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GA-10146

FAST REACTOR SPECTRUM MEASUREMENTS

QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING APRIL 30, 1970

MASTER

Prepared under
Contract AT(04-3)-167
Project Agreement No. 35
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

May 15, 1970

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Gulf General Atomic

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P.O. Box 608, San Diego, California 92112

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GA-10146
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1. INTRODUCTION

This Quarterly Progress Report describes the work performed during the period from February 1, 1970 to April 30, 1970, on the program of Fast Reactor Spectrum Measurements under Contract AT(04-3)-167, Project Agreement No. 35. Previous reports under this program are listed in Refs. 1 to 6.

During this quarter the main effort was directed towards the following:

1. Preparation of a topical report to document the data reduction codes used in reducing the raw time-of-flight data.
2. Re-analyses of the STSF-1A time-of-flight data
3. Design and load the STSF-7 core
4. Initiate the studies of proton recoil measurements
5. Initiate time and energy measurements utilizing a ^3He detector.

The topical report covering the data reduction codes CAGE-BIRD-SPEC has been written and will be distributed through the ANL code center early in the next quarter. These codes are used to correct the raw time-of-flight data for count losses in the electronics, backgrounds, detector efficiency, and the mean emission time of the neutrons in the assembly.

The neutron spectrum was measured, in 1968, in an assembly (STSF-1A) rich in keV neutrons. This assembly was designed to have a spectrum tailored to measure the ratio of capture-to-fission (α) of a

high purity ^{239}Pu sample in a joint effort with the Argonne National Laboratory. Since Argonne had performed proton recoil measurements in a similar assembly (ZPR-3, Assembly 57) we re-analyzed the STSF-1A data using our latest data reduction techniques. Comparison of the time-of-flight data to the proton recoil data has shown generally good agreement over most of the neutron energy range.

The first core (STSF-7) we plan to study this year has been designed and all approvals obtained for loading. The fuel drawers have been loaded and the assembly should be ready for time-of-flight studies early in June.

The proton recoil detectors have been checked and recalibrated where necessary. A LINAC run to make preliminary response function measurements for the proton recoil detectors has been scheduled for the first week in June.

A ^3He detector was ordered and has been received. The necessary electronics have been set up and preliminary studies have begun on this detector.

2. STSF-1A NEUTRON SPECTRUM ANALYSIS

2.1 INTRODUCTION

The neutron spectrum was measured in assembly STSF-1A approximately two years ago. Up to now, no detailed analysis of this spectrum had been made because the main purpose for building STSF-1A was to provide for the irradiation of ^{239}Pu samples in order to measure the ratio of capture-to-fission (α) in a spectrum rich in keV neutrons. The STSF-1A assembly was designed to have a soft spectrum mainly by the addition of BeO as a moderator. Since it is desirable to have a known spectrum to determine a spectral averaged α , a neutron spectrum was measured with excellent statistical precision between 8 MeV and 50 eV by the time-of-flight method. Recently, ZPR-3 Assembly 57 was built at ANL/Idaho. This assembly is similar to STSF-1A except for two details: (1) The ZPR assembly had an outer depleted uranium reflector approximately 16 cm thick in addition to the iron reflector present in STSF-1A, and (2) the positioning of the depleted uranium plates in the core drawer for the two assemblies. The major incentive for a detailed analysis of the STSF-1A time-of-flight data was to compare the time-of-flight spectrum with the spectrum measured at ANL/Idaho with a proton recoil detector. It is indeed the first time that the spectrum has been measured by both the time-of-flight and the proton recoil counter techniques. Figure 1 shows a radial layout of STSF-1A and Fig. 2 is a sketch of a core drawer. The neutron spectrum has been measured at the surface of the central BeO plate 8.9 cm apart from the reactor mid-plane. Table 1 lists the atom densities for STSF-1A.

Figure 1. Configuration of final loading of STSF-1A. The movable half of the core is shown.

