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Gamma-Ray Measurements with the Segmented Gamma Scan

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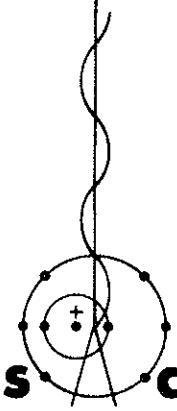

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GAMMA-RAY MEASUREMENTS WITH THE SEGMENTED GAMMA SCAN

by

E. R. Martin, D. F. Jones, and J. L. Parker

ABSTRACT

A revised and updated operation and maintenance manual for the segmented gamma-scan instrument is presented, which describes routine assay techniques as well as the theory of operation in sufficient depth that an experienced assayist can make nonroutine assays on a wide variety of materials and samples. In addition, complete electronic and electrical schematics of the Los Alamos Scientific Laboratory (LASL)-designed portions of the system are presented, along with sufficient system and circuit description to facilitate maintenance and troubleshooting. Complete software system descriptions are included, although detailed listings would have to be obtained from LASL in order to make machine-language code changes.

I. INTRODUCTION

Among the techniques for nondestructively determining quantities of nuclear materials, passive gamma-ray measurements provide one of the best quantitative methods available for those isotopes that decay with a unique

gamma-ray signature. The literature is replete with extensive discussions of nuclear gamma-ray emission,[1-4] and only items relevant to the application of the segmented gamma-scan instrument will be considered here. It is assumed that the reader is at least somewhat familiar with the operation of high-resolution gamma-ray detectors of the Ge(Li) and intrinsic germanium variety, with gamma-ray spectroscopy in general, and with the interactions of gamma rays in matter. The references cited give a broad background into these subjects.

The segmented gamma scan (SGS) is both a procedure and an instrument. It is a procedure for measuring fissile or fertile nuclear materials in matrices of low-Z material that quantitatively corrects for gamma-ray attenuation on a segment-by-segment basis. The procedure can be performed with a variety of equipment configurations, and is rather complex and tedious. The SGS is an instrument in that these complex procedures have been incorporated into a plant-tested automated instrument that is simple to operate. Except for some introductory remarks, this report will be concerned with the instrument, describing its operation in detail, the computational algorithms, the software that implements these algorithms and controls the scan operation, the hardware configuration, and its application to various sample sizes and isotopes.

Usually the most difficult problem in the passive gamma-ray assay of bulk samples is to correct for the gamma-ray attenuation within the sample itself. If one can do this, one has only to measure the number of gamma rays from the sample with the unique energy of the isotope being assayed and correct that measured number for attenuation, thus obtaining a number that is directly proportional to the quantity of material in the sample.

Unfortunately, gamma-ray attenuation is not only a function of energy but also the matrix material parameters such as density, atomic weights, etc. If the matrix material is unknown or nonuniform, it cannot readily be calculated. The segmented gamma scan uses a separate external transmission source, emitting gamma radiation close to the gamma-ray energy of the isotope being measured, to determine how much attenuation is suffered by the gamma rays from the sample. In this way, a correction factor can be determined, by which the actual gamma-ray intensity is multiplied to deduce how many gamma rays would have been measured in the absence of attenuating material.

Inhomogeneities of the sample under measurement further complicate the measurement. If the matrix material varies in the sample container, the measurement of transmission at one point may not yield the transmission at the location of the material emitting the gamma rays. When the sample is divided into collimator-defined horizontal segments, each of which is separately measured for its own attenuation, and the count rate from each individual segment corrected for the respective attenuation, the sum of segment-by-segment results will yield a better measurement of the total sample than a simple attenuation average over the whole sample. This vertical segmentation of the sample accommodates variations in matrix material and yields good results for a large variety of samples that otherwise are not easily measured. The fundamental assumptions on material homogeneity must be thoroughly understood and will be treated in the next section. The cited references all discuss in a general way the effects of geometry, attenuation, inhomogeneities, and other problems; a useful compendium of these topics is found in Reilly and Parker.[4]

II. THEORY OF OPERATION

A. General

The general technique of making a gamma-ray assay consists of counting the number of gamma rays detected in a full-energy peak unique to the isotope being measured, multiplying this quantity by a correction factor based on gamma-ray attenuation and rate considerations, and dividing the product by the calibration factor, or response of the system, to obtain as a result the grams of material assayed. Thus, the equation under consideration is:

$$\text{Isotope Mass} = \frac{C \cdot CF}{k} , \tag{1}$$

where C represents the number of counts in the gamma-ray full-energy peak, CF the relevant correction factor, and k the calibration constant relating corrected counts to mass of nuclear material.

All gamma-ray spectra have backgrounds (counts under the peak but not part of it) associated with any given peak due to events that come from Compton scattering of higher-energy gamma rays, electronic pileup, and other spurious sources. Various methods have been used to subtract these backgrounds from the gross peak count, the best of which involve elaborate peak fitting routines suitable only for computer analysis. For the well-resolved peaks used in the present assays, much simpler methods are available. The method employed in the present instrument, which gives a very adequate background subtraction, is a straight-line method based on a background region on each side of the peak being measured. The regions of interest are set on both

sides of the peak being measured as indicated in Fig. 1, and a background subtraction is made, based on a straight-line background between the average values of the two regions. Using the nomenclature of Fig. 1, the background-subtracted peak count and associated statistical error estimate are:

$$\text{Counts (peak)} = \Sigma B - \frac{\Delta B}{2}\left(\frac{\Sigma A}{\Delta A} + \frac{\Sigma C}{\Delta C}\right) \tag{2}$$

and

$$\sigma^2(\text{counts}) = \Sigma B + \left(\frac{\Delta B}{2 \cdot \Delta A}\right)^2 \Sigma A + \left(\frac{\Delta B}{2 \cdot \Delta C}\right)^2 \Sigma C \ . \tag{3}$$

The appropriate widths and positions of the regions of interest will be discussed in Section IV.

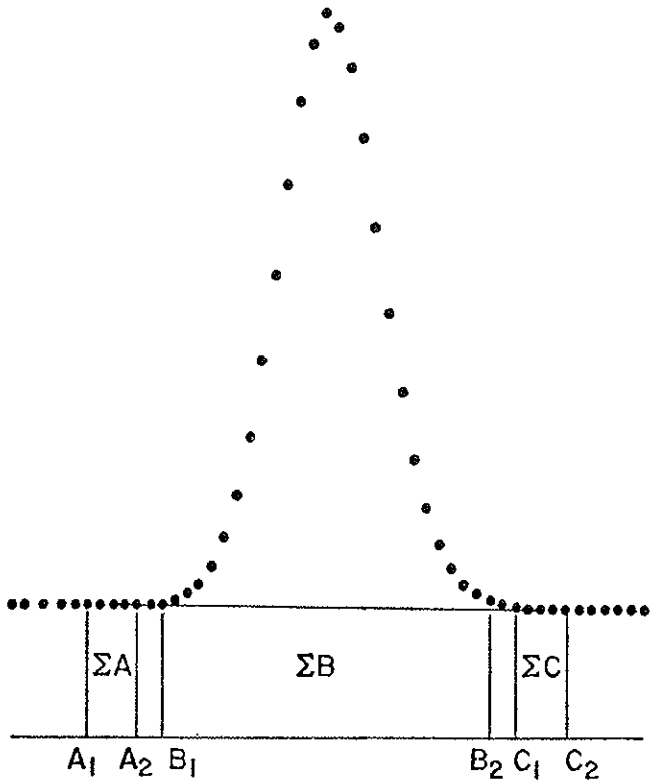


Fig. 1. Full energy peak indicating typical regions of interest for background subtraction. ΣA, ΣB, ΣC are the integrated counts in the respective regions. $\Delta A = A_2 - A_1 + 1$, $\Delta B = B_2 - B_1 + 1$, and $\Delta C = C_2 - C_1 + 1$ are the widths of the regions of interest.

B. Segmentation

As mentioned previously, the sample is assayed as a vertical sequence of collimator-defined horizontal segments, approximately 1.25 cm in height for small samples and 5 cm in height for drums, in order to minimize the effect of vertical inhomogeneities. The segment height is a compromise between increasing segment resolution and vanishing count rate, and is primarily determined by the dimensions of the collimator in front of the detector. Experience has shown that for samples up to about twenty liters in size, approximately one centimeter is a good segment height. For the larger drums, reasonable throughput and geometrical constraints make five centimeters the smallest segment height for normal use. It should be realized that the segments overlap somewhat, especially in the assay of drums with the larger collimator height. In the LASL segmented gamma-scan instrument, the small sample collimator is 1.3 cm high (by 10.2 cm long) while the large drum collimator is 5.1 cm high (by 17.8 cm long).

The segmentation procedure provides two benefits, the first being, as explained, an effective way of dealing with vertical nonuniformity in the assay samples, and the second being the freedom to use a single-assay geometry for all sample depths greater than a required minimum. These advantages are, however, obtained at the price of some loss of sensitivity; hence, the segmented gamma scan should usually not be used on samples containing < 1g of ^{239}Pu or ^{235}U. Furthermore, for the most accurate results from segmented gamma-scan assays, the assay sample should be as close as possible to the segment-defining collimator, and the depth of material in the sample should be ≥ 6 times the "thickness" of the segment. Keeping the sample as close as possible to the collimator maximizes the spatial resolution of the segments so that the measured transmission is more

clearly representative of the sample volume from which gamma rays reach the detector. Requiring the sample depth to be $\geq$ 6 times the segment thickness minimizes the end effect which is the second price paid for the advantages of segmentation. This end effect arises because, in general, the sample transmission measured as the top or bottom of the sample material moves across the collimator is somewhat too high, a consequence of the fact that only part of the gamma-ray beam from the transmission source is intercepted by the sample material during those intervals. An erroneously high transmission implies a too small correction factor so that the corrected count from such a segment is somewhat low. If the two criteria given above are met, the total end effect error should not ever exceed a few percent, with the greatest error occurring on samples of very low transmission.

C. Rotation

Rotating the sample is an effective way to reduce the effect of radial inhomogeneities and maintain the highest possible count rate. High count rate requires the detector to be as close as possible to the sample, whereas a large sample-diameter-to-detector-distance ratio introduces substantial count rate dependence upon radial inhomogeneities in the sample. From Fig. 2, the ratio of average count rate of a source rotating at a radius (a) to that of a source located at the center is given by

$$\frac{CR(a)}{CR(o)} = \frac{1}{1 - \left(\frac{a}{R}\right)^2},$$ where R is the distance from center of detector.

The effect of rotation of the sample on count rate variation is shown in Table I for several values of a/R.

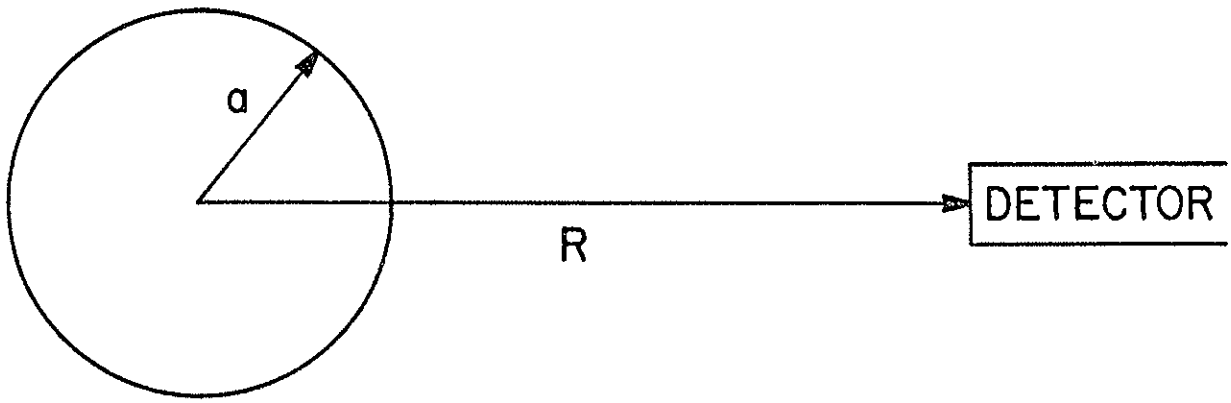


Fig. 2. Assay geometry, illustrating effect of sample rotation.

Table I
EFFECT OF ROTATION OF THE SAMPLE

a/R	CR(a)/CR(O) Rotating	CR(R-a)/CR(R) Nonrotating
1/2	1.33	4.0
1/3	1.125	2.25
1/4	1.067	1.78
1/5	1.042	1.56

Although the above expression and the results shown in Table I ignore the problem of self-attenuation, sample rotation clearly helps minimize the effects of radial inhomogeneity. For this reason, the sample is rotated in the

segmented gamma scan. In the LASL instrument the sample is rotated through two complete revolutions per segment.

D. Basic Assumptions

At this point, it is worth emphasizing the basic assumptions made on the sample in order to make reasonable assays with the segmented gamma scan. The fundamental assumption is that the mixture of material to be assayed and matrix (everything other than the assay material) is reasonably uniform and the particles of assay material are small enough to ignore self-attenuation within the individual gamma-ray emitting particles. In effect this assumption states that the sample attenuation (or at least that of a single segment) is characterized by a single linear attenuation coefficient. If this is not so, the correction factor computed from the measured transmission will not be accurate; unfortunately, the error will almost always be in the direction of a low assay. If, for example, the material emitting the gamma rays consists of bits of uranium metal imbedded in a low-density material, the transmission measurement of this sample would be some average of uranium metal and the low-density material; probably much closer to the attenuation of the light material since it would dominate the area of the sample seen by the transmission source, whereas the nuclear material gamma rays in this case would be attenuated mainly in the uranium metal from which they arise. The correction factor applied would then be low, yielding an assay value below the actual value (this effect can result in assays as much as a factor of two too low).

The assumption on sample uniformity imposes constraints on the general character of the sample. It requires that the material containing the nuclear isotope being assayed not be in lumps. Fuel pellets in a container of low-density waste does not, for example, meet the requirement of uniformity and will most certainly result in a low assay. On

the other hand, pure powders (PuO_2, UO_2, U_3O_8, etc.) do satisfy the assumption, as does most incinerator ash and well-mixed powder scrap. Solutions, of course, by definition satisfy the assumption on uniformity.

