A HYBRID COMPUTER FILTER FOR UNFOLDING GAMMA-RAY SPECTRA

A Thesis

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ABSTRACT

Interpretation of raw gamma spectra from NaI(Tl) scintillation systems is difficult because of complications introduced by a multiplicity of gamma interactions and light-emission processes within the detector. The application of computers to interpretation permits sophisticated spectral analysis through spectrum stripping or unfolding techniques. Although digital systems have been utilized previously, an analog-digital hybrid system offers the possibility of avoiding laborious and time-consuming parameter selection required for the purely digital approach. The hybrid system was applied to the Hyodo response function procedure by using the analog computer for empirical selection of fifth-order polynomial coefficients for seven required fitting functions; once fitted, the polynomials are employed by the digital system for actual spectrum unfolding. Two calibration spectra were employed for coefficient selection; the procedure was then applied to several "catalog" spectra to illustrate its generality. Unfolded spectra show the expected residual full-energy peaks, with only small Bremsstrahlung, non-rectangular Compton components, and adjacent-peak overlap components as interferences. It is possible that the general approach could be accomplished with a purely digital system by applying analog simulation language.

INTRODUCTION

Pulse-height distributions obtained from gamma radiation interactions in scintillation spectrometers are complicated representations of monoenergetic, line width, gamma rays (1). Thallium-activated sodium-iodide scintillators have the advantage of high interaction efficiencies in the range of 0 to 5 Mev (approximately 30% at 1 Mev); however, they suffer from spectrum distortion because of limited energy resolution (approximately 7% full-width-half-maximum at 1 Mev). The spectra are further complicated by the statistical nature of the counts in each channel as recorded by a multichannel analyzer.

The several complications, Compton areas, escape peaks, etc., of scintillation gamma-ray spectrometry make the interpretation of complex gamma spectra difficult. Analysis of such spectra has been approached through several computer techniques (2) known as "unfolding", which is an operational process on the measured pulse height distribution to obtain a better approximation of the incident gamma-ray spectrum. Of the various unfolding procedures, a number of them involve analytical and matrix inversion techniques for describing a monoenergetic gamma-ray spectrum with subsequent identification of the troublesome interactions generated within the spectrometer.

The approach presented in this thesis utilizes the digital computer less like a traditional numerical computational device and more like a "digital filter" (3). An analog computer generates the response parametric functions associated with the spectrometer and communicates this information to the filter. These parametric functions can be readily tuned up for any given experimental set-up with a minimal effort of potentiometer adjustments. Unfolding is performed in the order of milliseconds, and output is in graphical or numerical form, or displayed via digital-to-analog oscilloscope.

CHAPTER 1 MODEL (4)

Triangular Matrix

The pulse-height distribution of a scintillation spectrometer is related to the incident gamma-ray spectrum by the equation:

$$\int_{0}^{\infty} A_i(E')P(E')dE' = b_i + e_i, \qquad i = 1,2,....,n, \qquad (1)$$

in which:

b_i = the observed number of counts recorded in the i^{th} channel of a multichannel analyzer, (the channel responds to pulses from V_i to V_{i+1} in height);

e_i = the random statistical counting error;

$A_i(E')$ = the response function of the spectrometer (the probability that a monoenergetic photon source with energy E' and unit intensity will result in a count in the i^{th} channel); and,

$P(E')dE'$ = the number of photons in the incident spectrum between an energy of E' and $E' + dE'$.

Pulse height distributions are, in truth, a representation of the interactions of the incident gamma flux with the detector. These distributions include distortion and degradation of the true gamma spectrum resulting from Compton scattering, escape peaks, smearing, etc., in the detector itself, and by signal-handling characteristics of the subsequent electronic system.

It is difficult to unfold the response of a spectrometer exactly without introducing spurious features in the desired resulting spectrum. The major problem of the gamma scintillation spectrometer is not one of instrumental smearing, but rather derives from the fact that the monoenergetic response $A_i(E')$ has spurious peaks resulting from escape processes (pair-production annihilation photons, iodine X-rays, etc.), and a low-energy tail arising from internal and external Compton scattered photons. One approach is to accept the finite instrumental line width (produced by statistical broadening in the crystal and photomultiplier), and then try to remove the tails and spurious escape peaks from the result. The final estimated spectrum obtained will be denoted by $\bar{P}(E)$; this estimated spectrum is related to the true spectrum $P(E')$ by:

$$\bar{P}(E) = \int_0^\infty S(E,E')P(E')dE', \qquad (2)$$

in which $S(E,E')$ is the inherent smearing function. In other words, $\bar{P}(E)$ is the spectrum with some Gaussian smearing, and $P(E')$ is the true unbroadened spectrum.

The principal problem in obtaining the desired solution, in a discrete formulation, is finding a set of coefficients U_{ik}, $k = 1,2,\ldots n$, for each of the n response functions $A_i(E')$ such that

$$A_i(E') = \sum_{k=1}^{n} U_{ik}S(E_k,E'). \qquad (3)$$

A significant simplification can be achieved without obtaining numerical values for $A_i(E')$, if one accepts the restriction that a linear relation holds for E_k, $k = 1,2,\ldots,n$, to be the energies at which the main peaks of $A_i(E')$ vs E' are centered in channel k. A two dimensional sketch of $A_i(E')$ is given in Figure 1. Note that slices through this response surface parallel to the discrete channel number axis, $A_i(E')$ vs i, are the conventional pulse-height distributions for monoenergetic sources, but that slices through the response surface parallel to the energy axis, $A_i(E')$ vs E' for fixed i, are "efficiency functions" which give the efficiency of a single channel of a gamma photon.

In order to obtain a relation between the observed pulse height distribution, b_i, and the estimated spectrum, $\bar{P}(E)$, a finite set of simultaneous algebraic equations may be derived by substituting Eq. (3) into Eq. (1);

$$\int_0^\infty \left[\sum_{k=1}^{n} U_{ik} S(E_k,E')\right] P(E')dE' = b_i + e_i. \qquad (4)$$

By interchanging the order of integration and summation, the following results:

$$\sum_{k=1}^{n} U_{ik} \left[\int_0^\infty S(E_k,E')P(E')dE'\right] = b_i + e_i , \qquad (5)$$

and making use of the definition of $\bar{P}(E)$ given by Eq. (2), the final form is obtained:

$$\sum_{k=1}^{n} U_{ik}\bar{P}(E_k) = b_i + e_i, \quad i = 1,2,\ldots,n. \qquad (6)$$

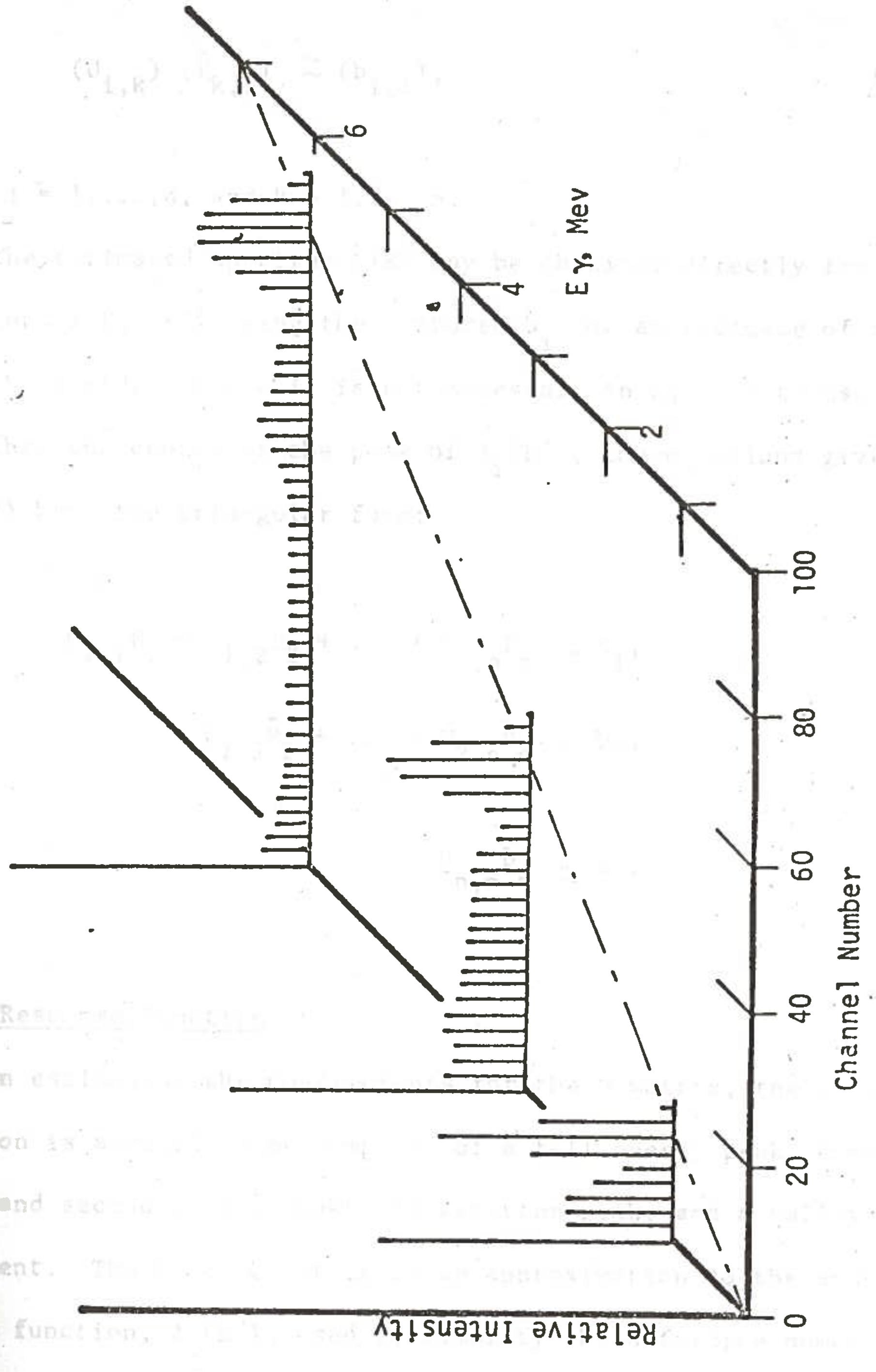

Figure 1

Response Function Surface

Finally, expressing Eq. (6) in matrix form and neglecting e_i:

$$(U_{i,k})\,(\bar{P}_{k,1}) \approx (b_{i,1}), \tag{7}$$

where i = 1,...,n, and k = 1,...,n.

