investigation of the high-energy discrepancies, comparisons using the evaluated iron cross sections from Westinghouse, tests of broad group calculations using constants weighted with the calculated fine group spectra, tests of *a priori* weighting techniques, and tests of combined group selection and *a priori* weighting.

Comparisons of Neutron Transport Calculations and Experiments for Iron

A. GGA Experiment

Subsequent to the measurement of the iron total cross section at Gulf General Atomic, a benchmark-type integral experiment was performed.⁸ In this experiment a hollow iron sphere with 38.1-cm outer radius and 7.62-cm inside radius surrounds a 3.81-cm radius uranium LINAC target which produces a nearly isotropic source of neutrons. Various reentrant holes were used to obtain measurements of the neutron flux spectra at various radii and angles by the time-of-flight method.

GGA calculations (few group discrete ordinates) of the experiment showed very large disagreements which were supposedly due to the use of incorrect iron cross sections (ENDF/B) in a broad group structure. This experiment has been calculated using ANISN with the 266-group structure cross sections using the ORNL-evaluated data which contain the GGA measured total cross

Fig. 5. Radial Distribution of Fluence From a Point Fission Source in a 1.5-Meter Radius Sphere of Iron for Energy Bins of 1-2, 2-4, and 4-6 MeV.

Fig. 6. Radial Distribution of Fluence ($0.1 < E < 1.0$ MeV) From a Point Fission Source in a 1.5-Meter Radius Sphere of Iron.

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Fig. 7. Radial Distribution of Fluence ($0.03 < E < 0.10$ MeV) From a Point Fission Source in a 1.5-Meter Radius Sphere of Iron.

Fig. 8. Radial Distribution of Fluence ($0.01 < E < 0.03$ MeV) From a Point Fission Source in a 1.5-Meter Radius Sphere of Iron.

sections. The ORNL calculation also disagrees violently with the experiment. For example, at 38.1-cm radius (the largest), which corresponds to a depth in iron of only 30.5 cm, the calculated 0-deg spectra agree in shape with the experiment but are low by a factor of seven. The comparisons of various calculations of the point fission source in the 1.5-meter iron sphere show that such a large disagreement at 30 cm is unlikely. The calculation indicates that at 30 cm only about 15% of the source neutrons have been absorbed. Thus, since the calculation agrees with the experiment at the target, the total flux disagreement at $r = 38.1$ cm should be less than 15%. GGA personnel have rechecked their data and the experiment is being recalculated by ORNL with the 296-group cross-section set in hopes of resolving the disagreement.

B. ORNL-TSF Experiments

1. Iron Cylinders

As part of the iron-pin-array-in-sodium-streaming-effect experiment performed at the TSF, measurements were made for 18-in.-diam. iron cylinders 8, 16 and 24 in. thick. The iron cylinders were surrounded radially by oil in a collar shield tank. The neutron source from the TSF-SNAP reactor has been calculated and measured several times and is well known. The neutron spectra transmitted through the iron were measured with the NE-213 detector for neutron energies between 0.8 and 15.0 MeV and with Benjamin detectors for neutron energies between 50 keV and 1.5 MeV.

Tables 16 and 17 present the experimentally-determined neutron spectra transmitted by 8-, 16-, and 24-in.-thick iron cylinders. Table 18 gives the comparison of the measured to calculated flux for the neutrons below 1.50 MeV. Table 19 gives the comparison for the high-energy neutrons at the NE-213 detector position. Results are shown for the case where a lead shield was inserted at the bottom of the oil collar shield in order to eliminate spurious effects from gamma rays which were streaming around the sides of the 18-in.-diameter iron sample. As can be seen, the agreement with the hydrogen counter results is fair, whereas the comparison with the NE-213 results deviate by factors as large as 6 for the 24-in. shield.

