A System for Detecting Neutrons in the Harsh Radiation Environment of a Relativistic Electron Beam

Lyle W. Kruse
SYNTEX FOR DETECTING NEUTRONS IN THE HARSH RADIATION ENVIRONMENT OF A RELATIVISTIC ELECTRON BEAM

Lyne W. Krusko

Beam Source Applications Division 5232
Sandia Laboratories
Albuquerque, NM 87185

ABSTRACT

Newly developed detectors and procedures allow measurement of neutron yield and energy in the harsh radiation environment of a relativistic electron beam source. A new photomultiplier tube design and special gating methods provide the basis for novel time-of-flight and total-yield detectors. The technique of activation analysis is expanded to provide a neutron energy spectrometer. There is a demonstrated potential in the use of the integrated system as a valuable diagnostic tool to study particle-beam fusion, intense ion-beam interactions, and pulsed neutron sources for simulating weapons effects. A physical lower limit of $10^8$ neutrons is established for accurate and meaningful measurements in the HEB environment.
ACKNOWLEDGMENTS

The author wishes to thank the personnel of Sandia Simulation Instrumentation Division 1126 for excellent oscilloscope coverage of the electron beam tests. Acknowledgment is also due to J. M. McKenzie and R. E. Jones of Sandia for their invaluable assistance in obtaining the code JUNFLD and discussing its applications. With the help of these individuals, a difficult task became manageable.
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A SYSTEM FOR DETECTING NEUTRONS IN THE HARSH RADIATION ENVIRONMENT OF A RELATIVISTIC ELECTRON BEAM

Introduction

Recently several laboratories have used relativistic electron beam (REB) accelerators to study controlled thermonuclear fusion,\(^1\) to generate intense ion beams,\(^2\) and to provide neutron sources for simulation of weapons effects.\(^3\) Useful diagnostics for neutrons produced by REB accelerators depend on detectors which can:

- Determine the total number of neutrons from a burst
- Define the temporal behavior of the neutrons
- Accurately determine the distribution of neutron energy
- Detect neutrons with high efficiency
- Operate satisfactorily in the harsh electromagnetic and x-ray environment of the REB.

Since a single detector could not meet the requirements, three separate systems were combined to achieve the desired results:

- A neutron time-of-flight spectrometer
- Detectors that determine total neutron yield
- A neutron energy spectrometer.

Several formidable problems related to background radiation must be overcome in order to detect neutrons from an REB experiment. Sources of the most serious background radiation are:

- The intense electromagnetic pulse produced by the fast-rise times and high currents of the advanced electron-beam fusion accelerators
- The large burst of bremsstrahlung which can render certain types of neutron detectors useless
- Nonthermonuclear neutrons, e.g., from photodisintegration or from interactions of ions accelerated by the diode fields.

The most direct method to measure the time history and, to some extent, energy distribution of a neutron pulse is time-of-flight. The short pulse of accelerator power (10- to 70-ns full width half maximum) and short burn (= 4 ns) of the thermonuclear pellet require a fast detector. A scintillation counter that combines a scintillator and a photomultiplier tube can meet the response time and detect neutrons with high efficiency.
In the high x-ray background, time-of-flight (TOF) alone cannot meet the detection requirements. Two additional detectors provide the remainder of the necessary information. A total-yield detector measures the total number of neutrons independent of energy. An activation analysis system, including a multi-material sample and a pneumatic transfer loop, is used to obtain neutron spectral information.

The complete neutron diagnostic system is shown in Figure 1. The system operates according to the following sequence:

- The activation sample is sent from the screened enclosure to the irradiation point
- The accelerator fires, automatically gating the TOF and total-yield detectors
- After the pulse, the activation sample is transferred to the counter within the screened enclosure
- Analysis begins as soon as the sample returns and continues for a predetermined count period; during that period, raw data obtained by the detectors is analyzed to provide as much information as possible on the neutron spectrum
- Analysis reveals the specific activity for each nuclide included in the sample
- Information on these specific activities, the time-of-flight (TOF) and total yield, is input into an integral unfolding code which determines the number of neutrons as a function of energy.

Figure 1. Neutron Diagnostic System
Neutron Time-of-Flight

The x-ray background from a typical REB is enough to overwhelm a bare photomultiplier tube. If a scintillator is added to the tube, x-rays completely saturate the tube, making measurements impossible. Shielding these detectors to prevent saturation requires such massive amounts of lead that only high-neutron yields ($> 10^{10}$) can be detected. Another problem with the use of lead shielding is the change of the neutron spectrum as shown in Figure 2. Here, a fission neutron spectrum was measured after it had passed through lead of various thicknesses. Attenuation alone occurs to a thickness of 25 cm, after which the neutron spectrum changes. Therefore, the TOF detectors were designed with less than 25 cm of shielding in order to maintain high-detection efficiency and prevent spectral degradation.

Figure 2. Fission Neutron Energy Spectra Changes Produced by Various Thicknesses of Lead
A substantial x-ray background remains even with 25 cm of lead. Since the x-ray pulse arrives before the neutrons, proper gating precludes detection of the remaining background while maintaining maximum neutron-detection efficiency. Several methods for gating photomultiplier tubes have been reported. Most have deficiencies which make them unsuitable for REB applications, e.g., their turn-on times are too slow and/or the attenuation ratio between their ON and OFF states is not high enough. In some instances, nonlinear response, ringing, and spurious pulses were encountered.

In this work, three gating methods were developed which eliminated these difficulties. Although all three are useful, only the last version, which uses an RCA photomultiplier tube built to the author's specifications, performed well in the most severe REB environment. Details of these gating methods are presented in Appendix A.

Figure 3 shows the basic construction of the final TOF detector. The external shield-can reduces electrical noise. The 20-cm lead used for x-ray shielding adequately excludes magnetic fields from the photomultiplier tube. Finally, a container that is 12 cm dia. by 12 cm long holds NE-224 liquid scintillator and is in intimate contact with the face of an RCA photomultiplier tube.
A combination of focus and dynode control gates the detector. Unitrode GA-201-A silicon control rectifiers (SCRs) are the active control devices in the gating circuit. Figure 4 is a schematic showing circuit wiring details of the photomultiplier base. In the OFF state, SCRs 1, 2, and 3 reverse the bias of the photocathode-focus region of the tube and SCRs 3 and 4 allow their respective dynodes to assume the potential of adjacent dynodes. In the OFF state, therefore, the SCRs exclude photoelectrons from the dynode structure, and curtail dynode multiplication. The trigger pulse shown allows the SCRs to return the controlled electrodes to their proper potentials, thereby gating the detector.