E. Calibration Standards

The fundamental assumption of segmented gamma scanning, applies as well to the calibration standards employed. Since there are minor geometric effects in the system setup, it is desirable to use a calibration standard as similar as possible geometrically to the assay samples, although a reasonable degree of compensation is usually possible if exact geometric similarity is not possible. The calibration standard is used to determine the response of the system in terms of corrected counts per gram of material being measured. Since the calibration curve is reasonably linear for a properly adjusted instrument, a single calibration standard can suffice, although it is desirable to have two or more standards spanning the expected range of transmission. A useful check of system performance not employing a standard at all is to measure empty air, which will give a zero result for a well-adjusted system. The calibration constant is not strictly constant for all conditions, but its variation with different size samples, provided the detector-sample geometry is unchanged, is not as important as the variation with measured transmission. For best accuracy, the calibration standards should also be as similar as possible to the measured samples in attenuation, since this is the overriding variable in determining the calibration constant.

F. Rate Corrections

We now consider the problem of corrections for the rate-related losses to the counts in the transmission and assay peaks (i.e., the full-energy peaks from the external

transmission source and the chosen gamma ray from the isotope being measured). During the time a datum is being processed by the ADC and computer system, the system is dead to further detector outputs that may occur. This system deadtime increases as the rates increase, resulting in a varying fraction of full-energy events being accepted and stored by the system. In other words, since the real measurement time for each segment is fixed, the actual time the system is available to accept data is less than the real time, requiring a correction to the observed count rate. In addition to this deadtime correction, there is yet another rate-dependent effect that must be considered. If two input pulses to the amplifier are sufficiently close together so that the amplifier pulse width is longer than the pulse separation, the output pulse resulting from these two inputs will be a single pulse whose amplitude is greater than either of the input pulses, the actual output amplitude depending on the pulse separation. What has changed in this case is that both real input pulses are lost to the measurement, and an incorrectly large pulse has been measured instead. Generally, this larger pulse will be outside the data windows for the peaks being measured, so that effectively the system deadtime has been increased. This so-called pileup effect is clearly rate dependent, since the probability of two inputs occurring sufficiently close together increases with rate.

Deadtime and pileup corrections can generally be made in any one of three ways. There are electronic modules that search for pileup pulses and automatically extend the counting time to compensate for this as well as ordinary deadtime, but these are complex in operating theory, and it is not at all clear that any of them currently make precisely the right correction. In addition, they add substantially to the system complexity and thus to potential unreliability.

A second method of rate correction is to use an external electronic pulser signal injected into the preamplifier. Since the pulser emits pulses at precisely known intervals, the number of pulses generated is a known quantity, against which the measured pulser peak can be compared to determine the amount of loss due to pileup and/or system deadtime. This method has the advantage of being able to place the pulser peak anywhere in the spectrum desired, since the pulser output height is variable. However, against these advantages must be weighed the fact that a pulser is a piece of electronic equipment, subject to instabilities due to temperature variations and component aging and therefore is subject to unreliability and variability, both in pulse amplitude and rate.

Experience at LASL indicates that usually the best method of making rate corrections is by using an appropriate external gamma-ray source to provide a livetime/pileup correction peak somewhat below the energy of the transmission and assay peaks. Since this livetime/pileup correction peak comes from a separate gamma source, it competes for system resources in exactly the same way as the peaks of interest, entering the system right at the detector, thus allowing a combined correction for deadtime and pileup for the whole system. Furthermore, the rate of emission from a gamma source is not affected by temperature, pressure, or other experimental conditions. Sometimes a portion of the assay spectrum is used where no conveniently obtainable source has an appropriate gamma ray, and hence a pulser must be used, but whenever the separate source method is possible, it is superior. All of the common assays with the SGS permit rate-related loss corrections to be made conveniently by use of a separate gamma source. While this complicates the analysis by adding another peak to be analyzed, the system computer is readily able to handle the

overhead. In using a separate livetime/pileup source, the normalization rate from the correction source is measured prior to making assay measurements, with no sample in the system. Then, during actual measurements, the rate from the correction source is again measured, and the ratio of the two values is precisely the correction factor that must be applied to all other peaks to correct for deadtime and pileup. This procedure assumes that all spectral peaks suffer the same fractional loss from pileup and deadtime, which assumption is true in theory and justified by experience. It should be said that the method of using an external gamma-ray source does not result in an absolute correction, but rather a normalization in which all results are corrected to the same fraction of rate-related losses as experienced in the normalization measurement.

G. Calculation of Corrected Counts

In the actual calculation of corrected counts, defined as the actual counts multiplied by a correction factor, the correction factor depends upon both attenuation and rate corrections. In fact, the total correction factor is defined as the product of three independent or nearly independent correction factors: one for the normalization of the rate-related losses to the counts in the full-energy peak of the gamma ray upon which the assay is based ($CF_{r\ell}$), one to correct the attenuation in the sample container (CF_{con}), and one for the correction of the self-attenuation in the sample itself (CF_{att}). Symbolically, the total correction factor is given by

$$CF_{tot} = CF_{r\ell} \cdot CF_{con} \cdot CF_{att} . \qquad (4)$$

case (defined as that situation where the dimensions of the sample are small compared to the distance to the detector). A first-order approximation to that exact formulation yields

$$CF \simeq \frac{-(\pi/4)\ \ell n(TR)}{1 - TR^{\pi/4}} \quad .$$

It is immediately noted that the form just given is identical to that for the slab geometry except that the transmission is raised to the $\pi/4$ power. Because the $\pi/4$ power arose from the approximation of a far field expression, and to determine whether it would yield appropriate values in a near field, collimated situation, a study was made of the general form

$$CF_{att} \simeq \frac{-A\ \ell n(TR)}{1 - TR^{A}} \qquad (6)$$

in order to find what value of A would give the most nearly correct values over a wide range of transmissions, sample diameters, and sample-detector distances. Figure 3 shows the variation from the exact far-field values as a function of A and TR. Within the normal range of transmission values, A = 0.82 yields accuracies within one or two percent. In the segmented gamma scan codes, CF_{att} is given by Eq. (6) with A = 0.82.

Finally, consider the last factor, CF_{con}. In actual practice, most samples are contained in a container that causes some attenuation itself, for which Eq. (6) is not a proper correction factor form. Since the container transmission is a constant, it can be separated from the transmission of the contents of the container and included as a constant factor in the expression for the total correction.

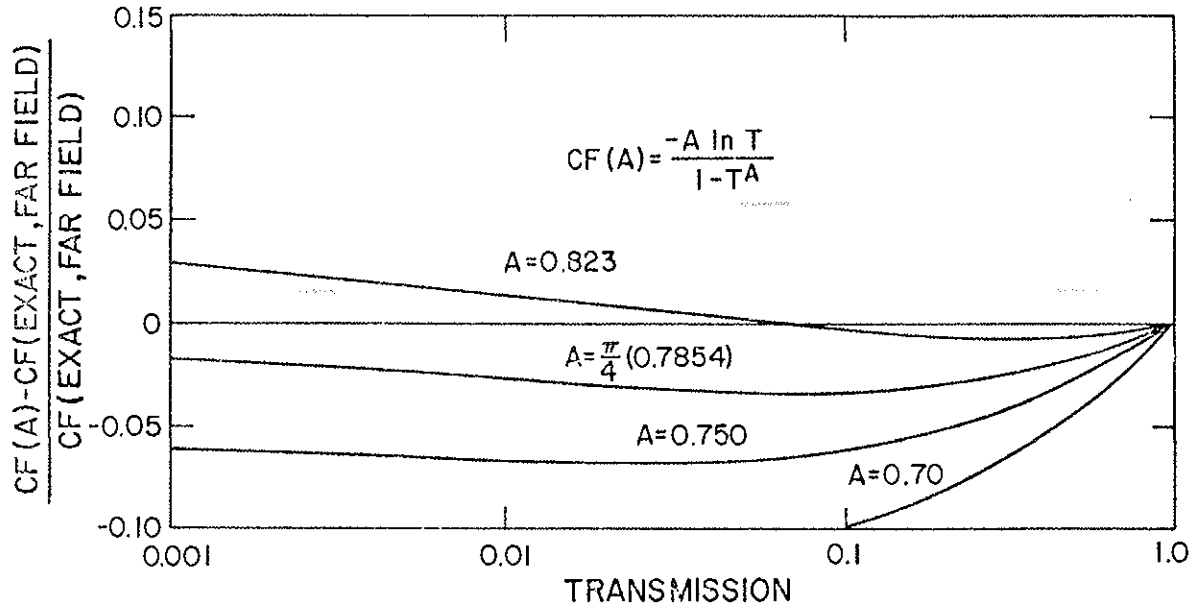


Fig. 3. Variations of the approximate correction factor values from the exact far-field values as a function of transmission TR and the parameter A.

It is easily measured in practice by simply assaying an empty container and reading off the transmission values from the printout. If it is assumed that all gamma rays from the sample pass through the minimum container thickness, the correction factor due to container transmission is:

$$CF_{con} = \frac{1}{\sqrt{TR_{con}}} , \tag{7}$$

where TR_{con} is the container transmission.

Then the final equation for the corrected counts in the i^{th} segment can be written as follows:

$$CC(i) = C(i) \cdot CF_{tot}(i) = C(i) \cdot CF_{r\ell}(i) \cdot CF_{att}(i) \cdot CF_{con}(i), \tag{8}$$

where C(i) is the full-energy peak count from the assay gamma ray and the various correction factors are as defined above in Eqs. (4), (5), (6), and (7). Transmission of the sample is given by

$$TR = \frac{T}{T_o} \cdot \frac{L_o}{L} \cdot \frac{1}{TR_{con}} = \frac{T}{T_o} \cdot CF_{r\ell} \quad CF_{con}^{2}, \tag{9}$$

where T and L are the full-energy peak counts from the transmission and correction gamma-ray spectral peaks, respectively, and the subscript "o" refers to values from the no-sample (or background) measurement.

The sum of the corrected counts for all segments is related to the quantity of material being assayed and is written as

$$CC_{total} = \sum_{i=1}^{N} CC(i), \tag{10}$$

which corresponds to C · CF in Eq. (1).

H. General Isotopic Measurements

For the general problem of measuring specific isotopic contents in nuclear materials, the energy to be measured must be determined, and suitable transmission and correction sources chosen. Some of the more common combinations of sources for given isotopes are given in Table II.

With the exception of the ^{235}U assay, or in the attempt to measure simultaneously more than one isotope of plutonium, all of these assays are three-peak measurements. Note that the transmission and rate correction gamma-ray energies are chosen lower in energy than the assay energy, when possible, in order to reduce the backgrounds that would result from Compton scattering of any additional higher energy gamma rays. Also, at all energies, but most

TABLE II

COMMON COMBINATIONS OF SOURCES FOR GIVEN ISOTOPES

Isotope (Gamma Energy)	Transmission (Source Energy)	Rate Corrections (Source Energy)
Pu-238 (766.4 keV)	Cs-137 (661.6 keV)	Ba-133 (356.3 keV)
Pu-239 (413.7 keV)	Se-75 (400.1 keV)	Ba-133 (356.3 keV)
U-235 (185.7 keV)	Yb-169 (177.2, 198.0 keV)	Co-57 (122.0 keV)
U-238 (1001.1 keV)	Mn-54 (834.8 keV)	Cs-137 (661.6 keV)
Np-237 (311.9 keV)	Hg-203 (279.2 keV)	U-235 (185.7 keV)

particularly at lower energies where the mass attenuation curves have steep slopes, the transmission peak energy should be as close as possible to the assay energy in order to reduce the energy-dependent effects of attenuation. Transmission peak attenuations that differ from the assay peak attenuation can be mathematically accommodated, as will be discussed later, but this requires additional knowledge about the matrix material that is not required when the transmission peak accurately reflects the attenuation experienced by the actual assay peak.

I. ^{235}U - A Four-Peak Assay

Because of its rather low assay energy (185.7 keV), ^{235}U requires special consideration in the measurement of its transmission. Fortunately, the ^{169}Yb decay produces two gamma rays that bracket the uranium assay energy, at 177.2 keV and 198.0 keV. In this energy region, the mass

attenuation coefficient is rapidly changing with energy, so that it is quite critical to determine the attenuation exactly at 185.7 keV to avoid undue error. The procedure here is to take peak information from both ^{169}Yb peaks and make a linear interpolation between them to obtain the transmission at 185.7 keV. This adds yet another gamma peak to the assay information and considerably complicates both the assay calculation and the error calculation. For this case, the transmission to be used in Eq. (9) becomes with good accuracy:

$$TR = 0.6 \cdot TR_{\ell} + 0.4 \cdot TR_{h}, \qquad (11)$$

where TR_{ℓ} and TR_{h} are the measured transmissions at the low and high transmission energies, namely, 177.2 keV and 198.0 keV.

As a practical matter, ^{169}Yb has the short half-life of only 32 days, which means that this source must be replaced frequently in order to provide sufficient counts for an accurate transmission measurement through denser materials. The ^{57}Co source used with uranium measurements has a half-life of 271 days, much better than the ^{169}Yb, but still requiring replacement (or at least position adjustment) about once a year.

Another method of determining the transmission at 185.7 keV exactly is to use ^{235}U itself as the transmission source, making a two-pass assay, once with the transmission source shuttered and once with it open, then making a subtraction to determine the contribution due to ^{235}U in the sample and that due to ^{235}U in the transmission source. This technique does, in fact, work well for some samples of low uranium concentration, but the problem is that the self-attenuation of uranium is so great that it is always

difficult and often impossible to obtain a source of sufficient intensity. The best method for segmented gamma-scan applications is the use of ^{169}Yb with its two transmission peaks, the short half-life notwithstanding.

J. Simultaneous ^{239}Pu, ^{241}Pu Assay

For most plutonium measurements, the percentage of ^{241}Pu is down several orders of magnitude from that of ^{239}Pu. However, since the intensity of the 208-keV gamma ray from the ^{237}U daughter of ^{241}Pu is several orders of magnitude greater than the 414-keV gamma ray from ^{239}Pu, the simultaneous measurement of these two isotopes is frequently feasible. The primary problem is finding a transmission gamma ray with which to determine the 208-keV attenuation. Another transmission source could be used, but aside from the physical difficulties of collimating two sources properly, the additional background from yet another source is undesirable. The alternative is to use another of the existing ^{75}Se source gamma rays. Selenium-75 has an intense gamma ray at 265 keV, which can be used to determine the transmission at 208 keV by making an adjustment to Eq. (6) that takes into consideration the variation of mass attenuation coefficients between the assay and transmission peaks. This requires some knowledge of the matrix materials, but for low-Z materials (up to about Z = 25 or so), the ratio of these mass attenuation coefficients can be taken to be about 1.2. The error incurred here will be discussed later in the section on mu-ratio considerations. In the case of ^{239}Pu, ^{241}Pu simultaneous measurements, five peak counts must be obtained for each segment; the usual three peaks plus an additional assay peak and transmission peak. In effect, two three-peak measurements are performed using the five-peak areas.