The estimated spectrum $\bar{P}(E)$ may be obtained directly from a solution of Eq. (7) using the measured b_i for an estimate of the right hand side. Since it is not necessary in Eq. (7) to use any E_k less than the center of the peak of $A_i(E')$, the equations given by Eq. (7) have the triangular form;

$$\begin{aligned}
U_{1,1}\bar{P}_1 + U_{1,2}\bar{P}_2 + \ldots + U_{1,n}\bar{P}_n &\approx b_1, \\
U_{2,2}\bar{P}_2 + \ldots + U_{2,n}\bar{P}_n &\approx b_2, \\
&\vdots \\
U_{n,n}\bar{P}_n &\approx b_n.
\end{aligned}$$

Hyodo Response Function

In estimating the coefficients for the U matrix, the response function is assumed to be composed of a full energy peak, Compton, first and second escape peaks, backscatter peak, and a valley fill component. The Hyodo U matrix is an approximation to the actual response function, $A_i(E')$, used to simplify the unfolding numerically. This model replaces the total energy peaks by isolated components on the diagonal of the matrix. This procedure can also be extended to other peaks in the response function. For instance, the broad escape peaks are replaced by a sharp ridge of components in the U coefficient matrix. A more complete analysis shows that the backscatter peak must be replaced by several components because its position does not vary much with the energy of the incident photons, as can be seen from the Compton equation for 180° backscatter:

$$E_s = \frac{0.51\ E_i}{0.51 + 2E_i},$$

in which E_s is the scattered photon energy and E_i is the incident photon energy. The continuum can be approximated by flat rectangular sections extending up to the pulse height of the Compton edge for the Compton area, and one small rectangle below the total energy peak for a valley fill function. The location of the escape peaks, the backscatter peak and the Compton edge are treated as being functionally related to the photopeak location. These approximations are represented schematically in Figure 2.

The resulting U matrix is composed of five components: (1) Compton fraction, (2) backscatter fraction, (3) first escape fraction, (4) second escape fraction, and (5) valley-fill fraction as follows:

$$\begin{array}{llll} U_{1,1} & U_{1,2} & \cdots\cdots & U_{1,n} \\ & U_{2,2} & \cdots\cdots & U_{2,n} \\ & & & \vdots \\ & & & U_{n,n}. \end{array}$$

where each column is composed of a combination of the components (above) depending upon the position of $U_{diagonal}$. The diagonal is

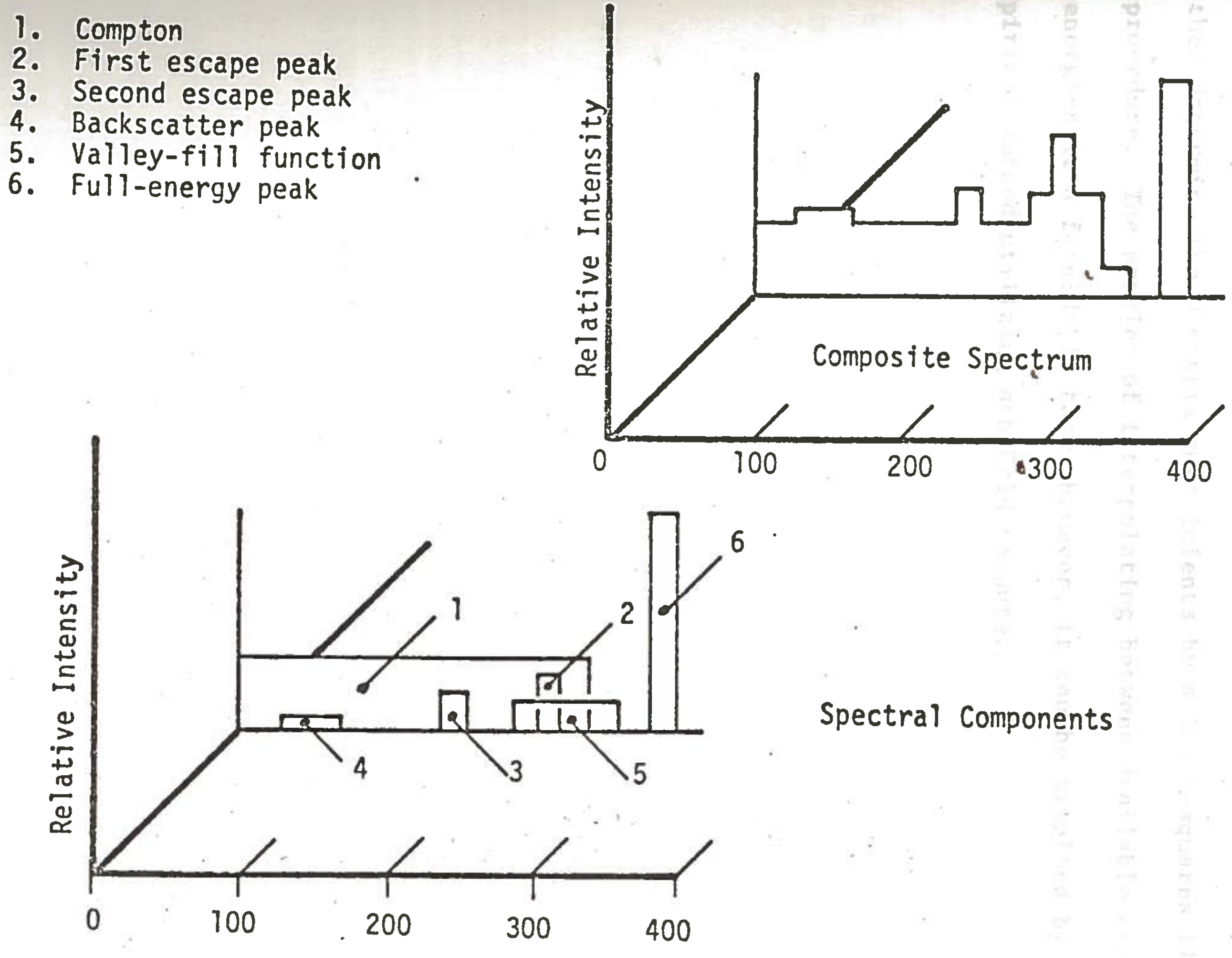

Figure 2
Hyodo Response Model

represented by the peak-to-total ratio.

If many monoenergetic calibration sources are available, one may interpolate by suitable functions between the calibration sources and then determine the U matrix coefficients by a least-squares fitting procedure. The problem of interpolating between available calibration energies is a formidable task, however, it can be simplied by an empirical method utilizing a hybrid computer.

CHAPTER 2 COMPUTER PROGRAM

A computer program was developed to (1) empirically determine the U matrix coefficients from calibration spectra obtained with a particular spectrometer; (2) unfold pulse-height distributions once the filter is calibrated; (3) output the unfolded spectra via digital plot, numerically, and/or digital-to-analog oscilloscope; and (4) provide overall control between the analog and digital computers. The program (listing in Appendix) consists of a main program plus the following subprograms:

A) Plot - provides digital plot routine, Fortran IV;
B) Scope - provides oscilloscope display of an array stored in the digital computer, Fortran IV and Assembly language;
C) Hybrid- digitizes analog function and stores as an array, Fortran and Assembly language.

Several library (hybrid) routines were utilized for operational control.

Generating U Matrix Coefficients

To calibrate the filter to unfold 4 Mev maximum distributions, sample spectra from the spectrometer (Cs-137,Na-24) are read in and stored in the digital computer One of the sample spectra is then selected for initial trial. If one considers the hybrid filter as a black box with variable "knobs", the philosophy of design is to provide a tuning adjustment for each objectionable feature of the pulse-height distribution which is to be "tuned out". The analog computer is patched (wired) to generate a fifth order polynomial with variable coefficients. Control is shifted to the analog computer and the polynomial is displayed. The five coefficients simulated by potentiometers on the analog computer, can be varied while the resulting Compton function is displayed, and an empirical trial array is digitized and stored in the digital computer. Another five coefficients are obtained for the backscatter function, etc. After all the arrays (Compton, backscatter, first and second escape, valley-fill) are produced, control is transferred to the digital computer for unfolding. The resulting spectrum is filtered by the digitized empirical polynomial function, and displayed on the oscilloscope. Imperfections are then corrected by adjustments of the polynomial coefficients, and the filtering process repeated. After several trials, a nearly perfect filtered spectrum can be displayed. A second calibration spectrum is then selected, and the coefficients for the polynomial are further refined to obtain the spectral components relationship as a function of energy. The ultimate set of coefficients is thus generated by successive trials on several calibration spectra.

Unfolding

Once the response function parameters, in the form of a 5th order polynomial coefficients, are obtained and stored, general unfolding can be initiated for any distribution obtained from the same spectrometer from which the calibration spectra were obtained. Unfolding is accomplished entirely within the digital computer.

