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DETERMINATION OF CONTINUOUS GAMMA-RAY SPECTRA OVER THE ENERGY RANGE 0.1 TO 8 MeV

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August 2, 1978

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ABSTRACT

We have established an experimental facility at LLL to characterize radiation fields produced by a variety of sources and transmitted through various shielding materials. We discuss specific techniques for acquiring and reducing continuous gamma-ray energy spectra, including NaI(Tl) detectors. Use of several detector sizes allowed us to study a wide variety of source intensities and to calculate response matrices for a number of collimated detector configurations. We describe a computer program to perform the data reduction by an iterative unfolding process. Our reduction technique discloses the continuous gamma-ray energy spectrum over the range 0.1 to 8 MeV as opposed to the traditional peak intensity analysis.

INTRODUCTION

In the intrinsic radiation facility at LLL, we characterize the neutron and photon energy spectra and radiation doses of a variety of sources. Of particular interest is the radiation transmitted through various shielding materials. To accomplish this, neutron and photon spectrometer systems have been developed to measure continuous energy distributions of photons in the range 0.1 to 8 MeV and neutrons in the range 0.05 to 20 MeV. This document describes the equipment and data reduction techniques used to measure the energy spectrum of transmitted and scattered photons in the energy range of interest. The data obtained in these measurements is used to guide future weapon design, to estimate personnel radiation exposure during fabrication and handling, to guide the arrangement and shielding of storage facilities, and to verify transport calculations involving complex geometries. Table 1 outlines the measurement capability of the facility.

The sources analyzed vary widely in both physical size and intensity. It is desirable to measure the continuous photon distribution, to at least 7 MeV to include the photons from ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ reaction. The NaI(Tl) detectors, with their high peak-to-total ratio, are used to acquire the continuous pulse height distributions. Several different detector sizes are used to measure a wide variety of source intensities, as well as spectra at a fixed position. Collimation and shielding minimize the effects of a generally high and variable background.

The facility (Fig. 1) is located in a high bay where sources and detectors are mounted on a platform 5.2 m high. The nearest walls are 1/2-mm-thick aluminum 12 m from the center of the platform. We used a multipurpose shield-and-collimator assembly mounted on alignment rails; it can be positioned from 0.2 to 3 m from the center of the source stand. The shield and collimator assembly is designed to accept gamma detectors up to 3 in. in diameter (Fig. 2). The shield is made in two pieces using steel-encased lead with a hollow center. Both halves of the shield are suspended in a framework and can be separated to insert or remove the detectors. A 9-in. aperture was machined in the shield assembly for the collimator. Small lead blocks are inserted between the collimator and the sides of the aperture to maintain positioning.

Table 1. Measurement capabilities of the LLL Intrinsic Radiation Facility.

Type	Range	Comments
Neutron spectrum	0.05 to 20 MeV	Continuous spectrum
Neutron dose	—	Dose
Gamma (GEL 1)	50 KeV — 15 MeV	Pulse height spectrum for isotopic analysis
Gamma (NaI)	50 KeV — 8 MeV	Continuous spectrum for dose assessment and shield and packaging design
Gamma dose		Dose

Fig. 3. The conventional data acquisition system used for the intrinsic radiation facility data collection. Data are collected in 1024 channels in the multichannel analyzer.

DATA UNFOLDING PROCESS

Primarily, this code determines the differential flux of gamma rays [$\phi(E)$ photons/cm²-s-MeV] as a function of energy. In addition, it supplies photon spectral-intensity measurements to verify transport calculations in complex geometries and deep-penetration problems. These measurements are also used to confirm tissue dose-rate measurements and evaluate proposed changes in shielding and to determine the contribution of bremsstrahlung radiation to total photon intensity and tissue dose rates.

It is relatively simple to determine the intensity of unscattered photons emitted in the detector photopeak area during radioactive decay; but measuring a continuous spectrum of scattered and bremsstrahlung photons is much more complicated. The latter requires a response function unfolding method. In principle, the unfolding problem is defined as

$$P(x) = AT \int_0^\infty R(E_0, x) \phi(E_0) dE_0, \quad (1)$$

where

$P(x)dx$ = number of detector pulses with amplitude h such that $x \leq h \leq x + dx$,

T = duration of exposure (s),

A = Area of detector entrance window perpendicular to radiation (cm²),

$\phi(E_0)dE_0$ = photon intensity in the energy range E_0 to $(E_0 + dE_0)$,

$R(E_0, x)dx$ = probability that a photon of energy E_0 that enters the detector entrance window will interact to produce a pulse height h such that $x \leq h \leq x + dx$.

In the spectral unfolding problem, one first determines $R(E_0, x)$ by either experiment or calculation. Then $P(x)$ is measured and Eq. (1) solved for $\phi(E)$. Equation (1), however, is a Fredholm integral equation of the first kind,⁶ and its solution is not easily found.

In practice, the pulse-height distribution is known only at a finite number of points, and $P(x)$ is measured over a number of bins of nonzero widths. So the solution, $\phi(E)$, is defined as a vector whose components are the spectral intensity at a finite number of points, and $\phi(E)$ is redefined as

$$P_i = AT \sum_j R_{ij} \phi_j \quad (2)$$

or

$$\underline{P} = AT \underline{R} \underline{\phi} \quad (3)$$

for the measured pulse-height vector, P , the response matrix R , and the solution vector ϕ , where

- P_i = pulse heights in the i th bin, i.e. the number of detector pulses with amplitude h in the range $x_i \leq h \leq x_{i+1}$,
- ϕ_j = photon differential intensity (photons/cm²-s-MeV) at energy E_j ,
- R_{ij} = probability that photon of energy E_j passing through the detector entrance window will interact to produce a pulse in the i th bin, i.e. of amplitude h in the range $x_i \leq h \leq x_{i+1}$.

We can describe the detector response using either a square or rectangular matrix R . With a rectangular matrix, there may be more energies (columns) than pulse heights (rows). The problem is then "underdetermined," and some *a priori* information must be introduced to obtain a solution ϕ . If there are fewer energies than pulse heights, the problem is "overdetermined." In this case, a fitting procedure may supply a solution for an optimization criteria such as least squares or minimum chi squared; this solution would be a function of the optimization criteria. In both cases the solution to Eq. (3) is not unique, but is determined by the additional criteria imposed and by the method of solution. Finally, if R is a square matrix, an exact solution to Eq. (3) exists and may be found by inverting R . However, that approach often leads to such nonphysical solutions as discussed later.

Determination of R

A γ ray entering a NaI(Tl) or Ge detector interacts with the detector in one or more of the following processes:

- Photoelectric absorption accompanied by a photoelectron at energy $E_e \approx E_\gamma$ (neglecting the electron-separation energy).
 - Compton scattering accompanied by production of a "Compton electron" at energy $E_e = E_\gamma - E_\gamma'$
- where

$$E_e = \frac{E_\gamma}{1 + \frac{m_e c^2}{E_\gamma (1 - \cos \theta)}}$$

and for $E_\gamma > 2m_e c^2$.

- Pair production in which an e^+e^- pair are produced with a total energy of $E_e = E_\gamma - 2m_e c^2$ and in which both annihilation photons escape the detector.
- Pair production in which an e^+e^- pair are produced and one of the annihilation photons escapes the detector causing a net electron energy $E_e = E_\gamma - m_e c^2$.
- Pair production in which an e^+e^- pair are produced and both annihilation photons are absorbed, producing electrons with total energy $E_e \approx E_\gamma$.

Figure 4a shows the pulse-height spectrum of monoenergetic γ rays at energy $E_\gamma < m_e c^2$ in a NaI(Tl) detector. Besides the photo peak, the Compton-scattered electron distribution forms a continuum up to

$$E_{e\max} = \frac{E_\gamma}{1 + \frac{m_e c^2}{2 E_\gamma}}$$

The spectrum is distorted by:

- Compton-scattered photons that interact in the detector before escaping.
- Energetic photo-electrons that escape the detector before dissipating their energy.
- Bremsstrahlung radiation produced by photoelectrons both inside and outside the detector. When bremsstrahlung radiation is produced inside, it escapes, reducing the energy collected and, thus, the pulse height. Outside, it acts as a background radiation with an intensity proportional to the photon source to be measured, thus contributing to the detector response function.

Figure 4b shows the pulse-height spectrum resulting from monoenergetic photons at energy $E_\gamma > 2m_e c^2$ in a NaI(Tl) detector. The features are similar to the photons at $E < m_e c^2$, except for two additional peaks caused by the escape of one or both annihilation photons. These peaks are called the "single escape peak" (SEP) and "double escape peaks" (DEP); the photoelectron peak is the "full energy peak" (FEP).

a. Spectrum of monoenergetic γ rays at energy $E_\gamma < m_e c^2$, (^{137}Cs)

b. Spectrum of monoenergetic photons at energy $E_\gamma > 2m_e c^2$, (^{24}Na)

Fig. 4. Pulse height spectrum in an NaI(Tl) detector.

The detector-response matrix is defined in such a way that each column contains the pulse-height spectrum produced when one photon enters the detector at energy E_j , where j is the column number. There are not enough monoenergetic gamma-ray sources available to measure pulse-height spectra at all energies of interest. Consequently, each column of the response matrix has been calculated using the SANDYL code.⁷ These calculations include transport of electrons and secondary photons in the detector and its environment. Details are given later.