![Figure 4. Wiring of Photomultiplier Base](Image)
Details of the response of the TOF detector are included in Appendix A. The detector has operated satisfactorily in the environment of the HERMES II accelerator\textsuperscript{11} which produced 3000 R x-ray dose at one meter. Deployed at a distance of 7 m, these devices were able to detect as few as $10^7$ neutrons in a single pulse. In Section II, additional experimental results are discussed.

**Total Neutron Yield**

In early 1966, Los Alamos Scientific Laboratories (LASL)\textsuperscript{12} developed the silver counter which has been widely applied as a total-yield detector. Figure 5 shows a cross-sectional view of the silver-activation detector. Four Geiger Mueller (GM) tubes in parallel are individually wrapped with silver foil and imbedded in a polyethylene moderator. Incident neutrons are moderated by the polyethylene and activate the silver foil from the two capture reactions:

$$^{107}\text{Ag}(n,\beta^+)_{108}\text{Cd}$$

$$^{109}\text{Ag}(n,\beta^+)_{110}\text{Cd}$$

A scaler counts the $\beta^+$ decay for one minute after a neutron burst.

![Figure 5. Cross Section of Silver Activation Detector](image-url)
The basic limitation of the silver counter is that, by using GM tubes, discrimination against
radiation other than \( \beta^- \) decay is impossible. This results in a detector that has a background on
the order of 200 cpm; its inherent sensitivity of 1 count/4 \( \times 10^4 \) neutrons at 12 cm requires at
least \( 10^7 \) neutrons before good statistics can be obtained.

A new total-yield detector developed to eliminate these sensitivity and background problems is
shown in Figure 6. Heavy water moderates incident neutrons which then undergo \((n, \alpha)\) reactions in
the scintillator. Because the \( \alpha \) particle produces such a large light output in the scintillator, pulse-
height discrimination can readily exclude other radiations.

![Diagram of Total Yield Detector](image)

Figure 6. Total Yield Detector (\(^{10}\)B liquid scintillator)

Figure 7 shows the characteristic features of thermal neutron buildup and subsequent decay
following a burst. The time delay between the initial burst and peak population is the moderation
time \( t_m \). \( \text{D}_2\text{O} \) was selected because the low capture cross section provides the longest detector
active time \( t_d \) of any moderator. This active time is the net diffusion time resulting from leakage
and capture. The counter is gated to count for time \( t_d \).

![Graph of Detector Active Time](image)

Figure 7. Detector Active Time
For the D₂O moderator, (t_m = 50 μm and t_d = 0.5 μm) as compared to polyethylene where
(t_m = 20 μm and t_d = 300 μm). The detector uses a cylindrical container of D₂O moderat or that is
12 cm in diameter and 12 cm long. Inside the moderator cylinder is a water-loaded container of
NE-110A² that is 5 cm in diameter and 3 mm thick. The scintillator is in contact with an RCA
7265-13 photomultiplier tube. Construction of this detector is similar to that of the TOF detector
pictured in Figure 1, but includes a wrapping of boron-loaded plastic between the moderator and
the external shield can. This wrapping prevents scattered thermal neutrons from entering the
detector.

The circuitry for the total-yield detector is similar to that shown in Figure 4 except for the
SCRs and the triggering method. In this case, the SCRs are Uni-tron D-200 ¹/² photo-SCRs.
Each uses a Monsanto ¹³ MV10-A light-emitting diode (LED) as a combination trigger and driver.
In order to operate over a period of 0.5 s, the SCRs must maintain low resistance. This is done
by leaving the LED drivers on during the detector's active phase.

Because of the long delay time and because the small scintillator is insensitive to x-rays,
these total-yield detectors do not have lead shielding. The background was found to be as low as
one or two counts per active period. The detector has a high inherent sensitivity of 1 count/10⁶
neutrons. This system requires as few as 10⁴ neutrons for good statistics in comparison with the
10⁸ needed for the silver counter.

Neutron Activation Analysis

The technique of activation analysis has been used for many years for neutron dosimetry and
spectral analysis.¹⁴,¹⁵ Neutron activation is accomplished by using nuclear reactions to change
stable isotopes within a given sample into radioactive isotopes. The radiations emitted by the
activation products are then measured and their spectra analyzed. The activation system consists of

a. A Pneumatic transfer¹⁶ system for sample transfer.
b. An Ortec 6240 ¹⁷ 4096-channel multichannel analyzer (MCA) and several single-
channel analyzers to analyze the spectrum and measure the decay constants of
the nuclides produced,
c. An interactive link to the Sandia Time-Share Computing System for handling
and analyzing data.

By using a number of isotopes, each with different energy-dependent cross sections, it is possible
to infer the energy spectrum of the incident neutron beam. The differential neutron spectrum can
be obtained from the activated isotopes as a solution to the integral equation

\[ a_1 = \int_{E_1}^{E_h} a_1(E) \varphi(E) dE \]
where

\( a_i \) is the activation of the \( i \)th isotope

\( \sigma_i \) is the differential cross section of the \( i \)th isotope

\( L_1 \) and \( L_2 \) are the energy limits of the neutron spectrum

\( \Phi \) is the unknown neutron spectrum to be estimated.

The nuclides used in the sample were chosen according to their threshold energy, activation cross section, and the half-life of the reaction products. These criteria are in keeping with the need to acquire accurate data within a few hours of the irradiation. For a given sample, nuclides are also selected to prevent overlap of the photopeaks.

Figure 8 shows the results of a calculation of detectable neutron yield which is typical of the useful nuclides.
Half lives of up to as much as 20 hours, combined with the need to obtain a few hundred counts in a decay photopeak within 1 hour, limit accurate measurements to fluences greater than $10^7$ neutrons cm$^{-2}$.

A pneumatic transfer system (rabbit) places the sample container inside a LiF diode as close to the neutron source as practical. It also allows minimum-delay counting of the short half-lived (on the order of seconds) samples. After it is irradiated, the sample is transferred to a Gamma Spectroscopy System (GSS) to be measured.

To enhance the energy spectrum definition, sulfur and copper are activated independent of the rabbit system. The activated sulfur is $eta$-unstable and is counted in a shielded enclosure with a GM tube. The $^{62}$Cu nuclide from the $^{63}$Cu(n, 2n) reaction emits a positron which is counted by a standard gamma-gamma spectroscopy system which measures annihilation radiation.

Initially, the proof-of-principle system used NaI(Tl) detectors which were able to resolve the photopeaks of a maximum of four nuclides per rabbit sample. These samples plus the copper and sulfur provide a minimum of six sets of activation data for use in unfolding the neutron spectrum.