Fig. 2. Typical core drawer loaded in STSF-1A

Table 1
ATOM DENSITIES IN STSF-1A

Nuclide	Concentration (cm ⁻¹ /barn)	
	Core	Reflector
²³⁵ U	0.004130	---
²³⁸ U	0.006408	---
Be	0.039345	---
O	0.039409	---
Al	0.0057	0.00457
Fe	----	0.07127

2.2 NUMERICAL ANALYSIS

Assembly STSF-1A has been calculated according to the method described in a previous progress report.⁽¹⁾ All cross sections are from ENDF/B (version I). The core cell has been calculated with the P-3, S₁₂ transport approximation in slab geometry. The over-all reactor has been calculated in spherical geometry in the same P₃, S₁₂ approximation. The transport calculations have been performed with the code 1DF⁽⁷⁾ with 29 broad energy groups (Table 2). The actual core was 40.60 cm long and 37.70 cm in diameter. A spherical core 20 cm in radius surrounded by an iron reflector with a 60-cm outer radius was found to have a k_{effective} of 0.9617. This value is probably close to the actual one but corresponds to a critical mass 19% lower than the actual one. The reason for this discrepancy is not clear but it is interesting to observe that the calculated spectrum is harder than the measured one (see Section 2.3), which corresponds indeed to a more reactive core. A possible source of trouble is the large self-shielding of ²³⁵U in enriched plates. This effect means that resonance calculations will depend heavily on a correct estimation of

Table 2

BROAD ENERGY GROUP BOUNDARIES FOR STSF-1A CALCULATIONS

<u>Group</u>	<u>Upper Boundary (eV)</u>	<u>Group</u>	<u>Upper Boundary (eV)</u>
1	1.4918×10^7	16	1.1709×10^4
2	8.1873×10^6	17	9.1188×10^3
3	5.4881	18	7.1017
4	3.6788	19	6.3074
5	2.4660	20	3.3546
6	1.6530	21	2.6126
7	1.1080	22	1.5846
8	6.0810×10^5	23	7.4852×10^2
9	3.3373	24	4.5400
10	1.8316	25	3.5358
11	8.6517×10^4	26	2.7536
12	4.0868	27	1.0130
13	3.1827	28	3.7266×10^1
14	2.4786	29	5.0435×10^0
15	1.9305		4.1399×10^{-1}

the space-energy distribution of the flux in the enriched uranium plates. However, GGC-4,⁽⁸⁾ which has been used for these calculations, assumes a flat spatial distribution and a $1/E$ energy distribution. Further calculations in the framework of this program will make use of GGC-5, which is an improved version of GGC-4.

2.3 COMPARISON BETWEEN CALCULATION AND EXPERIMENT

The experimental data have been corrected for background, electronic count losses, detection efficiency, flight path transmission, and neutron emission time effects with the codes BIRD and SPEC, which have been described in previous reports.⁽¹⁾ As an example, Fig. 3 shows the correction factor computed by BIRD and used to correct the raw data for the mean emission time of neutron and detector efficiency for the time-of-flight spectrum obtained with the Lithium-glass detector between 10 MeV and 10 keV. Details about the way this curve was obtained are given in Section 3. Figure 4 shows a comparison between the experimental data (grouped according to the 29 broad groups as listed in Table 2) and the result of a transport Q-calculation weighted by the fine structure of the angular flux obtained from cell calculations.⁽¹⁾ The measured and calculated spectra have been normalized on the basis of equal power level:

$$\int_0^{\infty} \sigma_{\text{fis}, 235}(E) \phi(E) dE = 1 \quad .$$

Figure 5 shows a ratio of the measurement to the 1DF calculation for STSF-1A. Figure 6 displays a similar result obtained with a MACH-1 22-group calculation performed at ANL/Lemont with a cross section set generated by MC².⁽⁹⁾ Figures 5 and 6 show basically the same trends.