Table 16

MEASURED NEUTRON FLUXES FOR IRON SHIELDS FOR ENERGIES BELOW 1.50 MeV

Measured Flux, n/cm ² sec MeV Watt							
Upper Energy (MeV)	24-in. Shield				16-in. Shield		
	1 atm. ^a	3 atm.		10 atm.	1 atm.	3 atm.	10 atm.
		Run 1	Run 2				
1.50				4.31+1			5.32+2
1.22				1.67+2			1.04+3
1.00				3.24+2			1.86+3
0.821				6.58+2			2.85+3
0.672				1.43+3			5.68+3
0.550		1.41+3	1.61+3	1.50+3		5.01+3	5.07+3
0.450		1.86+3	2.00+3			6.06+3	6.23+3
0.369		3.81+3	4.21+3			1.13+4	
0.302		4.52+3	5.00+3			9.16+3	
0.247	4.26+3	4.50+3	4.32+3		1.10+4	1.22+4	
0.202	6.24+3	6.22+3	6.10+3		1.54+4	1.45+4	
0.166	9.10+3	9.29+3	9.05+3		2.06+4	1.93+4	
0.136	1.21+4	1.08+4	7.57+3		2.65+4	1.76+4	
0.111					2.09+4		
0.067							

^aRefers to hydrogen pressure in counter. Distance of counter below bottom of core, 77 cm.

Table 17

MEASURED NEUTRON FLUXES FOR IRON SHIELDS FOR
NEUTRON ENERGIES FROM 0.8 TO 10 MeV

Measured Flux, ^a n/cm ² sec MeV Watt						
Upper Energy (MeV)	24-in. Shield			16-in. Shield		8-in. Shield
	No Pb	2-in. Pb	4-in. Pb	Run 1	Run 2	
10.0	2.05-3 ^b	8.73-4	4.16-4			6.58-2
9.05	2.06-3	1.25-3	8.27-4	5.07-3		9.10-2
8.19	1.77-3	1.55-3	1.04-3	6.85-3		1.28-1
7.41	3.37-3	1.48-3	1.55-3	1.06-2		2.30-1
6.70	7.10-3	3.78-3	2.52-3	1.45-2	1.48-2	3.41-1
6.06	9.63-3	5.34-3	2.64-3	1.66-2	1.56-2	4.63-1
5.49	9.02-3	3.87-3	3.08-3	2.34-2	1.95-2	5.98-1
4.97	1.38-2	5.73-3	3.71-3	3.82-2	3.18-2	8.56-1
4.49	1.62-2	5.72-3	4.15-3	4.12-2	3.87-2	1.09+0
4.07	1.23-2	5.87-3	3.81-3	3.77-2	3.62-2	1.31+0
3.68	1.36-2	4.06-3	3.84-3	4.55-2	3.75-2	1.52+0
3.33	1.61-2	5.44-3	4.87-3	7.60-2	7.42-2	2.42+0
2.73	2.51-2	1.10-2	1.00-2	1.69-1	1.75-1	4.42+0
2.23	1.75-2	2.26-2	2.36-2	3.73-1	3.83-1	7.67+0
1.83	8.92-2	5.19-2	5.19-2	7.48-1	7.88-1	1.25+1
1.50	2.34-1	1.44-1	1.37-1	1.58+0	1.62+0	1.90+1
1.22	3.84-1	3.51-1	2.98-1	3.11+0	3.00+0	
1.00	1.48+0	6.47-1	4.82-1	5.16+0	4.46+0	
0.821						

^aMeasurements made with NE-213 counter. Distance of counter from bottom of core, 888 cm.

^bRead as 2.05×10^{-3} .

