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Computer-Oriented Gamma Scan System

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COMPUTER-ORIENTED GAMMA SCAN SYSTEM

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E. R. Martin and D. F. Jones

ABSTRACT

A general operating and maintenance manual for the upgraded segmented gamma scan assay system is presented. The system, employed for the assay of ^{238}Pu and ^{239}Pu , is built around a Northern Scientific 710 Pulse Height Analyzer and uses a minicomputer on line for data acquisition and reduction. It gives segment-by-segment assay for fissile content profile as well as final sample assay and propagated statistical error.

I. INTRODUCTION

The general philosophy and some specific instrumentation involved in measuring the fissile content of various material samples by means of passive segmented gamma scan have been described in several previous reports.^{1, 2} Basically, the assay is accomplished by using the gamma rays spontaneously emitted by the fissile material being measured, with matrix and material attenuation and rate pileup corrections made by means of counting separate live-time and transmission sources. The sample is further rotated and split into individual segments for scanning purposes, under the assumption that the attenuation and matrix constants will be reasonably uniform over a small region. In this way, each individual segment involved in the measurement has its transmission and live time measured separately and the assay peak count for that segment individually tallied. The problem here is to find sources with gamma lines sufficiently close to the gamma line being measured such that the mass attenuation coefficients

can be considered reasonably linear between the two lines.

A method of measuring fissile content via a gamma measurement technique has been applied to the measurement of ^{238}Pu and ^{239}Pu at the LASL plutonium facility at DP-Site. The apparatus previously used consists of a large scan table on which the sample to be measured can be both rotated and moved vertically through the gamma beam from the transmission source, a Ge(Li) detector to detect the gamma signatures, and a Northern Scientific 710 Pulse Height Analyzer with teletype printout. The DP-Site system was used on a more-or-less routine basis for over a year now with reasonable results. However, several of the shortcomings of that system are (1) the table and collimator are not really designed for segmented scans; the present measurement is more an average over the whole sample at once rather than a segmented assay, which has larger matrix errors than a scan technique, (2) after the channel counts are made, hand calculation is necessary to

relate the peak numbers to fissile content, and (3) no provision whatsoever is made for any estimate of measurement error due to counting statistics.

In order to rectify these shortcomings and provide for better and simpler measurements, we have reanalyzed that system and redesigned the assay instrument around a small minicomputer, attempting to utilize present equipment wherever possible to keep down the cost, while at the same time upgrading the system to a more versatile and accurate assay instrument.

The equipment resulting from this effort, together with its associated software and analysis programs, is the subject of this report, which will attempt to describe not only the detailed operation of the device, but permit maintenance on the equipment as well.

II. THEORY OF OPERATION

One of the principal applications of the gamma scan instrument is in the measurement of ^{238}Pu and ^{239}Pu . Although in principle ^{235}U can be measured by the very same equipment, plutonium provides a particularly simple application, since its measurement requires only a single transmission peak, sources of the required gamma energy being readily available. In general, a good measurement of uranium dictates the inclusion in the analysis of two transmission peaks.

For the measurement of plutonium we need analyze only three peaks: the live-time (pileup) peak, for which we use the 356-keV gamma line from ^{133}Ba ; the transmission peak, for which we use either ^{137}Ce or ^{75}Se sources; and the plutonium peak itself. In the case of ^{238}Pu , we generally use the 661-keV gamma peak from ^{137}Ce , since the peak being assayed is at 765-keV energy; while for ^{239}Pu we use the 400-keV peak from ^{75}Se , since the peak being measured is at 414 keV. The barium source has a half life of 10.4 years, and the cesium source a half life of 30 years; however, the selenium has a half life of only 120 days, a

nuisance when one has to have the source periodically rejuvenated.

Each peak being measured requires the simultaneous measurement of two backgrounds, one on either side of the peak, in order to permit a background subtraction. The background is considered to be linear between the two background points on either side of the peak, and this linear background is subtracted from the peak value according to Eq. (1). In this way, the measurement of three peaks requires the simultaneous storage of information from nine different pulse height windows.