Fig. 3. Correction factor for STSF-1A computed by BIRD

Fig. 4. Comparison between experimental data and 1DF calculation

Fig. 5. Ratio of measurement to 1DF calculation

Fig. 6. Ratio of measurement to ANL calculation

It should be noted that the statistical error for the experimental data is of the order of one percent up to 2 MeV. For the two highest groups on Fig. 4, the error is respectively 4% and 17%. Therefore, the discrepancies indicated by Figs. 5 and 6 are real, either due to instrumental error or to calculation errors (resonances in ^{235}U and ^{238}U). It is interesting to note that the fission ratio $^{238}\text{U}/^{235}\text{U}$ obtained from the time-of-flight spectrum is 0.0405 and that the calculated one is 0.0418. This excellent agreement is of course due partly to error cancellation, as it can be inferred from Fig. 5.

Another important result is obtained by comparing the time-of-flight spectrum with the one obtained with proton recoil detectors.⁽¹⁰⁾ Figure 7 shows such a comparison. Error bars are indicated in regions where they are significantly larger than the point size. The two results have been normalized arbitrarily so that a good overlap would be achieved. The agreement between the two results is generally satisfactory. Some differences can, however, be observed:

- The resonances at high energy ($E > 200$ keV) are better resolved by time-of-flight measurements.
- Between 6 keV and 150 keV, the proton recoil detectors see more neutrons. This is in agreement with the calculation (see Figs. 5 and 6).
- The proton recoil spectrum indicates several resonances due to Al that are almost not observed in the time-of-flight measurements. The reason for this is probably that the gas detectors are actually completely surrounded by a layer of ~ 3 mm Al since a full drawer section has been removed to house the detector inside the core.
- Aside the Al resonances, the proton recoil detector spectrum shows several oscillations which are apparently larger than the quoted statistical error and that cannot be attributed to identified resonances. It is suspected that at least some of these oscillations are the results of some instabilities in the data reduction process.

Fig. 7. Comparison of time-of-flight data to proton recoil data

To conclude this analysis, let us point out that:

- Good agreement (better than 20% discrepancy) is obtained between calculated and measured spectra in STSF-1A between 5 MeV and 1.5 keV. The origin of discrepancies below 1.5 keV has not been identified yet.
- Equally good agreement exists between time-of-flight and proton recoil spectrometer results. This is an encouraging result. However, it should be borne in mind that the comparison between the two sets of data has been greatly simplified by the fact that the spectrum at the surface of the BeO plate (where the time-of-flight spectrum has been obtained) is very close to the average scalar spectrum in the core cell.

3. EVALUATION OF THE Li-GLASS DETECTOR EFFICIENCY VIA TIME-OF-FLIGHT SPECTRA COMPUTATIONS

3.1 INTRODUCTION

In previous reports of this series^(1, 5) it has been pointed out that measured neutron spectra in various STSF assemblies studied so far were consistently harder than calculated ones. At first, it was believed that most of this effect was due to spatial and energetic harmonics contamination from the source which was not properly taken care of by one-dimension transport calculation. Careful measurements of the neutron source distribution did actually show an important anisotropy of the high energy neutron distribution in the vicinity of the source. However, one was also able to show that the effect of this spatial anisotropy on the measured time-of-flight spectra is quite small.⁽¹⁾ Since the origin of the discrepancy between calculation and experiment is not the neutron source, it is likely due, to a large extent, to our somewhat poor knowledge of the Li-glass detector efficiency at high energies (above 2.5 MeV). In order to verify that fact, a detailed analysis of the neutron time-of-flight spectra (counts versus time channel) was conducted for STSF-1A, STSF-5, and STSF-6. The reasoning is as follows:

- Since, in highly multiplying systems, neutron emission time effects are very important, the effective detector efficiency at time-of-flight t is

$$\epsilon^*(t) = \int_{E_t}^{\infty} \epsilon(E) T\left(E, t - \sqrt{\frac{m}{2}} L^2/E\right) dE \quad (1)$$

where L is the flight path length and $\epsilon(E)$ the detector efficiency. This equation shows that at a given time-of-flight t corresponding to a neutron energy E_t (assuming instantaneous neutron emission), the number of counts in the channel of the time analyzer will depend not only on $\epsilon(E_t)$ but also on $\epsilon(E)$ for $E_t \leq E \leq \infty$ to an extent which depends on the particular time-dependent behavior of the assembly.