K. Two-Pass Assays

Up to now, we have been discussing assays in which both the transmission and assay peaks (and, of course, the correction peak) are measured on the same pass through the sample. In fact, the transmission gamma ray was specifically chosen at a lower energy than the assay gamma ray in order to minimize Compton interference with the latter. There are, nevertheless, cases where backgrounds from the transmission source interfere with the assay peak and where it becomes desirable to minimize this effect. In the case of uranium, for example, some interference at 185.7 keV is inevitable from the ^{169}Yb gamma rays of 198.0 and 177.2 keV.

One solution to this problem is to assay the sample in two passes, once with the source open to measure the transmission, and again with the source shuttered to measure the assay peak. This procedure improves the precision and often the accuracy of the measurement, but it becomes particularly relevant in the case of uranium or small amounts of plutonium. It also increases the assay time by a factor of two, so careful consideration must be given in each case to determine whether two passes will result in significant improvement of the measurement result. The calculation is considerably more complex in the case of two pass assays, since the livetime-pileup correction peak must be measured for both cases. Also, if two-pass assays are to be made, the background (straight through) run must be a two-pass run as well, because typically the background run is done once per day and serves for all subsequent assay, one-pass or two-pass. Here, one rate correction would be applied to the transmission peak, and another to the assay peak. The rate-loss correction factor for the assay peak, $CF_{r\ell}$, should always be referenced to the second background pass (transmission source shut off) because of its lower fraction of

loss and because the correction peak value will change more slowly with time (see Section II-N for a full explanation of this effect). It is also clear that rate losses in the transmission peak should be referenced to the first-pass (shutter open) of the background run.

In order to eliminate unnecessary use of the two-pass option and yet preserve its better precision and accuracy when necessary, it is convenient to invoke a computer check automatically on the data as they are received to decide after the first pass has been completed whether another pass is necessary or not. It is a simple matter to take full data on the first pass, and have the computer check the assay peak to background ratio, and determine whether another pass would be useful. In this way, the operator is relieved from the task of making an arbitrary decision on the matter, and maximum throughput consistent with best statistical accuracy is maintained. In the LASL segmented gamma-scan system, if the sum over all segments examined of the variances of the assay peak areas is greater than twice the sum of the assay peak areas, a second pass is required. This criterion is plausible when one remembers that the variance of the peak area of a no-background peak is the peak area itself.

Four types of assay procedures have now been discussed:

(a) three-peak, one-pass assays,
(b) four-peak, one-pass assays,
(c) three-peak, two-pass assays, and
(d) four-peak, two-pass assays.

For the sake of clarity, all the expressions relating to each type of assay are collected and presented below. The subscript 1 refers to passes with the transmission source open and the subscript 2 refers to passes with the

transmission source shuttered, for either background runs or assay runs. Also, as before, the subscript o refers to background run values while the subscripts ℓ and h refer to the low and high energy transmission peaks respectively in four peak (two transmission peaks) assays.

The general form for the corrected count from a segment is given by (dropping the segment subscript)

$$CC = C \cdot CF_{r\ell} \cdot CF_{att} \cdot CF_{con},$$

where the forms for CF_{att} and CF_{con} are as always

$$CF_{att} = \frac{-A\ \ell n(TR)}{1 - TR^{A}}$$

and

$$CF_{con} = \frac{1}{\sqrt{TR_{con}}} \cdot$$

For one-pass assays the forms for C, $CF_{r\ell}$ and TR are:

$$C = C_1$$

$$CF_{r\ell} = L_{o2}/L_1$$

$$TR = \frac{T_1}{T_{o1}} \cdot \frac{L_{o1}}{L_1} \cdot CF_{con}^2 \qquad \text{(For three-peak assays)}$$

$$TR = (0.6)TR_{\ell} + (0.4)TR_h \qquad \text{(For four peak assays)}$$

with

$$TR_{\ell} = \left(\frac{T_1}{T_o}\right)_{\ell} \cdot \frac{L_{o1}}{L_1} \cdot CF_{con}^2$$

and

$$TR_h = \left(\frac{T_1}{T_{o1}}\right)_h \cdot \frac{L_{o1}}{L_1} \cdot CF_{con}^2 \quad .$$

For two-pass assays the forms for C, $CF_{r\ell}$ and TR are:

$$C = C_2$$

$$CF_{r\ell} = \frac{L_{o2}}{L_2}$$

$$TR = \frac{T_1}{T_o} \cdot \frac{L_{o1}}{L_1} \cdot CF_{con}^2 \qquad \text{(For three-peak assays)}$$

$$TR = (0.6)TR_{\ell} + (0.4)TR_h \qquad \text{(For four-peak assays)}$$

with

$$TR_{\ell} = \left(\frac{T_1}{T_{o1}}\right)_{\ell} \cdot \frac{L_{o1}}{L_1} \cdot CF_{con}^2$$

$$TR_h = \left(\frac{T_1}{T_{o1}}\right)_h \cdot \frac{L_{o1}}{L_1} \cdot CF_{con}^2 \quad .$$

L. Error Calculations

Next of concern is the estimation of the random errors associated with the segmented gamma-scan technique. Systematic errors are not readily amenable to calculation, and can be partially discovered and evaluated only by use of information not usually obtainable by the computer during an assay run.

There are two general sources of error in the final assay values; the statistical error in the corrected counts,

and the error in the calibration constant that relates corrected counts to mass of material. The former is of primary concern at assay time, since the computer has the data available to evaluate statistical random errors in the corrected counts, which are based solely on the accumulated counts in several gamma-ray spectra peaks.

Thus, for the following discussion, the propagation of error includes only that from Poisson counting statistics; no contributions from electronic instabilities or from calibration uncertainty are considered.

With each gamma-ray peak bracketed by counting windows as indicated in Fig. 1, Eqs. (2) and (3) indicate the calculations of background-subtracted peak counts and the associated statistical error. Note that if the background were much less than the peak, the error estimate of the peak counts (Eq. (3)) reduces to the familiar square root of the peak number. Unfortunately, in actual practice, backgrounds can be quite large, and the final two terms in Eq. (3) cannot be neglected in making error estimates for each peak used in the assay calculation.

The estimates of precision are derived from the expressions for the corrected count per segment by use of the formula for the variance of a function of n independent variables; that is,

$$\sigma^2[V(x_1,x_2,\ldots x_n)] = \left(\frac{\partial V}{\partial x_1}\right)^2 \sigma^2(x_1) + \left(\frac{\partial V}{\partial x_2}\right)^2 \sigma^2(x_2) + \ldots + \left(\frac{\partial V}{\partial x_n}\right)^2 \sigma^2(x_n).$$

The expressions for the corrected counts are written in terms of the measured independent quantities, namely the full-energy peak areas of the assay, transmission and correction peaks that have been denoted C, T, and L, respectively with appropriate subscripts. The values of the

correction and transmission peaks from the background run (both passes) are assumed to have no random error because they enter into a long series of assay measurements as constants. They are measured typically only once per day and then to high precision by averaging over a large number of segment values. Thus, even on a long-term basis there is very little random variation associated with the values from the background and it is reasonable to assume none. The correction factor for the container, $CF = \sqrt{1/TR_{con}}$, is also assumed to have no random error. As discussed above there are four types of assay runs with slightly different expressions for the corrected count and each consequently has a somewhat different expression for the estimated precision. The complexity of the expressions varies because the number of independent variables with respect to which derivatives must be taken ranges from three (three-peak and one-pass assays) to five (four-peak and two-pass assays). The three-peak two-pass assays and the four-peak one-pass assays have four independent variables. The expressions will not be derived here but the results will be given, expressed not in terms of the actual independent variables but simplified by expressing them in terms of the corrected counts, the correction factors, the transmissions and the relative standard deviations of the independent variables. The complexity, even so, of the resulting expressions emphasizes the necessity for automatic computational capability when dealing with any but the simplest of gamma-ray assay procedures. After the estimates of the precision for the corrected count of each segment have been computed, the square root of the sum of the squares of the segment estimates yields the precision estimate for the total corrected count.

The expressions for the precision estimate for the four types of assay are given below. For simplicity the segment

subscript has been omitted as it applies to all quantities except A, the constant in the expression for CF_{att}, and CF_{con}, the container correction factor that is assumed constant. Note again that the relative standard deviation has been used where by definition $\sigma_r(V) = \sigma(V)/V$ with the standard deviations being estimated by Eq. (3). It must be remembered that the actual forms of CC, $CF_{r\ell}$, and TR vary with the type of assay. Finally, the appearance of the final expressions may be simplified by making a substitution for a complex factor appearing in all four of them.

By letting

$$K = \frac{A}{CF_{att}} \cdot \frac{\left(1 - TR^{A} \cdot CF_{att}\right)}{1 - TR^{A}}$$

the following expressions are obtained.

For the three-peak, one-pass assay

$$\sigma^2(CC) = CC^2 \cdot \left[\sigma_r^2(C_1) + K^2 \cdot \sigma_r^2(T_1) + (1-K)^2 \cdot \sigma_r^2(L_1)\right] .$$

For the three-peak, two-pass assay

$$\sigma^2(CC) = CC^2 \cdot \left\{\sigma_r^2(C_2) + \sigma_r^2(L_2) + K^2\left[\sigma_r^2(T_1) + \sigma_r^2(L_1)\right]\right\} .$$

For the four-peak, one-pass assay

$$\sigma^2(CC) = CC^2 \cdot \left\{\sigma_r^2(C_1) + K^2 \cdot \left[\left(\frac{TR_\ell}{TR}\right)^2 \cdot \sigma_r^2(T_{1\ell}) + \left(\frac{TR_h}{TR}\right)^2 \cdot \sigma_r^2(T_{1h})\right] + (1-K)^2 \cdot \sigma_r^2(L_1)\right\} .$$

For the four-peak, two-pass assay

$$\sigma^2(CC) = CC^2 \cdot \left\{ \sigma_r^2(C_2) + \sigma_r^2(L_2) + K^2 \cdot \left[\left(\frac{TR_\ell}{TR} \right) \cdot \sigma_r^2(T_{1\ell}) + \left(\frac{TR_h}{TR} \right)^2 \cdot \sigma_r^2(T_{1h}) + \sigma_r^2(L_1) \right] \right\} .$$

The quantity K is always less than 1.0 and in the range $0.1 \leq TR \leq 0.7$, $0.29 \leq K \leq 0.39$.

M. Varying the Mu Ratio

All equations derived up to this point have assumed that the transmission gamma-ray and assay gamma-ray energies are sufficiently close together that their mass attenuation coefficients are essentially the same. However, this is not always the case, particularly in the case of ^{241}Pu assay, where the 208-keV assay energy is corrected for transmission as measured by the 265-keV ^{75}Se gamma ray. In the cases where the transmission energy differs significantly from the assay energy, Eq. (6) is no longer a correct expression for the correction factor, and since the correction factor is multiplied by the actual counts to yield corrected counts, errors in the correction factor are reflected directly into assay errors.

Figure 4 shows a plot of the correction factor vs mu ratio for several values of transmission, where the mu ratio is the ratio of μ_a, the mass attenuation coefficient at the assay energy and μ_t, the mass attenuation coefficient at the transmission energy. Note that at very high transmissions (low attenuation), the effect of the mu-ratio variation is negligible. However, at high attenuation, using an incorrect mu ratio can result in large errors in the correction factor, and hence, in the assay results.

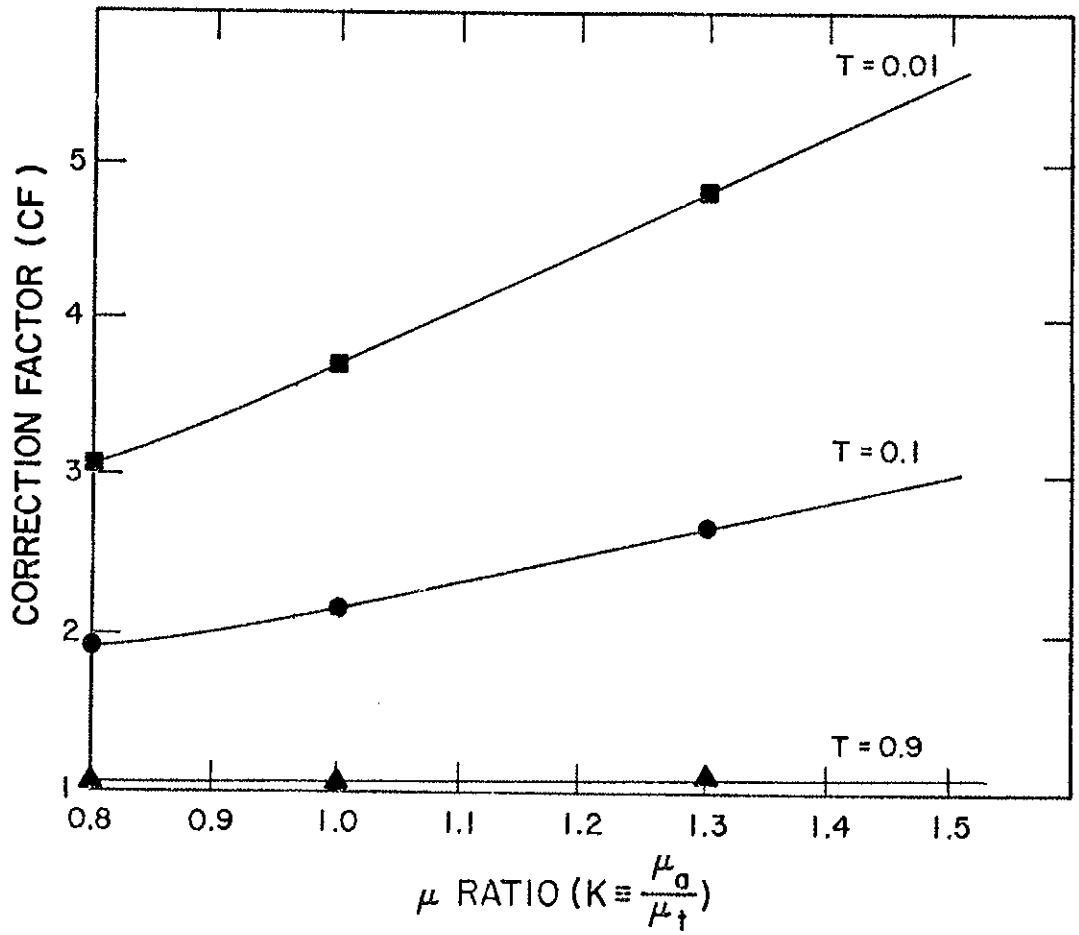


Fig. 4. Plot of the correction factor vs the mu ratio for several values of transmission.