After a pulse-height distribution has been read in and stored, and following matrix equation exists:

$$\begin{bmatrix} U_{1,1} & U_{1,2} \cdots & U_{1,n-1} & U_{1,n} \\ & U_{2,2} \cdots & & U_{2,n} \\ & & & \vdots \\ & & U_{n-1,n-1} & U_{n-1,n} \\ & & & U_{n,n} \end{bmatrix} \begin{bmatrix} \bar{P}_1 \\ \bar{P}_2 \\ \vdots \\ \bar{P}_{n-1} \\ \bar{P}_n \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{n-1} \\ b_n. \end{bmatrix}$$

By solving first for $\bar{P}_n$, and then working backwards toward $\bar{P}_1$, the triangular matrix can be reduced to the solution. The results of the unfolding procedure will then be related to the true incident gamma spectrum by Eq. (2). Thus the effect of the Hyodo model is to produce a smeared approximation to the desired spectrum, with the degree of smearing given essentially by the resolution of the detector.

CHAPTER 3 RESULTS

Response Function

Of the nine required functions, the first two (peak-to-total and intrinsic efficiency) were simulated from data obtained from Heath (1) for a 3" x 3" scintillation crystal. The remaining seven functions (Compton, first escape, second escape, backscatter, and three valley-fill functions) were generated as fifth-order polynomials by an empirical selection of potentiometer settings for the five necessary coefficients. Cesium-137 and Na-24 spectra were employed for progressive trial and error refinements of the necessary potentiometer settings. These spectra were chosen because they provide a wide energy range and relatively uncomplicated distributions.

The general shapes of the seven empirically fitted polynomials are presented in Figures 3 and 4. The functional coefficients (potentiometer settings) can be selected within 30 minutes utilizing a hybrid computer.

Unfiltered and filtered (Cs-137 and Na-24) spectra are illustrated in Figures 5 and 6, respectively, to present a measure of "goodness" for the technique. As apparent from the figures, the unfolded spectra fulfill the objectives of removal of the complicating features, except for Bremsstrahlung in the Na-24 distribution. The criteria for setting an individual channel to zero was plus or minus the reciprocal of the plotting scale height (e.g., = 0.01 for a scale height of 100) times the maximum count.

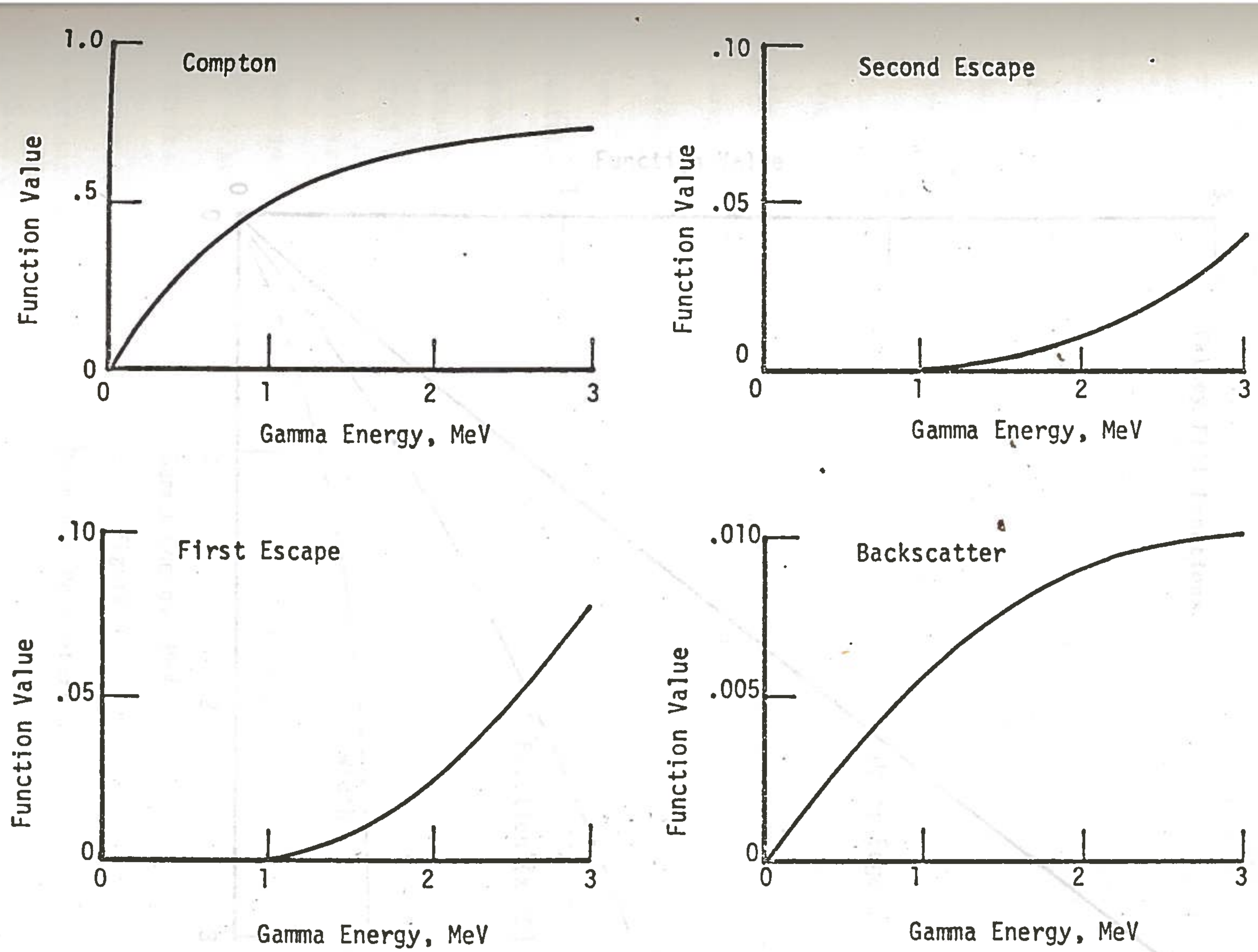

Figure 3
Response Parameters

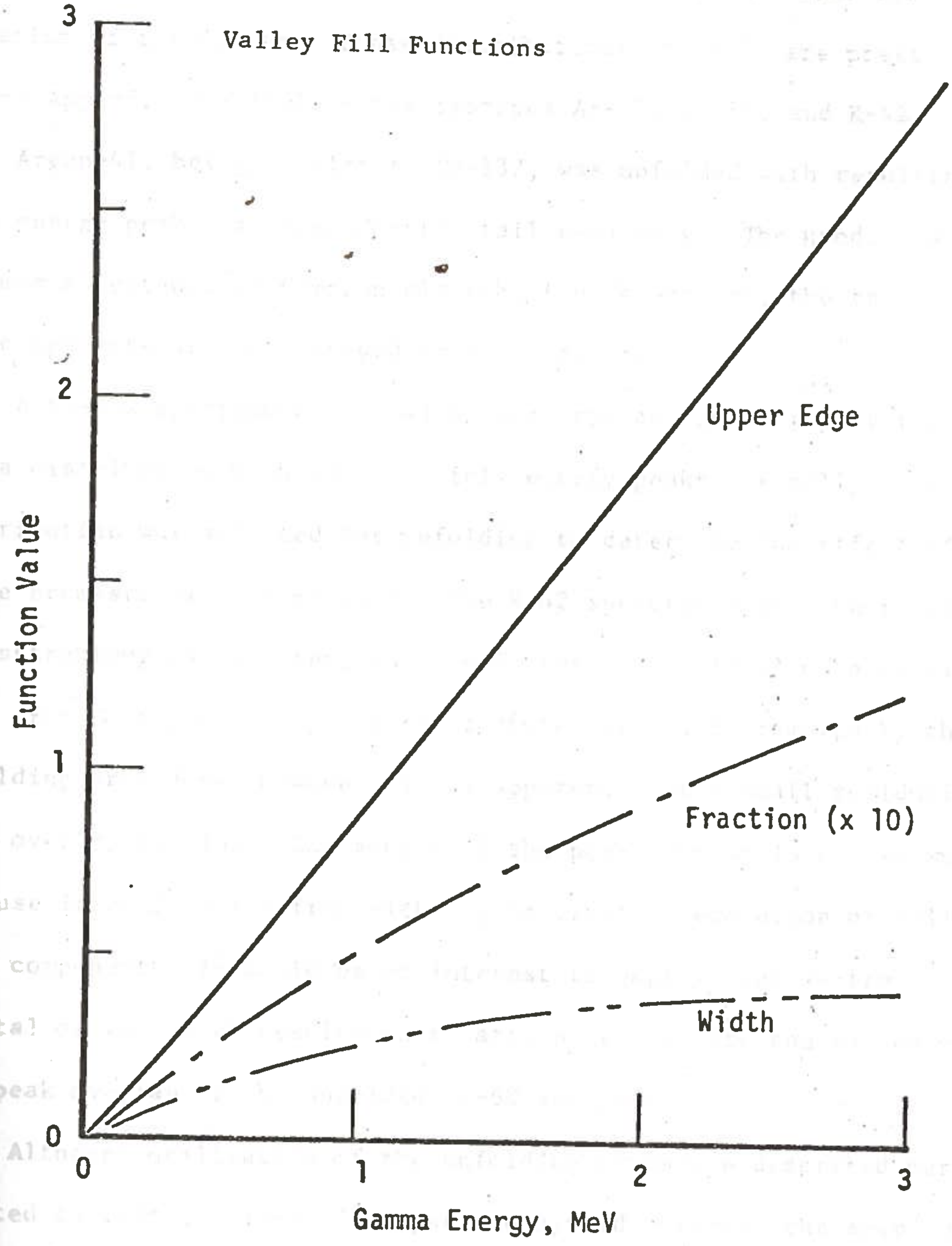

Figure 4

Response Parameters

Filter

Additional spectra from Heath (1) were unfolded to test the operation of the filter. These distributions (folded) are presented in the Appendix and include the isotopes Ar-41, Co-60, and K-42.