Corrected Peak Value =

$$\sum B - \frac{(B_2 - B_1)}{2} \left(\frac{\sum A}{A_2 - A_1} + \frac{\sum C}{C_2 - C_1} \right) \quad (1)$$

where $\sum A$, $\sum B$, and $\sum C$ are raw counts in the respective counting windows; A and C refer to left and right background windows, respectively; and B is the peak window.

Following the determination of these three corrected peak values for each segment, the corrected peak counts, related to fissile content, are determined from the following equation

$$\text{Corrected Counts (i}^{\text{th}} \text{ segment)} = CC_i = \quad (2)$$

$$C_i \frac{LT_o}{LT_i} \cdot CF_s(T_i') \cdot CF_{can}$$

$$\text{where } CF_s(T_i') = \frac{-AK \ln T_i'}{1 - (T_i')^{AK}}$$

$$\text{and } CF_{can} = \frac{1}{\sqrt{T_c}}$$

$$\text{and } T_i' = \frac{T_i}{T_o} \cdot \frac{LT_o}{LT_i} \cdot \frac{1}{T_c}$$

$$\text{and } K = \frac{\mu_a}{\mu_t}$$

The T_c in the equations is the transmission of the container material. The A is a geometric constant, while the K is the ratio of the attenuation coefficients of the gamma energies for the material being assayed and the transmission source, respectively. These constants are determined through a long history of measurements and are generally known for the assay at any given time.

The LT_0 and T_0 , live-time and transmission peaks, are experimentally determined in a background run with no sample in the assay system. They represent therefore the transmission source directly, and the live-time or pileup correction with no assay peak present, and no matrix attenuation.

Following the measurement of corrected counts for each segment, the operator then determines which segments should be included in the total assay results (i. e., which segments contain fissile material). The corrected counts for these segments are then added, and the result divided by the number of counts per gram fissile material for the final assay answer. The determination of the statistical error on the measurement will be discussed in a subsequent section of this report.

A. Operation

The computer-oriented segmented gamma scan system is shown in Fig. 1. The teletype is used for hardcopy printout of the assay results and for data entry to the computer. The electronics rack contains the NIM bin at the top with the detector main amplifier and pulse height analyzer gain stabilizer. Not shown is the high voltage power supply, which will also reside in the NIM bin. Below the NIM bin is the Northern Scientific 710 Analyzer which displays the spectra from the Ge(Li) detector and digitizes the detector output for the computer. Its display is used to determine the numerical channel numbers for data windows in a manner to be described presently. Below the analyzer is the computer-analyzer interface module with its four pushbuttons and two toggle switches,

Fig. 1. The computer-oriented gamma scan system in operation.

and the main power switch. The last unit in the rack, just above the rack fan, is the minicomputer, a Data General Nova 1210, which digests the data from the pulse height analyzer and computes the assay, both for each individual segment, as well as for the aggregate total.

Figure 2 is a close-up view of the relevant controls. The first step in the operation consists of entering certain initial data and window limits before assay operations can be performed. However, once this initialization process is complete, many assays can be made without repeating this entry routine. For completeness here, let us assume that the system is "virgin"--i. e., no assays have yet been made and no constants or window limits yet entered.

Fig. 2. Close-up view showing system controls.

B. Initialization

Depending upon whether the material to be assayed contains ^{238}Pu or ^{239}Pu , the transmission source chosen will generally be ^{137}Ce or ^{75}Se , respectively, as described previously. The live-time source is usually ^{133}Ba , which with the assay peak itself, yields three gamma peaks for the assay. The first step in the initialization process is to make a short spectrum run with the analyzer in the stand-alone mode to determine the channel settings of the respective peaks. Referring to Fig. 2, the analyzer can be used in a stand-alone mode by placing the COINC-ANTICOINC switch in the far lower righthand corner of the unit in the upper COINC position. In this position the

analyzer will function as a stand-alone unit independent of the computer, and can thus be used to take the necessary spectrum.