Specific activity measurements are insufficient by themselves to allow for an energy-spectrum solution because $\ln (\phi(E))$ is mathematically underdetermined. However, there is additional information relative to $\phi(E)$ which can be used to solve the equation.

The integral unfold code IUNFLD$^\dagger$ can provide a mathematically rigorous solution based on use of the total neutron yield, a trial spectrum, the first and second derivatives $(\phi'(E), \phi''(E))$, and equality or inequality constraints such as $\phi(0)=0$, or $\phi(E)>0$. Even an approximation to the above quantities is useful, provided their uncertainties are known. The code has the capability of weighting the data according to its uncertainty. Propagation of the weights through $\phi$ in IUNFLD statistical package provides the basis for assigning a confidence level to the unfolded spectrum.

Data obtained from the TOF and the total-yield systems can provide the additional information required to achieve a solution. Total-yield gives the total integral which constrains the solution. The TOF data provides inequality constraints so that $\phi'(E)$ can be estimated. Although the magnitude of $\phi'(E)$ may be uncertain, in practice knowing the direction or sign of $\phi'(E)$ aids the solution.

IUNFLD represents $\phi(E)$ as a linear sum of basis functions according to the equation

$$\phi(E) = \sum_{j=1}^{N} C_j \psi_j(E)$$

[2]
where

\[ \phi_j(E) \text{ are the basis functions} \]

\[ c_j \text{ are amplitude terms} \]

\[ N \text{ is the number of functions} \]

Since the distribution of the basis functions is somewhat arbitrary, proper selection can be used to advantage. The code can be started by placing more than one basis function near a structure (e.g., a spike of monoenergetic neutrons) in \( \phi(E) \).
Section II. Experimental Results

Time-of-Flight and Total Yield

As a partial test of the neutron diagnostic technique, two TOF and several total-yield detectors were used to measure neutrons from the HYDRA accelerator. The accelerator parameters for this experiment were a 500-kV, 110-kA, 120-ns electron beam pulse.

The experimental arrangement is shown in Figure 9. The TOF detectors were placed in the laboratory at forward angles of 42° and 32° and were gated on after the x-ray burst. Neutrons were produced via ion acceleration, using the 

\[ ^7 \text{Li}(d,n)^{11}\text{Be} \quad (Q = 3.3 \text{ MeV}) \]

and

\[ ^7 \text{Li}(d,n)^{14}\text{N} \quad (Q = 15.0 \text{ MeV}) \]

reactions. Neutrons from a deuterated polyethylene film on the anode were accelerated across the diode and, at the cathode, interacted with target materials consisting of LiCl and/or TiO₂.

![Figure 9. Schematic of the Experimental Layout Used for HYDRA Measurement. The anode-cathode separation was 1 cm.](image)

These reaction mechanisms could be expected to occur with the failure of a fusion-target experiment. Should the target leak, fail to compress properly, or disassemble, deuterium and/or tritium would enter the diode. The ions thus released would be accelerated by the fields in the diode and would interact to produce neutrons of non-thermonuclear origin. In general these neutrons will possess large amounts of center-of-mass energy and will be distributed anisotropically. TOF deployment at different angles and distances can discriminate both of these effects.
Figure 10 shows TOF data for several possible reactions. When there is no neutron-producing material in the diode, no signal is present from either detector. The spectrum for the d-Li target may be noted to be a composite of the spectra of the deuterium and lithium targets respectively.

![Figure 10. Scope Traces of Detector Response from Several HYDRA Experiments.](image)

Timing information obtained from shots in which both neutron groups are present is illustrated in Figure 11. The neutron arrival time at each detector is plotted against the detector's distance from the source. Instrumental delay times have been removed. Each data point is averaged from three shots and the size of each square represents the error in measurement. The arrow indicates the time at which diode current begins to rise in the accelerator.
The slopes of the solid lines in Figure 11 were calculated from the geometric position of the detectors by assuming a 500-keV incident deuteron energy and by solving the exoergic kinematics equation for the reactions. These slopes were then drawn through the data to be consistent with neutron generation time. The dashed lines were obtained by following similar procedures except that thermal energies were assumed for the deuterons.

The time of initiation of neutron generation, deduced from the solid lines, is the same for both neutron groups within the experimental accuracy. This generation time agrees well with independent Faraday-cup measurements of the ion current at the cathode. The fit of the solid lines to the data (Figure 11) and the anisotropy (Figure 10) clearly indicate an incident deuteron energy of 500 keV.
The TOF detectors are deployed at different angles to the diode axis so that isotropic fusion neutrons can be distinguished from anisotropic beam-target neutrons. The distances \( r \) selected to facilitate measurement of neutron center-of-mass energy. These distances represent a required minimum yield of \( 10^7 \) neutrons for this experiment.

**Full System Measurements**

As a further test of the full system, an experiment was performed using the three types of detectors and a rabbit sample consisting of roughly equal amounts of Na, F, Mg, and Fe (sample details are listed in Appendix A). The HERMES II accelerator generated \( 11^{13} \) neutrons from the \(^7\text{Li} (d, n)^6\text{Be}\) reaction. The rabbit, sulfur, and copper samples experienced a fluence of \( 10^8 \) n/cm\(^2\).

Figure 12 shows data with the TOF detectors at 27 meters. Energies listed under T-O-F are deduced from the labeled structure of the scope traces. Maximum expected energies as calculated from the kinematics equations are also listed.

![Scope Traces, Time-of-Flight Neutron Energies, and Kinematic Energies for the Three Reactions Induced by the HERMES II Accelerator](image)

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<td>b</td>
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The curve energies in Figure 12 may correspond to a number of \(^7\)Li reactions. The possibilities are:

1. \(^7\)Li + d, \(^3\)He, \(10.2\) MeV
2. \(^7\)Li + d, \(^7\)Be
   - excited states of \(^7\)Be at 3.9, 6.0, and 11.4 MeV
3. \(^7\)Li + d, \(^9\)Be, \(15.12\) MeV
4. \(^7\)Li + d, \(^6\)Li, \(5.7\) MeV
5. \(^7\)Li + d, \(^7\)Li, \(2.2\) MeV
6. \(^7\)Li + d, \(^4\)He, \(4.9\) MeV

Another contribution to the neutron spectrum results from bremsstrahlung which produces an uncharacteristic type of deuterium. This \(\gamma,\text{d} \) yield was determined experimentally by placing a neutron radiator just outside the diode and adjacent to the anode. In this manner, all neutrons except those produced by the desired reaction were eliminated. For this experiment, the \(\gamma,\text{d} \) yield was \(10^{10}\) neutrons for each of the desired reactions identified in Figure 12.