- Therefore two points can be made:
 1. It is impossible to overlap safely two spectra of the same neutron population taken by two different detectors (for instance Li-glass and NE-213) unless either the function $\epsilon(E)$ is known precisely all over the energy range of the neutron spectrum for both detectors or, $\epsilon(E)$ is known for both detectors over a limited energy span and the dieaway of the system is so short that, in Eq. 1 one has

$$\epsilon^*(t) \simeq \epsilon(E_t) \quad .$$
 2. Because of the folding of $\epsilon(E)$ into the neutron time-of-flight spectrum, it is not possible to determine from the comparison between calculation and the fully reduced measured spectrum if, and in what energy range, $\epsilon(E)$ might be at fault.
- In view of the above and in view of the consistent experimental-theory discrepancies in earlier STSF assemblies it has been useful to compare directly for STSF-1A the neutron time-of-flight spectrum (multi-channel analyzer spectrum - counts per time channel) obtained with both the Li-glass and the NE-213 detectors to the corresponding time-of-flight spectra as calculated by the code BIRD. (11)

Before discussing the results of such a comparison, let us briefly quote the last annual report (GA-9946):

"The NE-213 efficiency is known between 6 MeV and 0.8 MeV with a precision equal or better than 8 percent. (12)

The Li-glass detector has been calibrated against a low pressure ^3He detector up to 720 keV with an accuracy of $\pm 7\%$ and from 720 keV to 1.3 MeV with an accuracy of $\pm 10\%$.⁽¹³⁾ An error of 13% (in the resulting spectrum) should therefore probably be attached to the overlapping of the two detector efficiencies. "

The following section will show that the statement concerning a 13% error for the detectors overlapping is not correct because the importance of the two points mentioned above had not been recognized.

3.2 TIME-OF-FLIGHT SPECTRA ANALYSIS

The computer code BIRD is currently used to compute the correction factors to be applied to the time-of-flight spectrum in order to convert the raw data into a spectrum in terms of neutrons per unit of lethargy $\phi(u)$.⁽¹⁾ These correction factors are obtained from the ratio of two calculated neutron spectra. One is obtained if the neutrons are emitted instantaneously from the reactor and the flight path transmission $\mu(E)$ and the detector efficiency $\eta(E)$ are taken as unity; the other is obtained when the neutron emission times and the actual $\mu(E)$ and $\eta(E)$ are taken into account. Therefore one obtains from BIRD a time-of-flight spectrum readily comparable to the measured one either with the NE-213 liquid scintillator or with the Li-glass. Figure 8 shows a comparison of the measured and calculated time-of-flight spectra obtained for STSF-1A with the NE-213. The experimental data has only been corrected for background and analyzer deadtime and shape-wise normalized to the calculation. The excellent over-all agreement demonstrates the reliability of the time-dependent calculations. Now, Fig. 9 shows the same type of comparison for the Li-glass detector. Two calculated curves are shown. One corresponds to an efficiency curve $\epsilon(E)$, labeled set No. 2. This is the

Fig. 8. Comparison of time-of-flight data to BIRD calculation for the NE-213 detector

Fig. 9. Comparison of time-of-flight data to BIRD calculation for the Li-glass detector

efficiency that was obtained last year by comparison with the NE-213 and has been used to analyze the spectra measured in STSF-2, -5, and -6.⁽¹⁾ There is a marked disagreement between calculation and experiment. In view of this, a second calculation was made, this time using for $\epsilon(E)$, the curve (labeled set No. 1) which had been obtained when the Li-glass detector was calibrated for the first time by J. M. Neill, et al.⁽¹³⁾ (see Fig. 10). This calculation gave a much better result, showing that the latest measurement of $\epsilon(E)$ was somehow faulty. However, since remaining discrepancies were showing above 4 MeV, set No. 1 was arbitrarily modified and the resulting curve, labeled set No. 4, is also shown in Fig. 10. Figure 11 shows the type of agreement which is presently obtained between calculated and measured time of flight with the Li-glass detector. This figure displays three sets of results, namely the intercomparison between the neutron spectrum measured with the NE-213 on one hand and the Li-glass sets No. 1, No. 2, and No. 4, respectively. It can be observed that set No. 4 provides an excellent overlap of the two spectra from 0.5 MeV up to 4.5 MeV. Efficiency No. 4 is presently being used to reanalyze the spectra measured in STSF-5 and -6 (which were in serious disagreement with calculations) and will also be used for the STSF-2 measurements.⁽¹⁾ Such a comprehensive analysis of four widely different assemblies will ascertain the validity of set No. 4 until new direct measurement of the Li-glass detector efficiency in this questionable energy range is available.