We are dealing with many detector-collimator combinations and column energies, and it is not possible to calculate and store all possible response matrices at once. Instead, the response matrices have been decomposed into modules following the approach of Berger and Selzer⁵; each is based on a particular type of photon interaction. The contribution of each interaction to the pulse-height spectrum is determined as a function of energy so that simple analytical or tabular functions can rapidly generate one column of R for any photon energy and detector-collimator configuration. As a result, a new response matrix may be readily calculated by the executing code each time it is run. Similar analytical approximations to the pulse-height spectra have been proposed by others,^{8, 9} but the approach here will follow that of Ref. 5, which is summarized below.

The response function $R(E_0, x)$ is written as the convolution of the energy-deposition spectrum $D(E_0, E)$ and a detector-resolution function $G(E, x)$ multiplied by the detection efficiency $\eta(E_0)$:

$$R(E_0, x) = \eta(E_0) \int_0^{E_0} D(E_0, E) G(E, x) dE, \quad (4)$$

where

$\eta(E_0)$ = the probability that a photon entering the detector will interact,

$D(E_0, E) dE$ = the probability that a photon interacting at energy E_0 will deposit an energy E in the range $E \leq E \leq (E + dE)$,

$G(E, x) dx$ = the probability that deposition of energy E will give rise to a pulse height h in the range $x \leq h \leq (x + dx)$.

Resolution functions are represented by a Gaussian, i.e.

$$G(E, x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2} \left(\frac{E - x}{\sigma}\right)^2\right), \quad (5)$$

where σ is the resolution of a particular detector and is related to the full width at half max by

$$\sigma = \frac{FWHM}{2\sqrt{2\ln 2}} \quad (6)$$

and x is measured in energy units.

Generally, the detector resolution is represented by

$$\sigma = \sigma_0 + \sigma_1 E_\gamma, \quad (7)$$

A deposition function $D(E_0, E)$ is constructed from a continuous distribution and three delta functions as follows:

$$D(E_0, E) = C(E_0, E) + P_0 \delta(E - E_0) + P_1 \delta(E - E_0 - m_e c^2) + P_2 \delta(E - E_0 - 2m_e c^2), \quad (8)$$

where P_0, P_1, P_2 are the relative areas of the FEP, SEP, and DEP, respectively. Naturally P_1 and P_2 are zero for $E \leq 2m_e c^2$. In general, P_0, P_1 , and P_2 are represented by exponential functions of the form

$$\ln P = a_0 + a_1 \ln E + a_2 (\ln E)^2 + a_3 (\ln E)^3 \quad (9)$$

where the coefficients a_0, a_1, a_2, a_3 have been determined for each detector-collimator configuration by calculating P at many different energies using the SANDYL coupled photon-electron transport code, then finding the a 's by linear regression on the resulting data. Coefficient values determined in this way are given later.

Monte-Carlo calculations are used to determine the continuum $C(E_0, E)$. A table of results is compiled for each detector-collimator configuration: in Appendix B and is linearly interpolated to obtain $C(E_0, E)$. To reduce the explicit dependence on E_0 , four tables are used in four separate energy ranges:

- For $E_0 \leq 1.2$ MeV,

$$C(E_0, E) = C_1(E_0, h) \left[\frac{1 + \frac{m_e c^2}{2E_0}}{E_0} \right] \quad (10)$$

$$h = \frac{E}{E_0} \left(1 + \frac{m_e c^2}{2E_0} \right) \quad (11)$$

For $E_0 > 1.2$ MeV the deposition spectrum is tabulated over three regions:

- For $E < E_0 - 2m_e c^2$,

$$C(E_0, E) = \frac{C_2(E_0, y)}{E_0 - 2m_e c^2} \quad (12)$$

$$\text{where } y = \frac{E_0}{E_0 - 2m_e c^2} \quad (13)$$

- For $E_0 - 2m_e c^2 \leq E \leq E_0 - m_e c^2$,

$$C(E_0, E) = \frac{C_3(E_0, Z)}{2m_e c^2} \quad (14)$$

$$\text{where } Z = \frac{E - (E_0 - 2m_e c^2)}{2m_e c^2} \quad (15)$$

- For $E_0 - m_e c^2 \leq E \leq E_0$,

$$C(E_0, E) = \frac{C_4(E_0, Z)}{2m_e c^2} \quad (16)$$

The response matrix R is determined by first calculating the deposition spectrum $D(E_0, E)$ using tables C_1 , C_2 , C_3 , C_4 , and the functional representations for P_1 , P_2 , and P_3 . Then the resulting column is smoothed with a Gaussian filter and multiplied by the efficiency $\eta(E_0)$.

Detection efficiency $\eta(E_0)$ has been determined at many energies by calculations described earlier. The resulting data is well approximated by a functional representation of the form

$$\eta(E_0) = \eta_0 + \eta_1 \ln E_0 + \eta_2 (\ln E_0)^2 \quad (17)$$

Again, the parameters η_0 , η_1 , and η_2 are determined by linear regression. After the pulse-height response $R(E_0, x)$ has been calculated for each column, the experimental pulse-height data are unfolded to give a differential photon energy spectrum such as that described below.

Unfolding the Pulse Height Data to Obtain ϕ

The object of this code is to read the pulse-height vector $\underline{P}$, calculate the detector-response matrix $\underline{R}$ as described above, and then solve Eq. (3) for the photon differential intensity $\underline{\phi}$. Conceptually, the simplest way to obtain a solution is by inversion of $\underline{R}$:

$$\underline{\phi} = \frac{1}{AT} \underline{R}^{-1} \underline{P} \quad (18)$$

Although this is the only method that yields a unique solution, in practice, it is not useful. Because of statistical variations in the pulse-height data and the close similarity of adjacent rows or columns in the response matrix, Eq. (18) leads to solutions that generally exhibit large oscillations and are nonphysical because many of the intensities in $\underline{\phi}$ are negative. These difficulties are further aggravated by errors in the calculation of $\underline{R}$ and round-off errors during inversion. Consequently, we make a reasonable guess for $\underline{\phi}$ then iteratively refine that estimate as long as all elements of $\underline{\phi}$ remain nonnegative. The process of refinement stops when some convergence criteria is satisfied.

The pulse-height data are first rebinned into 64 channels to reduce the size of the detector-response matrix, and $\underline{R}$ is calculated. An initial estimate of the photon spectrum is made according to

$$(\underline{\phi}_0)_i = (\underline{P})_i \frac{1}{\eta(E_i) \Delta E_i},$$

where ΔE_i is the energy width (MeV) of the i th pulse-height bin, and E_i is the corresponding energy deposition.

We then carry out an iterative procedure in which the ratio of the refold pulse-height spectrum to the experimental pulse-height spectrum is used to refine the estimate of $\underline{\phi}$. Because the procedure is multiplicative, $\underline{R}$ and $\underline{P}$ will always be positive and will insure that $\underline{\phi}$ will be nonnegative. The procedure is carried out as follows:

- The refold pulse height spectrum $\underline{H}$ is calculated according to

$$\underline{H}_n = \underline{R} \underline{\phi}_n, \quad (19)$$

where $\underline{H}_n$ is the refold pulse height spectrum following the n th iteration and $\underline{\phi}_n$ the n th estimate of $\underline{\phi}$.

- Then a new estimate of $\underline{\phi}$ is obtained according to

$$(\underline{\phi}_{n+1})_i = (\underline{\phi}_n)_i \left(\frac{(\underline{P})_i}{(\underline{H}_n)_i} \right)^\gamma, \quad (20)$$

where γ is a convergence velocity parameter. Normally $\gamma = 1$.

- After each iteration, the refold $\underline{H}_n$ is compared to $\underline{P}$ and χ^2 is calculated according to Eq. 21.

$$\chi^2 = \frac{1}{N} \sum_{i=1}^N \frac{((\underline{H}_n)_i - (\underline{P})_i)^2}{(\underline{P})_i} \quad (21)$$

When χ^2 is reduced below a preset value or 100 iterations have been carried out, the iterative procedure is stopped and the most recent estimate of $\underline{\phi}$ is reported as the solution.

This procedure has been used successfully by others^{1, 2, 10, 11} and has proven very efficient in the present application. Examples will be given later where very complex spectra are unfolded to give $\chi^2 < 3$ in 10 to 50 iterations.

The parameterized response functions are incorporated into several tables, each containing a full set of parameters describing the response of one detector-shield-collimator system. Each time a set of pulse-height data is unfolded, the table containing parameter values appropriate to the system used for measurement is interrogated and a complete response matrix is calculated. Then the pulse-height data is unfolded as described above.

THE UNFOLDING PROGRAM RETECTUR

RETECTUR is an interactive program to reduce gamma-ray pulse-height data obtained from a NaI detector. In addition to providing spectral data in both graphic and tabular form, the program also provides for viewing data on the LLL TMDS system at the time of reduction, automatic output of data to the LLL RIET system, background (or scatter) subtraction, and spectrum-refold overlay. All options and debugging aids are selectable and may be turned on or off during execution. Operation of the program is described in Appendix A, and a sample output is given in Appendix C.

RETECTOR exists as a library file that contains, in addition to the main program (REDUX), a set of detector parameter tables (PARAMDATA), and a stand-alone, interactive help program (HELPER). The main program was designed to accept data files from the DEKODE program presently used at the Intrinsic Radiation Facility. RETECTOR is written in extended Fortran IV (LRLTRAN).

The response matrix is calculated in two parts as described earlier. First the photo-peak response is determined based on photo-peak parameters from PARAMDATA. Then the continuum is calculated using the "C" tables, which contain values of C_1 , C_2 , C_3 , and C_4 ; it is added to the peak response to give the total response.