The result of a measurement\(^{21}\) of the energy-dependent neutron yield from \(^7\)Li reactions is shown in Figure 13. This spectrum was used to test the activation system. With a preliminary neutron sample, only the neutron peak from the Na reaction was resolved. This peak plus those from the copper and sulfur samples provided a relatively good match to the reference \(d,\text{Li} \) spectrum based on observed activities.

![Neutron Yield by \(^7\)Li Reactions](image)

**Figure 13. Neutron Yield by \(^7\)Li Reactions**
Activation peaks from three other groups of nuclides in the rabbit were masked by the coincidence-sum effect of the NaI(Tl) well-crystal which was used as a detector (this effect is discussed in Appendix A). As a result, insufficient information was available for IUNFLD to produce a solution. To provide the best possible spectrum solution, a higher resolution detector system is being developed.

**Measurement Uncertainties**

The dominant uncertainties in the measurements are related to:

- TOF neutron energy determination
- Cross section uncertainties
- Data handling procedures.

For yields on the order of $10^7$ to $10^8$ neutrons, the exoergic energy release cannot be measured to great accuracy. This uncertainty has been found to be approximately ±50 keV for all incident ion energies above 200 keV. As the total yield increases, accuracy is limited to an energy increment corresponding to 10 percent of the TOF oscilloscope sweep speed or the detector-response time, whichever is greater. When a 50-ns/cm sweep is used, for example, TOF is usually limited to ±5 ns. For faster sweeps, overall accuracy is limited by the detector response time of 2 ns.

The total-yield detectors are calibrated with monoenergetic neutron sources. The scattering cross section variation of D$_2$O coupled with the lack of knowledge of the experimental spectrum limits total-yield accuracy to a factor of two. This factor is the tolerance which is input to IUNFLD. For the special case of monoenergetic neutrons, total yield can be measured to within ±15 percent.

The largest sources of error in the activation analysis are based on cross-section uncertainty and the behavior of the PEAKDAT code for the NaI(Tl) detector data. The cross sections for the reactions listed in Table A-2 are ±10 percent accurate. As shown in Appendix B, PEAKDAT will calculate specific activity to within ±6 percent. The sum of these is used as a best estimate tolerance of ±16 percent for IUNFLD.

The uncertainty of the IUNFLD solution is not the same as the cumulative error from the measurements. Since IUNFLD effects a minimal-norm solution to the given data within tolerances, the Chi-squared output provides a confidence level to which the solution spectrum can be believed. For the differential spectrum, values of 70 to 80 percent are good with the latter considered excellent (90% confidence is best thought of as obtaining the same spectrum, within tolerance, 90 times if the experiment were conducted 100 times). Values near or in the 90 percent range are unrealistic because uncertainties in the data do not justify such confidence in the results.
Section III. Future System Improvements

To overcome difficulties experienced when measuring activation, a new detector system is being developed. Two Ortec TEC-20 Ge(Li) detectors have been multiplexed in a face-to-face geometry. Although this system has an overall efficiency of only 28 percent of that of a NaI(Tl)-well crystal, the high resolution (e.g., 2.1 keV at 1.33 MeV) allows the effective use of up to four times as many nuclides per sample. The decreased efficiency coupled with an increased peak-to-Compton ratio combine to reduce the minimum detectable fluence by a factor of only two. Therefore, the lower limit of $10^8$ neutrons into 4s should be realized for the upgraded activation system.

Section IV. Conclusions

A neutron detection system capable of operating in the harsh radiation environment of a RIB has been developed and tested. By employing three different types of detectors, the system can perform energy-spectrum and total-yield measurements.

If a single measurement (using only one method) were made, the inherent limitations of the detectors would make it difficult to meet the requirements outlined earlier. The difficult task of characterizing neutrons in the RIB environment has been accomplished by developing a consistent set of parameters from the many complimentary measurements.
References

8. RCA is a registered trademark of RCA Electronic Components, Harrison, NJ 07028.
10. Unitrode is a registered trademark of Unitrode Corp., Watertown, MA 02172.
13. Monsanto Corp., 10131 Bubb Road, Cupertino, CA 95014.
17. Ortec Inc., 100 Midland Road, Oak Ridge, TN 37830.
APPENDIX A

Details of Detector Development

Time-of-Flight (TOF)

The earliest version of TOF detectors used a 12.7-cm-diam x 12.7-cm long plastic scintillator coupled to a 12.7-cm-diam photomultiplier tube (RCA 4522). This detector proved worthless when exposed to the HERMES II environment.

Further problems became apparent after several failures. First, x-ray backgrounds, despite 45 cm of lead shielding, was intense enough to cause the high-resistivity S-11 photocathode of the 4522 to sag in potential. This sag takes time to correct and focus before the tube can be used again. Full recovery is impossible in the few hundred nanoseconds of neutron observation. Furthermore, 45 cm of lead shielding is not acceptable.

To overcome this problem, a new photomultiplier tube was fabricated to my specifications by RCA. This tube (7265-11) uses a 14-stage multiplier structure that incorporates an accelerator grid between the last two dynodes. The grid maintains proper electron focus which allows a high-linear-output current by using a tapered-chain divider.

The photocathode is multialkali (Na-K-Cs-Sb) with lower resistivity than an S-11 cathode. In addition, an internal metallic grid is deposited over the photocathode so that if local sag occurs, proper focus is maintained.

A plano-plano front end reduces the high capacitance which is normally present in a spherical-section input such as the 4522. This feature greatly reduces switching times when controlling the focus region of a photomultiplier tube.

At room temperature, a normal S-11 photocathode will sag in potential with $10^{-8}$ A of steady photocathode current. It was found to sag at 63-μA 120-ns pulsed current from HERMES II.