Argon-41, being similar to Cs-137, was unfolded with resulting full energy peak and upper Compton tail remaining. The Hyodo model assumes a rectangular Compton distribution; therefore, the true Compton components are not removed from the spectrum.

A Co-60 spectrum was tried to test the applicability of filtering a distribution with adjacent full energy peaks. Finally, a K-42 distribution was selected for unfolding to determine the effect of a large Bremsstrahlung component. The K-42 spectrum shows the residual Bremsstrahlung as expected, and demonstrates the effect of a continuum. For Co-60, the complicating features were well removed by the unfolding procedure; however, it is apparent that a small residual peak overlap remains. The source of the peak overlap is not known because it could arise from either poor crystal resolution or valley fill component. It would be of interest to employ spectra from a crystal of very high resolution to attempt to isolate the source of the peak overlap of the unfolded Co-60 spectrum.

Although utilization of the unfolding procedure described here is limited to installations of comparable hybrid systems, the speed with which the response functions can be fitted makes this operation attractive. It is possible that the procedure could be applied to purely digital systems by introduction of an analog simulation language.

Figure 5

Unfolded Cs-137 Spectrum
Pages 19 and 20

```
CHAN SPECT                         CS-137
           0..................................................
  1     0. 0
  2  1483. .
  3 25821. .                       x
  4 39892. .                                    *
  5  1746. .
  6     0. 0
  7     0. 0
  8     0. 0
  9     0. 0
 10     0. 0
 11     0. 0
 12     0. 0
 13     0. 0
 14     0. 0
 15     0. 0
 16     0. 0
 17     0. 0
 18     0. 0
 19     0. 0
 20     0. 0
 21     0. 0
 22     0. 0
 23     0. 0
 24     0. 0
 25     0. 0
 26     0. 0
 27     0. 0
 28     0. 0
 29     0. 0
 30     0. 0
 31     0. 0
 32     0. 0
 33     0. 0
 34     0. 0
 35     0. 0
 36     0. 0
 37     0. 0
 38     0. 0
 39     0. 0
 40     0. 0
 41     0. 0
 42     0. 0
 43     0. 0
 44     0. 0
 45     0. 0
 46     0. 0
 47     0. 0
 48     0. 0
 49     0. 0
 50     0. 0
 51     0. 0
 52     0. 0
```

```
 55      0. 0
 56      0. 0
 57      0. 0
 58      0. 0
 59   1005. 0
 60   3201. .*
 61   6077. .   *
 62  11844. .        *
 63  22252. .                *
 64  35252. .                            *
 65  46976. .                                     *
 66  53404. .                                            *
 67  49923. .                                        *
 68  39053. .                               *
 69  25915. .                    *
 70  14433. .          *
 71   6973. .    *
 72   2942. .*
 73   1210. .
 74      0. 0
 75      0. 0
 76      0. 0
 77      0. 0
 78      0. 0
 79      0. 0
 80      0. 0
 81      0. 0
 82      0. 0
 83      0. 0
 84      0. 0
 85      0. 0
 86      0. 0
 87      0. 0
 88      0. 0
 89      0. 0
 90      0. 0
 91      0. 0
 92      0. 0
 93      0. 0
 94      0. 0
 95      0. 0
 96      0. 0
 97      0. 0
 98      0. 0
 99      0. 0
100      0. 0
*STOP* 0
```

Figure 5a

Folded Cs-137 Spectrum
Pages 22 and 23

```
CHAN SPECT                          CS-137
             0..................................................
   1   6042. .   *
   2   7506. .     *
   3  31921. .                           *
   4  45993. .                                         *
   5   7773. .     *
   6   6031. .   *
   7   6009. .   *
   8   5955. .   *
   9   5645. .   *
  10   5721. .   *
  11   5849. .   *
  12   5750. .   *
  13   5694. .   *
  14   5933. .   *
  15   5950. .   *
  16   5920. .   *
  17   6509. .    *
  18   6884. .    *
  19   7071. .    *
  20   6773. .    *
  21   6499. .    *
  22   6205. .   *
  23   6081. .   *
  24   6096. .   *
  25   6267. .   *
  26   6247. .   *
  27   6234. .   *
  28   6124. .   *
  29   6103. .   *
  30   6086. .   *
  31   6010. .   *
  32   6003. .   *
  33   5879. .   *
  34   5951. .   *
  35   5904. .   *
  36   5935. .   *
  37   5871. .   *
  38   5977. .   *
  39   5947. .   *
  40   5979. .   *
  41   6172. .   *
  42   6271. .   *
  43   6534. .    *
  44   6416. .    *
  45   6129. .   *
  46   5893. .   *
  47   4837. .  *
  48   3877. . *
  49   2959. .*
  50   2330. .*
  51   1957. .
  52   1622. .
```

```
  55    1219. .
  56    1301. .
  57    1287. .
  58    1498. .
  59    1938. .
  60    3201. . *
  61    6077. .    *
  62   11844. .           *
  63   22252. .                     *
  64   35252. .                                     *
  65   46976. .                                                 *
  66   53404. .                                                         *
  67   49923. .                                                    *
  68   39055. .                                        *
  69   25915. .                          *
  70   14483. .             *
  71    6979. .     *
  72    2942. . *
  73    1210. .
  74     451. 0
  75     211. 0
  76      89. 0
  77      32. 0
  78      63. 0
  79      38. 0
  80       0. 0
  81       0. 0
  82       0. 0
  83       0. 0
  84       0. 0
  85       0. 0
  86       0. 0
  87       0. 0
  88       0. 0
  89       0. 0
  90       0. 0
  91       0. 0
  92       0. 0
  93       0. 0
  94       0. 0
  95       0. 0
  96       0. 0
  97       0. 0
  98       0. 0
  99       0. 0
 100       0. 0
*STØP* 0
```

Figure 6

Unfolded Na-24 Spectrum
Pages 25 through 30

```
CHAN SPECT                          NA-24
            0..................................................
   1      0. 0
   2  5421. .      *
   3  4024. .    *
   4  2173. . *
   5  1104. .
   6   521. 0
   7      0. 0
   8      0. 0
   9      0. 0
  10      0. 0
  11      0. 0
  12      0. 0
  13      0. 0
  14      0. 0
  15      0. 0
  16      0. 0
  17      0. 0
  18      0. 0
  19      0. 0
  20      0. 0
  21      0. 0
  22      0. 0
  23      0. 0
  24      0. 0
  25      0. 0
  26      0. 0
  27      0. 0
  28      0. 0
  29      0. 0
  30      0. 0
  31      0. 0
  32      0. 0
  33      0. 0
  34      0. 0
  35      0. 0
  36      0. 0
  37      0. 0
  38      0. 0
  39      0. 0
  40      0. 0
  41      0. 0
  42      0. 0
  43      0. 0
  44      0. 0
  45      0. 0
  46      0. 0
  47      0. 0
  48      0. 0
  49      0. 0
  50      0. 0
  51      0. 0
  52      0. 0
```

```
 55     0. 0
 56     0. 0
 57     0. 0
 58     0. 0
 59     0. 0
 60     0. 0
 61     0. 0
 62     0. 0
 63     0. 0
 64     0. 0
 65     0. 0
 66     0. 0
 67     0. 0
 68     0. 0
 69     0. 0
 70     0. 0
 71     0. 0
 72     0. 0
 73     0. 0
 74     0. 0
 75     0. 0
 76     0. 0
 77     0. 0
 78     0. 0
 79     0. 0
 80     0. 0
 81     0. 0
 82     0. 0
 83     0. 0
 84     0. 0
 85     0. 0
 86     0. 0
 87     0. 0
 88     0. 0
 89     0. 0
 90     0. 0
 91     0. 0
 92     0. 0
 93     0. 0
 94     0. 0
 95     0. 0
 96     0. 0
 97     0. 0
 98     0. 0
 99     0. 0
100     0. 0
101     0. 0
102     0. 0
103     0. 0
104     0. 0
105     0. 0
106     0. 0
107     0. 0
108     0. 0
```

```
111      0. 0
112      0. 0
113      0. 0
114      0. 0
115      0. 0
116      0. 0
117      0. 0
118      0. 0
119      0. 0
120      0. 0
121      0. 0
122      0. 0
123      0. 0
124   1732. .*
125   2352. . *
126   4001. .     *
127   6675. .         *
128   9283. .               *
129  13451. .                     *
130  17937. .                              *
131  23765. .                                        *
132  28817. .                                                  *
133  30642. .                                                      *
134  30489. .                                                     *
135  28392. .                                                 *
136  24325. .                                          *
137  20082. .                                  *
138  15035. .                         *
139  10719. .                 *
140   7305. .          *
141   4559. .      *
142   2535. .  *
143   1329. .*
144      0. 0
145      0. 0
146      0. 0
147      0. 0
148      0. 0
149      0. 0
150      0. 0
151      0. 0
152      0. 0
153      0. 0
154      0. 0
155      0. 0
156      0. 0
157      0. 0
158      0. 0
159      0. 0
160      0. 0
161      0. 0
162      0. 0
163      0. 0
164      0. 0
```

```
167      0. 0
168      0. 0
169      0. 0
170      0. 0
171      0. 0
172      0. 0
173      0. 0
174      0. 0
175      0. 0
176      0. 0
177      0. 0
178      0. 0
179      0. 0
180      0. 0
181      0. 0
182      0. 0
183      0. 0
184      0. 0
185      0. 0
186      0. 0
187      0. 0
188      0. 0
189      0. 0
190      0. 0
191      0. 0
192      0. 0
193      0. 0
194      0. 0
195      0. 0
196      0. 0
197      0. 0
198      0. 0
199      0. 0
200      0. 0
201      0. 0
202      0. 0
203      0. 0
204      0. 0
205      0. 0
206      0. 0
207      0. 0
208      0. 0
209      0. 0
210      0. 0
211      0. 0
212      0. 0
213      0. 0
214      0. 0
215      0. 0
216      0. 0
217      0. 0
218      0. 0
219      0. 0
220      0. 0
```

```
223     0. 0
224     0. 0
225     0. 0
226     0. 0
227     0. 0
228     0. 0
229     0. 0
230     0. 0
231     0. 0
232     0. 0
233     0. 0
234     0. 0
235     0. 0
236     0. 0
237     0. 0
238     0. 0
239     0. 0
240     0. 0
241     0. 0
242     0. 0
243     0. 0
244     0. 0
245     0. 0
246     0. 0
247     0. 0
248     0. 0
249     0. 0
250     0. 0
251   321. 0
252  1002. .
253  2216. . *
254  3013. .  *
255  3679. .    *
256  4516. .     *
257  5483. .      *
258  6593. .        *
259  7715. .          *
260  8693. .            *
261  9679. .             *
262 10165. .              *
263 10653. .               *
264 10392. .              *
265 10248. .              *
266  9736. .             *
267  8953. .            *
268  7832. .          *
269  6852. .         *
270  5882. .       *
271  5024. .      *
272  4225. .    *
273  3366. .   *
274  2662. .  *
275  2122. . *
276  1685. .*
```

```
 279    782. .
 280      0. 0
 281      0. 0
 282      0. 0
 283      0. 0
 284      0. 0
 285      0. 0
 286      0. 0
 287      0. 0
 288      0. 0
 289      0. 0
 290      0. 0
 291      0. 0
 292      0. 0
 293      0. 0
 294      0. 0
 295      0. 0
 296      0. 0
 297      0. 0
 298      0. 0
 299      0. 0
 300      0. 0
*STθP* 0
```