With the Ge(Li) detector properly positioned, the sample in place, and the barium and transmission sources properly positioned, turn on the high voltage to the detector and check the gain adjustment on the main amplifier. The controls on the Tennelec TC 203BLR amplifier will usually be set roughly as follows

course gain = 200	} depending on the pream- plifier characteristics and hv setting
fine gain = 3-4	

time constant = 1 microsecond

prompt output = DIRECT

base line restorer (BLR) = IN

rate = HI

delayed output = INVERTED

The front-panel connecting cables between units are as shown in Fig. 2, with the cable disappearing into the top of the figure coming from the pre-amplifier. For the initial run, leave the mode switch on the Northern stabilizer in the OFF position.

Set the switches on the pulse height analyzer in the positions shown in Fig. 2 and make a short run, just long enough to give well-defined peaks. Identify the barium live-time peak, transmission source peak, and assay peak by their respective heights and spectrum positions and carefully select analysis windows as follows. With the display selector switch set in the CHANNEL NO. position, use the channel selector knob to move the intensified dot on the display along the display spectrum. The operator should now determine which peak he desires to stabilize on, determine the channel number of this peak from the display on the PHA, and set this number into the center channel switches on the Northern stabilizer. The stabilizer mode switch can now be set at ON, and the stabilizer will lock the PHA onto the peak. In

general, the live-time peak is a good one to use for stabilization, since it will not vary significantly in rate during the assay. The disadvantage of this peak is that it is rather far removed from the transmission and assay peaks; however, our experience has been that the system is sufficiently stable such that no discernible drift has ever been seen with the stabilizer locked onto the live-time peak. Start at the left of the barium (live-time) peak and pick a background window on the left side of this peak. Try to select a region to the immediate left of the peak which is relatively flat and about five or six channels wide. Sometimes a smaller region than this will have to be chosen if the spectrum is particularly mountainous. Read off the channel numbers for the limits of this window from the display lights and write them down. Now select another region which spans the peak itself, and write down its limits. Do the same for another background region to the immediate right of the peak and write down its limits. Repeat this process for each of the other 2 peaks, so that finally 9 separate regions are defined by 18 channel numbers--3 regions for each peak.

With this information in hand, one is now prepared to begin computer operation. Make certain the teletype local-line switch is in the LINE position. For entering all constants the toggle switch immediately above the ENTER pushbutton should be in the upper, or WINDOWS AND CONSTANTS, position. Press the ENTER pushbutton on the interface panel. Reference is now made to Fig. 3 for the entry of constants. The computer will immediately type out the top line shown in Fig. 3, asking for the entry of the scan time in seconds. To each of the following queries the operator is expected to enter a number. These constants may be entered in any legitimate numerical format, i.e., E-format, F-format, or fixed point integers. Each entry by the operator is terminated by a carriage return, which will then elicit the next response by a further query. Note that if the

```
READY
SCAN TIME (SECONDS)? 10
COUNTS PER GPM? 114.6
CORRECTION FACTOR? .785
CONTAINERS TRANSMISSION? .9
NO CORRECTION FACTOR? .95
DO YOU WISH TO ENTER WINDOWS? Y
ENTER WINDOW LIMITS FOR LT, T AND PEAK
336-348, 241-253, 351-256
439-442, 443-454, 455-461
486-494, 495-507, 508-517
```

```
READY
32 SEGMENTS
LIVE TIME PEAK IS +5256.9
TRANSMISSION PEAK IS +6745.3
```

```
READY
32 SEGMENTS
RUN STOPPED
```