The work function of the modified photocathode is approximately 1.1 eV. Since scintillator photons are predominately 2.7 eV, 1.6 eV photoelectrons are generated at the photocathode. In the OFF state (Figure A1), dynode 1 and the focus plane are tied together to prevent a potential well. These electrodes are then tied to +52.4 V. The photocathode is tied to +104.8 V resulting in the reverse field shown in Figure A1.
The potential in space at point b (1 mm from the photocathode) is 1.5 eV; the electron trajectory shown can be calculated as:

initial velocity: \( \frac{1}{2}mv^2 = KE \Rightarrow v = \frac{2(1.6 \times 10^{-19})(1.5 \text{ eV})}{9.11 \times 10^{-31} \text{ kg}} \)  

\[ V = 7.49 \times 10^5 \text{ m/s} \]

At point b the electron velocity is zero so the field acceleration can be calculated

\[ 0 = v = (7.49 \times 10^5) + 2(-a)(1 \times 10^{-7}) \Rightarrow a = -2.81 \times 10^{14} \text{ m/s}^2 \]  

Time from electron emission to subsequent collection at the photocathode in the OFF state is then:

\[ (-2.81 \times 10^{14})t^2 + (8.38 \times 10^5)t = 0 \]

\[ t = \frac{8.38 \times 10^5}{2.81 \times 10^{14}} = 2.96 \text{ ns} \]

This single electron treatment is valid only to the limit of the space charge which can be sustained under these conditions. The space charge-limited current can easily be calculated for the plano-plano front end as:

\[ \text{lb} = \frac{2.336 \times 10^6 e_b^{3/2}}{d^2} \text{ (amp/cm}^2) \]

\[ \text{lb} = \frac{2.336 \times 10^6 (15.87)^{3/2} 17.35 \text{ cm}^2}{(3.3)^2} \]

\[ \text{lb} = 235 \times 10^{-6} \text{ A} \]
This value of current is four times the pulsed sag current observed and, in fact, the tube has successfully gated a $4 \times 10^{-7}$ A 250-ns photocathode current pulse without a sag.

The second problem encountered was choosing a scintillator. The x-ray background was sufficiently intense to create high levels of excitation of a 100-ns component in the plastic scintillator. Although secondary components are present in all scintillators, they are normally of such low intensity that they do not interfere with the primary component. However, there was enough light in the 100-ns component to overwhelm the photomultiplier tube when it was gated on after the x-rays. Previous experience with light pipes made of plastic indicates that the efficiency of this component may be related to a lattice that allows transfer of this fluorescence. A similar 100-ns component can be directly excited in non-scintillator plastic.

In changing to the 124 liquid scintillator, the 100-ns component was reduced by a factor of 150. Response of the detector, using the new tube and scintillator in the HERMES II environment, is shown in Figure A2.

![Figure A2. Detector Response in HERMES II Environment](image)

4 x $10^8$ total neutrons d-d and d-7 tritium

1.6 V/div 100 ns/div

It was finally determined that when gating is done only by controlling the dynodes, as with earlier detector versions, it is not enough to prevent saturation of the photomultiplier tube. Adding the reverse-bias front end resulted in such insensitivity to saturation that the TOF detector finally chosen has not become saturated even with a total dose of 2000 Rad in 120 ns. Fast switching times and linear response have not suffered; detector rise time from OFF to ON state is 16 ns, the signal rise time 2 ns, and linear output 1.2 A into 50 ohms.

Activation Analysis

As previously mentioned, samples to be activated are constructed by loading a Rabbit capsule with a homogeneous mechanical mix of powder containing the isotopes. Table A1 shows two samples suitable for NaI(Tl).
TABLE A1

Activation Samples

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Number Density (atoms/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>$4.76 \times 10^{21}$</td>
</tr>
<tr>
<td>Si</td>
<td>$7.55 \times 10^{21}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$9.52 \times 10^{21}$</td>
</tr>
<tr>
<td>O</td>
<td>$2.84 \times 10^{22}$</td>
</tr>
<tr>
<td>Na</td>
<td>$1.55 \times 10^{22}$</td>
</tr>
<tr>
<td>F</td>
<td>$1.55 \times 10^{22}$</td>
</tr>
</tbody>
</table>

Sample 1

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Number Density (atoms/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>$1.79 \times 10^{22}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$1.75 \times 10^{22}$</td>
</tr>
</tbody>
</table>

Sample 2

The compounds, such as $S_i$O$_2$, MgO, and NaF, are powders so that the final number densities are slightly lower than normal solid densities.

The detector chosen for the early tests was a NaI(Tl) well crystal, but the coincidence-sum of the principle radiations from the high-speed sample masked all but the lowest energies, such as the 439-keV photopeak from the $^{23}$Na(n,p)$^{23}$Ne reaction. Although this effect is discussed by Heath, its severity is best illustrated in Figure A3.

Figure A3 illustrates two separate spectrum results from a standard 0.1 uCl $^{22}$Na source. The source has the same physical dimensions as the Rabbit capsule and was placed inside the well to obtain A3(a). The same source, on the face of the detector, yielded A3(b). Nothing in published literature indicated that the full energy summation could be as severe as discovered. Therefore, despite low cost, this type of detector is clearly not acceptable for multinuclide analysis.

Multiplexing two GeLi detectors in a face-to-face geometry maintains good efficiency while eliminating coincidence-sum effects. Although total price is higher, it is probably the only reasonable choice.
Figure A3. NaI(Tl) Coincidence-sum Effect

a: backscatter
b: annihilation
c: a + b
d: 1b
e: PhotoPeak
f: bee
g: dee

A3(a)

A3(b)

Figure A3. NaI(Tl) Coincidence-sum Effect
As a final aspect, the pneumatic transfer system allows activation products with a short half-life to be measured. The cross-section library in my version of the IUNFLD code has been expanded to the 22 reactions in Table A2. While not a complete list of usable reactions, it represents the types of applicable reactions. In addition to the nuclide selection criterion previously discussed, uncertainty of cross-section values is the single largest source of errors in activation analysis. For this reason, not all nuclides which survived prior tests are suitable for use. It is not uncommon in some cases to find cross-section values which are uncertain by as much as 50 percent or more. Therefore, except in extreme cases, it is best to avoid these nuclides.

### Table A2

<table>
<thead>
<tr>
<th>IUNFLD Poll No.</th>
<th>Configuration</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>239Pu 1</td>
<td>H(^{10}) + Cd cover</td>
<td>(n, f)</td>
</tr>
<tr>
<td>238U 2</td>
<td>H(^{10}) + Cd cover</td>
<td>(n, f)</td>
</tr>
<tr>
<td>237Np 3</td>
<td>H(^{10}) + Cd cover</td>
<td>(n, f)</td>
</tr>
<tr>
<td>32Si 4</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>235U 5</td>
<td>H(^{10}) + Cd cover</td>
<td>(n, f)</td>
</tr>
<tr>
<td>58Ni 6</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>56Fe 7</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>24Mg 8</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>23Na 9</td>
<td>Cd cover</td>
<td>(n, γ)</td>
</tr>
<tr>
<td>27Al 10</td>
<td>Bare</td>
<td>(n, α)</td>
</tr>
<tr>
<td>54Fe 11</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>115In 12</td>
<td>Bare</td>
<td>(n, γ)</td>
</tr>
<tr>
<td>232Th 13</td>
<td>Cd cover</td>
<td>(n, f)</td>
</tr>
<tr>
<td>127I 14</td>
<td>Bare</td>
<td>(n, γ)</td>
</tr>
<tr>
<td>28Si 15</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>16O 16</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>23Na 17</td>
<td>Bare</td>
<td>(n, α)</td>
</tr>
<tr>
<td>23Na 18</td>
<td>Bare</td>
<td>(n, α)</td>
</tr>
<tr>
<td>13C 19</td>
<td>Bare</td>
<td>(n, p)</td>
</tr>
<tr>
<td>19F 20</td>
<td>Bare</td>
<td>(n, α)</td>
</tr>
<tr>
<td>65Cu 21</td>
<td>Bare</td>
<td>(n, 2n)</td>
</tr>
<tr>
<td>63Cu 22</td>
<td>Bare</td>
<td>(n, 2n)</td>
</tr>
</tbody>
</table>
APPENDIX B