Equation (6) is corrected for the mu-ratio variation by changing the geometric factor, A, to an AK, where K is now the mu ratio as just defined. This same substitution must be made in all subsequent equations, including error calculations, wherever the geometric factor A appears. Note that if the mu ratio is different than unity, assumptions have been made implicitly concerning the nature of the matrix

material in the sample being measured. It is always best to use the transmission and assay energies sufficiently close together to make the difference in attenuation negligible. However, in the case of ^{241}Pu and other special cases where the energies are quite different, the system can include a mu ratio different than unity.

N. Time Dependence of Calibration Constant

Let us remind ourselves that the correction for the rate-related losses (deadtime and pileup) made by the use of the livetime-pileup correction peak in the reference spectrum is actually a normalization rather than an absolute correction. The correction factor LT_o/LT does not in fact make a full correction for all rate-related losses but rather normalizes all results to the fraction of losses in the reference spectrum. Thus, if 90% of full-energy events are stored in the full-energy peaks of the reference spectrum, the corrected count finally computed will only be 90% of what it would have been if complete correction had been made for the rate-related losses. As the sources involved in the reference run decay, the gross rate of detector interactions decreases and the fraction of full-energy events stored in the full-energy spectral peaks will slowly increase. One result of this situation is that the system calibration constant will slowly increase with time. This slow increase in calibration constant is of no particular disadvantage, for daily calibration checks must be made in any proper use of the segmented gamma-scan assay system. However, it is operationally desirable to have the calibration constant remain as nearly constant as possible. This can be accomplished by using a reference run which does not involve the shorter half-lived transmission sources (^{169}Yb - 32 days and ^{75}Se - 120 days) but only the longer-lived reference sources (^{57}Co - 271 days and ^{133}Ba - 11 years).

A two-pass background run is thus required for all assays (one pass with both reference source and transmission source and one pass with only the reference source),but that is necessary at any rate if the two-pass assay option is to be permitted at all. The important point of this discussion is that a slow change in the calibration constant may be expected but does not matter. The advantage in using the gamma-ray source method for rate-related loss correction (better referred to as normalization) more than outweighs the slight inconvenience of a calibration constant, which changes slowly with rate correction source decay.

O. Detector Resolution

Another important parameter in monitoring system performance is the detector resolution. The analysis system computes this parameter automatically, checking the resolution every time a background run is taken. In the present system, the program assumes that a three-peak or five-peak assay utilizes the 356-keV ^{133}Ba gamma line as the rate correction peak, determines the full-width-at-half-maximum in channel numbers, divides the center peak value by 356 keV to determine the system calibration in terms of channels per keV, and prints out the system resolution as a regular part of the background run printout. In the case of uranium, the program assumes the 122-keV energy peak from ^{57}Co as the rate correction peak. In this way, a running check on system resolution is maintained, with hard copy data to guarantee that the detector system was functioning properly at the time of each background run.

It should be added and emphasized that a detector of good resolution is highly desirable for it will yield better precision and accuracy than a detector of relatively poor resolution. Without going into a lengthy discussion of detector performance and specifications, experience

indicates that a detector capable of $\leq$ 2.0-keV resolution at 1332 keV and $\leq$ 1.00 keV at 122 keV is satisfactory for measurements done with the segmented gamma scan. With fairly short amplifier time constants (1.5 μs to 2.0 μs) and gross count rates of approximately 20000 s^{-1}, the system resolution at the correction peak energies should preferably be $\leq$ 1.1 keV at 122 keV (^{235}U assays) and $\leq$ 1.3 keV at 356 keV (^{239}Pu and/or ^{241}Pu assays).

P. Extensive Peak Fitting

As a final comment on the general theory of system operation, it is appropriate to remark that with a computer as an integral part of the system, the potential exists to do extensive peak fitting on the spectra as they are received in each assay. This permits, for example, extraction of isotopic information from data where peaks overlap. It should be remarked, however, that the codes required to accomplish extensive spectral fitting are quite complex and would require considerably more memory than the 2^{14} (16384) words used in the LASL segmented gamma-scan system.

III. SYSTEM SOFTWARE

A. General

Software for computer-controlled instruments such as the segmented gamma scanner can be written, in general, in any one of three broad categories of programming languages, assembly (machine) language, compiler language, or interpreter language. Assembly language permits maximum optimization of system resources, speed, and memory size. Compiler language permits somewhat more flexible programming without serious time loss in most calculational tasks, but must be compiled before the program can be loaded into the system and run. Interpreter languages permit maximum ease in programming, but are the most memory inefficient (since the interpreter

must be resident while the program is executing) and tend to run the slowest. One can argue persuasively for any of the three methods of programming, but in the safeguards field one overriding consideration is gradually emerging that will likely eliminate the interpreter mode from consideration. A program written in interpreter language is easy to change on-line to give whatever result the operator desires without detection, since it has available at run time all the system resources necessary to make program changes. This threat to the system software security will probably result in a mandate that software be handled in either compiler language or assembler language, both of which require separate programs to generate the object code for actual running, so that it often requires more system resources to make the compilation or assembly than are actually available at the instrument itself. Such codes are almost impossible to change on-line, and are thus much more secure.

The sections of code that actually interact with peripheral equipment (stepping motors, ADC interfaces, scopes, teleprinters, etc.) are almost always written in assembly language, but may be written as compiler-callable subroutines. In the long run, the most likely mode for producing instrument codes for safeguards equipment will probably consist of I/O drivers written in assembler language, embedded as callable subroutines in compiler-language programs.

The present instrument uses codes written in Data General^{R}-compatible assembly language, which permits maximum software flexibility, maximum hardware-software optimization, minimum core size (which substantially increases system reliability), and fast computer operation. The present codes fit into 8K words of 16-bit core memory, but a 16K board is used to permit possible system expansion or linking to a central accounting computer if desired. The

code is broken into four relocatable routines that generally handle interrupt, display, calculational, and floating point operations, respectively. In this system, all calculations are performed with floating point numbers and software subroutines that generally require a few milliseconds for a floating point operation. The display routines generate plots on a point-by-point basis, with the computer generating a digital number for each x,y point to be displayed, and the storage scope used to hold the information. Each DAC used for the display has 10-bit resolution, so that 1024 points can be displayed on each axis of the scope.

B. Detailed Flow Charts

The software system is split into several relocatable sections as mentioned above, which we will now discuss as flow charts of the program flow. The state of the computer is characterized by its interrupt situation; i.e., which external (or internal) devices can interrupt it at any given time. Table III indicates the five conditions permitted in the segmented gamma-scan software. Basically, Condition 1 is the idle state where no operation is underway, and the computer is ready to accept interrupts from the switch panel, by which all operations are controlled. As soon as one of the front-panel switches gives an interrupt, the machine enters one of the other conditions, depending upon which instruction is given. Condition 2 is a run condition, in which the only interrupts permitted are from the ADC or scan table, or the system stop switch. Condition 3 is a cursor display condition, where the display is being used interactively to enter windows or locate spectral peaks with the intensified cursor. Condition 4 is a general busy situation, where only a system stop will be permitted, as for example, when a display is being updated, or extensive calculations are being made. Condition 5 is a special

TABLE III

COMPUTER INTERRUPT CONDITIONS

Condition	Interrupts Enabled	Mask
1	RANGE SWITCH, ALL "READY" SWITCHES Enter Constants a Start Background Start Assay[a] Start Setup[a] Start Cursor Start Analyze Start Integrate DYMAC Transfer	10767_8
2	ADC, "SYSTEM STOP"	5777_8
3	RANGE SWITCH, "SYSTEM STOP", "START WINDOW", "STOP WINDOW"	13777_8
4	"SYSTEM STOP"	15777_8
5	RANGE SWITCH, "SYSTEM STOP"	11777_8

[a]There is a hardware mask that permits "start assay", and "start background" only when the "computer-local" switch is in the "computer" position, in which case "start setup" is locked out; conversely, in the "local" position, "start setup" is permissive and "start assay" and "start background" are locked out.

NOTE: Table end-of-assay and end-of-segment interrupts are always enabled.

situation of Condition 4, where, however, a change of the range switch is permitted to update the display.

Figure 5 shows the flow chart of the start of the program. From the Condition 1 idle loop, the interrupt is identified and appropriate action taken. The small circles with letters indicate another entry point to a subsequent

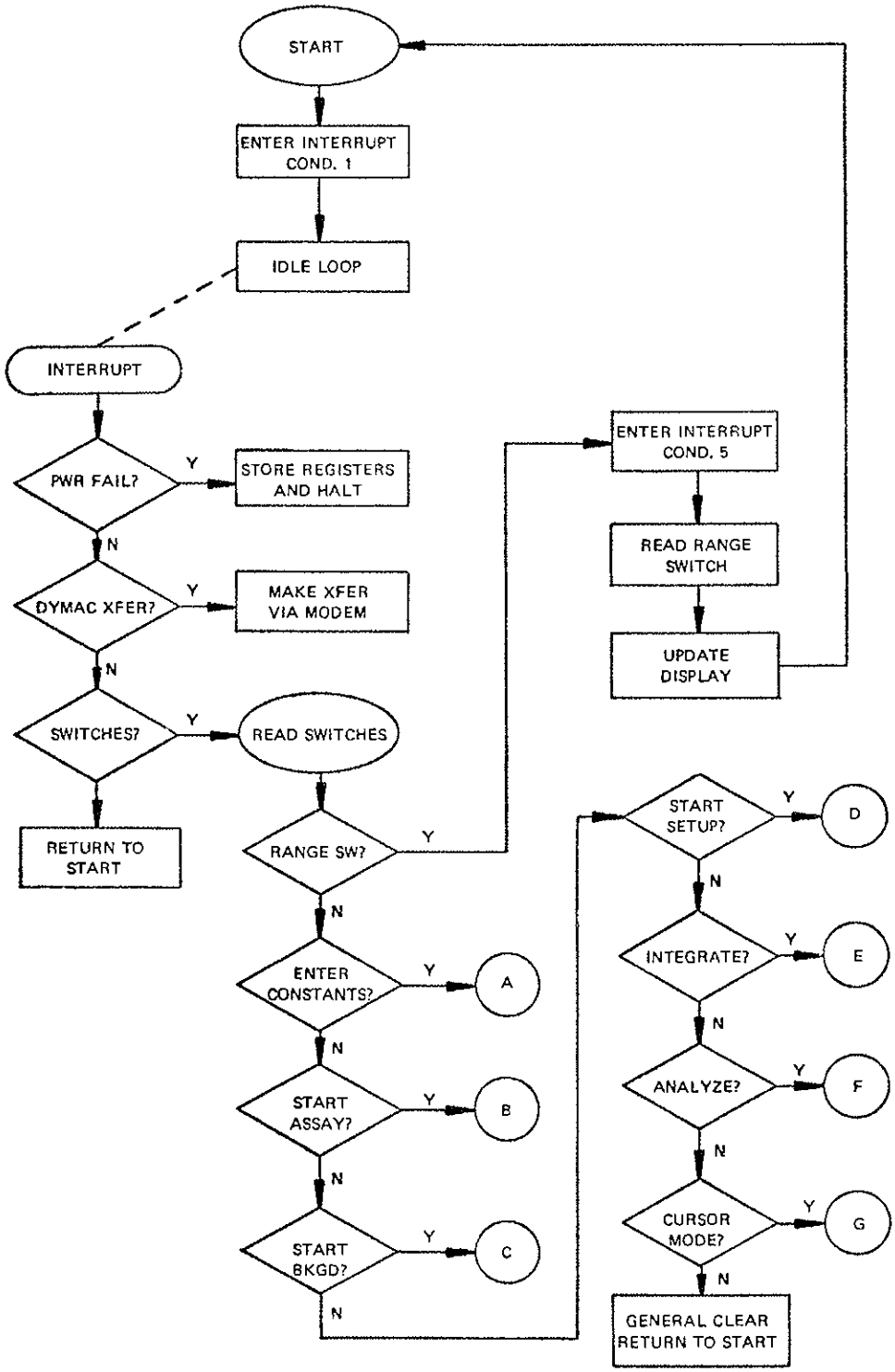


Fig. 5. Flow chart for first portion of the SGS analysis program.

flow chart. "DYMAC XFER" refers to an option in the system, not generally used except at LASL, for transferring data in serial form to a central accounting facility directly from the segmented gamma-scan computer with operator intervention.

Figures 6-16 indicate detailed operation of the program with its various branches and options, and they are self-explanatory. Detailed operation of the actual system controls will be given in the next section.