Figure 6a

Folded Na-24 Spectrum

Pages 32 through 37

```
CHAN SPECT                      [illegible]
            0.................................................
  1   8960. .          *
  2  13493. .                 *
  3  12200. .               *
  4  10384. .            *
  5   9339. .           *
  6   8793. .          *
  7   8337. .         *
  8   8207. .         *
  9   7998. .         *
 10   7799. .        *
 11   7510. .        *
 12   7463. .        *
 13   7364. .        *
 14   7279. .        *
 15   7200. .       *
 16   7227. .       *
 17   7104. .       *
 18   7285. .        *
 19   7531. .        *
 20   7613. .        *
 21   8332. .         *
 22   8712. .          *
 23   9109. .          *
 24   8702. .          *
 25   8431. .         *
 26   7650. .        *
 27   7407. .        *
 28   7146. .       *
 29   7044. .       *
 30   7009. .       *
 31   6985. .       *
 32   7019. .       *
 33   7067. .       *
 34   7026. .       *
 35   7055. .       *
 36   6983. .       *
 37   6791. .       *
 38   6613. .       *
 39   6521. .      *
 40   6497. .      *
 41   6497. .      *
 42   6417. .      *
 43   6387. .      *
 44   6472. .      *
 45   6349. .      *
 46   6410. .      *
 47   6511. .      *
 48   6614. .       *
 49   6953. .       *
 50   7347. .        *
 51   7534. .        *
 52   7400. .        *
```

```
 55  6353. .          *
 56  6233. .          *
 57  6219. .          *
 58  6089. .          *
 59  6136. .          *
 60  6162. .          *
 61  5970. .          *
 62  5999. .          *
 63  6144. .          *
 64  6169. .          *
 65  6226. .          *
 66  6153. .          *
 67  6220. .          *
 68  6203. .          *
 69  6165. .          *
 70  6219. .          *
 71  6249. .          *
 72  6011. .          *
 73  6343. .          *
 74  6443. .          *
 75  6433. .          *
 76  6469. .          *
 77  6591. .            *
 78  6475. .          *
 79  6615. .            *
 80  6690. .            *
 81  6783. .            *
 82  6843. .            *
 83  7142. .            *
 84  7266. .             *
 85  7403. .             *
 86  7353. .             *
 87  7483. :             *
 88  7481. .             *
 89  7410. .             *
 90  7383. .             *
 91  7522. .             *
 92  7609. .             *
 93  7745. .             *
 94  7697. .             *
 95  7646. .             *
 96  7683. .             *
 97  7697. .             *
 98  8017. .               *
 99  8005. .               *
100  8032. .               *
101  8115. .               *
102  8233. .               *
103  8161. .               *
104  8227. .               *
105  8273. .               *
106  8404. .               *
107  8175. .               *
108  8306. .               *
```

```
111   7323. .         *
112   6659. .        *
113   6084. .       *
114   5444. .      *
115   4967. .     *
116   4479. .    *
117   3962. .    *
118   3634. .   *
119   3444. .   *
120   3337. .   *
121   3252. .  *
122   3226. .  *
123   3462. .   *
124   3767. .   *
125   4620. .     *
126   6111. .       *
127   8173. .          *
128  11513. .               *
129  15896. .                      *
130  20255. .                            *
131  25959. .                                     *
132  30283. .                                           *
133  32949. .                                                *
134  32855. .                                               *
135  30693. .                                            *
136  26741. .                                      *
137  22299. .                               *
138  17296. .                        *
139  13085. .                 *
140   9573. .            *
141   6824. .        *
142   4886. .     *
143   3803. .   *
144   2985. .  *
145   2585. . *
146   2349. . *
147   2239. . *
148   2158. . *
149   2016. . *
150   2100. . *
151   2121. . *
152   1963. .*
153   2057. . *
154   2049. . *
155   2071. . *
156   2141. . *
157   2182. . *
158   2271. . *
159   2280. . *
160   2397. . *
161   2631. . *
162   2941. .  *
163   3093. .  *
164   3391. .   *
```

```
167  3745. .   *
168  3741. .   *
169  3713. .   *
170  3682. .   *
171  3526. .   *
172  3388. .   *
173  3418. .   *
174  3259. .  *
175  3211. .  *
176  2992. .  *
177  3055. .  *
178  3043. .  *
179  2976. .  *
180  2882. .  *
181  3025. .  *
182  2952. .  *
183  2939. .  *
184  3022. .  *
185  3000. .  *
186  3074. .  *
187  3028. .  *
188  3104. .  *
189  3059. .  *
190  3147. .  *
191  3063. .  *
192  3117. .  *
193  3141. .  *
194  3114. .  *
195  3207. .  *
196  3145. .  *
197  3183. .  *
198  3105. .  *
199  3138. .  *
200  3146. .  *
201  3214. .  *
202  3072. .  *
203  3122. .  *
204  3116. .  *
205  3209. .  *
206  3263. .  *
207  3301. .   *
208  3524. .   *
209  3623. .   *
210  4149. .    *
211  4339. .    *
212  4737. .     *
213  5307. .      *
214  5517. .      *
215  5903. .      *
216  6247. .       *
217  6462. .       *
218  6585. .       *
219  6433. .       *
220  6202. .       *
```

```
223  5298. .      *
224  5153. .     *
225  5103. .     *
226  4700. .     *
227  4602. .    *
228  4437. .    *
229  4259. .    *
230  4187. .    *
231  4150. .    *
232  4111. .    *
233  4126. .    *
234  4067. .    *
235  4128. .    *
236  3933. .   *
237  3763. .   *
238  3767. .   *
239  3579. .   *
240  3373. .   *
241  3252. .  *
242  2969. .  *
243  2867. .  *
244  2641. .  *
245  2436. . *
246  2225. . *
247  2056. . *
248  1999. . *
249  1864. .*
250  1923. .*
251  1979. . *
252  2167. . *
253  2516. . *
254  3013. .  *
255  3673. .   *
256  4516. .    *
257  5483. .      *
258  6593. .        *
259  7715. .         *
260  8693. .           *
261  9679. .            *
262 10165. .             *
263 10653. .              *
264 10392. .             *
265 10243. .             *
266  9736. .            *
267  8953. .           *
268  7832. .         *
269  6852. .        *
270  5882. .      *
271  5024. .     *
272  4225. .    *
273  3366. .   *
274  2662. .  *
275  2122. . *
276  1683. .*
```

```
279   782. 0
280   580. 0
281   443. 0
282   344. 0
283   267. 0
284   260. 0
285   205. 0
286   182. 0
287   163. 0
288   142. 0
289   139. 0
290   154. 0
291   123. 0
292    97. 0
293    97. 0
294    99. 0
295   105. 0
296    90. 0
297    86. 0
298    86. 0
299    99. 0
300   103. 0
*STOP* 0
```