Energy bins for the output $\phi(E)$ are not uniform in width but are chosen to approximate a fixed fraction of the detector resolution at the bin energy:

$$\Delta E = \text{CONST} \times \text{FWHM}(E).$$

To simplify calculation, the approximation $\Delta E = \alpha (E)^{1/2}$ was used. Thus the upper energy bound of each bin, E_i , is given by

$$E_i = E_{\min} + (h_i \alpha)^2 + 2 (E_{\min})^{1/2} \alpha h_i, \quad (22)$$

h_i = pulse height (channel number) at i th channel,

$h_{\max}$ = pulse height (channel number) at highest channel,

$E_{\min}$ = lower bound of the first energy bin,

$E_{\max}$ = upper bound of the highest energy bin,

where

$$\frac{1}{\alpha} = \frac{h_{\max}}{(E_{\max})^{1/2} - (E_{\min})^{1/2}}. \quad (23)$$

This nonlinear compression of the pulse-height data helps preserve the resolution of the detector/electronics system at the low-energy end of the spectrum. The number of channels in the compressed spectrum can be varied up to about 75 channels. It is presently set at 64 channels.

A stand-alone program (GAMI00) was developed to calculate just the response matrix. (See Appendix D). This code can be used to test new parameter tables or generate fixed-response matrices for other codes.

CONCLUSION

The program RETECTOR has been tested by unfolding pulse-height spectra from a number of relatively simple sources. For the majority of sources tested, convergence to a χ^2 per degree of freedom less than three occurred in 40 to 50 iterations. In only one case was the maximum iteration limit reached with a χ^2 of 4.5.

Estimates of result precision and the response-matrix parameters were determined by refolding the theoretical line spectrum of the source and comparing the refold to the pulse-height spectrum. Table 2 summarizes some of these comparisons. Matrix parameters are determined primarily by Monte Carlo calculation; some adjustments were made based on a few well characterized sources. A nonzero continuum between the photo peaks for well known sources is observed, but is small in value. It is difficult to estimate how much of this continuum comes from scattering in the source and how much from systematic errors in the unfolding process.

Complex spectra from common radioactive sources generally require more iterations to converge; some extremely complicated spectra may never converge. In addition, overestimation of the intensity in a column of the response matrix generates fictitious fluxes and may prevent convergence. To prevent oscillations in the results, we must adhere to the rather stiff requirement that the pulse height spectra go to zero at high energy.

Several simple gamma ray sources were exposed to a NaI (Tl) detector and the data unfolded. The differential flux $\phi(E)$ was integrated over the unfolded spectrum and compared to the total photon flux of the source. The results are shown in Table 2.

The program RETECTOR performs well in the interactive mode and may be used to display the unfolded results on a television monitor as they are generated. This allows the operator to make serial runs using the feedback from each run to guide processing of the next. The output tables produced by the program include the differential flux $\phi(E)$ and the dose rate as a function of energy, as well as group fluxes corresponding to the MORSE-L structure.

Table 2. Comparison of the calculated photon intensity to the unfolded photon intensity.

Source	Energy, MeV	Source intensity $\gamma/\text{cm}^2 \cdot \text{s}$	$\int_0^\infty \Phi(E)dE,$ $\gamma/\text{cm}^2 \cdot \text{s}$	Error, %
^{22}Na	0.511	8.06	8.15	1.12
^{137}Cs	0.662	5.105	5.41	5.97
^{56}Co	0.846	9.87	9.46	4.15
^{60}Co	1.037	1.269	1.57	23
^{60}Co	1.173	4.506	4.83	7.5
^{56}Co	1.238	6.551	4.58	16
^{22}Na	1.274	4.031	4.20	4.19
^{60}Co	1.332	4.506	4.84	7.5
^{56}Co	1.771	1.591	1.87	17.6
^{56}Co	2.598	1.693	1.75	3.55
^{56}Co	3.253	1.289	0.896	30

APPENDIX A— OPERATIONS MANUAL

Description of Pulse Height Spectrum Data Files

RIETECTOR is designed to accept pulse-height data files written by the routine DEKODE, which was developed by J. Parlegreco. The data file consists of three header lines followed by the data (in 1017 format).

The header lines are:

- Line 1. 14X, file name (A6), 16X, ISIZE (I4), 17X, SEQ (I3), 17X, DET (I3)
- Line 2. 16X, MKL (I4), 16X, MKR (I4), 14X, ET (I6), 14X, TOD (I6)
- Line 3. 16X, INTL (I4), 16X, INTR (I4)

Definitions

- Data* — The name of your data file (pulse-height data).
- DET* — The number of the detector used to acquire this data set.
- E_{max}* — The energy (MeV) of the last channel of *RAW* data (even if the last channel is not to be included in the analysis).
- Endchn* — Given after "startchn" to specify the last acceptable channel in the *RAW* data. Default is ISIZE.
- ET* — Elapsed time from ID record generator; not used as elapsed time in calculation.
- File Name* — A sequence number established by the ND-100 ID record generator, can be any ASCLL file name six characters or less, left justified.
- Heading Info* — Up to 70 columns of information used to label output graphs and tables.
- INTL* — Left intensified region.
- INTR* — Right intensified region.
- ISIZE* — The number of data channels. Channel zero of the pulse-height data is counted in ISIZE; it is reserved for the true elapsed time (dead time corrected) of the spectrum. This time is used in the analysis.
- MKL* — Left marker channel.
- Option* — Any of the available options (or none of them).
- SEQ* — An arbitrary sequence number, used for a family of files.
- Startchn* — Given after the data statement to specify the first acceptable channel in the *RAW* data. Default is 1.
- Thres* — The energy (MeV) of the first channel of *RAW* data (even if the first channel is not to be included in the analysis).
- TOD* — Time of day from ID record generator.

Options

B file—This option specifies a file as a background to be subtracted from data, if *file* = OFF it turns off the background subtraction option. The background subtract option must be selected just before each data file. It does not carry over from one unfolding to the next.

CHP—The CHP allows certain process parameters to be modified for this run only. You will be prompted for the mutable parameters. Typing "RETURN" will select default parameters.

- DEBUG**—Where *n* < 0, DEBUG creates the re-fold overlay
- = 0, DEBUG goes into normal processing
 - > 0, DEBUG prints the response matrix in output
 - = 2, DEBUG graphs the photon-run conversion
 - = 3, DEBUG plots each response column.

HELP a—This option initializes the help package and sends a help message to the TTY. The argument *a* is usually null. But, if given after the OK: prompt, it will return the *a* help pack instead of the OK: package.

RJ n—This is on RJET option where *n* can be null, the RJET number or the word OFF. The box and ID information given on execution are used to assign output.

TV n—This is a TMDS option where *n* can be null, the monitor number, or the word OFF. If *n* is null you will be prompted for the monitor number.

Summary of Usage Forms

FORM I

USER: RETECTUR/*tv*
ROUTINE: OUTFILE:
USER: *filename*
ROUTINE: BOX & ID
USER: *BOX No. id*
ROUTINE: OK:
USER: *option*
•
•
•
ROUTINE: OK:
USER: *data startchn endchn*
ROUTINE: HEADING:
USER: *heading info*
ROUTINE: THRES EMAX:
USER: *thres emax*
USER: OK:
USER: END
ROUTINE: ALL DONE

FORM II

The ! character is the LINEFEED echo.

USER: RETECTUR *outfile* *BOX No. id*
ROUTINE: OK:
USER: *option ! option ! data ! thres emax*
ROUTINE: HEADER:
USER: *heading info*
ROUTINE: OK:
•
•
•
USER: END
ROUTINE: ALL DONE

More than one file may be put on one input line by "linefeed" delineating in the order "OPTION ! DATA ! THRES EMAX !....".

For example:

TV 402 ! B FILE1 ! FILE2 ! -.013 4.8 ! FILE3 ! .064 6.8 calls for TV #402, subtracts FILE 1 from FILE 2 processes FILE 2 from -.013 to 4.8 MeV, and processes FILE 3 from 0.064 to 6.8 MeV.

Output

Tabular and graphic descriptions of the output are included as Appendix C. Smoothed final estimates are shown in Figs. A-1 through A-7.

Fig. A-1. Final estimated $\phi(E)$ for ^{137}Cs .

Fig. A-2. Final estimated $\phi(E)$ for ^{60}Co .

Fig. A-3. Final estimated $\phi(E)$ for ^{22}Na .

Fig. A-4. Final estimated $\phi(E)$ for ^{24}Na .

Fig. A-5. Final estimated $\phi(E)$ for ^{88}Y .

Fig. A-6. Final estimated $\phi(E)$ for ^{56}Co .

Fig. A-7. Final estimated $\phi(E)$ for ^{46}Ca .

APPENDIX B— RESPONSE MATRIX PARAMETER TABLES

Included in this appendix are the detector efficiency parameters η [c.f. Eq. (17)], peak fractions P_0 , P_1 , P_2 , P_3 , and P_4 [c.f. Eqs. (8) and (9)], and the C functions $C_1(E_0, x)$, $C_2(E_0, y)$, $C_3(E_0, z)$ and $C_4(E_0, z)$ defined in Eqs. (10), (12), (14), and (16). These response function parameter sets are given in Tables B-1 through B-12 for the 3×3 , 1×1 , and 2×2 NaI(Tl) detectors in the small aperture collimator.