Figure 11 also shows a very important feature which motivated the statement made in Section 3.1 concerning the impossibility of overlapping the results of two detectors when both efficiencies are not known over the entire energy range above the overlapping region. It can indeed be seen that although efficiencies set No. 2 and set No. 4 are identical up to 1.6 MeV, the two time-of-flight spectra exhibit differences down to 0.8 or

Fig. 10. Li-glass efficiency as a function of neutron energy

Fig. 11. Comparison of Li-glass to NE-213 for three sets of Li-glass efficiencies

0.9 MeV. This is, of course, due to the fact that, because of the rather large neutron multiplication taking place in the systems, high energy neutrons are detected with apparent time of flights longer than the actual one. The obvious result is that, although the efficiency set No. 2 is correct up to at least 1.5 MeV, its use leads to poor overlapping between the NE-213 and the Li-glass spectral data from STSF assemblies in the energy range from 0.8 to 1.5 MeV. Figure 11 dramatically illustrates this point.

4. NE-213 TWO-PARAMETER MEASUREMENTS

In Section 3, evidence was presented demonstrating that the calibration of the lithium glass detector at high energies performed last year was in error. This calibration was performed during the same experiment in which the response functions on the NE-213 detector were measured. It may be recalled that the integral of these response functions above a fixed bias did not correspond to the calculated efficiency of the detector at the same bias. This was difficult to explain since the standard flux in which the calibration was made had in turn been measured by the same NE-213 detector at a lower integral bias where the calculated and measured efficiencies of the detector had been found to agree.⁽¹²⁾ The suggestion has therefore been made that the same difficulties which affected the lithium glass detector calibration may have affected the response function measurements of the NE-213 detector. We are speculating at this point that electronics overload caused by the "gamma flash" could have been the source of our difficulties although we had no evidence at the time that this was the case. We presently believe that it would be desirable to remeasure the responses of both detectors in an improved geometry, i. e., one in which the LINAC beam direction and the flight path axis are at a greater angle to each other. It would also be useful to make two other improvements:

1. Utilize pulse shape discrimination in the NE-213 to eliminate gamma-ray backgrounds and hence improve the statistics of the response functions above 10 MeV.

2. Utilize a beryllium target whose greater neutron production above 10 MeV would enhance the counting statistics in that energy range.

Before undertaking such new experiments, we will investigate the use of the present response functions in two-parameter measurements in STSF-7. In addition, we may see if response measurements performed under another program⁽¹⁴⁾ at GGA, though intended for a different dynamic range, can be utilized instead.

5. DESCRIPTION OF STSF-7

The first core to be studied during this contract year has been designated STSF-7; it is identical to ZPR-3 Assembly 11 which contained a mixture of ^{238}U and ^{235}U . The ZPR-3 Assembly 11 has been thoroughly studied at ANL and has been designated as one of the benchmark problems. A thorough study of the kinetics and neutron spectra in STSF-7 will add vital information to supplement the experiments which have already been performed at ANL and elsewhere.⁽¹⁵⁾ The assembly is also a relatively clean two-zone system which will enable us to check many of the problems associated with calculating spectra in fast reactors.

The proposed loading of STSF-7 is 108.7 kg of ^{235}U as compared to the measured critical value of 240.6 kg of ^{235}U for the ZPR-3 Assembly 11. A typical drawer loading is shown in Fig. 12. Also shown is the re-entrant tube to a ^{235}U plate.