C. Interrupts, Storage, and Pointers

The inhibit masks that control the various machine conditions as described above are controlled by software bits on the data lines. These are established by an MSKO command, as follows in Table IV:

TABLE IV

MASK BIT ASSIGNMENT AND COMPUTER RECOGNITION CODES FOR EXTERNAL DEVICES

Device	Mask Bit	Device Code
ADC	3	44_8
Range Switch	4	42_8
Window Switches	5	42_8
"Ready" Condition	6	42_8
Storage Scope	-	34_8
Scan Table	-	74_8

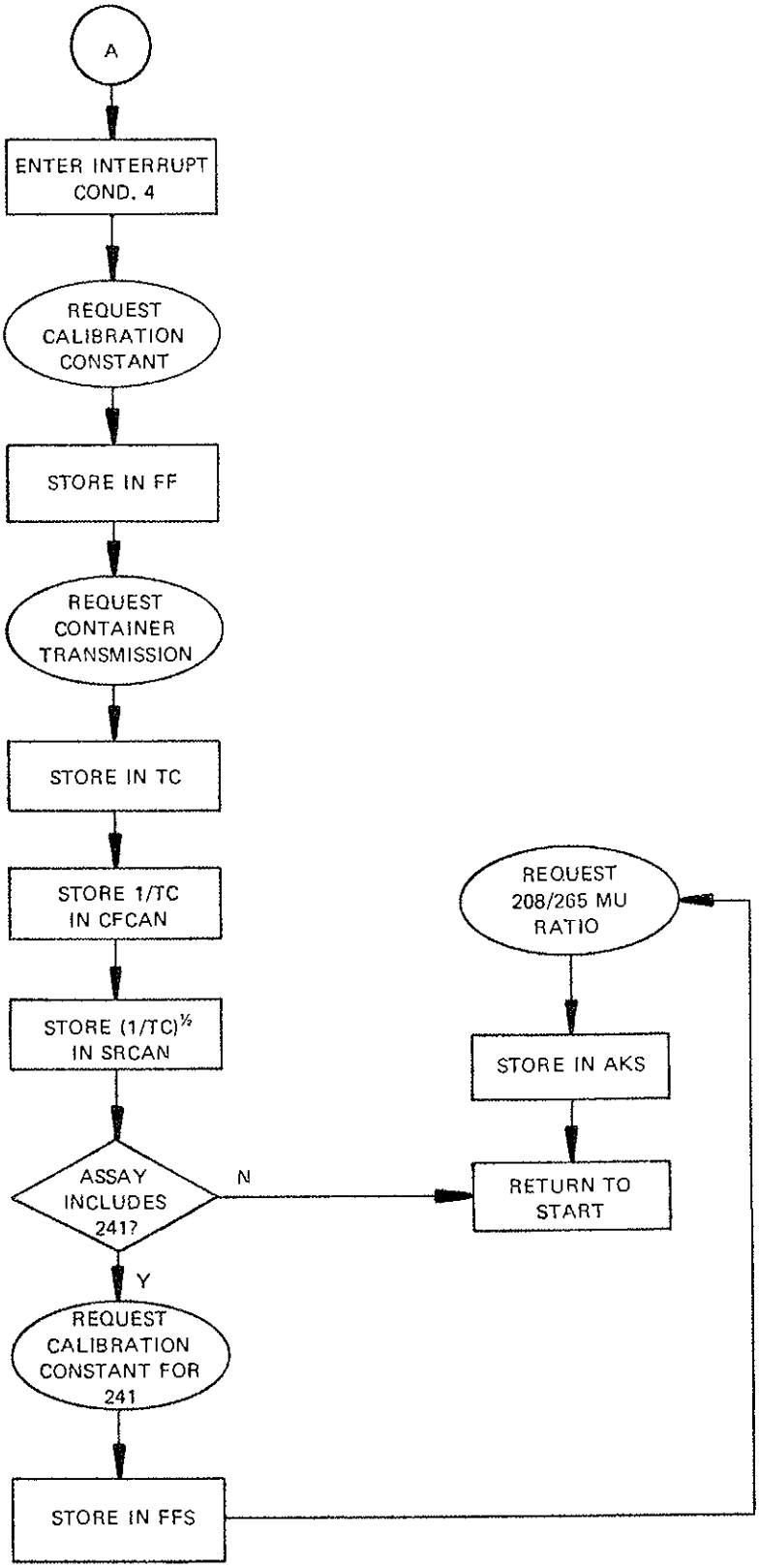


Fig. 6. Partial flow chart for the SGS analysis program.

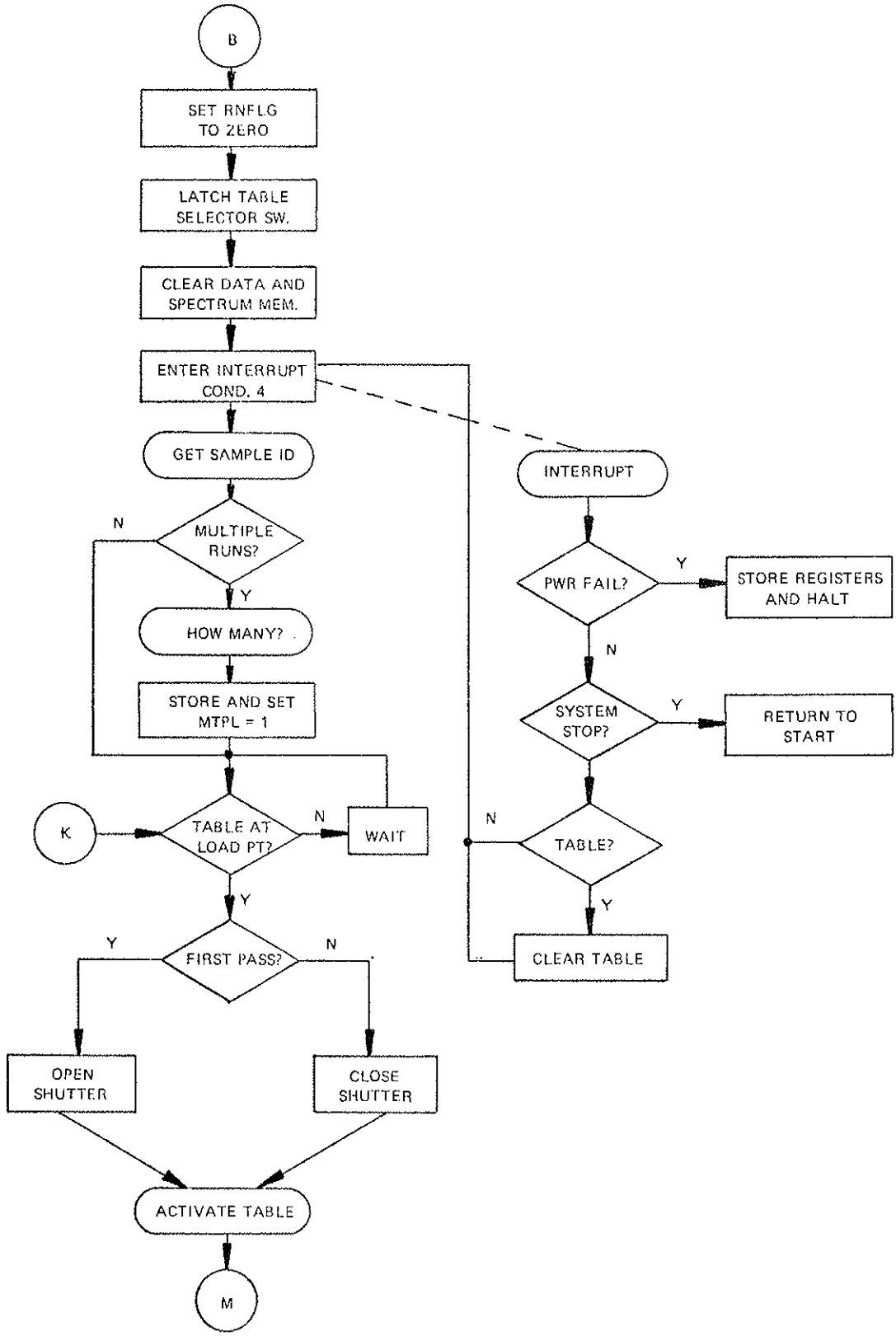


Fig. 7. Partial flow chart for the SGS analysis program.

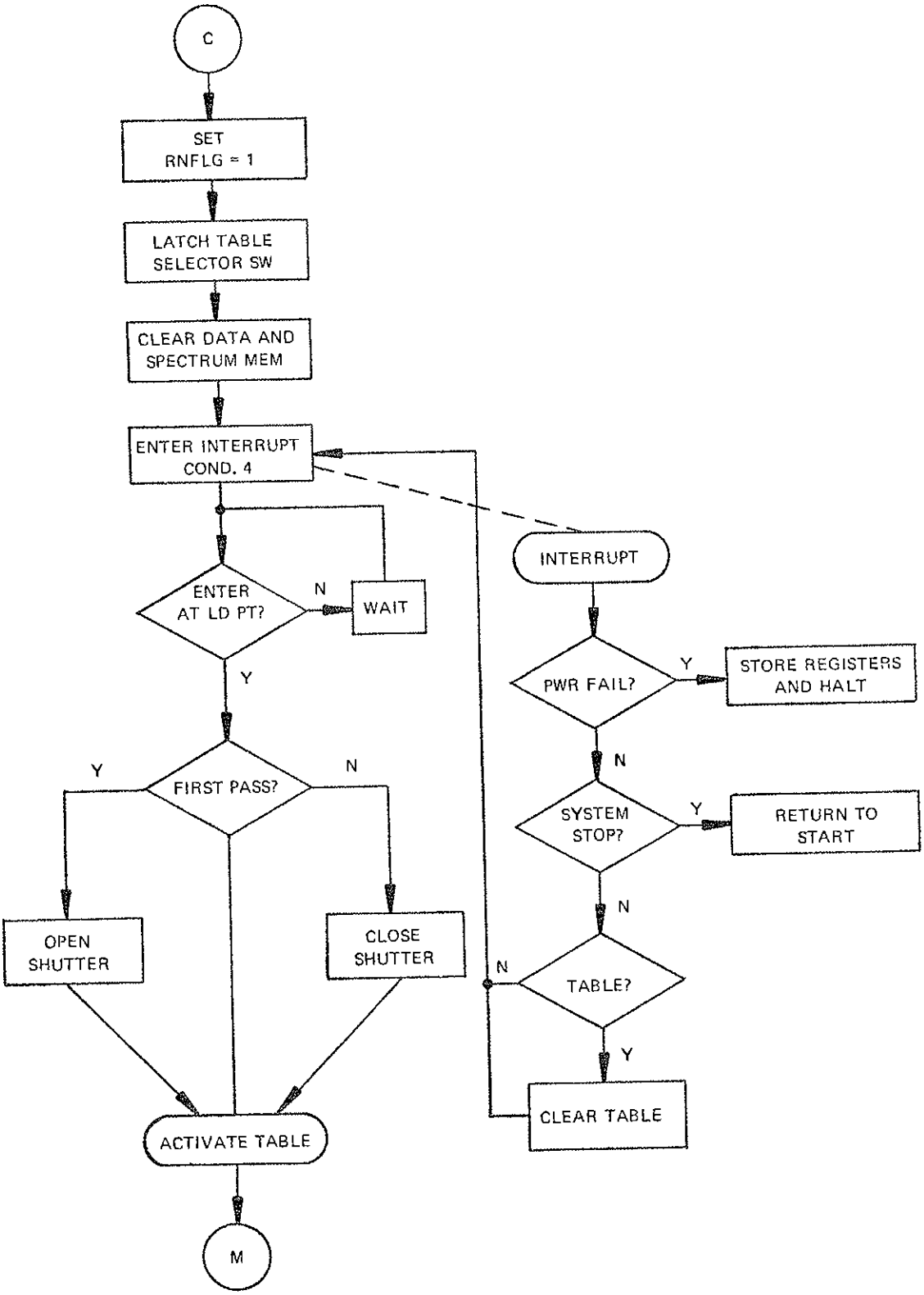


Fig. 8. Partial flow chart for the SGS analysis program.

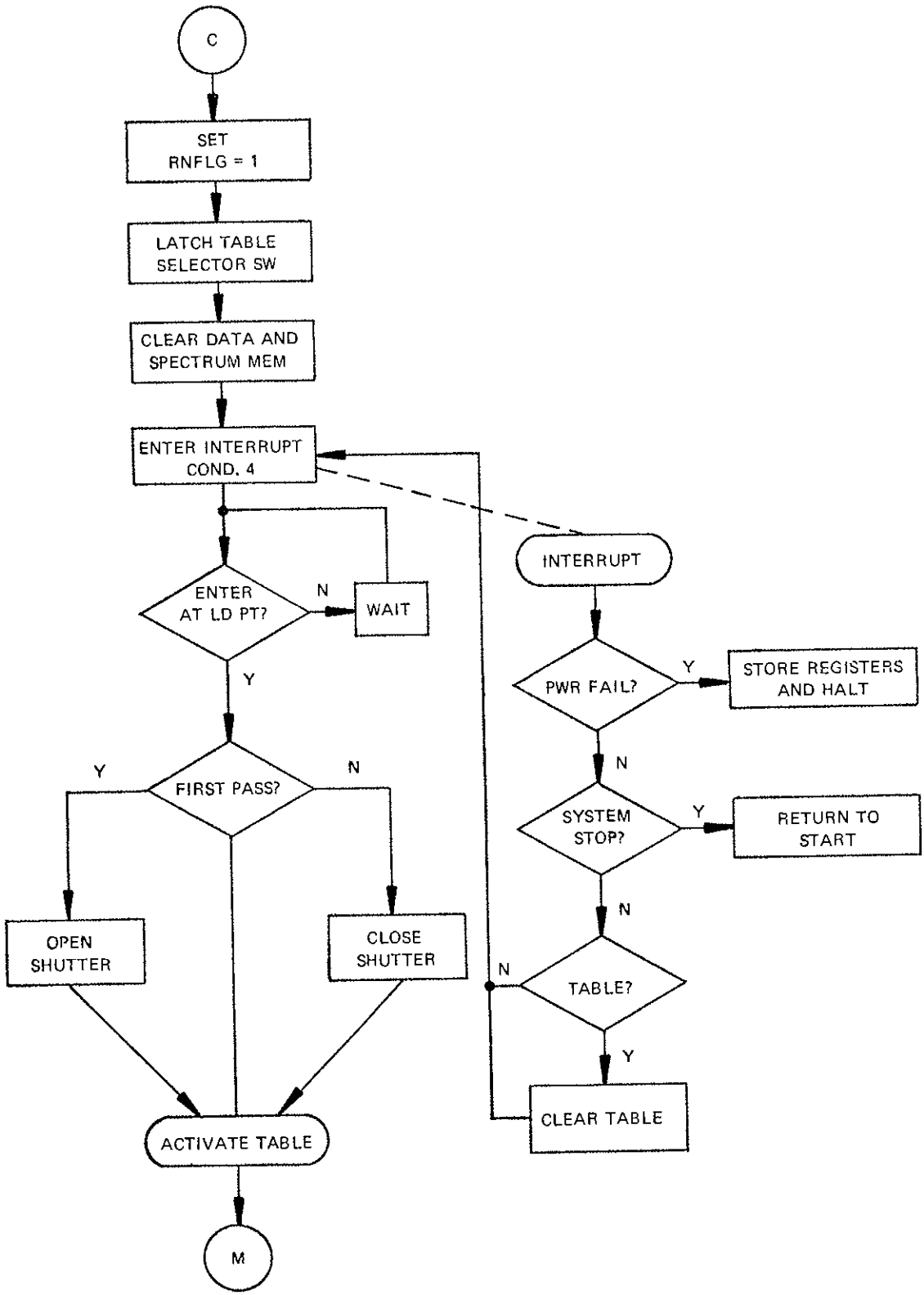


Fig. 8. Partial flow chart for the SGS analysis program.