Discussion of Computer Codes

Program PEAKDAT Printout

00400 PROGRAM PEAKDAT (INPUT, OUTPUT, TAPE20, TAPE30)
00410 DIMENSION BAD(10)
00420 DIMENSION Y(1024), Y1(1024), X(1024), Y2(1024), P(90), SUM(90), PT(90)
00430 CALL 3.046
00450 PRINT ** "----PROGRAM START----"
00460 PRINT ** "NA-I GAMMA SPECTRUM ANALYSIS"
00470 PRINT ** "DATA FILE OMEGAM RETRIEVED FOR PROGRAM"
00480 PRINT ** "111 CAL=" "CAL=" K.E.V./CHANNEL"
00490 CALL GETF(ER1, 20, 6HOMEGAM)
00500 PRINT ** "ER1"","ER1"
00500 TCDP=2.5
00510 ASUM=0.
00520 SER=7.
00530 PRINT ** "126 SER=" '"SER=" 1ST DERIVATIVE SEARCH LEVEL"
00540 P=5.
00550 PRINT ** "128 R=" '"R=" CHANNELS +/- AROUND PEAK"
00560 R=PCAL
00570 READ(20, 23) (Y(I), I=1, 1024)
00580 23 FORMAT (4X, 10F7.0)
00590 PRINT ** "120 TCDP=" '"TCDP=" SECONDS FOR SAMPLE TRANSFER"
00600 SAM=2.
00610 PRINT ** "142 SAM=" '"SAM=" STANDARD SAMPLE NUMBER"
00620 TO=INT(Y(1)/60.)*100.+.5)/100.
00630 TV(1)=(-1.)
00640 PRINT ** "LIVE TIME = " "TO=" MINUTES"
00650 WRITE(30, 19) " SMOOTHED FIRST DERIVATIVE OF RAW DATA "
00660 I=2
00670 I52 ASUM=ASUM+Y(I)
00680 X(I)=1
00690 I=I+1
00700 IF(I=1024) 152, 160, 160
00710 160 I=2
00720 161 I=I+1
00730 V(I)=Y(I-2)+Y(I-1)+Y(I)+Y(I+1)+Y(I+2)/5.
00740 IF(I=1022) 161, 164, 164
00750 164 I=O
00760 165 I=I+1
00770 J=O
00780 Y(I)=Y(I+1)+Y(I)+Y(I-1))/3.
00790 Y(I)=Y(I+1)-Y(I-1),
00800 IF(I=1024) 165, 168, 168
00810 168 I=O
00820 169 I=I+1
00830 J=O
00840 V(I)=Y(I+1)+Y(I)+Y(I-1))/3.
00850 Y(I)=Y(I+1)-Y(I-1)
00860 IF(I=1024) 169, 172, 172
00870 172 I=O
00880 173 I=I+1
00890 J=O
00900 V(I)=Y(I+1)+Y(I)+Y(I-1))/3.
00910 Y(I)=Y(I+1)-Y(I-1)
00920 IF(I=1024) 173, 176, 176
00930 176 I=O
00940 177 I=I+1
00950 J=O
00960 V(I)=Y(I+1)+Y(I)+Y(I-1))/3.
00970 Y(I)=Y(I+1)-Y(I-1)
00980 IF(I=1024) 177, 180, 180
00990 180 I=I+1
01000 181 I=I+1
01010 182 I=I+1
01020 CALL GETF(ER1, 20, 6HOMEGAM)
01030 PRINT ** ""
01040 20 READ(20, 23) (Y(I), I=1, 1024)
01050 190 CONTINUE
01060 I=60
01070 192 IF(I=1024) 194, 340, 340
01080 194 I=I+1
01090 200 I=I+1
01100 205 GO TO 192
01110 220 IF(Y(I)-SER)=200+220+220
01120 220 J=J+1
01130 230 GO TO 220
01140 240 P(J)=1
01150 PRINT ** ""
01160 PRINT ** "LOCATION OF PEAK IS CHANNEL ", P(J)
01170 6=ALDBAS(6)
01180 6=ALDBAS(6)
01190 H=C**2.
PEAK ENERGIES AND INTEGRATED COUNTS ABOVE BG ---

PEAKS HAVE BEEN IDENTIFIED

SAMPLE NO. 1

SAMPLE NO. 2

SAMPLE NO. 3

SAMPLE NO. 4

SAMPLE NO. 5

SAMPLE NO. 6

SAMPLE NO. 7

SAMPLE NO. 8

SAMPLE NO. 9

SAMPLE NO. 10

SAMPLE NO. 11

SAMPLE NO. 12

SAMPLE NO. 13

SAMPLE NO. 14

SAMPLE NO. 15

SAMPLE NO. 16

SAMPLE NO. 17

SAMPLE NO. 18

SAMPLE NO. 19

SAMPLE NO. 20

SAMPLE NO. 21

SAMPLE NO. 22

SAMPLE NO. 23

SAMPLE NO. 24

SAMPLE NO. 25

SAMPLE NO. 26

SAMPLE NO. 27

SAMPLE NO. 28

SAMPLE NO. 29

SAMPLE NO. 30
02710 60 TO 563  
02720 755 EN=PQR/(1.-EXP(T*1.8241E-02))  
02730 EM=EM/EXP(-TCOR*1.8241E-02)  
02740 EM=EM/2.212058E=22  
02750 PRINT "'SP.ACT. FOR IUNFLD FOIL NO. 17 = "-EN.  
02760 GO TO 563  
02770 760 EM=PQR/(1.-EXP(T+7.46203E-05))  
02780 EM=EM/2.502241E=22  
02790 PRINT "SP.ACT. FOR IUNFLD FOIL NO. 7 = "-EN.  
02800 GO TO 563  
02810 765 PRINT "'THIS PEAK IS DECAY COMBINATION OF FOILS 8 AND 17"  
02820 GO TO 563  
02830 770 EM=PQR/(1.-EXP(T=6.08024E-02))  
02840 EM=EM/EXP(-TCOR*6.08024E-02)  
02850 EM=EM/2.212058E=22  
02860 PRINT "'SP.ACT. FOR IUNFLD FOIL NO. 18 = "-EN.  
02870 GO TO 563  
02880 775 EM=PQR/(1.-EXP(T=7.46203E-05))  
02890 EM=EM/2.502241E=22  
02900 EM=EM/29  
02910 PRINT "'SP.ACT. FOR IUNFLD FOIL NO. 7 = "-EN.  
02920 GO TO 563  
02930 780 EM=PQR/(1.-EXP(T=7.46203E-05))  
02940 EM=EM/1.705904E=22  
02950 PRINT "'SP.ACT. FOR IUNFLD FOIL NO. 8 = "-EN.  
02960 GO TO 563  
02970 785 CONTINUE  
02980 END  
READY.