READY SEL #	LIVE TIME	TRANSMISSION	PEAK	CORR FACTOR
1	+9971	+13350	+1398.5	+1.2020
2	+9825	+13345	+1516.5	+1.2113
3	+1.0001	+1.3112	+1477.9	+1.2309
4	+1.2212	+1.3139	+1331.3	+1.2079
5	+9827	+9933	+1563.1	+1.2157
6	+1.3867	+9928	+1611.7	+1.2159
7	+1.0219	+1.4152	+1263.4	+1.2074
8	+9998	+1.0117	+1259.1	+1.2267
9	+1.2211	+1.3297	+1451.4	+1.2320
10	+1.2179	+1.3213	+1341.9	+1.2351
11	+9891	+1.2274	+1116.2	+1.2194
12	+9871	+1.0031	+1328.5	+1.2129
13	+1.3357	+1.3099	+1371.5	+1.2394
14	+1.3169	+1.0326	+1355.1	+1.2099
15	+9963	+1.9269	+1367.7	+1.2266
16	+1.0001	+1.9269	+1543.8	+1.2030
17	+1.0086	+1.0126	+1565.6	+1.2084
18	+9888	+9838	+1292.4	+1.2194
19	+1.1489	+9858	+1507.3	+1.2186
20	+1.0037	+9962	+1446.3	+1.2146
21	+9985	+9840	+1465.3	+1.2178
22	+1.0147	+1.4351	+1417.3	+1.2233
23	+1.3194	+1.3193	+1279.2	+1.2269
24	+1.3203	+1.3279	+1338.4	+1.2102
25	+1.3186	+9960	+1344.2	+1.2106
26	+9999	+9894	+1345.3	+1.2172
27	+9725	+9562	+1350.2	+1.2304
28	+1.2568	+9963	+1251.2	+1.2146
29	+1.2247	+1.2265	+1481.4	+1.2332
30	+9984	+9973	+1462.3	+1.2142
31	+9742	+9817	+1347.2	+1.2292
32	+9981	+9795	+1402.6	+1.2211

FIRST AND LAST SEGMENTS FOR ASSAY? 1,32

TOTAL CORRECTED COUNTS = +369421.78

ASSAY = -3223.57 EST. STD. DEV. = +11.25

READY

Fig. 3. Sample printout from an actual assay.

operator makes a mistake in entering these constants, he must press the ENTRY pushbutton again and start over from the beginning.

The scan time is the interval defined by the operator for each segmented scan of the sample. Ten seconds is a reasonable sample scan time for most samples, but this can be varied as desired. A smaller nonhomogeneous sample may well require a smaller scan time to split the sample into smaller assay slices, and a very large sample will generally require longer times. The only constraint here is that the maximum number of segmented assay scans for any one sample is

computer-limited to 32, and during any one segment scan, the maximum count permitted in any one channel of the spectrum is 65,000. These are not stringent requirements for any normal assay.

The "counts per gram" is a calibration constant which will be divided into the corrected counts at the end of the run to determine the assay. If unknown, it is simply set to one. It must be determined from the assay of known samples.

The correction factor, container transmission, and mu correction factor are generally known from previous runs. They correspond respectively to A , T_c , and K in Eq. (2). After these constants have been entered, the computer will ask "Do you wish to enter windows?" as shown in Fig. 3. The operator responds with a "Y" or "N" depending upon whether the window limits, determined from the previous run with the pulse height analyzer in the stand-alone mode, have been previously entered. For the initial run, these will not have been entered, so the operator types a "Y", after which the computer asks for the entry of the windows.

Note that in entering the window limits the peaks must be entered in the order listed by the computer, namely the live-time peak first, followed by the transmission peak, and finally the assay peak. The peaks need not appear in this order in the PHA spectrum, but they must be entered in this order for the computer. Also, each peak must have its limits entered in ascending order, i.e., left background window limits first, then peak window limits, and finally righthand window limits. If an error is made in entering these limits, and the operator catches the error before completing the number in which the error is made, he can simply press the RUBOUT key on the teletype and start that number over again. However, if he notices the error after he has already gone on to the next number, he must start over entering the window limits again starting at the beginning of the series. The separator for these entries can be any symbol on the keyboard other than a number,

except that it is well to use symbols which make for easy reading. Figure 3 shows a dash used between limits of the same window, and a comma separating different windows. This has proved to be a straightforward convention.

After all window limits have been entered, the computer will give a "ready" indication, signifying that further action can now be initiated by the operator. It is important that the COINC-ANTI-COINC switch in the rightmost lower corner of the PHA be set in the ANTICOINC position before any runs are taken with the computer, since this is the "busy" input from the computer to the PHA. The first run to be made with the computer before assay can begin is a background run, in which the computer will calculate the live-time and transmission constants to be used in further assay calculations. This background run is accomplished by simply removing the sample from the scan system, setting the assay toggle switch on the computer interface panel to the BACKGROUND position, pressing the START ANALYSIS pushbutton on the PHA, and pressing START on the computer interface. The system will automatically take thirty-two 10-second runs now without a sample, calculate the average of the transmission and live-time peaks, normalize these numbers to the scan time selected by the operator in a previous step, and store these constants for future calculation. At the end of this 5-minute background run, the computer will print out on the teletype "32 segments" and then print the value of the live-time and transmission peaks for operator reference. When "ready" is again typed, the system is prepared for actual assay runs.