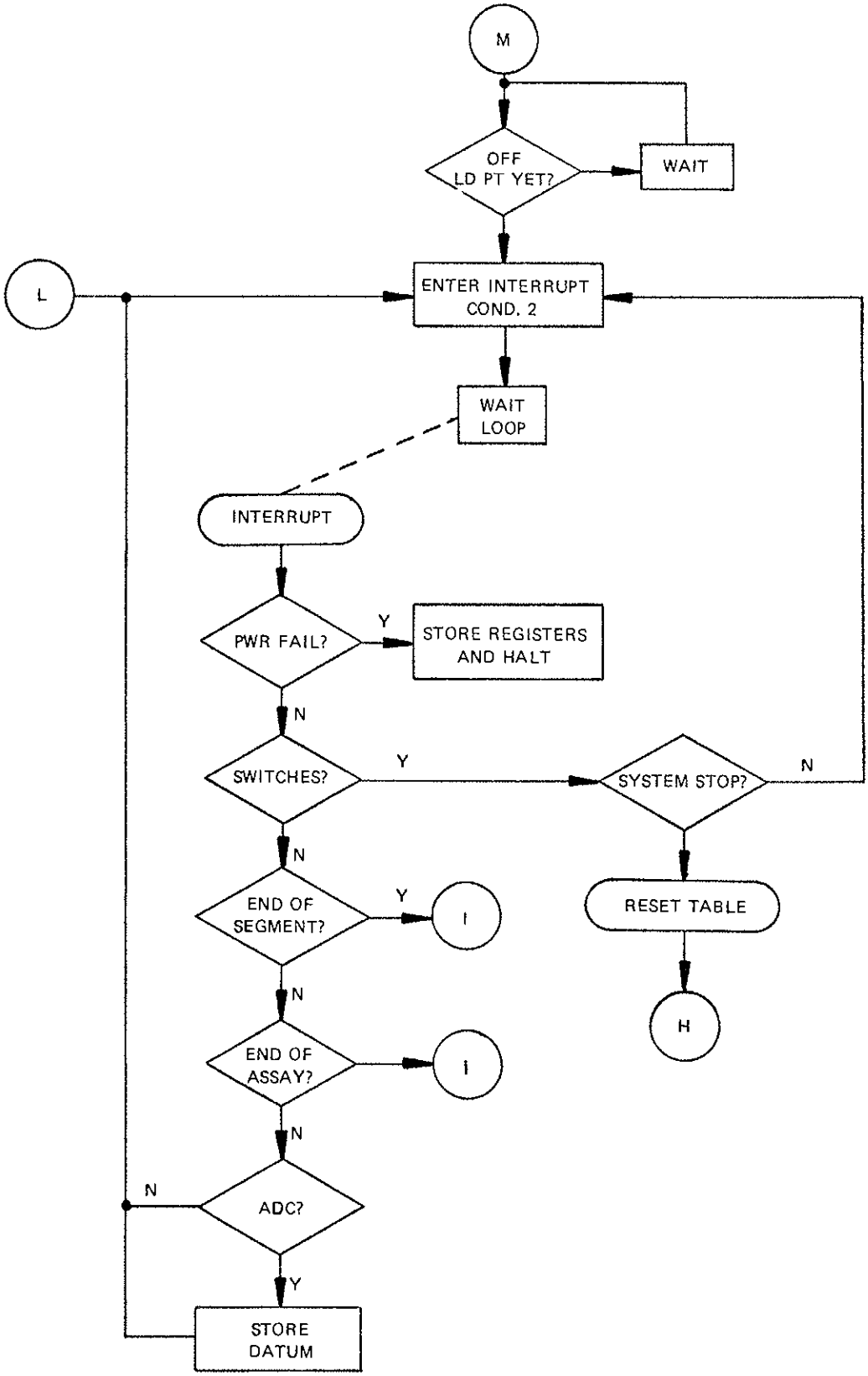


Fig. 9. Partial flow chart for the SGS analysis program.

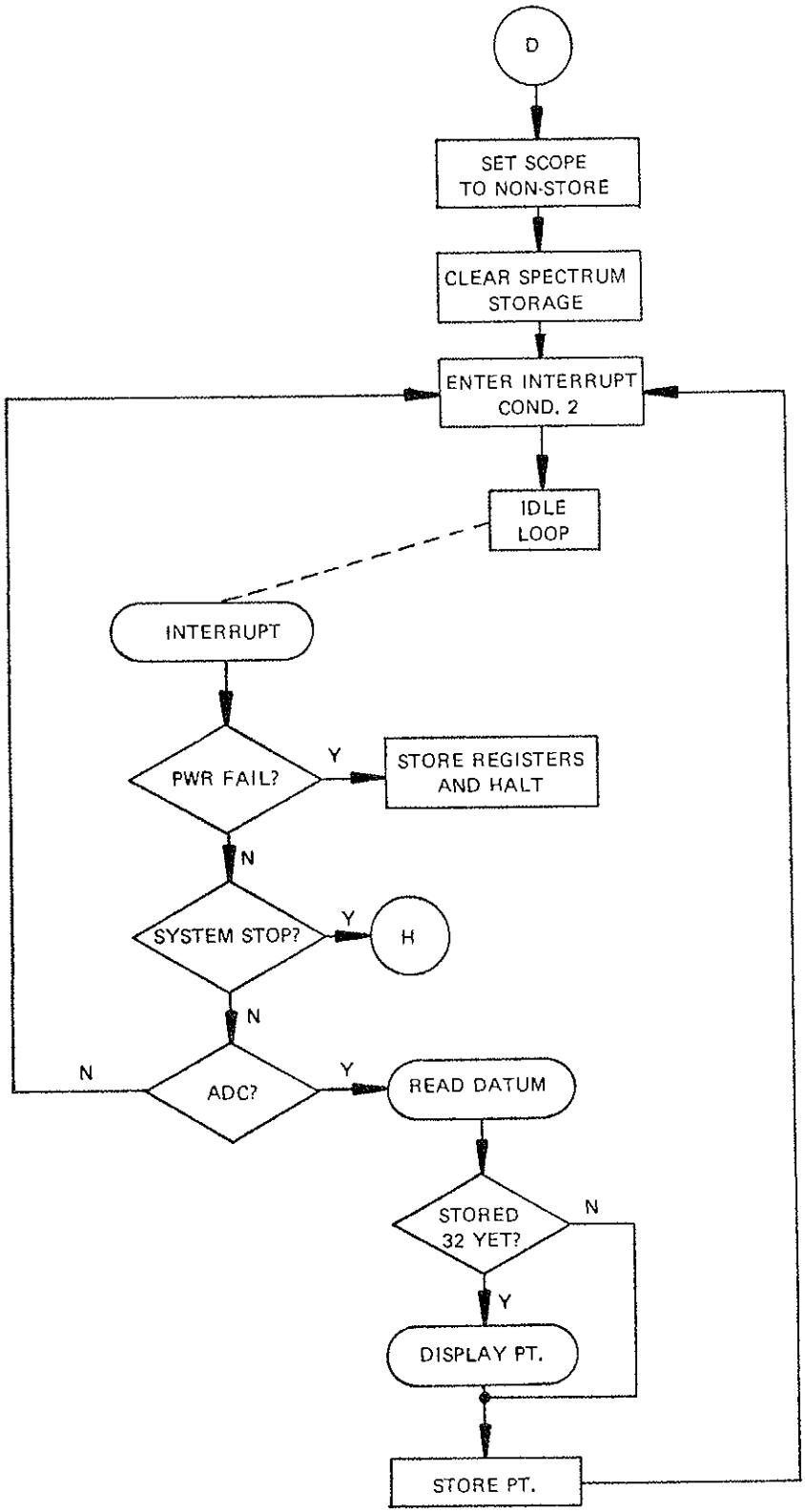


Fig. 10. Partial flow chart for the SGS analysis program.

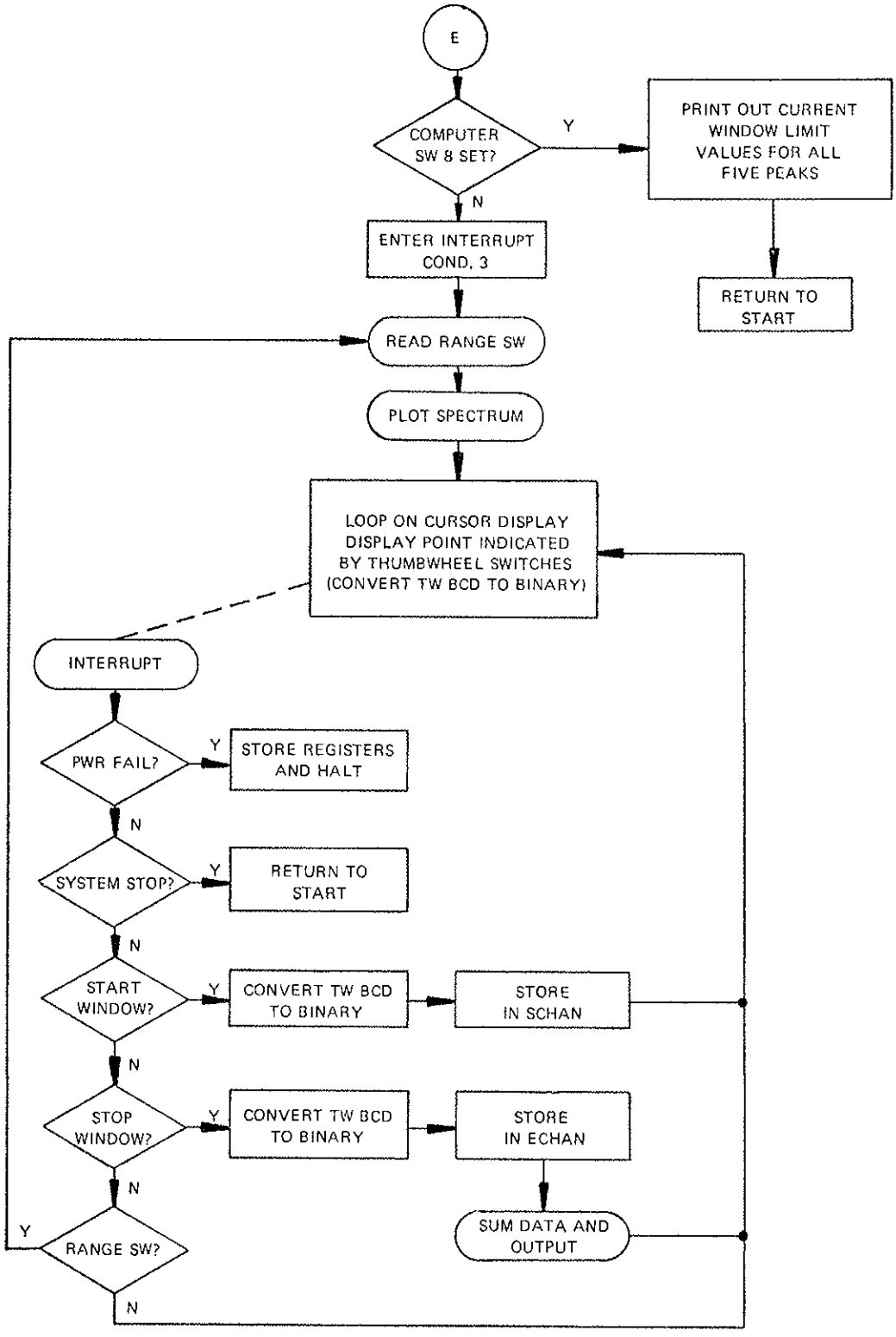
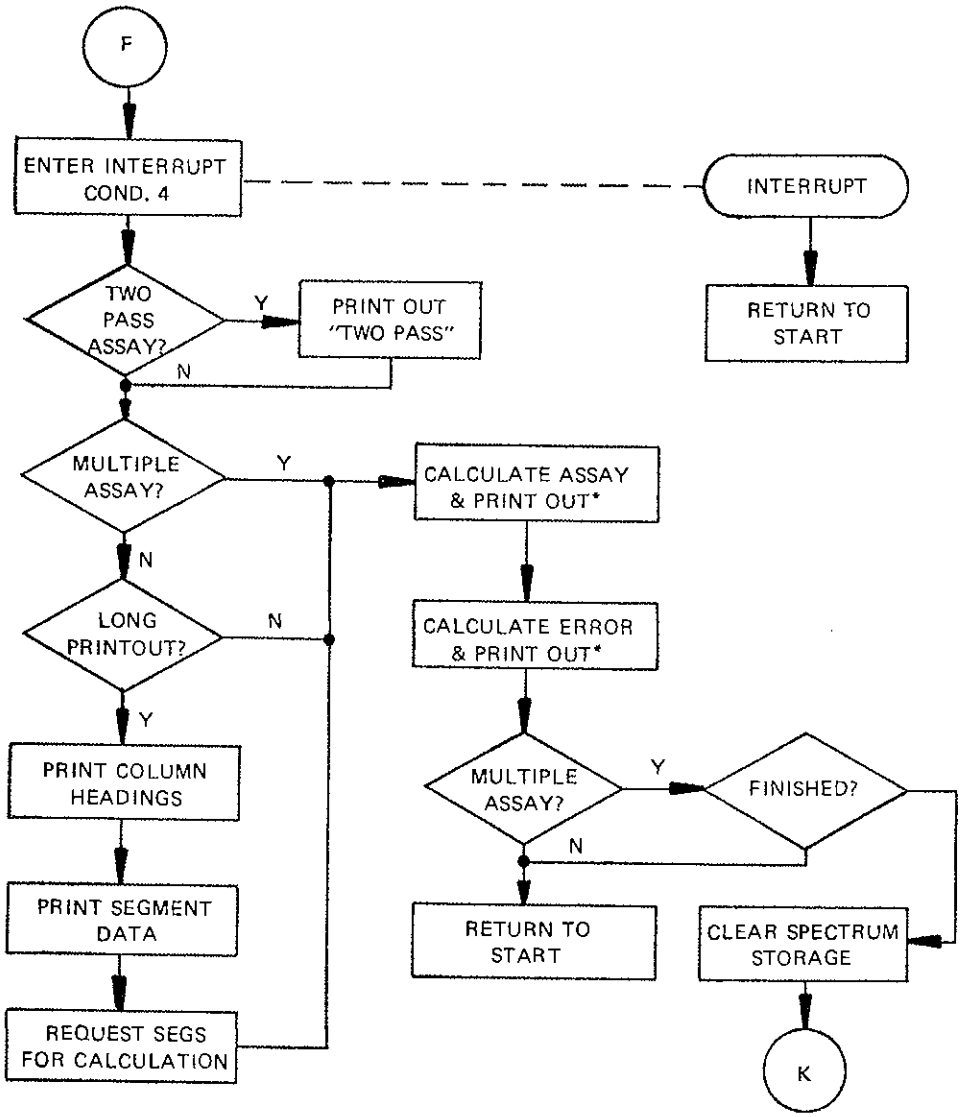


Fig. 11. Partial flow chart for the SGS analysis program.