Table B-1. The 3×3 NaI(Tl) SANDYL 12 response in the small aperture collimator. A det = 45.6 cm², A_{111} (100 cm) = 57.7 cm², Ratio = 1.265.

nE_0	E_0	$\eta(E_0)$	$\eta^*(E_0)$ (corr. for attenuation)	P_0	P_1	P_2	P_3	P_4
-2.303	0.1	1.0	0.904	0.963				
-1.897	0.15	1.0	0.957	0.909				
-1.609	0.2	0.999	0.956	0.894				
-1.204	0.3	0.984	0.942	0.813				
-0.916	0.4	0.946	0.904	0.721				
-0.6931	0.5	0.929	0.885	0.646				
-0.5108	0.6	0.892	0.854	0.572				
-0.2231	0.8	0.847	0.808	0.480				
0	1.0	0.827	0.792	0.414				
0.1823	1.2	0.789	0.762	0.377				
0.4055	1.5	0.740	0.720	0.330	0.006	0.003		
0.6931	2.0	0.705	0.685	0.278	0.0199	0.00725		0.0014
1.099	3.0	0.671	0.656	0.203	0.0592	0.0230		0.0130
1.386	4.0	0.662	0.650	0.154	0.0832	0.0297		0.0183
1.609	5.0	0.662	0.650	0.126	0.0897	0.0390		0.0215
1.792	6.0	0.666	0.653	0.102	0.110	0.0340		0.0264
1.946	7.0	0.662	0.650	0.0872	0.0994	0.0461		0.0266
2.079	8.0	0.670	0.659	0.0739	0.0914	0.0364		0.0284

$$\eta(E_0) = 0.7806 - 0.1443 \ln E_0 + 0.01473 (\ln E_0)^2 + 0.01797 (\ln E_0)^3 - 0.002390 (\ln E_0)^4$$

Detector area = 45.6 cm²

Table B-2. The $C_1(E_0, x)$ function for the 3×3 NaI(Tl) detector, where $C_1(E_0, x) = \left(\frac{E_0}{1 + \frac{mc^2}{2E_0}} \right) C(E_0, E)$
 $X = \frac{E}{E_0} \left(1 + \frac{mc^2}{2E_0} \right) \quad E = X \left(\frac{E_0}{1 + \frac{mc^2}{2E_0}} \right)$

$E_0 =$	0.1	0.15	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.2
X	B.S.	B.S.								
0	0	0	0.032	0.11	0.16	0.22	0.29	0.32	0.41	0.39
0.05	0.0005	0.006	0.032	0.12	0.18	0.23	0.31	0.33	0.41	0.42
0.1	0.0009	0.0087	0.032	0.13	0.19	0.24	0.32	0.34	0.43	0.44
0.2	0.0018	0.0105	0.032	0.13	0.19	0.25	0.35	0.37	0.47	0.47
0.3	0.0014	0.0096	0.032	0.11	0.20	0.27	0.38	0.41	0.52	0.51
0.4	0.0006	0.0079	0.033	0.11	0.21	0.30	0.40	0.47	0.49	0.53
0.5	0.0007	0.0074	0.033	0.10	0.23	0.35	0.40	0.46	0.49	0.52
0.6	0.0022	0.0086	0.034	0.10	0.23	0.31	0.40	0.46	0.55	0.48
0.7	0.0098	0.019	0.035	0.11	0.24	0.31	0.40	0.47	0.53	0.54
0.8	0.017	0.028	0.036	0.17	0.27	0.35	0.40	0.51	0.60	0.68
0.9	0.024	0.0505	0.039	0.25	0.32	0.39	0.45	0.58	0.67	0.83
0.95	0.028	0.0635	0.040	0.17	0.33	0.38	0.54	0.72	0.78	0.94
0.975	0.031	0.0707	—	0.16	0.21	0.32	0.47	0.61	0.76	0.83
1.0	0.012	0.0165	0.041	0.097	0.17	0.23	0.25	0.33	0.34	0.44
1.1	0.0005	0.0018	0.044	0.068	0.10	0.12	0.11	0.12	0.10	0.074
1.2	0	0	0.046	0.075	0.10	0.10	0.076	0.061	0.036	0.030
1.3			0.047	0.081	0.095	0.086	0.059	0.036		
1.4			0.047	0.084	0.085	0.079	0.046			
1.6			0.050	0.092	0.075					
1.8			0.051	0.10	0.05					
2.0			0.051	—	—					
2.2			0.03							

Table B-3. The $C_2(E_0, y)$ function for the 3×3 NaI(Tl) detector, where $C_2(E_0, y) = (E_0 - 2mc^2) C(E_0, E)$

$$y = \frac{E}{E_0 - 2mc^2} \quad E = y \times (E_0 - 2mc^2)$$

$E_0 =$	1.2	1.5	2	3	4	5	6	7	8
y									
0	0.069	0.148	0.22	0.37	0.39	0.44	0.62	0.74	0.49
0.05	0.070	0.158	0.26	0.37	0.51	0.56	0.54	0.57	0.80
0.1	0.071	0.160	0.30	0.43	0.45	0.43	0.48	0.45	0.42
0.2	0.073	0.172	0.32	0.37	0.39	0.36	0.39	0.28	0.37
0.3	0.075	0.186	0.31	0.33	0.34	0.34	0.35	0.32	0.35
0.4	0.076	0.213	0.27	0.33	0.33	0.32	0.33	0.32	0.35
0.5	0.077	0.239	0.27	0.35	0.36	0.34	0.33	0.33	0.38
0.6	0.079	0.206	0.27	0.36	0.37	0.38	0.37	0.37	0.45
0.7	0.080	0.206	0.28	0.38	0.42	0.43	0.45	0.45	0.56
0.8	0.082	0.200	0.30	0.42	0.48	0.52	0.57	0.60	0.73
0.9	0.083	0.148	0.33	0.45	0.60	0.70	0.80	0.87	1.00
0.95	0.084	0.198	0.35	0.47	0.70	0.82	1.00	1.29	1.40
0.975	0.085	0.195	0.38	0.48	0.55	0.74	1.25	1.20	1.29
1.0	0.085	0.192	0.40	0.50	0.54	0.64	1.59	0.99	1.08

Table B-4. The $C_3(E_0, z)$ function for the 3×3 NaI(Tl) detector where $C_3(E_0, z) = 2mc^2 C(E_0, E)$

$$z = \frac{E - E_0 + 2mc^2}{2mc^2} \quad E = (E_0 - 2mc^2) + 2mc^2 z.$$

$E_0 =$	1.2	1.5	2	3	4	5	6	7	8
z									
0	0.49	0.47	0.41	0.35	0.35	0.37	0.368	0.39	0.39
0.1	0.52	0.44	0.37	0.38	0.42	0.40	0.405	0.38	0.37
0.2	0.55	0.45	0.38	0.37	0.38	0.41	0.399	0.38	0.35
0.3	0.55	0.47	0.40	0.35	0.32	0.31	0.266	0.28	0.30
0.4	0.50	0.49	0.44	0.33	0.30	0.25	0.204	0.21	0.21
0.5	0.55	0.49	0.49	0.32	0.28	0.22	0.184	0.17	0.13

Table B-5. The $C_3(E_0, z)$ function for the 3×3 NaI(Tl) detector.

$E_0 =$	1.2	1.5	2	3	4	5	6	7	8
0.5	0.55	0.62	0.59	0.50	0.44	0.41	0.378	0.31	0.29
0.6	0.71	0.66	0.66	0.55	0.43	0.40	0.327	0.40	0.28
0.7	0.86	0.78	0.63	0.48	0.45	0.38	0.266	0.31	0.25
0.75	0.97	0.84	0.56	0.31	0.32	0.28	0.22	0.18	0.18
0.8	0.41	0.24	0.11	0.15	0.19	0.17	0.164	0.10	0.13
0.85	0.13	0.13	0.072	0.061	0.10	0.05	0.092	0.026	0.051
0.9	0.072	0.087	0.046	0.031	0.02	0.006	0.041	0.010	0.005
1.0	0.030	0.051	0	0	0.0	0	0.010	0	0

Polynomial representations for NaI parameters are:

(1) $n(E_0) = a_0 + a_1 nE_0 + a_2 (nE_0)^2 + \dots$

(2) $P_0 = e^{-x_0}$
 where $x_0 = a_0 + a_1 nE_0 + a_2 (nE_0)^2 + \dots$

(3) $P^1 = 0$ for E_0 1.5 MeV

$P_1 = e^{-x_1}$ for E_0 1.5 MeV.

(4) $P_2 = 0$ for E_0 1.5 MeV

$P_2 = e^{-x_2}$ for E_0 1.5 MeV.

(5) $P_3 = e^{-x_3}$ for E_0 1.5 MeV

$P_3 = 0$ for E_0 1.5 MeV.

(6) $P_4 = 0$ for E_0 1.5 MeV

$P_4 = e^{-x_4}$ for E_0 1.5 MeV.

NOTE: Difference here

Table B-6. Parameters for NaI detectors.