C. Assay Runs

In order to make an assay run, the initialization must have been done. Once initialization is complete, however, it need not be repeated until the fissile material being assayed is changed (e.g. from ^{238}Pu to ^{239}Pu), or until different constants or window limits are desired. Whenever constants

or windows are changed, it is necessary to take a new background run to reset the transmission and live-time constants. Also, occasional background runs give proof of system stability.

To make an assay, make sure the interface toggle switch above the START button is in the ASSAY position and the PHA switch is in the ANTI-COINC position. Place the sample to be assayed on the scan table, move it to the bottom position, start the table rotating, then start the vertical motion of the table. Now push the START ANALYSIS button on the Northern Scientific PHA, and push the START pushbutton on the computer interface. Data are now automatically gathered and stored by the computer until the operator presses the STOP pushbutton on the PHA, or until 32 segments have been assayed. In either case, the computer will print out "run stopped". In the latter case, it will also print "32 segments". The prompt "ready" is also given, indicating that the operator can now initiate further action. Generally the next step will be to complete the analysis by pressing ANALYZE on the interface panel. If the run just taken is not desired, one can simply press START, which erases previous data and starts a new run. When the ANALYZE button is pressed, the computer then prints out the data gathered on a segment-by-segment basis as shown in Fig. 3.

The purpose for printing the segment data is to give the operator an indication of valid assay information and a profile indication of fissile material contained in the sample. If the transmission numbers get very small or negative, or if the correction factors in the last column reach 6.0000, it is a good indication that the assay is suspect. This printout also permits the operator to select which segments should be used in the final assay calculation. At the termination of segment printout, the teletype will ask for the first and last segments, which the operator selects on the basis of information just printed out, and types into the computer as shown. This information from the operator

consists of two integer numbers, separated by a comma or a space and terminated by a carriage return. If the operator sets in illegal numbers (i.e., zero for the first segment or more than 32 for the last segment), the computer simply requests the numbers be entered again. This will be repeated until correct segment numbers are given. Then the total corrected counts, based on the segments requested by the operator, will be calculated and printed, together with the assay and the estimated standard deviation. This latter quantity will be treated in greater detail in the section on error analysis in this report.

The assay is now complete, and the computer types "ready", indicating the next assay can begin.

For purposes of labeling a sample being assayed, or setting the date, or giving other information pertinent to the run being taken, the operator can cause his own comments to be written on the teletype output, by simply pressing TTY ECHO on the computer interface panel and typing whatever he wishes. The computer causes an asterisk to be typed as a prompt that the operator can now type his comments. A carriage return must be typed to return control to the computer. This feature performs the same function as, but obviates the need for, turning the teletype local-line switch to LOCAL and then back to LINE.

II. HARDWARE CONFIGURATION

This section will treat in detail the construction and operation of the interface between the Northern Scientific pulse height analyzer and the Nova 1210 computer. Its purpose is to permit troubleshooting and maintenance on the system as well as expansion capability when further devices may be added. Specifically, it will permit simple implementation of automatic computer surveillance of the scan table operation whenever that feature is desired, the electronic interface necessary having already been incorporated into the system.

Fig. 4. Top view of PHA-computer interface unit.

Fig. 5. Bottom view of PHA-computer interface unit.

Figure 4 is a top view of the interface pulled out of its rack, and Fig. 5 is a bottom view showing the cabling. As is readily apparent, the construction method chosen permits easy access to both wiring and circuit boards. The boards are numbered 1 through 11, which correspond to the schematics of Figs. 7 through 16. The construction is on Wyle cards, which permit easy troubleshooting and maintenance. Figure 5 shows the power supply for the interface to the left, with the

ac control modules near the front of the interface. The four pushbutton switches for the front panel are readily visible. Their schematic is given in Fig. 17.