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APPENDIX

APPENDIX A

COMPUTER PROGRAM LISTING

Pages 41 through 52

```
      DIMENSIØN X(400),ISPECT(400),ID(5)
      DIMENSIØN EFF(400),PT(400),CØM(400),BSP(400),
     1VFP(400),VFWH(400),VFED(400),FESC(400),SESC(400)
      DIMENSIØN E(6),P(6),C(6),B(6),
     1VP(6),VW(6),VE(6),F(6),S(6)
      DIMENSIØN IPØLY(4),PØLYVL(4),IRES(6)
      LØGICAL TRSL
      DATA IPØLY/64,40,65,70/
      DATA PØLYVL/.25,.50,.75,.125/
      DATA IRES/62,67,72,77,82,100/
      K=0
      NRESP=400
      DØ500I=1,4
C
C     SETS UP PØLYNØMIAL
C
500   CALL SPØT(IPØLY(I),PØLYVL(I))
C
C     READ IN PØLYNØMIAL CØEFFICIENTS
C
      READ(5,508)(E(I),I=1,6)
      READ(5,508)(P(I),I=1,6)
      READ(5,508)(C(I),I=1,6)
      READ(5,508)(B(I),I=1,6)
      READ(5,508)(VP(I),I=1,6)
      READ(5,508)(VE(I),I=1,6)
      READ(5,508)(VW(I),I=1,6)
      READ(5,508)(F(I),I=1,6)
      READ(5,508)(S(I),I=1,6)
508   FØRMAT(6F10.4)
C
C     READ IN SPECTRUM ID AND CALIBRATIØN
C
100   READ(5,105)ID,NCHAN,CHANWH
105   FØRMAT(5A4,I10,F10.5)
      IF(NCHAN.EQ.0)GØTØ9999
C
C     READ IN SPECTRUM
C
      READ(5,110)(ISPECT(I),I=1,NCHAN)
```

```
110   FØRMAT(12X,10I6)
C
C     WRITE SPECTRUM
C
      WRITE(6,111)ID
111   FØRMAT('1',35X,5A4,///)
      WRITE(6,112)(ISPECT(I),I=1,NCHAN)
112   FØRMAT(10I12)
      DØ120I=1,NCHAN
120   X(I)=ISPECT(I)
C
C     DIGITAL PLØT ØF INPUT SPECTRUM
C
      CALL PLØT(NCHAN,ID,X)
      CALL SAMØ('IC')
      WRITE(102,125)
125   FØRMAT(//)
      READ(101,126)K
126   FØRMAT(I1)
C
C     DISPLAY INPUT SPECTRUM VIA ØSCILLØSCØPE
C
      CALL SCØPE(NCHAN,X)
      IF(K.EQ.2)GØTØ600
C
C
C     RESPØNSE FUNCTIØN RØUTINE
C
C
510   WRITE(6,511)
511   FØRMAT('1EFF',//)
      CALL SSRM(64)
      CALL HYBRID(K,NRESP,IRFS,E,ISPECT,EFF)
      DØ513I=1,NRESP
513   EFF(I)=EFF(I)/20.
      WRITE(6,509)(EFF(I),I=1,NRESP)
509   FØRMAT(10F10.4)
515   WRITE(6,516)
516   FØRMAT('1PT',//)
      CALL HYBRID(K,NRESP,IRFS,P,ISPECT,PT)
```

```
      WRITE(6,509)(PT(I),I=1,NRESP)
      IF(K.EQ.1)GØTØ580
520   WRITE(6,521)
521   FØRMAT('1CØM',//)
      CALL SSRP(64)
      CALL HYBRID(K,NRESP,IRFS,C,ISPECT,CØM)
      WRITE(6,509)(CØM(I),I=1,NRESP)
      IF(K.EQ.1)GØTØ580
525   WRITE(6,526)
526   FØRMAT('1BSP',//)
      CALL SSRP(64)
      CALL HYBRID(K,NRESP,IRFS,B,ISPECT,BSP)
      DØ527I=1,NRESP
527   BSP(I)=BSP(I)/10.
      WRITE(6,509)(BSP(I),I=1,NRESP)
      IF(K.EQ.1)GØTØ580
530   WRITE(6,531)
531   FØRMAT('1VFP',//)
      CALL SSRP(64)
      CALL HYBRID (K,NRESP,IRES,VP,ISPECT,VFP)
      WRITE(6,509)(VFP(I),I=1,NRESP)
535   WRITE(6,536)
536   FØRMAT('1VFED',//)
      CALL HYBRID (K,NRESP,IRES,VE,ISPECT,VFED)
      DØ538I=1,NRESP
538   VFED(I)=VFED(I)*10.
      WRITE(6,509)(VFED(I),I=1,NRESP)
540   WRITE(6,541)
541   FØRMAT('1VFWH',//)
      CALL HYBRID (K,NRESP,IRES,VW,ISPECT,VFWH)
      WRITE(6,509)(VFWH(I),I=1,NRESP)
      IF(K.EQ.1)GØTØ580
545   WRITE(6,546)
546   FØRMAT('1FESC',//)
      CALL SSRP(64)
      CALL HYBRID (K,NRESP,IRES,F,ISPECT,FESC)
      WRITE(6,509)(FESC(I),I=1,NRESP)
550   WRITE(6,551)
551   FØRMAT('1SESC',//)
      CALL HYBRID (K,NRESP,IRES,S,ISPECT,SESC)
```

```
      WRITE(6,509)(SESC(I),I=1,NRESP)
580   CALL SAMO('IC')
      DO590I=1,NCHAN
590   ISPECT(I)=X(I)
C
C
C     UNFOLDING ROUTINE
C
C
C     DIAGONAL CALCULATION
C
800   DO900I=1,NCHAN
      KT=NCHAN-I
      CHAN=KT
C
C     ESCAPE PEAK CALCULATION
C
      ESC=.511/CHANWH
      KESC1=CHAN-ESC
      KESC2=CHAN-2.*ESC
C
C     COMPTON EDGE CALCULATION
C
      ENERGY=CHAN*CHANWH
      EDGE=ENERGY/(1.+.2555/ENERGY)
      EDGECH=EDGE/CHANWH
      KEDCH=EDGECH
      COMHT=COM(KT)/EDGECH
C
C     VALLEY FILL CALCULATION
C
      IFILED=VFED(KT)/CHANWH
      IFILWH=VFWH(KT)/CHANWH
      IFILDE=IFILED-IFILWH
      VFWC=VFWH(KT)/CHANWH
      VFHT=VFP(KT)/VFWC
C
C     BACKSCATTER CALCULATION
C
      KB=KT-KEDCH
```

```
      KBEND=KB+3
      KBBE=KB-3
C
C     NØRMALIZATIØN WITH PEAK-TØ-TØTAL RATIØ
C
      XPT=X(KT)/PT(KT)
      IF(KT-1)900,900,805
C
C     CØMPTØN FILTER
C
805   IF(KEDCH)850,850,810
810   DØ815L=1,KEDCH
815   X(L)=X(L)-XPT*CØMHT
C
C     ESCAPE PEAKS FILTER
C
      IF(KESC1)840,840,820
820   X(L)=X(L)-XPT*FESC(KT)
      IF(KESC2)840,840,825
825   X(L)=X(L)-XPT*SESC(KT)
C
C     BACKSCATTER FILTER
C
840   IF(KB)850,850,845
845   DØ846L=KBBE,KBEND
846   X(L)=X(L)-XPT*BSP(KT)
C
C     VALLEY FILL FILTER
C
850   IF(IFILED)900,900,855
855   DØ860L=IFILBE,IFILED
860   X(L)=X(L)-XPT*VFHT
900   CØNTINUE
      CALL SCØPE(NCHAN,X)
C
C
C     CØNTRØL RØUTINE
C
C
      IF(TRSL(0).AND.TRSL(1))GØTØ906
```

```
906    IF(TRSL(0).AND.TRSL(1))GØTØ990
       K=1
       DØ907I=1,NCHAN
907    X(I)=ISPECT(I)
       IF(TRSL(0))GØTØ910
910    IF(TRSL(0))GØTØ510
       IF(TRSL(1))GØTØ911
911    IF(TRSL(1))GØTØ520
       IF(TRSL(2))GØTØ912
912    IF(TRSL(2))GØTØ525
       IF(TRSL(3))GØTØ913
913    IF(TRSL(3))GØTØ530
       IF(TRSL(4))GØTØ914
914    IF(TRSL(4))GØTØ545
       GØTØ800
990    CALL PLØT(NCHAN,ID,X)
       K=2
       GØTØ100
999    CALL RELECE
       END
```

```
      SUBROUTINE PLOT(NCHAN,ID,Z)
      DIMENSION Z(400)
      DIMENSION Y(111)
      DIMENSION ID(5)
      DATA BLANK,DOT,STAR,ZERO/' ','.','*','0'/
700   CTMAX=0.0
      DO705I=1,NCHAN
      TERM=Z(I)
      IF(TERM.GT.CTMAX)CTMAX=TERM
705   CONTINUE
      WRITE(6,710)ID
710   FORMAT('1CHAN',1X,'SPECT',1X,'COUNT',20X,5A4)
      DO715I=1,111
715   Y(I)=DOT
      Y(11)=ZERO
      WRITE(6,720)(Y(J),J=1,111)
720   FORMAT(19X,111A1)
      DO730I=1,111
730   Y(I)=BLANK
      DO750I=1,NCHAN
      L=(Z(I)*100.)/(CTMAX)
      Y(L+11)=STAR
      Y(11)=DOT
      IF(L.EQ.0)Y(11)=ZERO
      WRITE(6,740)I,Z(I),L,(Y(J),J=1,111)
740   FORMAT(I4,1X,F6.0,1X,I4,3X,111A1)
750   Y(L+11)=BLANK
      RETURN
      END
```

```
      SUBROUTINE SCOPE(NCHAN,Z)
      DIMENSION Z(400)
      LOGICAL TRSL
      DISMAX=0.0
      DO401I=1,NCHAN
      ANS=Z(I)
      IF(ANS.GT.DISMAX)DISMAX=ANS
401   CONTINUE
400   DO405I=1,NCHAN
      FRACT=Z(I)/DISMAX
      IDAM5=FRACT*32767.
S         WD,0         X'E131'
S         LW,1         I
S         LW,2         *NCHAN
S         CI,1         1
S         BNE          &10
S         LI,10        X'0400'
S         WD,10        X'E121'
S10       LCW,5        IDAM5
S         WD,5         X'E065'
S         CW,2         1
S         BNE          &405
S         LI,10        X'0400'
S         WD,10        X'E123'
405   CONTINUE
      IF(TRSL(5))GOTO410
410   IF(.NOT.TRSL(5))GOTO400
      RETURN
      END
```

```
      SUBROUTINE HYBRID(K,NRESP,IRES,A,ISPECT,Z)
      DIMENSION IRES(6),A(6),ISPECT(400),Z(400)
      LOGICAL TRSL
      K1=0
300   DO310I=1,6
310   CALL SPOT(IRES(I),A(I))
      IF(K.EQ.1)GOTO328
312   CALL PARA
      CALL HYAIT(5,NRESP,ISPECT,KH)
315   IF(KH.LT.NRESP)GOTO315
      CALL SAMO('IC')
      DO320I=1,NRESP
320   Z(I)=FLOAT(ISPECT(I))/32767.
      IF(K.EQ.0)RETURN
      IF(K1.EQ.5)RETURN
328   CALL STCS('NM')
      CALL SAMO('PF')
      IF(TRSL(5))GOTO330
330   IF(.NOT.TRSL(5))GOTO330
      CALL SAMS('PC')
      DO335I=1,6
      CALL SACO('R',IRES(I))
335   CALL DVMR(A(I))
      WRITE(6,325)(IRES(I),A(I),I=1,6)
325   FORMAT(I10,F10.4)
      K1=5
      GOTO312
      END
```

```
          DEF       HYAIT
HYAIT     WD,3      X'0037'
          LI,3      X'FE00'
          WD,3      X'1102'
          LW,3      XPSD
          XW,3      X'60'
          STW,3     SAVE
          LW,3      *15
          LW,3      *3
          WD,3      X'E134'
          MTW,1     15
          LW,3      *15
          BCR,1      $+2
          LW,3       *3
          LW,3      *3
          STW,3     COUNT
          MTW,1     15
          LW,3      *15
          BCR,1      $+2
          LW,3       *3
          AND,3     WORD
          OR,3      STO
          STW,3     STORE
           MTW,1    15
          LW,3      *15
          STW,3     ADDR
          LI,3      0
          STW,3     *ADDR
GO        RD,3      X'E226'
          CW,3      MASK
          BANZ      GO
          MTW,1     15
          LI,3       X'8000'
          WD,3      X'1202'
          WD,3      X'0021'
          LW,3      WONE
          WD,3      X'E121'
          B         *15
XPSD      GEN,8,7,17    X'CF',0,TRANS
          BOUND     8
```

```
TRANS     DATA      0,0,INT,0
STO       DATA      X'35300000'
WORD      DATA      X'0001FFFF'
COUNT     DATA      0
MASK      DATA      X'0004'
SAVE      DATA      0
REG       DATA      0
ADDR      DATA      0
WONE      DATA      X'0001'
INT       STW,3     REG
          WD,3      X'E135'
          MTW,1     *ADDR
TEST      RD,3      X'E226'
          CW,3      MASK
          BANZ      TEST
          RD,3      X'E235'
STORE     DATA      0
          MTW,1     STORE
          MTW,-1    COUNT
          BE        XIT
RETURN    LW,3      REG
          GEN,12,3,17   X'0E3',0,TRANS
XIT       LI,3      X'7E00'
          WD,3      X'1302'
          LW,3      WONE
          WD,3      X'E123'
          LW,3      SAVE
          STW,3     X'60'
          WD,3      X'0027'
          LW,3      INHBT
          AND,3     TRANS+1
          STW,3     TRANS+1
          B         RETURN
INHBT     DATA      X'F8FFFFFF'
          END
```

```
         DEF        PARA
PARA     LI,6       X'0300'
         WD,6       X'E02A'
         LI,6       0
         WD,6       X'E023'
         WD,6       X'E029'
         LI,6       X'0200'
         WD,6       X'E023'
         LI,6       X'0100'
         WD,6       X'E02A'
         B          *15
         END
```