1×1	a_0	a_1	a_2	a_3	a_4
$\eta(E_0)$	0.4002	-0.1832	0.09263	0.006893	-0.0104
x_0	1.618	1.079	0.04151	0.03505	0.04161
x_1	18.35	-2813	17.08	-3.346	—
x_2	7.063	-6.363	2.077	—	—
x_3	6.070	0.6768	0.1817	—	—
x_4	9.846	-6.357	1.661	—	—
3×3					
$\eta(E_0)$	0.7806	-0.1443	0.01473	0.01797	-0.002390
x_0	0.8268	0.6095	0.1121	—	—
x_1	7.016	-5.459	1.563	—	—
x_2	7.517	-4.713	1.289	—	—
x_3	6.445	0.6551	-0.3133	—	—
x_4	16.66	-22.46	13.17	-2.600	—

Table B-7. The 1×1 NaI(Tl) SANDYL 12 response in the small aperture collimator. $\left[A_{\text{coll}} = 5.067 \text{ cm}^2, A_{\text{III}} (100 \text{ cm}) = 20.81 \text{ cm}^2, \text{Ratio} = 4.107, P = \text{Ratio} \times \left(\frac{\text{area}}{\eta(E_0)} \right) \right]$

E_0	E_a	$\eta(E_a)$	P_a	P_1	P_2	P_3	P_4
-2.303	0.1	0.923	0.937	—	—	0.028	—
-1.897	0.15	0.914	0.929	—	—	0.016	—
-1.609	0.2	0.865	0.851	—	—	0.010	—
-1.204	0.3	0.709	0.705	—	—	0.0093	—
-0.9163	0.4	0.607	0.516	—	—	0.0061	—
-0.6391	0.5	0.549	0.416	—	—	0.0026	—
-0.5108	0.6	0.495	0.344	—	—	0.0025	—
-0.3567	0.7	0.472	0.303	—	—	0	—
-0.2231	0.8	0.443	0.244	—	—	0.0037	—
-0.1054	0.9	0.433	0.206	—	—	0.0024	—
0	1.0	0.421	0.178	—	—	0.0024	—
0.2231	1.25	0.376	0.155	—	—	0.002	—
0.4055	1.5	0.352	0.128	—	0.0070	—	—
0.6931	2.0	0.336	0.0966	0.0025	0.0324	0.0018	—
1.099	3.0	0.303	0.0610	0.0339	0.0757	0	0.0075
1.386	4.0	0.286	0.0259	0.0273	0.104	0	0.016
1.609	5.0	0.289	0.0192	0.0345	0.102	0	0.01
1.792	6.0	0.292	0.0155	0.0345	0.0872	0	0.031
1.946	7.0	0.296	0.00971	0.0278	0.0860	0	0.016
2.079	8.0	0.310	0.00530	0.0242	0.0623	0	0.026

Table B-8. Response function parameters for P_1 and P_2 in the 1×1 NaI(Tl) detector, where $\frac{SL_a}{SL_1} = \frac{8.33 \times 10^{-4}}{5.067 \times 10^{-4}} = 1.645$, and $\eta(E_0) = P_1 P_2$, where $P_1 = \frac{\phi_1(E_0)}{\phi_0(E)} \frac{SL_a}{SL_1}$, $P_2 = 1 - \frac{\phi_2}{\phi_1}$.

$1 - e^{-\mu L}$	E_0	ϕ_1	ϕ_2	ϕ_3	P_1	P_2	$\eta(E_0)$
1.0	0.1	0.2211	0	0.3942	0.923	1.0	0.923
0.997	0.15	0.2309	0.00140	0.4219	0.920	0.994	0.914
0.945	0.2	0.2279	0.01490	0.4054	0.925	0.935	0.865
0.793	0.3	0.2349	0.0575	0.4117	0.939	0.755	0.709
0.656	0.4	0.23315	0.08365	0.4050	0.947	0.641	0.607
0.589	0.5	0.2290	0.0950	0.40155	0.938	0.585	0.549
0.527	0.6	0.2325	0.1117	0.4014	0.953	0.520	0.495
0.496	0.7	0.2368	0.1200	0.4073	0.956	0.493	0.472
0.470	0.8	0.2349	0.1267	0.4019	0.962	0.461	0.443
0.450	0.9	0.2330	0.1276	0.4000	0.958	0.452	0.433
0.435	1.0	0.2327	0.1311	0.3971	0.964	0.437	0.421
0.406	1.25	0.2364	0.1440	0.4040	0.963	0.391	0.376
0.374	1.5	0.2367	0.1518	0.3966	0.982	0.359	0.352
0.324	2	0.2453	0.1626	0.4050	0.996	0.337	0.336
0.289	3	0.2435	0.1683	0.4083	0.981	0.309	0.303
0.279	4	0.2371	0.1681	0.3974	0.982	0.291	0.286
0.277	5	0.2312	0.1619	0.3945	0.964	0.300	0.289
0.278	6	0.2347	0.1644	0.3963	0.974	0.300	0.292
0.282	7	0.2383	0.1664	0.3991	0.982	0.302	0.296
0.286	8	0.2393	0.1638	0.4003	0.983	0.316	0.310

Table B-9. The $C_1(E_0, x)$ function for the 1×1 NaI(Tl) detector, where $C_1(E_0, x) = \frac{E_0}{1 + \frac{mc^2}{2E_0}} C(E_0, E)$
 $E = x \frac{E_0}{1 + \frac{mc^2}{2E_0}}$

E_0	0.1	0.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.25
$x = 0$	0.0068	0.031	0.114	0.275	0.464	0.487	0.758	0.739	0.788	0.85	0.892	0.78
0.05	0.0068	0.032	0.111	0.275	0.470	0.563	0.724	0.74	0.770	0.736	0.860	0.81
0.1	0.0062	0.032	0.109	0.313	0.470	0.827	0.707	0.74	0.758	0.820	0.836	0.84
0.2	0.0056	0.032	0.104	0.311	0.470	0.612	0.673	0.74	0.728	0.722	0.820	0.87
0.3	0.0052	0.032	0.098	0.308	0.478	0.579	0.652	0.744	0.716	0.848	0.797	0.84
0.4	0.0045	0.031	0.094	0.300	0.483	0.582	0.631	0.769	0.703	0.848	0.800	0.82
0.5	0.0042	0.029	0.088	0.285	0.500	0.663	0.619	0.733	0.703	0.820	0.781	0.82
0.6	0.0042	0.028	0.088	0.259	0.500	0.513	0.619	0.677	0.716	0.799	0.757	0.89
0.7	0.0051	0.027	0.091	0.243	0.500	0.513	0.631	0.692	0.758	0.792	0.741	0.99
0.8	0.011	0.040	0.104	0.267	0.500	0.539	0.656	0.739	0.819	0.820	0.740	1.12
0.9	0.019	0.083	0.123	0.318	0.488	0.662	0.758	0.821	0.928	0.946	0.980	1.24
0.95	0.017	0.039	0.088	0.324	0.439	0.821	0.968	0.872	0.994	1.25	1.39	1.35
0.975	0.016	0.022	0.058	0.170	0.342	0.827	0.640	0.564	0.788	1.05	0.916	1.35
1.0	0.014	0.019	0.035	0.146	0.244	0.463	0.253	0.282	0.261	0.519	0.478	0.83
1.1	0.011	0.0066	0.014	0.058	0.049	0.093	0.101	0.082	0.121	0.140	0.112	0.100
1.2	0.0079	0.0055	0.014	0.019	0.049	0.079	0.063	0.077	0.067	0.112	0.064	0.010
1.3	0.0045	0.0055	0.015	0.013	0.059	0.079	0.083	0.062	0.030	—	—	—
1.4	0.0034	0.010	0.016	0.026	0.083	0.066	0.126	—	—	—	—	—
1.6	0.0034	0.014	0.021	0.068	0.156	—	—	—	—	—	—	—
1.8	0.0051	0.016	0.044	0.091	0	—	—	—	—	—	—	—
2.0	0.0068	0.018	0.091	0	—	—	—	—	—	—	—	—
2.2	0	0	0	—	—	—	—	—	—	—	—	—

Table B-10. The $C_2(E_0, y)$ function for the 1×1 NaI(Tl) detector, where $C_2(E_0, y) = (E_0 - 2mc^2) C(E_0, E)$,
 $E = y(E_0 - 2mc^2)$

E_0	1.25	1.5	2	3	4	5	6	7	8
$y = 0$	0.169	0.373	0.499	0.771	0.968	1.72	1.59	3.26	3.32
0.02	0.170	0.370	0.509	0.890	1.18	2.19	2.39	3.71	3.98
0.04	0.171	0.366	0.528	1.11	1.27	2.03	2.74	2.75	2.23
0.06	0.173	0.362	0.538	0.910	1.31	1.59	2.14	1.55	1.57
0.08	0.173	0.361	0.548	0.851	1.28	1.28	1.39	1.35	1.22
0.1	0.174	0.359	0.567	0.811	0.893	1.07	1.10	1.20	1.05
0.2	0.178	0.349	0.626	0.613	0.670	0.637	0.772	0.807	0.768
0.3	0.180	0.344	0.626	0.514	0.625	0.656	0.722	0.837	0.733
0.4	0.182	0.344	0.489	0.514	0.581	0.577	0.687	0.747	0.733
0.5	0.186	0.359	0.469	0.524	0.536	0.541	0.687	0.688	0.663
0.6	0.190	0.335	0.460	0.534	0.491	0.625	0.687	0.646	0.660
0.7	0.192	0.292	0.440	0.574	0.521	0.648	0.697	0.658	0.698
0.8	0.193	0.290	0.421	0.613	0.611	0.648	0.846	0.837	0.803
0.9	0.192	0.306	0.401	0.623	0.938	0.780	1.02	1.08	1.26
0.95	0.192	0.311	0.396	0.593	0.521	0.895	1.05	1.14	1.43
0.975	0.191	0.312	0.400	0.574	0.447	0.576	0.996	0.777	1.47
1.0	0.919	0.316	0.41	0.554	0.372	0.597	0.854	0.538	0.80

Table B-11. The $C_3(E_0, z)$ function for the 1×1 NaI(Tl) detector, where $C_3(E_0, z) = 2mc^2 C(E_0, E)$, $E = (E_0 - 2mc^2) + z \times 2mc^2$.