Table 18

COMPARISON OF MEASUREMENTS AND DOT CALCULATIONS FOR IRON SHIELDS
FOR NEUTRON ENERGIES LESS THAN 1.5 MeV

Upper Energy (MeV)	Ratio of Measured to Calculated Flux						
	24-in. Shield				16-in. Shield		
	1 atm. ^a	3 atm.		10 atm.	1 atm.	3 atm.	10 atm.
		Run 1	Run 2				
1.50				1.91			2.54
1.22				2.22			1.96
1.00				2.16			1.80
0.821				2.32			2.12
0.672				1.12			1.25
0.550		1.22	1.39	1.29		1.38	1.40
0.450		1.72	1.85			1.79	1.84
0.369		1.12	1.24			1.14	
0.302		1.54	1.70			1.10	
0.247	1.43	1.51	1.45		1.33	1.48	
0.202	1.44	1.43	1.40		1.42	1.34	
0.166	1.84	1.88	1.83		1.67	1.56	
0.136	1.57	1.40	0.983		1.53	1.02	
0.111					1.36		
0.067							

^aRefers to pressure in hydrogen counters. Distance of counter from the bottom of the core, 77 cm.

Table 19
COMPARISON OF DOT CALCULATIONS AND EXPERIMENTS FOR IRON
SHIELDS FOR NEUTRON ENERGIES FROM 0.8 TO 10 MeV

Upper Energy (MeV)	Ratio of Measured ^a to Calculated Flux			
	24-in. Shield		16-in. Shield	
	2-in. Pb	4-in. Pb	Run 1	Run 2
10.0	1.62	0.772		
9.05	1.26	0.835	2.15	
8.19	2.79	1.87	3.83	
7.41	0.809	0.847	2.14	
6.70	2.68	2.77	3.54	3.61
6.06	2.78	1.38	2.99	2.81
5.49	1.97	1.57	3.34	2.78
4.97	3.03	1.96	6.04	5.03
4.49	3.27	2.37	7.38	6.94
4.07	3.43	2.23	5.47	5.25
3.68	2.43	2.30	4.98	4.11
3.33	2.22	1.99	3.29	3.21
2.73	3.64	3.31	4.77	4.94
2.23	5.29	5.53	4.72	4.84
1.83	4.63	4.63	2.67	2.81
1.50	7.62	7.25	3.49	3.58
1.22	6.22	5.28	2.45	2.37
1.00	5.22	3.89	2.25	1.95
0.821				

^aMeasurements made with NE-213 counter. Distance of counter from bottom of core, 888 cm.

Figures 9 and 10 show the comparison of unfolded spectra from the Benjamin detectors and the DOT calculations which used a 40-group set of cross sections from the ORNL (Irving) evaluation with a $1/E \sigma_T$ weighting. The agreement between calculation and experiment is much better than for the GGA experiment. It is important to note that the calculation and the experiments are on an absolute basis (flux per watt). The reactor power was determined by foil measurements taken during each spectrometer measurement. The analysis of the GGA experiment gave good agreement in spectral shape while disagreeing seriously in magnitude, and this effect has been observed in many previous analyses. It is therefore concluded that a comparison of only the relative shapes of measured and calculated neutron spectra in a transport experiment provides little confidence in the calculational method.⁹

The high-energy comparison with the NE-213 results for this experiment is not meaningful to the evaluation of transport calculations for iron. Above an energy of 3 MeV the iron is a much better shield than the oil, and consequently the experiment measures transmission through oil rather than iron. Even so, the discrepancy between the measurement and the calculation is so large that the experimental results are suspect. This shield was so thick to fast neutrons that a sizeable background was present which may not have been correctly determined in the NE-213 measurements. Below 3 MeV, the oil is a much better shield than the iron, and the hydrogen counter data for energies less than 1.5 MeV are most probably valid for this reason and because of the more favorable geometry.

2. Iron Plates

Before the hydrogen counter comparisons for 16- and 24-in.-thick iron shields were made, it was observed that for unknown reasons there were no successful absolute comparisons of experiment and calculation for iron. It was thus desirable to make comparisons for relatively thin iron transmission experiments. Since the source has been correctly calculated, a progression in iron thickness should provide a continuous transition from good to bad in the calculational comparisons and should also provide some clue to the source of the disagreement. Also, in order to avoid unnecessary complications, 5-ft-square iron plates were used with no

Fig. 9. Comparison of DOT (40 groups) Calculation with Hydrogen Counter for 16-in.-thick-Iron Shield.