APPENDIX B.

SELECTED PULSE-HEIGHT DISTRIBUTIONS

Pages 54 through 66

```
CHAN SPECT                             A-41
            0..................................................
   1 12000. .        *
   2 12735. .         *
   3 15079. .           *
   4 14793. .           *
   5 16886. .            *
   6 14047. .          *
   7 12447. .        *
   8 11130. .       *
   9 10432. .       *
  10  9673. .      *
  11  9274. .      *
  12  9093. .     *
  13  9080. .     *
  14  8782. .     *
  15  8802. .     *
  16  8983. .     *
  17  8946. .     *
  18  9266. .      *
  19  9547. .      *
  20 10457. .       *
  21 11296. .       *
  22 11077. .       *
  23 10329. .       *
  24  9442. .      *
  25  9013. .     *
  26  8942. .     *
  27  8785. .     *
  28  8598. .     *
  29  8375. .     *
  30  8314. .     *
  31  8213. .     *
  32  8190. .     *
  33  8161. .     *
  34  8133. .     *
  35  8085. .     *
  36  8193. .     *
  37  8011. .     *
  38  7963. .     *
  39  7969. .     *
  40  8193. .     *
  41  8150. .     *
  42  7911. .    *
  43  8013. .     *
  44  8011. .     *
  45  8053. .     *
  46  8048. .     *
  47  7959. .    *
  48  7917. .    *
  49  7900. .    *
  50  8027. .     *
  51  8105. .     *
  52  8143. .     *
```

```
 55  7991. .     *
 56  8005. .     *
 57  8341. .     *
 58  8010. .     *
 59  8087. ,     *
 60  8240. .     *
 61  8278. .     *
 62  8270. .     *
 63  8335. .     *
 64  8523. .     *
 65  8516. .     *
 66  8444. .     *
 67  8414. .     *
 68  8640. .     *
 69  8684. .     *
 70  8538. .     *
 71  8725. .     *
 72  8870. .     *
 73  8813. .     *
 74  9205. .      *
 75  9277. .      *
 76  9351. .      *
 77  9647. .      *
 78  9685. .      *
 79  9879. .      *
 80  9903. .      *
 81  9985. .      *
 82  9933. .      *
 83 10002. .      *
 84 10059. .      *
 85 10361. .       *
 86 10357. .       *
 87 10621. :       *
 88 10432. .       *
 89 10651. .       *
 90 10814. .       *
 91 10829. .       *
 92 10985. .       *
 93 11185. .       *
 94 11232. .       *
 95 11523. .        *
 96 11526. .        *
 97 11932. .        *
 98 11962. .        *
 99 11833. .        *
100 11743. .        *
101 11489. .        *
102 10894. .       *
103 10006. .      *
104  9138. .      *
105  8019. :     *
106  6972. .    *
107  6031. .   *
108  5024. .  *
```

```
111  3030. .*
112  2932. .*
113  2543. .*
114  2456. .*
115  2603. .*
116  3005. .*
117  3810. . *
118  5127. .  *
119  8212. .     *
120 12630. .         *
121 19207. .              *
122 28111. .                      *
123 38032. .                               *
124 47623. .                                       *
125 54148. .                                             *
126 56900. .                                                *
127 55161. .                                              *
128 49739. .                                         *
129 41269. .                                  *
130 31509. .                         *
131 22749. .                 *
132 15573. .           *
133 10108. .      *
134  6310. .   *
135  3899. . *
136  2473. .*
137  1545. .
138  1025. 0
139   711. 0
140   505. 0
141   394. 0
142   322. 0
143   263. 0
144   227. 0
145   193. 0
146   161. 0
147   103. 0
148   130. 0
149   119. 0
150    99. 0
151   111. 0
152   121. 0
153    87. 0
154   101. 0
155   100. 0
156   107. 0
157   107. 0
158   106. 0
159    80. 0
160   100. 0
161   102. 0
162    98. 0
163    82. 0
164   109. 0
```

```
  167     87. 0
  168     84. 0
  169     77. 0
  170     92. 0
  171     71. 0
  172     84. 0
  173     90. 0
  174     75. 0
  175     97. 0
  176     84. 0
  177     77. 0
  178     69. 0
  179     62. 0
  180     59. 0
  181     63. 0
  182     61. 0
  183     76. 0
  184     63. 0
  185     47. 0
  186     53. 0
  187     60. 0
  188     50. 0
  189     61. 0
  190     59. 0
  191     44. 0
  192     66. 0
  193     59. 0
  194     71. 0
  195     40. 0
  196     66. 0
  197      0. 0
  198      0. 0
  199      0. 0
  200      0. 0
*STOP* 0
```

```
CHAN SPECT                           Co-60
           0..................................................
  1 16300. .        *
  2 16400. .        *
  3 16912. .         *
  4 16373. .        *
  5 16285. .        *
  6 15760. .        *
  7 16040. .        *
  8 16056. .        *
  9 15671. .        *
 10 15563. .        *
 11 15495. .        *
 12 15680. .        *
 13 15492. .        *
 14 15681. .        *
 15 15814. .        *
 16 15825. .        *
 17 16191. .        *
 18 16464. .        *
 19 17165. .         *
 20 19137. .          *
 21 20645. .           *
 22 21034. .           *
 23 19904. .           *
 24 18353. .          *
 25 17505. .         *
 26 17053. .         *
 27 17033. .         *
 28 17066. .         *
 29 16853. .         *
 30 17328. .         *
 31 17137. .         *
 32 16807. .         *
 33 16643. .        *
 34 16391. .        *
 35 16315. .        *
 36 16273. .        *
 37 16231. .        *
 38 16004. .        *
 39 15931. .        *
 40 15991. .        *
 41 16035. .        *
 42 16002. .        *
 43 16081. .        *
 44 16165. .        *
 45 16001. .        *
 46 16397. .        *
 47 16484. .        *
 48 16622. .        *
 49 16300. .        *
 50 16833. .         *
 51 16741. .         *
 52 17093. .         *
```

```
 55 17027. .         *
 56 17142. .         *
 57 17013. .         *
 58 17443. .         *
 59 17269. .         *
 60 17476. .         *
 61 17605. .         *
 62 17800. .         *
 63 18177. .         *
 64 18277. .          *
 65 18323. .          *
 66 18707. .          *
 67 19035. .          *
 68 18869. .          *
 69 18890. .          *
 70 18999. .          *
 71 19395. .          *
 72 19737. .          *
 73 19922. .           *
 74 20114. .           *
 75 20507. .           *
 76 20675. .           *
 77 21032. .           *
 78 20996. .           *
 79 21140. .           *
 80 22030. .            *
 81 21965. .            *
 82 22886. .             *
 83 23300. .             *
 84 23386. .             *
 85 23747. .             *
 86 23709. .             *
 87 24021. .             *
 88 24225. .             *
 89 24215. .             *
 90 24086. .             *
 91 23536. .             *
 92 22755. .            *
 93 22009. .            *
 94 20521. .           *
 95 19752. .          *
 96 18180. .         *
 97 17254. .         *
 98 16303. .        *
 99 15754. .        *
100 15206. .        *
101 14883. .       *
102 14979. .       *
103 14935. .       *
104 14832. .       *
105 14765. .       *
106 14824. .       *
107 16080. .        *
108 18319. .          *
```

```
111 41686. .                           *
112 53931. .                                   *
113 65896. .                                            *
114 73834. .                                                 *
115 75932. .                                                   *
116 71762. .                                                *
117 61383. .                                        *
118 49003. .                                *
119 36471. .                       *
120 25877. .                *
121 18613. .           *