$E_0 =$	1.25	1.5	2	3	4	5	6	7	8
$z = 0$	0.859	0.675	0.409	0.503	0.521	0.332	0.399	0.356	0.276
0.1	0.818	0.685	0.511	0.511	0.429	0.296	0.296	0.307	0.261
0.2	0.807	0.695	0.572	0.444	0.348	0.266	0.225	0.266	0.235
0.3	0.823	0.634	0.572	0.337	0.281	0.245	0.174	0.204	0.184
0.4	0.879	0.695	0.583	0.266	0.210	0.230	0.153	0.129	0.102
0.5	0.981	0.787	0.613	0.230	0.164	0.220	0.123	0.0766	0.0767

Table B-12. The $C_4(E_0, z)$ function for the 1×1 NaI(Tl) detector.

$E_0 =$	1.25	1.5	2	3	4	5	6	7	8
0.5	0.981	0.787	0.613	0.404	0.261	0.286	0.123	0.11	0.332
0.6	1.10	0.848	0.705	0.450	0.332	0.281	0.102	0.153	0.118
0.7	1.24	1.02	0.807	0.460	0.230	0.189	0.133	0.051	0.0664
0.75	1.40	1.26	0.889	0.204	0.0766	0.0766	0.133	0.036	0.0562
0.8	0.358	0.429	0.327	0.0613	0.0409	0.0358	0.051	0.026	0.0460
0.85	0.164	0.092	0.153	0.0204	0.0153	0.0153	0.031	0.015	0.0360
0.9	0.061	0.051	0.061	0.010	0.010	0.015	0.010	0.010	0.0301
1.0	0.010	0.010	0.010	0	0	0	0	0.005	0.020

APPENDIX C— SAMPLE RETECTOR OUTPUT

PROCESS. 8 040817
PROCESS: 040816
COBALT 56
040817 SUBTRACTED. SCALE = 1.000000

10:08:24R 06/22/78

PROCESSING DATA FROM FILE: 040816
PHS LOW CHANNEL LIMIT: 15
PHS HIGH CHANNEL LIMIT: 1024
PHS THRESHOLD ENERGY: -0.013 MEV
PHS ENOPOINT ENERGY: 4.775 MEV
ELAPSED TIME: 2000 SEC

DETECTOR TYPE NUMBER: 813
A 3X3 NaI(TL) LEAD SHIELD TUNED M.C. RESPONSE.

INPUT DATA REBINNED INTO 64 CHANNELS.
BINS ARE NON-LINEAR
THRESHOLD ENERGY: 0.053 MEV
ENDPOINT ENERGY: 4.775 MEV

1 COBALT 56

10:08:24R 06/22/78

ITERATION NO.	1	CHISO PDF=	1.696E+04
ITERATION NO.	2	CHISO PDF=	1.107E+04
ITERATION NO.	3	CHISO PDF=	7.394E+03
ITERATION NO.	4	CHISO PDF=	5.048E+03
ITERATION NO.	5	CHISO PDF=	3.523E+03
ITERATION NO.	6	CHISO PDF=	2.512E+03
ITERATION NO.	7	CHISO PDF=	1.920E+03
ITERATION NO.	8	CHISO PDF=	1.355E+03
ITERATION NO.	9	CHISO PDF=	1.023E+03
ITERATION NO.	10	CHISO PDF=	7.844E+02
ITERATION NO.	11	CHISO PDF=	6.102E+02
ITERATION NO.	12	CHISO PDF=	4.810E+02
ITERATION NO.	13	CHISO PDF=	3.835E+02
ITERATION NO.	14	CHISO PDF=	3.090E+02
ITERATION NO.	15	CHISO PDF=	2.512E+02
ITERATION NO.	16	CHISO PDF=	2.069E+02
ITERATION NO.	17	CHISO PDF=	1.701E+02
ITERATION NO.	18	CHISO PDF=	1.414E+02
ITERATION NO.	19	CHISO PDF=	1.183E+02
ITERATION NO.	20	CHISO PDF=	9.953E+01
ITERATION NO.	21	CHISO PDF=	8.417E+01
ITERATION NO.	22	CHISO PDF=	7.152E+01
ITERATION NO.	23	CHISO PDF=	6.105E+01
ITERATION NO.	24	CHISO PDF=	5.234E+01
ITERATION NO.	25	CHISO PDF=	4.505E+01
ITERATION NO.	26	CHISO PDF=	3.894E+01
ITERATION NO.	27	CHISO PDF=	3.378E+01
ITERATION NO.	28	CHISO PDF=	2.941E+01
ITERATION NO.	29	CHISO PDF=	2.569E+01
ITERATION NO.	30	CHISO PDF=	2.252E+01
ITERATION NO.	31	CHISO PDF=	1.981E+01
ITERATION NO.	32	CHISO PDF=	1.748E+01
ITERATION NO.	33	CHISO PDF=	1.548E+01
ITERATION NO.	34	CHISO PDF=	1.374E+01
ITERATION NO.	35	CHISO PDF=	1.224E+01
ITERATION NO.	36	CHISO PDF=	1.094E+01
ITERATION NO.	37	CHISO PDF=	9.766E+00
ITERATION NO.	38	CHISO PDF=	8.800E+00
ITERATION NO.	39	CHISO PDF=	7.926E+00
ITERATION NO.	40	CHISO PDF=	7.159E+00
ITERATION NO.	41	CHISO PDF=	6.482E+00
ITERATION NO.	42	CHISO PDF=	5.883E+00
ITERATION NO.	43	CHISO PDF=	5.353E+00
ITERATION NO.	44	CHISO PDF=	4.882E+00
ITERATION NO.	45	CHISO PDF=	4.453E+00
ITERATION NO.	46	CHISO PDF=	4.089E+00
ITERATION NO.	47	CHISO PDF=	3.754E+00
ITERATION NO.	48	CHISO PDF=	3.453E+00
ITERATION NO.	49	CHISO PDF=	3.183E+00
ITERATION NO.	50	CHISO PDF=	2.940E+00