Figure 18 is the schematic of the 110-V ac power line control circuitry. This permits all power to ancillary units of the system to be controlled either by a single switch on the interface panel (when the power toggle switch is in the ON OR OFF position) or by the main keyed power switch on the computer itself (when the interface toggle is in the COMPUTER position). As the schematic indicates, the power indicator LED will light whenever regulated five-volt power is on the interface unit.

For an overall description of system operation, the user is now referred to Fig. 6, where the block diagram of the interface is given. Referring to Fig. 6, it is clear that provision has been made in the electronics for implementing computer indication of the scan table position and condition. In the present device being used at DP-Site, this provision is not utilized, but is nonetheless available for future simplification of the system. Three pulse receivers and two level receivers are provided for table signals, which would correspond to the following table indications (1) Continuous-Segmented = a signal indicating whether the table will move continuously or be started and stopped for each segment scan, (2) Rotating = a signal indicating whether the sample is being rotated or not, (3) End = a signal indicating that the table has moved the sample to the end of its scanning run and the assay should be terminated, (4) Start = a signal used only in segmented mode, indicating that the table has stopped and a new segmented scan can begin, and (5) Stop = a signal used in conjunction with the START signal to indicate that the segmented scan for this segment is complete, and scanning should be stopped preparatory for table movement to another scanning position. These signals are received through

Fig. 6. Block diagram of PHA-computer interface unit.

light-coupled isolators as shown in the detailed schematics in order to eliminate the possibility of noise pickup on these long lines. The optically-coupled isolators used are HP-5082-4360 units which require 5 to 10 milliamp for reliable operation. The forward drop across the LED of the unit is about 1.5 volts, so if driven from a 5-volt source, 330 ohms is a reasonable value for the series resistor, allowing about 8.2 milliamp to flow. These can be readily driven from standard TTL buffers if negative logic levels are used, so that the ON state corresponds to the TTL output low level. With these indicator lines implemented, it would be possible, for example, to have the run stopped and started from the scan table controls without the necessity of separate computer controls. Also, the possibility of making a bad assay due to improper conditioning of the scan table is eliminated, thus removing another potential source of human error.

Referring again to the block diagram of Fig. 6, the toggle and pushbutton switches located on the front panel of the computer interface are shown as inputs, together with "inhibit" and "R" + " $\overline{A \cdot R}$ " coming from the pulse height analyzer. The "inhibit" line is used by the computer to prevent "stop" interrupts or new data from the pulse height analyzer when no run has been started; the "R" and " $\overline{A \cdot R}$ " lines are used to signal an interrupt to the computer whenever the pulse height analyzer is put into a "stop" or "readout" mode. The computer can be interrupted only by either this signal from the pulse height analyzer, the three table indicator signals, or by one of the four pushbutton switches. During a run it can also be interrupted by data from the PHA. A computer interrupt is generated when the BUSY flipflop is set, thus enabling the "D" input on the INTR flipflop, so that the next "request enable" pulse from the computer will set it and signal the computer that an interrupt has occurred. The information from each of these pushbuttons, the table indicators, and the PHA

"stop" condition, as well as PHA data, is saved in data latches as shown, which can then be read by the computer, which gives a DATIA pulse along with the relevant device code. The device code for the switches is 36₈, for the table indicators is 35₈, and for the PHA data interface is 34₈. The SELB line permits the computer to identify the source of any given interrupt by a simple polling procedure, which also permits software-controlled priority on the interrupting devices. The IORST pulse is a system reset which clears all flipflops in the entire interface. The CLR pulse permits selective clearing by requiring a device code along with the clear pulse.