122 14390. .       *
123 14183. .       *
124 17087. .          *
125 23443. .              *
126 32192. .                    *
127 42603. .                            *
128 51209. .                                 *
129 58744. .                                      *
130 60310. .                                       *
131 57082. .                                     *
132 51182. .                                 *
133 42199. .                          *
134 32521. .                    *
135 23622. .              *
136 16115. .        *
137 10545. .    *
138  6394. .  *
139  4043. ..
140  2562. .
141  1607. .
142  1082. 0
143   710. 0
144   591. 0
145   434. 0
146   383. 0
147   354. 0
148   300. 0
149   273. 0
150   253. 0
151   217. 0
152   242. 0
153   181. 0
154   213. 0
155   213. 0
156   201. 0
157   197. 0
158   200. 0
159   230. 0
160   203. 0
161   206. 0
162   215. 0
163   200. 0
164   163. 0
```

```
   167    209. 0
   168    158. 0
   169    196. 0
   170    213. 0
   171    172. 0
   172    185. 0
   173    203. 0
   174    183. 0
   175    185. 0
   176    186. 0
   177    184. 0
   178    203. 0
   179    186. 0
   180    193. 0
   181    185. 0
   182    157. 0
   183    193. 0
   184    172. 0
   185    189. 0
   186    193. 0
   187    167. 0
   188    190. 0
   189    175. 0
   190    175. 0
   191    187. 0
   192    191. 0
   193    169. 0
   194    199. 0
   195    165. 0
   196    187. 0
   197    181. 0
   198    187. 0
   199    206. 0
   200    176. 0
*STOP*  0
```

```
CHAN SPECT                            K-42
            0..................................................
  1 43131.  .                                      *
  2 53006.  .                                                *
  3 49594.  .                                            *
  4 40160.  .                                   *
  5 35607.  .                               *
  6 31896.  .                            *
  7 29223.  .                         *
  8 27060.  .                       *
  9 24507.  .                     *
 10 22383.  .                   *
 11 20355.  .                 *
 12 19215.  .                *
 13 17616.  .              *
 14 16567.  .             *
 15 15405.  .            *
 16 14396.  .           *
 17 13789.  .           *
 18 12925.  .          *
 19 12016.  .         *
 20 11732.  .         *
 21 11607.  .        *
 22 11292.  .        *
 23 10715.  .        *
 24  9983.  .       *
 25  9385.  .      *
 26  8804.  .      *
 27  8545.  .      *
 28  8555.  .      *
 29  9245.  .      *
 30 10277.  .       *
 31 10374.  .        *
 32 10191.  .       *
 33  8355.  .     *
 34  7257.  .    *
 35  6440.  .    *
 36  6244.  .   *
 37  5920.  .   *
 38  5711.  .   *
 39  5578.  .   *
 40  5429.  .   *
 41  5420.  .   *
 42  5296.  .  *
 43  5231.  .  *
 44  5170.  .  *
 45  5274.  .  *
 46  5099.  .  *
 47  5202.  .  *
 48  5312.  .   *
 49  5478.  .   *
 50  5360.  :   *
 51  5292.  .  *
 52  5186.  .  *
```

```
 55  4709. .  *
 56  4561. .  *
 57  4655. .  *
 58  4663. .  *
 59  4533. .  *
 60  4507. .  *
 61  4339. .  *
 62  4364. .  *
 63  4392. .  *
 64  4453. .  *
 65  4340. .  *
 66  4324. .  *
 67  4240. . *
 68  4337. .  *
 69  4336. .  *
 70  4262. .  *
 71  4163. . *
 72  4241. .  *
 73  4305. .  *
 74  4334. .  *
 75  4225. . *
 76  4227. . *
 77  4223. . *
 78  4413. .  *
 79  4325. .  *
 80  4370. .  *
 81  4382. .  *
 82  4377. .  *
 83  4380. .  *
 84  4349. .  *
 85  4507. .  *
 86  4503. .  *
 87  4526. .  *
 88  4599. .  *
 89  4641. .  *
 90  4569. .  *
 91  4569. .  *
 92  4504. .  *
 93  4533. .  *
 94  4551. .  *
 95  4683. .  *
 96  4631. .  *
 97  4939. .  *
 98  5025. .  *
 99  5232. .  *
100  5359. .   *
101  5461. .   *
102  5597. .   *
103  5513. .   *
104  5586. .   *
105  5501. .   *
106  5394. .   *
107  5354. .   *
108  5293. .  *
```

```
111   5354. .   *
112   5325. .   *
113   5500. .   *
114   5436. .   *
115   5533. .   *
116   5713. .   *
117   5680. .   *
118   5632. .   *
119   5820. .   *
120   5842. .   *
121   5666. .   *
122   5541. .   *
123   5592. .   *
124   5275. .  *
125   4930. .  *
126   4393. .  *
127   4006. . *
128   3673. . *
129   3226. . *
130   2950. .*
131   2524. .*
132   2335. .*
133   2067. .
134   1913. .
135   1774. .
136   1765. .
137   1703. .
138   1915. .
139   2232. .*
140   2773. .*
141   4002. . *
142   5983. .   *
143   8722. .      *
144  11852. .         *
145  15456. .            *
146  19193. .               *
147  21810. .                 *
148  23562. .                   *
149  23853. .                   *
150  22503. .                  *
151  19674. .               *
152  16449. .            *
153  13103. .         *
154   9673. .      *
155   7002. .    *
156   4800. .  *
157   3223. . *
158   2103. .
159   1396. .
160    933. 0
161    575. 0
162    420. 0
163    296. 0
164    213. 0
```

```
167     122. 0
168      91. 0
169     101. 0
170      87. 0
171      75. 0
172      66. 0
173      53. 0
174      60. 0
175      74. 0
176      55. 0
177      61. 0
178      54. 0
179      72. 0
180      74. 0
181      73. 0
182      57. 0
183      57. 0
184     103. 0
185      95. 0
186      95. 0
187      94. 0
188      74. 0
189      72. 0
190      61. 0
191      51. 0
192      57. 0
193      53. 0
194      43. 0
195      45. 0
196      52. 0
197      36. 0
198      29. 0
199      43. 0
200      24. 0
201      41. 0
202      30. 0
203      22. 0
204      46. 0
205      31. 0
206      35. 0
207      35. 0
208      47. 0
209      45. 0
210      44. 0
211      44. 0
212      37. 0
213      40. 0
214      45. 0
215      50. 0
216      40. 0
217      33. 0
218      50. 0
219      35. 0
220      38. 0
```

```
 223      29. 0
 224      39. 0
 225      51. 0
 226      41. 0
 227      36. 0
 228      35. 0
 229      31. 0
 230      41. 0
 231      36. 0
 232      36. 0
 233      42. 0
 234      42. 0
 235      23. 0
 236      32. 0
 237      25. 0
 238      32. 0
 239      45. 0
 240      31. 0
 241      32. 0
 242      26. 0
 243      17. 0
 244      21. 0
 245      26. 0
 246      26. 0
 247      18. 0
 248      13. 0
 249      15. 0
 250       0. 0
*STOP* 0
```

VITA

James Paulsen was born in Pampa, Texas, on June 17, 1936. He completed his secondary education at Franklin High School, Franklin, Louisiana, in May, 1954, and attended Louisiana State University until 1958. He entered the U.S. Navy in 1958 and was discharged in November 1964. He attended Louisiana State University from February, 1965, until May, 1967, at which time he received his Bachelor of Science degree in Chemical Engineering. He entered the Louisiana State University Graduate School in September, 1967, and is at present a candidate for the Master of Science degree in Nuclear Engineering.

EXAMINATION AND THESIS REPORT

Candidate: James A. Paulsen

Major Field: Nuclear Engineering

Title of Thesis: A Hybrid Computer Filter For Unfolding Gamma-Ray Spectra

Approved:

Myron H. Young

Major Professor and Chairman

Max Goodrich

Dean of the Graduate School

EXAMINING COMMITTEE:

Bert Wilkins Jr.

Frank A. Iddings

David B. Greenberg

Robert C. McAllmon

Date of Examination:

July 22, 1970