TOTAL COUNTS IN REBINNED SPECTRUM: 2.5703E+06

	INPUT SPECTRUM COUNTS	CHECK SPECTRUM COUNTS	(ENERG) (MEV)	SMOOTH FINAL PHILE	ERROR BARS	INTEGRAL FLUX PH/CM2 SEC	DIFFER DOSE R/HR-MEV	INTEGRAL DOSE R/HR-	
1	3.881E+04	3.881E+04	6.747E-02	2.828E+01	1.414E+00	3.910E+01	3.507E-06	5.240E-04	1
2	4.781E+04	4.773E+04	8.428E-02	1.425E+01	7.124E-01	3.875E+01	1.937E-06	8.495E-06	2
3	9.780E+04	9.774E+04	1.030E-01	4.089E+01	2.045E+00	3.823E+01	6.564E-06	2.076E-07	3
4	1.573E+05	1.672E+05	1.235E-01	7.915E+01	3.958E+00	3.700E+01	1.525E-05	5.209E-07	4
5	4.835E+04	4.824E+04	1.559E-01	7.82PE+00	3.910E+01	3.602E+01	1.818E-06	5.616E-07	5
6	4.526E+04	4.563E+04	1.702E-01	4.447E+00	2.223E+01	3.588E+01	1.249E-06	5.919E-07	6
7	5.500E+04	5.307E+04	1.964E+01	6.468E+00	3.234E-01	3.573E+01	2.182E-06	6.490E-07	7
8	6.143E+04	6.126E+04	2.244E+01	8.294E+00	4.524E-01	3.551E+01	3.793E-06	7.590E-07	8
9	6.951E+04	6.980E+04	2.543E-01	9.422E+00	4.711E-01	3.523E+01	4.455E-06	8.952E-07	9
10	6.797E+04	6.811E+04	2.860E-01	8.663E+00	4.332E-01	3.495E+01	5.114E-06	1.034E-06	10
11	6.760E+04	6.799E+04	3.196E-01	7.948E+00	3.974E-01	3.467E+01	4.899E-06	1.199E-06	11
12	6.266E+04	6.322E+04	3.551E-01	6.196E+00	3.098E-01	3.442E+01	4.305E-06	1.352E-06	12
13	6.148E+04	6.181E+04	3.925E-01	6.344E+00	3.172E-01	3.418E+01	4.946E-06	1.692E-06	13
14	6.139E+04	6.345E+04	4.317E-01	8.276E+00	4.139E-01	3.389E+01	7.236E-06	1.820E-06	14
15	6.839E+04	6.839E+04	4.728E-01	1.070E+01	5.352E-01	3.350E+01	1.051E-05	2.252E-06	15
16	1.812E+05	1.811E+05	5.153E+01	6.124E+01	3.082E+00	3.196E+01	6.765E-05	5.159E-06	16
17	1.595E+05	1.594E+05	5.686E+01	4.132E+01	2.066E+00	2.986E+01	5.114E-05	7.467E-06	17
18	7.016E+04	7.077E+04	6.073E-01	8.116E+00	4.058E+01	2.851E+01	1.164E-05	8.010E-06	18
19	6.116E+04	6.205E+04	6.559E-01	6.232E+00	3.141E-01	2.816E+01	9.286E-06	8.461E-06	19
20	4.639E+04	4.713E+04	7.063E-01	4.706E+00	2.353E-01	2.788E+01	7.178E-06	8.823E-06	20
21	4.361E+04	4.378E+04	7.586E-01	6.579E+00	3.290E-01	2.750E+01	1.036E-05	3.366E-06	21
22	6.216E+04	6.216E+04	8.128E-01	1.595E+01	7.677E-01	2.697E+01	2.598E-05	1.077E-05	22
23	2.745E+05	2.785E+05	8.688E-01	3.116E+02	6.578E+00	2.284E+01	2.217E-04	2.320E-05	23
24	1.024E+05	1.024E+05	9.268E-01	4.057E+01	2.328E+01	1.786E+01	7.079E-05	2.730E-05	24
25	2.893E+04	3.330E+04	9.865E-01	5.546E+00	2.773E-01	1.694E+01	1.003E-05	2.790E-05	25
26	5.113E+04	5.117E+04	1.048E+00	1.686E+01	6.329E-01	1.579E+01	3.124E-05	2.982E-05	26
27	3.208E+04	3.204E+04	1.112E+00	9.271E+00	4.636E-01	1.497E+01	1.809E-05	3.037E-05	27
28	1.893E+04	1.822E+04	1.177E+00	3.033E+00	1.818E-01	1.454E+01	7.747E-06	3.147E-05	28
29	2.008E+05	1.009E+05	1.244E+00	5.410E+01	2.705E+00	1.259E+01	1.136E+01	3.911E-05	29
30	8.451E+04	8.450E+04	1.313E+00	4.658E+01	2.323E+00	9.115E+00	1.017E-04	4.614E-05	30
31	9.925E+04	1.923E+04	1.384E+00	6.004E+00	3.002E-01	7.249E+00	1.353E-05	4.711E-05	31
32	1.430E+04	1.439E+04	1.457E+00	2.420E+00	1.210E-01	6.942E+00	5.711E-06	4.752E-05	32
33	1.279E+04	1.319E+04	1.532E+00	1.105E+00	6.923E-02	6.807E+00	2.908E-06	4.774E-05	33
34	1.162E+04	1.127E+04	1.609E+00	3.349E-01	4.517E-02	6.730E+00	2.723E-06	5.790E-05	34
35	9.533E+03	9.765E+03	1.687E+00	7.915E-01	3.955E-02	6.656E+00	2.101E-06	4.807E-05	35
36	2.145E+04	2.140E+04	1.767E+00	9.085E+00	4.590E-01	6.270E+00	2.535E-05	5.011E-05	36
37	2.240E+04	2.234E+04	1.850E+00	1.117E+01	5.588E-01	5.437E+00	3.213E-05	5.275E-05	37
38	6.932E+03	6.781E+03	1.934E+00	1.073E+00	4.489E-02	4.962E+00	2.676E-06	5.237E-05	38
39	1.399E+04	1.333E+04	2.020E+00	5.219E+00	2.626E-01	4.652E+00	1.629E-05	5.377E-05	39
40	1.642E+04	1.839E+04	2.107E+00	7.507E+00	3.610E-01	4.093E+00	2.446E-05	5.652E-05	40
41	1.042E+04	1.084E+04	2.197E+00	1.046E+00	4.744E-02	3.710E+00	3.157E-06	5.680E-05	41
42	9.232E+03	9.580E+03	2.289E+00	7.889E+00	3.943E-02	3.626E+00	2.721E-05	5.705E-05	42
43	7.024E+03	7.186E+03	2.382E+00	5.389E-01	2.689E-02	3.964E+00	1.916E-06	5.732E-05	43
44	4.839E+04	4.899E+03	2.477E+00	4.157E-01	1.649E-02	3.518E+00	1.214E-06	5.734E-05	44
45	1.134E+04	1.130E+04	2.574E+00	5.889E+00	2.959E-01	3.212E+00	2.249E-05	5.953E-05	45
46	1.745E+04	1.743E+04	2.673E+00	1.024E+01	5.240E-01	2.414E+00	4.102E-05	6.359E-05	46
47	7.662E+03	7.885E+03	2.774E+00	1.003E+00	4.095E-02	1.847E+00	3.289E-06	6.382E-05	47
48	5.184E+03	5.552E+03	2.877E+00	4.190E-01	3.072E-02	1.774E+00	1.691E-06	6.405E-05	48
49	4.345E+03	4.542E+03	2.982E+00	5.199E-01	2.589E-02	1.725E+00	2.198E-06	6.432E-05	49
50	2.855E+03	2.877E+03	3.088E+00	8.017E-01	3.766E-02	1.655E+00	3.276E-06	6.467E-05	50
51	4.457E+03	4.457E+03	3.196E+00	3.543E+00	1.753E-01	1.419E+00	1.560E-05	6.636E-05	51
52	8.829E+03	8.829E+03	3.307E+00	8.167E+00	4.215E-01	7.740E+00	5.832E-05	7.089E-05	52
53	1.717E+03	1.717E+03	3.495E+00	1.822E-01	6.373E-02	2.142E-01	7.770E-06	7.146E-05	53
54	7.202E+02	7.200E+02	3.533E+00	7.390E-01	3.639E-02	6.822E-02	3.442E-06	7.165E-05	54
55	1.595E+02	1.583E+02	3.649E+00	1.618E-01	1.190E-02	1.605E-02	7.218E-07	7.193E-05	55
56	1.068E+01	1.631E+01	3.737E+00	4.250E+03	1.137E-05	6.288E-03	1.057E-10	7.193E-05	56
57	2.236E+01	2.226E+01	3.886E+00	3.446E+03	7.639E-03	5.827E-03	1.787E-08	7.194E-05	57
58	1.743E+01	1.830E+01	4.007E+00	2.062E-03	4.915E-04	5.433E-03	1.038E-09	7.194E-05	58
59	2.054E+01	2.474E+01	4.311E+00	6.653E-04	1.606E-04	5.313E-03	3.742E-09	7.194E-05	59
60	1.500E+01	1.509E+01	4.256E+00	4.314E-03	1.101E-03	4.988E-03	2.224E-08	7.194E-05	60
61	1.600E+01	1.600E+01	4.383E+00	6.745E-03	2.466E-03	4.095E-03	5.296E-08	7.195E-05	61
62	9.222E+00	9.222E+00	4.512E+00	9.432E-03	2.656E-03	2.944E-03	4.336E-08	7.195E-05	62
63	1.778E+01	1.778E+01	4.642E+00	1.721E-02	4.287E-03	1.249E-03	9.966E-09	7.197E-05	63
64	1.000E+00	1.000E+00	4.775E+00	1.607E-03	1.048E-03	3.441E-13	5.808E-09	7.197E-05	64

15 GROUP THEORY

GP NO	ENERGY (MEV)	PHI(L) PHO/SQCM-SEC
1	0.0000	0.
2	1.8960	0.
3	7.0700	0.
4	4.9280	0.
5	4.5940	3.505E-03
6	3.6840	1.650E+00
7	3.01710	1.820E+00
8	2.47090	8.75E-01
9	2.02360	2.239E+00
10	1.65720	5.304E-01
11	1.35720	7.372E+00
12	1.11150	2.613E+00
13	0.91030	1.000E+01
14	0.74550	7.802E-01
15	0.61050	3.218E+00

35 GROUP THEORY

GP NO	ENERGY (MEV)	PHI(L) PHO/SQCM-SEC
1	0.0000	0.
2	0.82320	0.
3	7.78490	0.
4	6.86880	0.
5	6.06040	0.
6	5.34720	0.
7	4.71800	5.147E-03
8	4.16280	9.056E-04
9	3.78290	8.442E-01
10	3.24070	8.944E-01
11	2.65930	1.460E+00
12	2.52280	4.007E-01
13	2.22590	1.069E+00
14	1.98400	1.472E+00
15	1.73290	5.503E-01
16	1.52890	4.739E-01
17	1.34900	6.355E+00
18	1.19030	1.536E+00
19	1.05020	1.383E+00
20	0.92660	9.084E+00
21	0.81760	1.741E+00
22	0.72130	4.577E-01
23	0.63650	5.544E-01
24	0.56160	3.103E+00
25	0.49650	1.770E+00
26	0.43720	4.265E-01
27	0.38570	2.858E-01
28	0.34030	2.817E-01
29	0.30030	2.965E-01
30	0.26490	2.849E-01
31	0.23380	2.580E-01
32	0.20630	1.848E-01
33	0.18200	1.190E-01
34	0.16060	9.828E-02
35	0.14170	1.306E-01

TOTAL 3.11E+01

3.552E+01

PROCESS: END

FIN 10:09:02R 06/22/78

Fig. C-1. Linear plot of the input pulse height spectrum.

Fig. C-2. Log plot of the input pulse height spectrum.

Fig. C-3. Final estimate of $\phi(E)$ unsmoothed.

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Fig. C-4. Input pulse height spectrum (x) and the final $\phi(E)$ ref. (lines) with residuals indicated in the lower graph.

Fig. C-5. Final estimated $\phi(E)$ after smoothing with a variable width Gaussian filter.

Fig. C-6. Differential dose, $D(E)$ inferred from final $\phi(E)$.

Fig. C-7. Final $\phi(E)$ regrouped to conform to 15 standard groups.

Fig. C-8. Final $\phi(E)$ regrouped to conform to 35 standard groups.