EVE

14.24.46 78/03/10.
OFF LITRUSE
TTY 050  1.000 CPU
The code PEAKDAT is a photopake analysis routine for NaI. The code is useful only if a thorough characterization is made of the detector used. It is convenient to break the detector response into three quantities which can easily be determined experimentally: resolution (FWHM photopeak as a function of energy), peak-to-total-ratio (ratio counts in photopeak to total counts), and detector efficiency.

Since the majority of the γ-rays observed are less than 3 MeV, the MCA is limited to 3 MeV maximum energy. This greatly simplifies detector characterization. Five calibrated standard γ-ray sources were used to determine detector response. The sources and γ-ray energies are listed in Table B1.

**TABLE B1**

<table>
<thead>
<tr>
<th>Source</th>
<th>γ-Ray Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹³⁷Cs</td>
<td>661.2 KeV</td>
</tr>
<tr>
<td>⁵⁴Mn</td>
<td>835.0 KeV</td>
</tr>
<tr>
<td>⁶⁵Zn</td>
<td>1.114 MeV</td>
</tr>
<tr>
<td>²⁲Na</td>
<td>511 KeV</td>
</tr>
<tr>
<td>⁶⁰Co</td>
<td>1.274 MeV</td>
</tr>
<tr>
<td>⁶⁰Co</td>
<td>1.17 MeV</td>
</tr>
<tr>
<td>⁶⁰⁰Co</td>
<td>1.33 MeV</td>
</tr>
<tr>
<td>²⁵⁰Co</td>
<td>2.60 MeV</td>
</tr>
</tbody>
</table>

γ-ray spectrum from each of the isotopes are measured. The system is calibrated to 3.0 keV/channel, using a ⁶⁰Co source and an Ortec 419 precision pulse generator. From the raw data, the location of each photopeak and count in that channel are recorded. The channel locations at half the peak count are then recorded. Where these points are between channels, linear interpolation is used to determine fractional parts of a channel. The full-width-half-maximum for each photopeak is then found by multiplying the difference in channel numbers by the calibration of 3 keV/channel.

A plot of this detector resolution data appears as a concave upward curve on semilog paper. γ-ray energy on a log scale vs resolution expressed as a percent is found by dividing FWHM value by full photopeak energy. A convenient function for detector resolution can therefore be generated by a nonlinear, least-squares fit of the data to the form of Equation (B1).

\[ R = a_0 + a_1 \log(\text{E}) + a_2 (\log \text{E})^2 \]  
(B1)
The Normal Equations for solution are:

\[
\begin{align*}
B_1 &= N_0 + \beta_{2a_1} + \beta_{2a_2} \\
B_6 &= \beta_{2a_0} + \beta_{3a_1} + \beta_{4a_2} \\
B_7 &= \beta_{3a_1} + \beta_{4a_1} + \beta_{5a_2}
\end{align*}
\]

where:

- \( N \) = number of measured values
- \( R \) = sum of resolution values
- \( B_2 = \sum \log_{10} E \), sum of log of photopeak energies
- \( B_3 = \sum (\log_{10} E)^2 \)
- \( B_4 = \sum (\log_{10} E)^3 \)
- \( B_5 = \sum (\log_{10} E)^4 \)
- \( B_6 = \sum (\log_{10} E) \times R \)
- \( B_7 = \sum (\log_{10} E) \times R^2 \)

The Normal Equations are solved for the coefficients in Equation (B1). Detector resolution is then calculated by the routine between lines 1170 and 1270 in the PEAKDAT code.

By calculating the peak-to-total-ratio of the \(^{137}\text{Cs}\) spectrum and knowing the calibrated activity of the source, I found the detector efficiency to be 51 percent. I assumed this efficiency would remain constant with energy. This, of course, is not the case but the difference can be accounted for in the peak-to-total function.

Using the total counts in a photopeak, the assumed efficiency value and the known source activities, peak-to-total ratios are calculated for each peak. Again, Equation (B1) is solved for the functional form of the peak-to-total ratio vs energy.

The code PEAKDAT operates as follows:

- a. The raw counts/channel MCA data is written into a file.
- b. The file is loaded into an array and smoothed.
- c. A first derivative is taken of the smoothed data.
- d. The code then begins looking for a first derivative value above some search level (SER).
When the condition is met, the first zero crossing of the first derivative is found (the location of a peak).

The code then continues until all the data has been examined. The search level can be changed and is useful in discrimination against noise.

After peak locations are found, the resolution and channel locations at FWHM are calculated for each peak. The peak area is found by summation of raw data counts above the FWHM level one. The area of a rectangle of half FWHM height and FWHM width is then added to the sum. If it is assumed that the photopeak is Gaussian, the total area can then be calculated by dividing the summation by a factor of 0.7071. The code then generates a true Gaussian based on photopeak height and full width at half maximum, which is determined from the resolution calculation and compares the two areas. If the true photopeak, the deviation from a true Gaussian is always less than 7%. For non-Gaussian or coincidences sum peaks, this deviation is generally greater than 40%.

The extinction and peak-to-total ratio are then used to determine the total number of photons emitted from the sample for a given photopeak. The code compares photopeak energies to those of expected γ-rays from the sample and calculates specific activity. Any decay during the sample transfer time is corrected.

The activities returned by PEAKDAT for the eight calibration-source energies were all within 6% of the expected values.

Several years ago, F. Higgs and D. Amos of Sandia developed program UNFOLD to solve integral equations of the first kind. R. E. Jones of Sandia has adapted this method to an interactive program UNFLD. The big advantage of these programs is that they allow the input of auxiliary information and do not specifically need a trial spectrum. The code is mathematically rigorous and has the advantage of being interactive.