*The algorithm used in the calculations varies, depending on whether the assay is one or two pass, and whether it is a three-peak (Pu–239 or Pu–238), a four-peak (U–235, or a five-peak (Pu–239 and Pu–241) assay.

Fig. 12. Partial flow chart for the SGS analysis program.

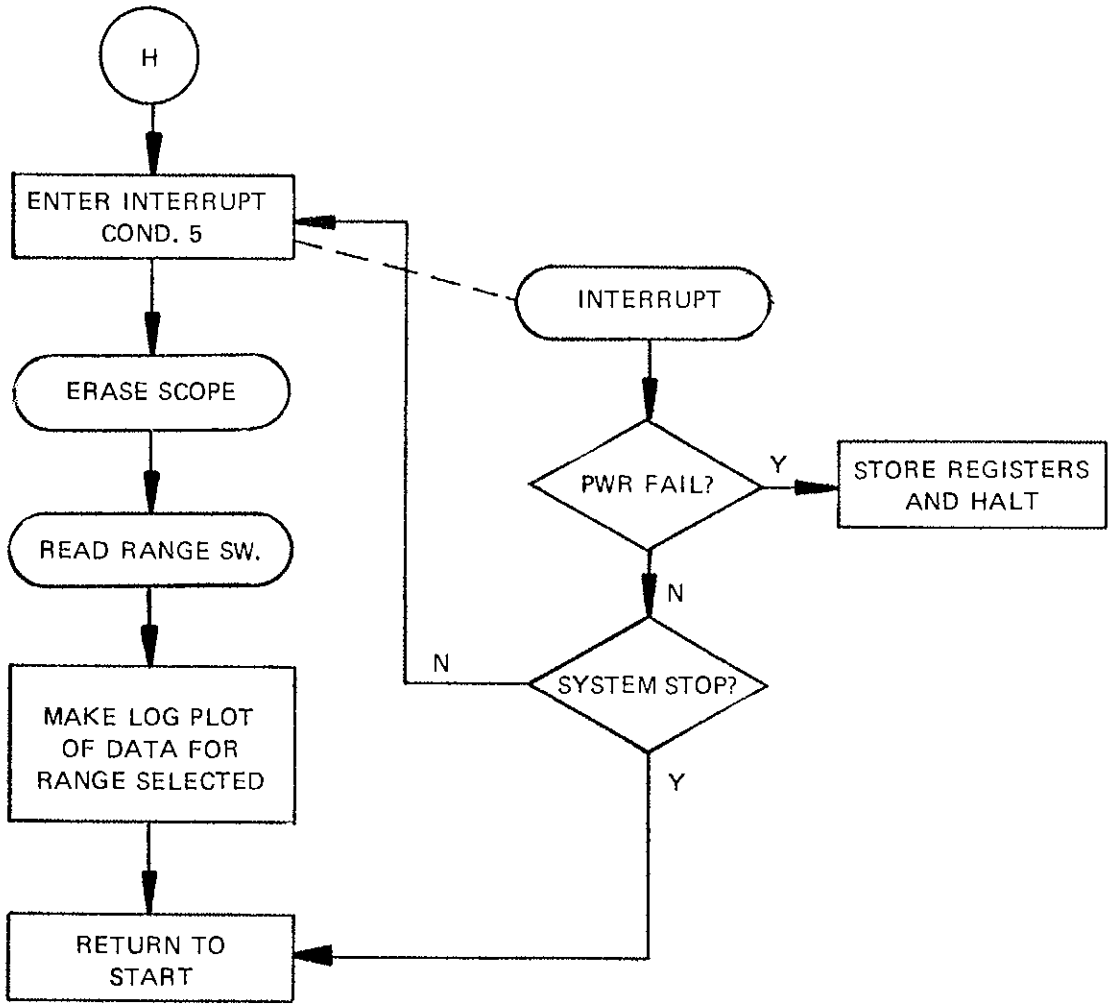


Fig. 13. Partial flow chart for the SGS analysis program.

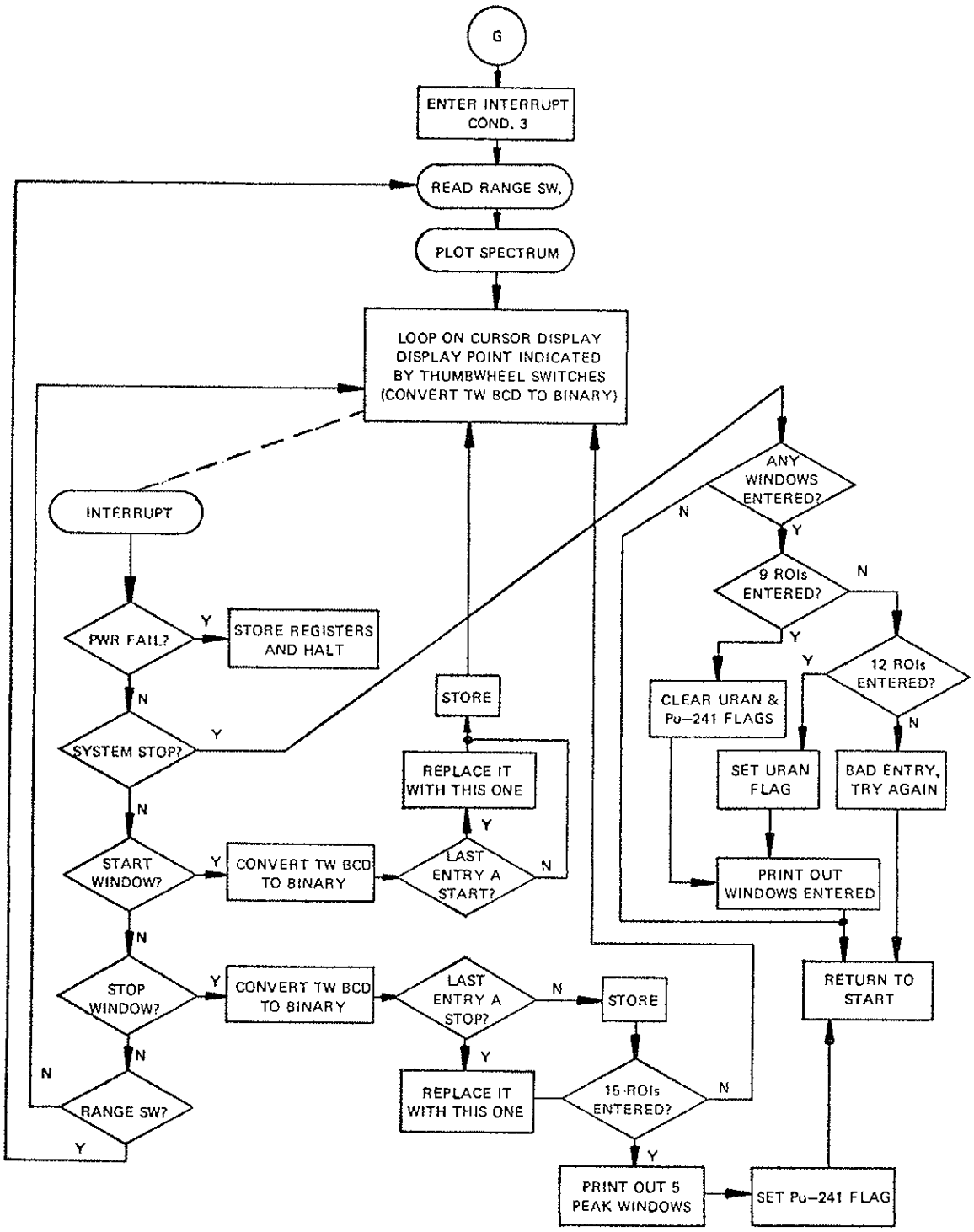


Fig. 14. Partial flow chart for the SGS analysis program.

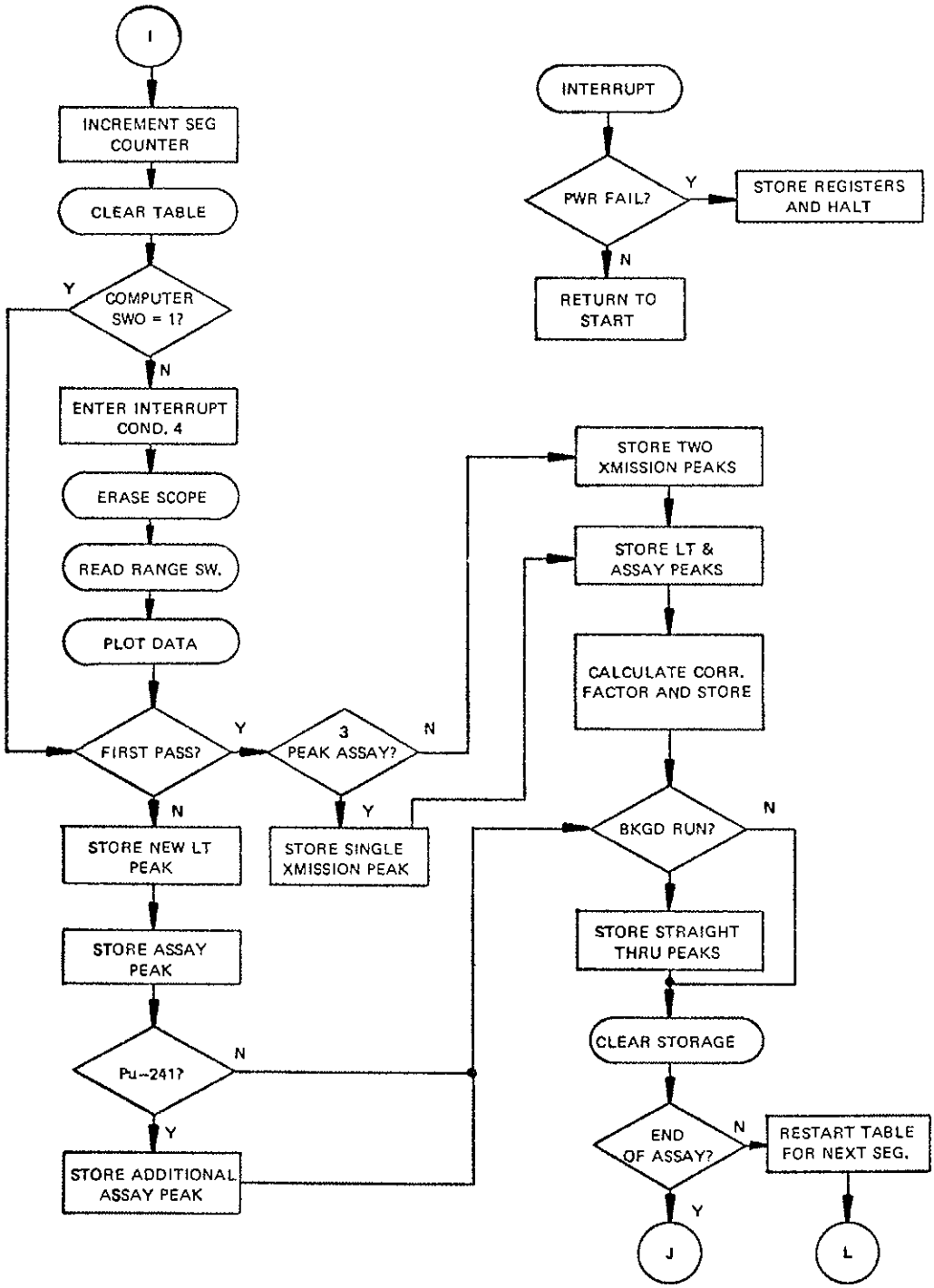


Fig. 15. Partial flow chart for the SGS analysis program.

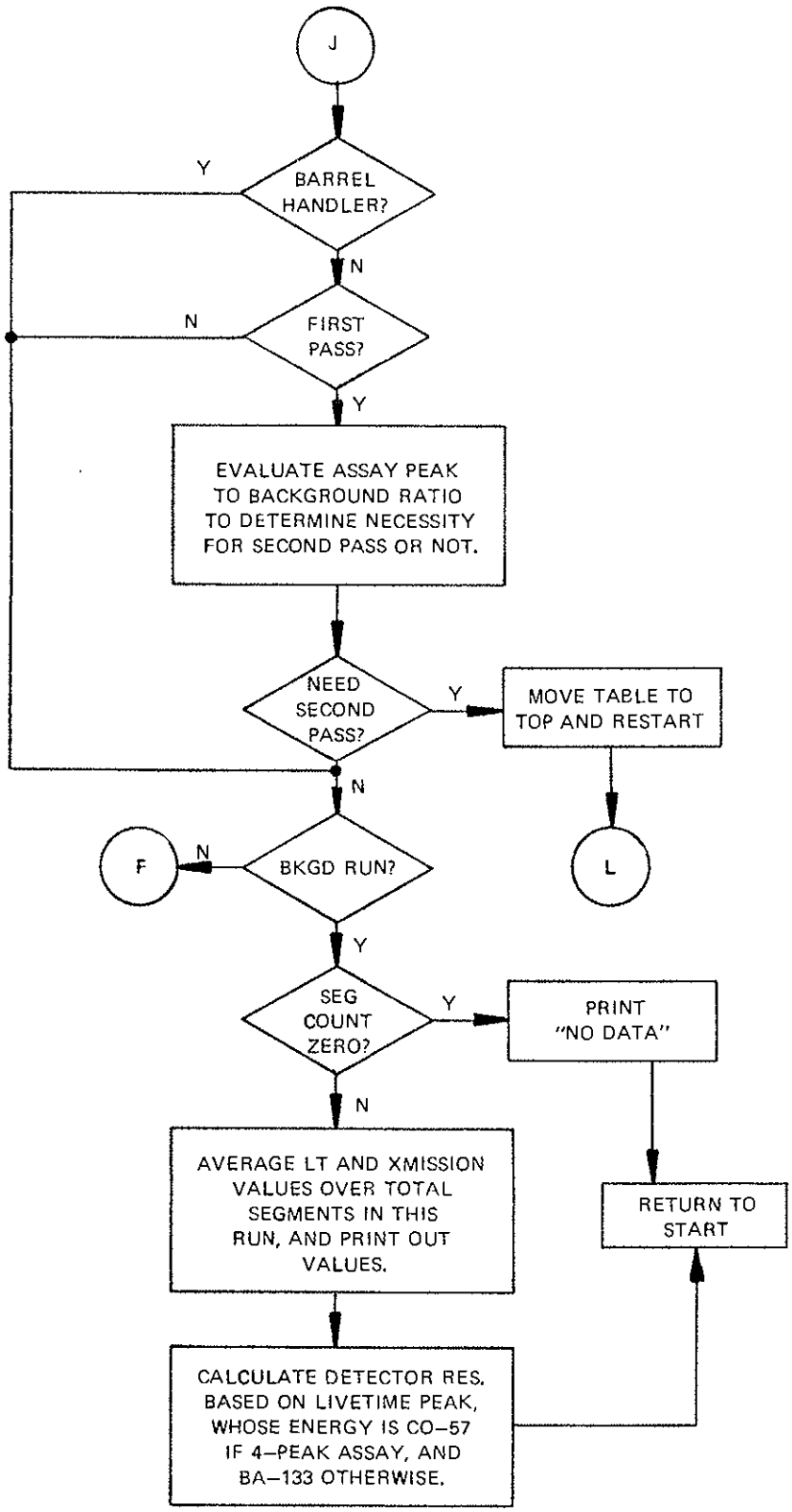


Fig. 16. Partial flow chart for the SGS analysis program.