Fig. 10. Comparison of DOT (40 groups) Calculation with Hydrogen Counter Results for 24-in.-thick-Iron Shield.

collar shield. Since another experiment was set up at that time over the NE-213 spectrometer position, only Benjamin counter data were taken for these thin plates.

Figures 11 and 12 show comparisons of DOT calculations with the unfolded spectra from the Benjamin counter for 2- and 4-in.-thick iron slabs. The agreement is good and supports the favorable comparisons reported in the previous section.

The status of iron calculation-experiment comparisons is still not good. The reasons for the extreme disagreement with the GGA sphere experiment have not been found. The discrete ordinates-Monte Carlo calculation comparisons suggest that the representation of structure in the cross section cannot explain the magnitude of the disagreement. The successful DOT and O6R calculations of the TSF iron experiments suggest that the cross sections are not seriously in error. In order to provide a more complete comparison with both NE-213 and Benjamin counter data in a clean geometry without the collar shield, a sequence of measurements is to be made using the 5-ft-square iron plates with the thickness incremented in about six steps from 1 in. to ~ 24 in.

C. AI-STIR Experiments

Neutron attenuation experiments have been performed at the AI-STIR lid-tank-type shielding test facility for sodium and stainless steel.¹⁰ The calculations of this experiment were done at Atomics International. One-dimensional kernels are used for laminated systems and the calculations ignore the transverse leakage of a shield sample which is longer than it is wide. These are considered to be rather poor approximations.

The comparisons of the AI calculated and measured spectra in the keV energy range show disagreements of factors of 2 to 3 at 60 cm and of one order of magnitude at 1-meter penetration in iron. The geometric approximations in the calculations make it difficult to determine the origin of the disagreements.

Fig. 11. Comparison of DOT Calculation (40 groups) with Hydrogen Counter Results for 2-in.-thick-Iron Shield.

Fig. 12. Comparison of DOT Calculation (40 groups) with Hydrogen Counter Results for 4-in.-thick Iron Shield.

VI. PRELIMINARY MATERIAL EVALUATION FOR THE FFTF GRID PLATE SHIELD

A sequence of one-dimensional ANISN calculations has been completed which provides a preliminary comparison of the effectiveness of several shield materials and gives insight for the interpretation of the ORNL-TSF iron-sodium shield experiment. The one-dimensional slab mockup of the FFTF below core axial zone configuration is shown below where the left boundary of the core is reflective:

1	2	3	4	5	6	7	8	
Core	Refl.	Refl. Grid	Shield	Trans.	Grid Plate Receptacles	EXT	Grid Plate	
0.0	45.72	60.94	67.54	115.8	145.8	190.9	213.1	228.4

Composition by Zone (atoms/bcm)

Material	1	2	3	5	6	7	8
Ni	.005758	.03248	.002458	.001305	.004278	.001305	.006844
Fe	.01577	.01332	.01332	.00707	.02318	.00707	.03709
Cr	.005631	.004757	.004757	.002525	.008279	.002525	.01325
Na	.008373	.009478	.016662	.0194	.01304	.0194	.007546
²³⁹ Pu	.001026						
²⁴⁰ Pu	.000139						
²³⁸ U	.004507						
²³⁵ U	.0003288						
O	.01200						

In the initial sequence of calculations, seven material compositions were used in the shield zone. These are given in the following table:

Material	Shield Number						
	1	2	3	4	5	6	7*
Na	0.0222		.013320	.01332	.01332	.01332	.01332
Fe		.0848	.03392	.02248			
Ni				.004147			
Cr				.00803			
C					.01089	.0316	.01933
^{10}B					.04355		
W							.01933

* WC at 15 gm/cc.

Although it is not desirable to have B_4^{10}C in the shield due to radiation damage, it was included in the study to determine the maximum effect of a carbide material with a large $1/v$ poison.