As mentioned in Section I, UNFLD represents $\psi(E)$ as a linear sum of basis functions. The basis functions are actually B splines:

$$ C_j = \sum_{i=1}^{N} C_j \int_{E_j}^{E_{j+1}} D_j(E) \sigma_i(E) dE = \sum_{i=1}^{N-1} C_j A_{ij}, $$

which results in a system of linear equations. The integral has a fixed value ($A_{ij}$) for each $D_j(E) \sigma_i(E)$. In matrix form, a least-square solution of the vector $C$ is required when $AC = G$.

Activation data is weighted according to its accuracy by dividing each row of the $A$ matrix and $G$ vector by the estimated error in $G$. A smaller error in the activation data therefore results
in a larger weight. These estimated errors are propagated and used in statistical tests; the solution accuracy statistics are available as part of the output package.

In order to fit the code into allotted file space of the time-share system and to provide the interactive capability, the code is broken into several files. A procedure file JUNPR2 attaches the compiled binary UNFOLD file IUNLG2 and R file.

### JUNPR2

```fortran
IF(FILE("R, HOT.LD">GET>R,
REWIND>R,PRIN.
FTN. I=R>B,PRIN.
ATTACH+IUNLG2/UN=PRINES.
ATTACH+CSLIB/UM=LIBRARY.
LIBRARY+CSLIB.
LOAD+IUNLG2.
LOAD>R,PRIN.
EXECUTE.
COMMENT. 1UNFLD EXECUTION COMPLETED. GOODBYE.
READY.
```

The R file is designated by the user to begin code execution:

```
-IUNPR2(R=SPLOOK)
```

This file retrieves the activation cross-sections library, contains the format to read the file, and calls the FINTRP interpolation routine to generate cross sections at energies between those in the library.

### SPLOOK

```fortran
FUNCTION R(T,1)  
DIMENSION XSAVE(70,22),YSAVE(70,22),N(22)  
COMMON/INPUT/X(69)  
DATA INIT/O/  
IF (INIT.EQ.0) GO TO 10  
INIT=1  
CALL GETF(IERR=21,55SPCTR)  
IF (IERR.NE.0) STOP 21  
REJIND 21  
DO 2 K=1,22  
J2=0  
1 J1=J2+1  
J2=J1+1  
READ(21,20) (XSAVE(J,K),YSAVE(J,K),J=J1,J2)  
2 IF(XSAVE(J,K).EQ.0) GO TO 3  
GO TO 1  
3 N(K)=J1  
CONTINUE  
CALL RETURNF(21)  
M=INT(X(I))  
P=FINTRP(T,XSAVE(I,M),YSAVE(I,M),M+1,0)  
IF (P.LT.0.) R = 0.  
20 FORMAT(F10.4,5F12.4)  
RETURN  
END
```

READY.
The values in the SPCTR R file are the dimension values indicating the numbers of cross sections included in the extended library shown in Table A2.

Additional cross sections can easily be added to the SPCTR cross-section library by changing the R file dimension statements and adding the desired cross sections. (Where the first entry is energy in MeV, the cross section follows in barns.) An example of a SPCTR printout follows:

```
SPCTR

<table>
<thead>
<tr>
<th>E</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0000E+00</td>
<td>0.0000</td>
<td>5.0000E-08</td>
<td>0.0000</td>
<td>1.0000E-05</td>
<td>5.237E-08</td>
</tr>
<tr>
<td>2.5000E+00</td>
<td>1.143E+00</td>
<td>5.0000E+02</td>
<td>1.174E+00</td>
<td>1.0000E-01</td>
<td>1.246E+00</td>
</tr>
<tr>
<td>1.0000E-01</td>
<td>1.323E+00</td>
<td>3.0000E-01</td>
<td>1.401E+00</td>
<td>5.750E-01</td>
<td>1.513E+00</td>
</tr>
<tr>
<td>1.0000E+00</td>
<td>1.729E+00</td>
<td>1.6000E+00</td>
<td>1.755E+00</td>
<td>1.9000E+00</td>
<td>1.369E+00</td>
</tr>
<tr>
<td>2.1000E+00</td>
<td>1.250E+00</td>
<td>2.1000E+00</td>
<td>1.956E+00</td>
<td>2.4000E+00</td>
<td>1.299E+00</td>
</tr>
<tr>
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</tbody>
</table>
```

As mentioned, the code is interactive allowing convenient entry of an input data file from a given set of measurements. The code is started by execution of the procedure file IUNPR2 and the correct R file designation based on cross-section library size. The code then allows a file to be built from new input.

```
-IUNPR2: P=PLNO

OLD OF NEW DATA SET? (O-N/EXIT)
NUMBER OF JOINTS
EQUALLY SPACED JOINTS? (Y-N)
TYPE THE JOINTS.
1-2-3-?
DO YOU WISH THE SOLUTION TO BE PERIODIC?
DO YOU WISH TO USE TOLERANCE MULTIPLIERS? (Y-N)
MULTIPLIERS ARE ALL 1.0
USER
CLOSE
INSERT, OR READ FILE? (1-R)
HOW MANY DO YOU WISH TO INSERT?
```
Typical input parameters from the REB neutron diagnostics are shown in the preceding printout. Nonsense input was entered to proceed rapidly through the input statements. There are additional input options available but these inputs typically cannot be generated from the TOF and total yield detectors.

As an example of solution data, a solution by J. M. McKenzie is presented. Here, 13 activation measurements, by Meason et al from the White Sands Missile Range Fast Burst Reactor, were used to calculate the differential neutron spectrum. Specific activation was entered in units of $10^{-12}$ nuclides/nuclide so that the fluence values in the following printout do not have exponents. The spectral solution and the differential and integral statistics are given.

The $X$ and $G$ values are the cross-section file foil numbers and the specific activities, respectively. All other input and output are self-explanatory.
<table>
<thead>
<tr>
<th>K</th>
<th>T</th>
<th>FPP</th>
<th>RESULT</th>
<th>SCALED DIF</th>
<th>TOL*M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.5000E-01</td>
<td>-.1090E+04</td>
<td>-.1077E+04</td>
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<tr>
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PPD PMean = .9740 PMean = -.984E-02 UNSCALED RMS
PPD CHISO = 1.0000 RMS = .495E-01 .603E-04

<table>
<thead>
<tr>
<th>M</th>
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<table>
<thead>
<tr>
<th>K</th>
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<th>SCALED DIF</th>
<th>TOL*M</th>
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<td>.150E+00</td>
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</tbody>
</table>

PPD PMean = .8743 PMean = .158E+00 UNSCALED RMS
PPD CHISO = .8743 RMS = .158E+00 .949E-01