APPENDIX D—

GAM100

The GAM100 computer code is a stand-alone subset of the RETECTUR code that calculates a parameterized NaI (Tl) detector response matrix for gamma rays at given source and deposition energies (up to 20 MeV) for various detector sizes. The code accounts for escape peaks, iodine x-ray escape, multiple scattering, and bremsstrahlung.

Input to the code consists of gamma-source and deposition energies (energies that fall below the source energies); the code will calculate the detector response at these energies in counts/MeV. Output consists of an echo of the gamma source energies and the deposition energy column, the calculated response matrix at the given deposition energies, and the total calculated response (200 internally calculated response points for each source energy). Also, plots of the response columns can be obtained.

Availability

GAM100 is written in Fortran IV (extended) for use on the CDC-7600s of the LLL Octopus timesharing system. The GAM100 code and Fortran source listing are available online by typing

ELF RDS .868441:CODES:GAMMA:GAM100

GAM100 is a library file that contains the executable program, binary file, LOD map, Fortran source listing, and detector-parameter library.

Modes of Operation

Three modes of operation exist in GAM100—the normal mode, the table mode, and the debug mode. Each mode requires the detector number, an ID line, the list of gamma source energies, and the deposition energy matrix as input.

Normal Mode

The normal mode of operation for GAM100 consists of setting the "imode" flag to "zero" (as defined in the next section). When running the code in this mode only the response file and the FR80 plot file are created. The response file contains the calculated response matrix at the input deposition energies. The FR80 plot file contains the plots of the calculated response at each of the gamma source energies.

Table Mode

This mode is selected by setting the 'imode' flag to "1" on the execution line. The table mode gives everything that the normal mode gives, as well as creating another output file, the table file. This file contains the total internally calculated response for each gamma source energy. Also, plots of the total internally calculated response are added to the FR80 plot file.

Debug Mode

The debug mode is selected by setting the 'imode' flag to "2" on the execution line. This mode outputs the response file, the FR80 plot file, the table file, and the debug file. The debug file repeats a list of selected variables from the program, giving their current values. This is useful to the programmer when the code is not operating correctly. The debug mode adds the plots of the unsmoothed total internally calculated response for each gamma source energy to the plot file. This mode is to be used only as a programmer's aid and is not recommended for use with matrices larger than 10×10 .

Operating Instructions

To execute the code, type

```
0
GAM100 1 / t v
2
OMIT.
```

where

- 0 sets the normal mode of operation.
- 1 sets the table mode of operation.
- 2 sets the dbug mode of operation.
- OMIT. defaults to the normal mode.

The code will then go into an interactive mode by the following method.

Type Input Filename, Box Number, and ID—

Type the name of the input file that contains the energy matrix for which the response matrix is to be calculated, or type the work "DUMMY," which signals the code to calculate a square energy matrix from minimum and maximum energies to be input later. Also type in your box number and a word of identification. If the box number is not input, the code will ask for it.

Smoothing Off?—

If the desired response matrix is to be calculated without taking the resolution of the detector into account, type "YES". Otherwise, type "NO" or a (Carriage-Return), and the smoothing will take place.

Type in Array Dimensions: EO, E—

Type in the size of the energy matrix space delimited. First type the number of source energies EO and then the number of deposition energies within each source energy. The values of EO and E cannot be larger than 100×100 .

At this point, if the word "DUMMY" was typed as the input file name, the code will prompt the user for the following information:

Give EMIN, EMAX, IDET: Type in the lower source energy EMIN, the upper source energy EMAX, and the detector number IDET, and the code will calculate a square energy and response matrix. See the detector library for a list of detectors and their numbers.

Give ID Line (70MAX): Up to 70 characters of identification can appear on the output and plots. Type them in at this time.

Input Format

The input file contains a list of gamma source energies, a matrix of deposition energies that fall within the individual source energies (not larger than 100×100), a detector number, and a line of identification (Table D-1).

The input file may be named anything except "END" or "DUMMY," these words are reserved. (For an example of the input file see the SAMPLE RUN section.)

Table D-1. GAM100 input format descriptions.

Card	Columns	Format	Variable	Description
1	1-5	I5	IDET	Detector number for which the response is to be calculated.
1	6-76	7A10	IGEN	Identification to appear on the output.
(2)	2-80	10E8.0	ENERGY	List of gamma source energies.
(3)	2-80	10E8.0	EMATRIX	List of deposition energies, starting with those for source energy ENERGY (Ref. 5).

* The parenthesis signifies that the card number represents groups of cards.

Output Description

Response File

The response file will be left on disk in the user's private file index under the name `RESP/xmmss`, where the `x` is the machine letter of the computer that the program was running on, and the `mm` and `ss` are the minutes and seconds of the time of day that the program was started. Upon completion, the program will notify the user of this name.

The response file contains an echo of the detector number and the ID line, the source-energy column, and the energy-deposition matrix. This is followed by the corresponding calculated response matrix.

The response file will take the form:

```
Det. #, ID
Energy column
Energy matrix
Response matrix
```

The contents of all sections of the output are marked. (For an example of the response file, see the SAMPLE RUN section.)

Table File

The table file will be left on disk in the user's private file index under the name `TABL/xmmss`; `xmmss` has been defined for the response file. Upon completion, the program will notify the user of this name.

The table file is only created when the `itab` flag is set on the execution line. This file contains the tabulated total calculated response for each gamma source energy, i.e. the complete internally calculated response and corresponding deposition energies.

The table file takes the form:

```
Response for source energy (1)
Response for source energy (2)
.
.
.
Response for source energy (n)
```

(For an example of the table file, see the SAMPLE RUN section.)

Plot File

The plot file is an FR80 file, and will be left in the user's private file index under the name `FX035GAM-A`. If a file already exists by this name the last character in the new filename will be incremented by one ASCII character.

The plot file contains plots of the calculated response at the given source and deposition energies. It will also contain plots of the smoothed total response for each source energy if the `itab` flag was set on the execution line. If the `idbug` flag was set on the execution line. If the `idbug` flag was also set on the execution line, then the plot file will also contain plots of the unsmoothed total response for each source energy. All plots are titled as to their contents.

An example of the file can be obtained online as follows:

```
ELF RDS .868441:CODES:GAMMA:FX035GAM-P
```

Dbug File

The dbug file will be left on disk in the user's private file index under the name `DEBUGTABLE`. If during a run that outputs a dbug file, the dbug file is filled, then a new file will be created, called `DEBUGTABLEF`, and output will continue into this file. If the new file is filled the same process will take place.

The dbug file contains a list of selected variables, from the program and their current values. This is only intended to help the programmer, who is familiar with the variable names, find errors that may exist in the program. This file should not concern the average user.

Execution Timing

Actual computer times* used for jobs consisting of the options listed below vary some depending on the resolution of the detector chosen and the options chosen. (See Table D-2).

Error Messages

Not Found, Detector # xxx

The code was instructed to use detector number "xxx," but no entry in the detector library exists for that detector number. The code will ask for a new detector number and then continue.

*****CAN'T OPEN: filename

The input file name given to the code does not exist or has been mistyped. The code will ask for a new input file name and then continue.

*****Not A Square Matrix.*****Try Again.

The code was instructed to calculate a square energy matrix. However, it has been given a nonsquare size. The code will ask for a new size and then continue.

Can't Get **PARAMADATA*

The detector library is either not on disk and not in the GAM100 library, or the computer is limited for space and cannot extract "PARAMADATA" from the GAM100 library at that time. The code will then terminate and should be retired.

*****Cannot Create Dropfile.*****Retry.

The code could not create it's dropfile. Either it tried to create it under a name that already existed on disk or there is not enough space on the computer to create the dropfile.

Sample Run

This section gives an example of the TTY interaction, the input file and the output file, for a sample run of GAM100. The FR80 plot file is not included here, however, the plot file, input file, and output file used here, are obtainable online as

```
ELF RDS .868441:CODES:GAMMA:FX035GAM-P
ELF RDS .868441:CODES:GAMMA:GAM/INP
ELF RDS .868441:CODES:GAMMA:GAM/OUT
```

Table D-2. Computer execution times for various options and matrices.

Options	10 × 10 Matrix	50 × 50 Matrix	100 × 100 Matrix
Table mode — OFF			
Debug mode — OFF	2.16 s	4.38 s	8.09 s
Smoothing — OFF			
Table mode — ON			
Debug mode — ON	13.72 s	60.52 s	Not timed
Smoothing — ON			
Resolution — 0.05			

*A CDC-7600 was used for timing.

TTY Interaction

Both of the following TTY interactions produced the same output. The difference is that the second example has the code calculate the square energy matrix that is being used in the first example.

```
GAM100 / 1 1
TYPE INPUT FILENAME, BOX #, AND ID
CAM/INP BOX T90 STROUT
SMOOTHING OFF ? (CR)
TYPE IN ARRAY DIMENSIONS : EO.E
10 10
OUTPUT FILENAME IS RESP/R5524
```

ALL DONE

* * * * *

```
GAM100 / 1 1
TYPE INPUT FILENAME, BOX #, AND ID
DUMMY BOX T90 STROUT
SMOOTHING OFF ? (CR)
TYPE IN ARRAY DIMENSIONS : EO.E
10 10
GIVE EMIN EMAX IDENT
1.0 10.0 813
GIVE ID LINE (70MAX)
THIS IS A SAMPLE RUN FOR -GAM100-.
OUTPUT FILENAME IS RESP/R4619
```

ALL DONE

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