These calculations were performed using a 30-energy group P_3 cross-section library that was previously developed for an FTR analysis. This library was used because the time-consuming spectral weighting of the core material cross sections, including cell disadvantage effects, had been performed. A disadvantage of using this library was that the cross sections are not identical to those used in the analysis of the sodium and iron shield experiment.

The results of the seven calculations are summarized in the following table:

ANISN Results for the FFTF Mockup Integral Over All Energies

Shield Material	Partial Current at Right Boundary of Shield	Total Current at Right Boundary of Shield	Total Flux Incident on Grid Plate	Absorptions in Grid Plate	Total Flux in Grid Plate
Na	1.87-1	3.12-2	1.02-2	4.22-4	7.03-2
Fe	2.18-2	3.69-3	1.18-3	5.20-5	7.97-3
Fe-Na	6.06-2	1.10-2	3.60-3	1.51-4	2.46-2
SS-Na	5.02-2	9.07-3	3.30-3	1.34-4	2.27-2
$\text{B}_4^{10}\text{C-Na}$	1.21-4	2.49-5	6.70-5	1.82-6	5.14-4
C-Na	1.11-1	2.77-2	1.64-3	7.54-5	1.10-2
WC-Na	2.19-3	3.26-4	1.56-4	6.55-6	1.07-3

The calculations indicate that the $B_4^{10}C$ -Na mixture is the best shield, in decreasing order of efficiency are WC-Na, C-Na, SS-Na, and Fe-Na. The best carbide material for the shield will depend on several factors such as cost, density after fabrication, and radiation damage effects. These results also indicate that SS-Na is only slightly more effective than Fe-Na and that the maximum attenuation with pure iron is only an order of magnitude greater than for pure sodium.

Another observation is that the ratio of Fe-Na over pure sodium as a shield is approximately 3.0 compared to the ratio of 1.4 predicted by the TSF experiments and the calculations of the experiment. Since these calculations cover a wider energy range than the experiment, a table was prepared for the energy range from 0.182 to 0.302 MeV as was observed in the experiment.

For Group 8 (0.183 to 0.302 MeV)

Shield Material	Partial Current at Right Boundary of Shield	Total Current at Right Boundary of Shield	Flux Incident on Grid Plate
Na	4.67-3	1.94-3	1.19-4
Fe	7.03-4	3.19-4	7.72-6
Fe-Na	2.09-3	9.24-4	3.08-5
SS-Na	1.91-3	8.15-4	3.17-5
$B_4^{10}C$ -Na	8.18-6	-1.87-6	2.42-6
C-Na	4.26-4	1.42-4	2.33-5
WC-Na	7.93-5	3.74-5	1.51-6

The ratio of the partial currents for sodium over iron-sodium is 2.2 compared to the ratio of 1.4 given by TSF experiments and calculations. This difference is either due to differences in the cross sections used in these calculations compared to those used in the experimental analysis, or to the fact that the observed attenuation of the shield is different

when the neutron source is a fast reactor rather than an homogeneous reactor. This will be checked by performing ANISN calculations for this assembly with the same cross sections that were used in the TSF experiment analysis.

These calculations show, as previously reported, that the grid plate receptacle zone provides more attenuation than the SS-Na shield. Thus, for effects on the grid plate, the streaming in the large sodium passages in the receptacles must be as important as that in the shield.

If possible, a high-efficiency poison-carbide shield material should be used. The use of a good shielding material will necessitate reconsideration of the streaming problem. It is the relatively poor attenuation property of the iron which insures the small streaming effects below 1 MeV in the iron-pin-sodium cell. When one looks at the total number of neutrons transmitted through an isolated iron-pin-sodium shield, the effect of streaming is small. However, a full calculation of the reactor assembly from core to grid plate should include streaming since the streaming effect on high-energy neutrons is significant and these neutrons could dominate the penetration of the material below the shield, thereby increasing the importance of the high-energy neutrons.