Once an interrupt is given, it is recognized by the computer via a polling procedure to identify the unit with its busy signal set. If it is the switch panel giving the interrupt (device code 42_8), the actual switch is recognized by checking the data bits set from the panel register, fetched via a DIA with device code 42_8, and checked against the following convention:

TABLE V

BIT ASSIGNMENTS FOR FUNCTION SWITCHES

Function	Bit Number
System Stop	15
Range Switch	14
Start Window	13
Stop Window	12
Enter Constants	11
Start Assay	10
Start Background	9
Start Setup	8
Start Integrate	7
Start Analyze	6
Start Cursor	5

Bits 4 through 1 give the setting of the range switch coded in Binary Coded Decimal (BCD) with bit 4 as the Least Significant Digit (LSD); bit 0 gives the setting of the printout mode switch (if the bit is set, the switch is set to "long" printout).

The scan table interrupts with busy set on device code 74_8 if the interrupt corresponds to the end of a segment, or with done set if it corresponds to the end of the assay (all segments complete).

In addition to storing the various constants that enter into the equations detailed earlier in this manual, certain large blocks of storage are allocated within the computer memory for specific data. These, together with the various software pointers, are indicated in Fig. 17. The notation here is the same as in the previous equations. Table VI gives the absolute addresses for some of the pointers and flags used in the software codes.

D. Plotting Routines

For purposes of writing on the scope, both x and y information must be given to the interface DACs, as well as an intensify pulse to store the information. All information is stored as dots on the oscilloscope. The maximum resolution of this device is 1024 dots in either coordinate; hence, 10-bit DACs are used, and 10 data bits must be given for each coordinate. This information is passed to the interface by giving a DOA instruction for the x-coordinates, and a DOB for the y, together with 10 bits of information passed on data lines 15 through 6 (15 is the LSB) together with device code 34_8. The intensify pulse is given by the "start" pulse appended to any instruction with device code 34_8. The IOPLS pulse and DC 34 will place the storage scope in the "nonstore" condition, from which it is returned to the store mode by giving an erase command, CLR with code 34_8, or an IORST.

HRZLN is a subroutine that writes a horizontal line on the scope. This subroutine expects the x and y coordinates of the starting point to be passed in accumulators 0 to 1, with the line length in dots in accumulator 2.

TABLE VI

SOFTWARE POINTERS AND BUFFER ADDRESSES FOR VARIOUS FLAGS AND STORAGE LOCATIONS

Mnemonic	Absolute Address (Octal)	Purpose
DATAD	121	Starting address of spectrum storage
BUFAD	116	Starting address of current plot
FLAG	161	Equals 0 if 2K points in plot Equals 1 if 256 points in plot
WNFLG	75	Equals -1 if previous entry was "stop" Equals 0 if previous entry was "start"
FF	140	Current value of counts/g
FFS	142	Current value of counts/g for ^{241}Pu
AK	154	Value of geometric factor multiplied by mu ratio value
AKS	216	Same as AK, except applied to ^{241}Pu
SRCAN	152	Square root of can transmission
RNFLG	104	Equals 0 if assay run Equals 1 if background run
SEGCT	105	Number of segments in current assay
SEGDT	124	Starting address of segment data storage

TABLE VI (cont)

Mnemonic	Absolute Address (Octal)	Purpose
SEGLK	125	Address of current segment storage
PO	244	Equals 0 if short printout Equals 1 if long printout
WINLM	122	Starting address of window limit storage
WNSTR	123	Floating pointer for window limits
BUMP	11732	Number of windows set in
AFLG	10451	Equals 0 if end of assay interrupt Equals -1 if end of segment interrupt
MTPL	165	Equals 0 if single run Equals 1 if multiple run
PASSF	50	Zero if first pass; one if second pass
F241	212	Zero if not ^{241}Pu, one if ^{241}Pu
URAN	136	One if uranium assay; zero if not
GRATF	166	Zero if window entry; one if integrate

FIND is a subroutine that interrogates the range switch and sets up the proper pointers to output the desired section of the spectrum from the data buffer. It also sets cell FLAG to zero if the entire 2K spectrum is to be plotted, or to -1 if 256 points are to be plotted. It then sets the appropriate starting address of the section to be plotted in BUFAD.

PLOT is a subroutine that interrogates FLAG and BUFAD and makes the appropriate display. It starts the display by

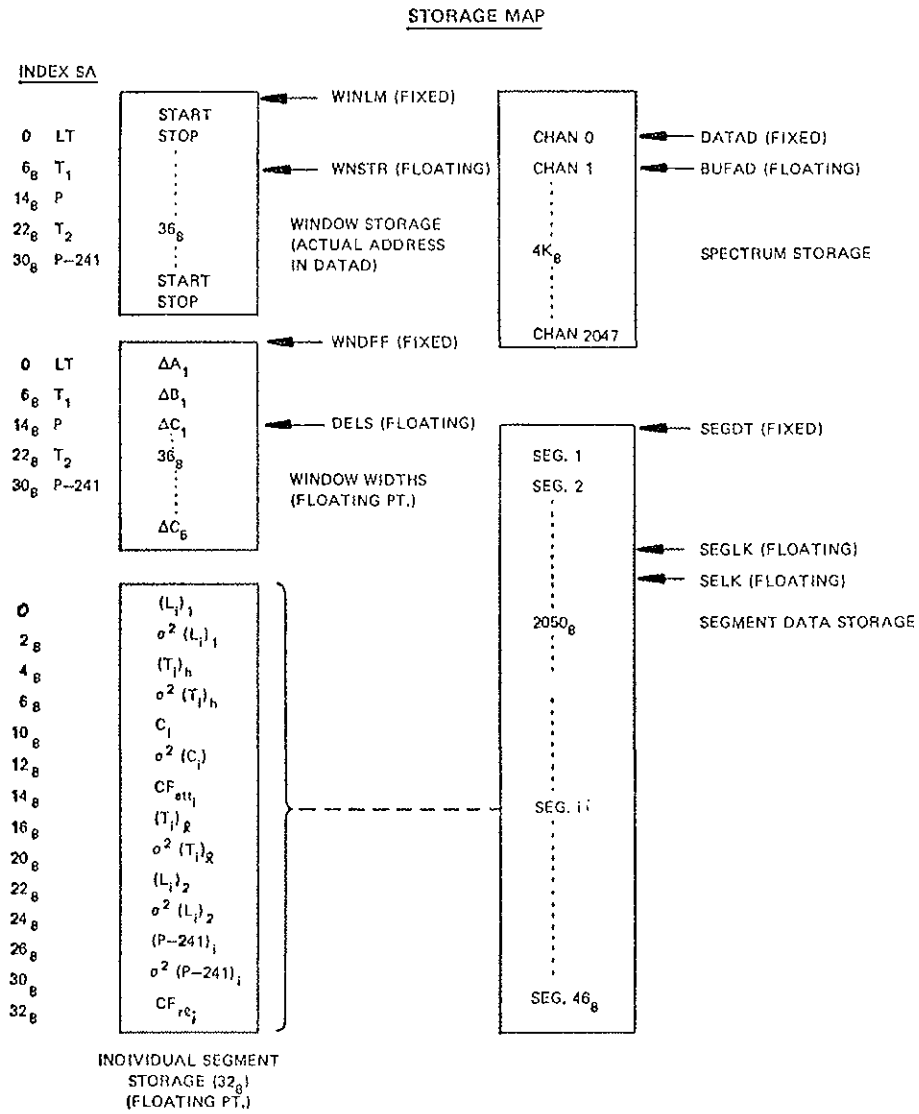


Fig. 17. Storage map for SGS analysis program.

making ordinate fiducials at the decade points of the graph. For a 256-point display each datum is plotted with four horizontal spaces between it and its neighbor. The full 2K spectrum demands that every two points be averaged and plotted as a single point. In either case, all points are plotted on a logarithmic scale; hence, the vertical scale runs from unity to 100K in decades.

E. Teleprinter Subroutines

Subroutines have been provided for printing on the terminal as well as for fetching characters from the keyboard. PUTC is a subroutine that requires either a starting address or an ASCII character in accumulator zero. If an ASCII character is passed, it will simply output the character and return. If an address is passed, it will output the entire message pointed to by the address, until a null word is detected. In either case, a carriage return (ASCII code 15_8) causes a line feed to be echoed as well. Hence, this subroutine can be used to output whole messages or single characters.

GETC is a subroutine that simply fetches a character from the keyboard and echoes it back to the printer as well as returning it to the program right-justified in accumulator zero. The floating point interpreter uses both of these subroutines in its operation. SBNDC is a subroutine to output the contents of a memory in decimal to the teletype with leading zeroes suppressed. DBIN is a subroutine that converts an ASCII character string from the teletype to internal binary numbers.

F. Handling the Window Limits

Window limits are set only when the cursor is on. This condition is handled by a subroutine called CURSE, which calls in FIND and PLOT to first output the desired data

display, and then continually reads the thumbwheel switches related to the cursor position and displays an intensified dot accordingly. These thumbwheel switches are read by a DIB command with device code 42_8. The data thus obtained are in the form of a four-digit BCD number, which the program then translates to binary and fetches the data from the cell thus addressed and displays it. This subroutine also allows for interrupts that will set window limits. Hence, the subroutine must be re-entrant.

WNFLG is a page-zero pointer that signals which window limit has just been entered, zero if "start" and -1 if "stop." STRWN is the subroutine that handles actual sorting of these limits as they are entered. At the termination of entering window limits, when SYSTEM STOP is pressed, subroutine DIFF determines the widths on regions of interest, signals the operator if any of these are negative, and stores the differences for future program use. Subroutine LIMS prints out in decimal the limits just entered for operator information.

G. Handling Data Runs

Upon receiving any interrupt that signals the start of a data run (setup, assay, or background), the interrupt program sets RNFLG accordingly and jumps to the appropriate subroutine.

SETUP handles setup runs by simply storing the data as received, and displaying every twentieth event in the non-store mode, so that the operator has an idea of where most data are being stored in the spectrum.

As regards data storage, both background and assay runs are identical. Subroutine PNT stores the data as they are received from the ADC. At the termination of each segment, data are sorted, the spectrum displayed, calculational values stored, and the buffer cleared for the next segment.

At the end of the run, a determination is made of whether a background or an assay run is involved. In the case of background runs, subroutine STHRU receives control and calculates the transmission and livetime peaks, printing out these values, two of each (for the transmission-open and shuttered cases), and storing the numbers for future use. The detector and system resolution at the rate-correction peak energy is also calculated and printed out at this time. In the case of an assay run, the analysis mode is automatically entered and the calculated data printed out.

Subroutine INIT is used to clear the relevant data storage and prepare the system for the beginning of a run or for the start of the next segment.

SEGCT is a page-zero cell used for counting the number of segments in the particular run. This number is used later for printout as well as for short form calculation.

H. Analysis Codes

At the termination of an assay run, or when the START ANALYZE interrupt is recognized, a determination is made whether short or long printout is desired by reading the toggle switch, and cell PO is set accordingly. Henceforth, all further analysis proceeds with the output determined by the setting of this flag. For a short printout, each segment is calculated and saved, but not printed out. For a long printout, the data are printed on the teleprinter. The calculation is made according to the equations previously described. Subroutine ANLYZ is used to perform this function, which draws heavily on the floating point interpreter for its calculations. If the long printout has been requested, the code gives the operator the choice of which segments to include in the final calculation and error analysis. In the case of a short printout, all segments involved in the run under analysis are included in the

calculation and error computation. In either case, STRT and ENDY contain the addresses of the starting and ending storage for the segments to be included.

Subroutine PKCOR is used to perform the background subtraction of the peak being analyzed. This is a linear subtraction based on the two windows bracketing the peak itself, and has been described previously. All calculations in the analysis codes are based on double-precision floating point numbers exclusively.

I. Floating Point Calculations

Calculations are made with floating point numbers via an interpreter to which program control is transferred for calculational purposes, rather than having special subroutines for each floating point function. In this way, programming for floating point calculations is simply an extension of machine language arithmetic instructions, and the interpreter is transparent to the programmer.

Floating point numbers are internally stored in two consecutive 16-bit words. Of these 32 bits, one is used for the sign of the number, seven are used for the characteristic, and 24 for the mantissa; hence, the approximate range of numbers that the interpreter can handle is from 2.4×10^{-78} to 7.2×10^{75}. The maximum error of a normalized mantissa is less than 6×10^{-8}.

The detailed algorithms will not be given here, but are standard in the industry, requiring milliseconds for their completion in this machine. In all calculations performed in the present codes, the maximum relative error is approximately 10^{-7}, which is much less than would be noticed for any of the numbers produced in these routines.

Note that

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Have been omitted

running average of the assay value with the associated propagated one sigma error estimate is printed.

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