The atom densities calculated for this core are given in Table 3. All of the drawers to be used in loading STSF-7 have been filled with the necessary materials.

Table 3

ATOM DENSITIES FOR STSF-7

<u>Element</u>	<u>Core cm⁻¹/barn</u>	<u>Reflector cm⁻¹/barn</u>
^{235}U	0.00466	0.00008
^{238}U	0.03616	0.03977
Al	0.00564	0.00564

The core should be loaded and ready for preliminary proton recoil measurements late in May.

Fig. 12. Typical drawer loading for STSF-7

6. THE ^3He NEUTRON SPECTROMETER

An ^3He neutron spectrometer Model No. 780 has been purchased from Ortec, Inc., and was received during the month of April. The detector is made of two surface barrier detectors in a face-to-face geometry delineating a volume of ^3He gas. The detector areas are approximately 220 mm^2 and are 1 mm apart. The detector is expected to enable us to obtain information on the time-energy behavior of the neutron flux in STSF for energies down to 1 MeV (hopefully 800 keV). The associated electronic components (see Fig. 13) are being assembled and plans for testing and calibration of the detector are being formulated.

Fig. 13. Block diagram for ^3He

7. PROTON RECOIL DETECTORS

Work has begun on the application of proton recoil detectors to the measurement of fast neutron spectra.

A number of detectors having different sizes, shapes, gas fillings, and pressures are available at Gulf General Atomic and their characteristics have been compared to establish which ones are the most suitable for the spectral measurements. The work done thus far has been mainly one of familiarization with both the physics and the techniques involved in measurements with proton recoil counters.

Ionization pulses in proportional gas chambers of the type to be used can be due to elastic collisions of neutrons with protons or to electrons produced in the walls of the counter by high energy gamma rays. Therefore, a very important aspect of these measurements is the discrimination between neutrons and gamma rays which produce ionization pulses of the same height. One technique for gamma discrimination is based on the fact that, after differentiation with a small time constant, the gamma pulses are smaller than the neutron pulses giving the same ionization

The arrangement of electronic components for pulse shape discrimination has been set up and checked with a PuBe source with satisfactory results. Also, the system of data collection⁽¹⁶⁾ which uses the CDC-1700 computer in a two-parameter operating mode has been reviewed.

The two-parameter program for the CDC-1700 which had been previously used for data collection had to be modified because of modifications which were made in the computer hardware since the time the program was used last.

Proton recoil detectors work efficiently within a certain dynamic range of energies. This range depends on the applied voltage, so that in order to cover a certain energy range, the high voltage of the detector may have to be changed, thus changing the gas multiplication factor. At any value of the gas multiplication factor the detectors should be energy calibrated. Therefore, the calibration procedure, which is based on the use of a high precision reference pulser, has also been reviewed.

A run on the accelerator has been scheduled early in June for the purpose of ascertaining if there are problems associated with the measurement of neutron response functions of these detectors.

If the gamma-ray background is not too high, the measurements of the response functions will essentially be a two-parameter measurement (pulse height versus time of flight), without the need for an elaborate system of pulse shape discrimination. If the gamma-ray background is high, the pulse shape discrimination cannot be avoided in the measurement of the response functions, and a three-parameter acquisition data system will be needed. Such a system is fortunately already in use at GGA.

8. AUTOMATIC PLOTS

A program has been written to plot neutron spectra from SPEC automatically using a CRT and microfilm recorder. The program inputs energy, flux, and fractional error and calls a previously existing plotting package for the 1108 computer which produces the plots such as those shown in Figs. 14 and 15. The data will be presented on a 4 x 6 log-log scale with low energies and less significant fluxes truncated if need be. Figure 14 illustrates the type of plot for typical data which has been grouped using a statistical criterion ($\Delta E/E$, $\Delta N/N$) while Fig. 15 shows the same data grouped according to input energy boundaries.

Fig. 14. Plot of typical data grouped as per $(\Delta E/E, \Delta N/N)$

Fig. 15. Plot of typical data grouped as per input energy bounds

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