APPENDIX A

HYDROGEN COUNTER CALIBRATION EXPERIMENT

Calibration and testing of the Benjamin-type spectrometer used in the LMFBR shield experiments at the TSF were accomplished at the 3-MeV Van de Graaff facility at the Oak Ridge National Laboratory. The spectrometer uses hydrogen-filled proportional counters whose pressures of 1, 3, and 10 atmospheres were selected to provide neutron energy coverage from about 50 keV up to 1.5 MeV. The hydrogen counters were exposed to essentially monoenergetic neutron beams and then the differential pulse-height count rate data were processed with the SPEC-4 code¹¹ to obtain a neutron flux. The neutron beam was produced by protons of selected energies impinging on targets of lithium and targets of tritium, the energies varying essentially from threshold for the particle reaction up to 2.5 MeV.

Experimental Configuration

The detectors used were a version of the Benjamin-type spherical proportional counter and they were built in the Instrumentation and Controls Division of ORNL according to the critical dimensions published by Benjamin, Kemshall, and Redfern.⁵ The radius, however, was increased from 1.97 cm (the size that Benjamin's group is currently using) to a radius of 2.36 cm. The counter was placed in line (0 deg direction) with the proton beam at a distance of approximately 24 in. from the Van de Graaff target.

Four targets in all were used, two of them containing tritium. One contained about 80 micrograms of titanium titride, and the other one contained about 300 micrograms of titanium titride. Measurements were made at the lower energies near the threshold for the tritium reaction using the thinner target. With the thicker target, proton energies were kept reasonably high because this large thickness corresponded to approximately 100-150 keV in proton energy. The lithium targets consisted of lithium metal evaporated onto nickel-plated platinum backing. These targets were chosen to be about a 5- to 10-keV proton equivalent thickness.

There were eight counters investigated with four filling pressures: 1/4 atmos., 1 atmos., 3 atmos., and 10 atmos. of pure hydrogen. Of these, only four proved to be satisfactory. The counter with the 1/4-atmos. pressure did not perform properly; consequently, it was not used in the TSF experiments. The remaining counters were discarded because of drifts in the alpha energy response. Initially, helium was used in the counters as a calibration source, but when flux measurements were made with these counters it was found that the ^3He peak caused errors in the unfolding process. Therefore, the helium was eliminated from the counters for the above tests and the succeeding group of TSF experiments. All counters had a small alpha source bonded to the center wire in the counter approximately half way along the distance of the wire. This source served not only as a calibration source, but also as a 4π solid angle check on the field distribution inside the counter. The placing of the alpha source on the exact center of the wire was extremely critical in determining the resolution of the calibration peak. On all the counters used in the experiment, the resolution on the alpha calibration peak was better than 15% which is quite good for detectors of this type.

Energy Calibration

In order to perform a precise check on the energy calibration of the counters, an accurate determination of the energy of the neutrons had to be made. Standard threshold determination measurements were made on each of the targets. The neutron energy produced by the Van de Graaff was calibrated to the threshold given in Marion and Fowler⁹ for the particular lithium or tritium p-n reaction. The proton energy is related to the magnetic field in the analyzing magnet of the Van de Graaff, which, in turn, is determined by the resonance frequency in a nuclear magnetic resonance device. This frequency is in turn related to the proton energy relationship $E_p = a\nu^2$, where ν is the frequency and a is a constant to be determined from the threshold measurement.

The next step was to define the equivalent neutron energy of the alpha calibration source. This was done by obtaining response curves for several different neutron energies. These energies were varied from that slightly below the useful range of the counter to that slightly above

it. The energy at which the Van de Graaff was operated for each run was then plotted versus channel number corresponding to the half height of the upper energy end of the pulse-height curve. A straight line, which fitted the data very well, was then drawn through these points and extrapolated to the channel number corresponding to the peak energy of the alpha particle.

This process was followed for all four counters.

From these curves then, it was possible to determine the amount of energy being deposited in the sensitive region of each counter from the plutonium alpha source on the center wire. From the alpha pulse-height curve we determined the channel number where the centroid of the alpha particle fell and this channel number was then assumed to correspond to the experimentally-determined alpha energy.

The pulse-height data for each neutron energy were then unfolded using the SPEC-4 code. Comparison of the centroid of the unfolded monoenergetic neutron peak with the energy calibration based on the alpha pulse-height curve served as a check on the energy determination procedure of the SPEC-4 code.

Absolute Count-Rate Calibration

A long counter was used as a monitor during every run in order to calibrate the hydrogen counters on an absolute count-rate basis. The long counter was placed in line with the beam and behind the hydrogen counter. In order to calibrate the long counter, a fast-neutron dosimeter was placed in the beam at the same location as the hydrogen counter. The neutron dosimeter gave a reading of neutron dose, which, using standard flux-to-dose conversion factors, was converted to neutron flux at the detector position. This flux value was then used to obtain the efficiency of the long counter as a function of energy. Once calibrated, the long counter gave an absolute count of the number of neutrons transmitted through the hydrogen counter.

For each neutron energy, measurements were made with and without the hydrogen detector in the beam. This was done to give the effect of the attenuation of the hydrogen counter on the count rate at the long

counter. A proton current integrator was used to normalize any differences in beam current between the detector-in and detector-out run. Since in most cases these runs were made in a very short period of time, variance in the beam current was small. Attenuation of the neutron beam by the hydrogen counter and holder was found to average 25% over the energy range considered. This experimentally-determined correction factor was applied in the absolute intensity calibration.

Comments on the Results

Typical response functions of the Benjamin-type spectrometer are shown in Figs. 13, 14, and 15 for the 1-, 3-, and 10-atmosphere counters, respectively. In order to put these curves on a per incident neutron basis, it was necessary to determine the efficiency for each counter as a function of energy. This efficiency was determined by the method found in SPEC-4 using a linear fit to the hydrogen cross section as a function of energy. The total counts determined from each measurement were then divided by the efficiency of the counter at the specific energy, and the pulse-height distribution was then normalized to this number.

Another contribution to the error in this range may have been due to the difficulty which the unfolding process had in handling the essentially zero flux values on either side of the peak. Since the slope of the pulse-height curve was not a monotonic decreasing function in these ranges, it was possible for negative values of the flux to appear. These were mostly the result of poor statistics in these areas due to the limited running time for each data point. The statistics in the energy ranges of interest, however, were maintained at a high level giving very low unfolding errors in the peak regions.

The energy calibration of the counters was verified by taking the neutron energy given by the Van de Graaff and comparing it to the energy of the unfolded peak given by the code SPEC-4. In almost all cases these results agreed within a few percent.

Preliminary results of the energy calibration for the 3- and 10-atmosphere pressure counters are shown in Table 20. The peak energy determined from the energy of the Van de Graaff beam is

Fig. 13. Response Function for the One-Atmosphere Hydrogen-Filled Counter.

Fig. 14. Response Function for the Three-Atmosphere Hydrogen-Filled Counter.

Fig. 15. Response Function for the Ten-Atmosphere Hydrogen-Filled Counter.

tabulated with the energy of the unfolded peak. These numbers are expected to be slightly different when further refinements in the Van de Graaff data reduction are included.

Table 20
THE UNFOLDED ENERGY PEAKS AND UNFOLDED NEUTRON FLUXES FROM
HYDROGEN COUNTER MEASUREMENTS COMPARED WITH THE
DIRECTLY DETERMINED VALUES

Energy of Peak, MeV		
Van de Graaff	Unfolded	Ratio, Unfold./ Van de Graaff
3-atm. pressure:		
0.289	0.29	1.00
0.289	0.29	1.00
0.417	0.42	1.01
0.495	0.50	1.01
10-atm. pressure:		
0.398	0.38	0.96
0.435	0.43	0.98
0.674	0.71	1.05
0.950	0.95	1.00

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