The block diagram for pulse height analyzer to computer data transfer is also given in Fig. 6. The AO through A11 lines coming from the PHA carry the digitized pulse information for each event accepted by the PHA. The computer interface makes a high and low hardware comparison of each event to eliminate events which do not fall within the region of interest for the peaks being assayed. In this way, the system deadtime can be significantly reduced, since a comparable software comparison requires at least several orders of magnitude more time than the hardware comparison. Events which pass this window test are presented to the "D" inputs of the data latches. These data will then be strobed into the data latches for transmittal to the computer, providing the input gate conditions are met. The input gate will be permissive, providing the PHA is not in a readout mode. The PO pulse is used to strobe the data into the data latches after a sufficient delay which guarantees that complete conversion has occurred within the PHA. The relevant delay is about 3 microseconds. The same pulse which strobes data into the latches is used to set the BUSY flipflop, thus generating a computer interrupt at the next request enable pulse from the computer, in the manner previously described. During the interface busy time, a level is also placed on

the BUSY line going to the coincidence input of the PHA to prohibit further events from occurring until the present one has been serviced. It will be seen from the software description that this busy time is not the time required by the computer to completely sort the event, but rather only that time required to make the data transfer to the computer. This permits, for example, another event to occur and be accepted and analyzed by the PHA during the computer sorting of the previous event. Due to the random nature of the events, this will permit higher instantaneous event rates than simply gating off the system during each event sorting.

The SELB, DATIA, CLR, IORST, and device code (in this case 34_8) pulses are used in the same manner as previously described. Note, however, that device code 37_8 is used in a special way. When coincident with a DATIA pulse, this code sets the inhibit flipflop, preventing interrupts from occurring from the PHA when no run is in progress. Device code 37_8 coincident with CLR resets this flipflop, as does IORST, making the PHA interrupt system again permissive.

Most of the individual board schematics are self-explanatory for the trained electronics technician, but a few words of explanation will be given for clarification. Board 1 shown in Fig. 7 consists simply of the computer data bus line drivers, terminated in such a manner as to reduce line ringing and pickup. Note that these lines are driven open collector, since this is a bus or-ed line. Board 2 (Fig. 8) is the device decoder which supplies the four different device codes for the entire interface system. Board 3 (Fig. 9) shows the details of control line suffering into the interface from the computer and the PHA. Board 4 (Fig. 10) contains the data line buffers from the pulse height analyzer. We have provided here for 12 data lines, even though only 10 are currently used with our 1024 channel PHA memory. This has been done so that more memory could be added to the Northern Scientific PHA if later desired without changing the

Fig. 7. Data buffers.

Fig. 8. Device code decoder.

Fig. 9. Control line buffers.

Fig. 10. PHA data buffers.

Fig. 11. Digital discriminators.

Fig. 12. PHA data latches.

computer interface. Boards 5 and 6 (Fig. 11) show the detail of the hardware data compare circuitry. The switches on these boards can be set by the operator for a low and high cutoff of data where desired. The switch code is in BCD since it is not expected that these switches will often be changed.

Board 7 (Fig. 12) shows the data latches with gates for the PHA data. Board 8 (Fig. 13) contains the control circuitry for the PHA and the switches. Note that the $\overline{BR}$ (buffered $\overline{R}$) input goes low during all readout modes for the PHA, and thus prevents the computer from accepting data during this time. The buffered PO (BPO) pulse goes high at the start of a PHA cycle. This triggers a 3-microsecond pulse in the first half of the 74123 dual monostable, whose falling edge triggers a 100-nanosecond pulse from the second half of the IC. This output pulse is used to read the PHA data lines into data latches at the proper time.

Board 9 (Fig. 14) shows details of the table signal receivers. Note the cautions already mentioned in conjunction with the description of this section of the circuitry. Board 10 (Fig. 15) contains the table and inhibit control circuitry which provides table information to the computer and permits the computer to inhibit PHA data interrupts whenever the code dictates. The buffered request enable pulse (BRQENB) is used to synchronize interrupts with the computer internal clock. Board 11 (Fig. 16) shows the latches for the pushbutton switches. The buffered $\overline{R}$ ($\overline{BR}$) signal goes low during any PHA readout mode, thus sending the computer an interrupt used to stop data taking, providing the inhibit is not on. The buffered A·R ($\overline{BA \cdot R}$) goes low during all stop or readout modes, which also sends the computer an interrupt for the same purpose.

The pushbutton switch boards (Fig. 17) on the back of each of the four pushbuttons simply provide a single pulse for each switch closure and eliminate contact bounce.

Fig. 13. PHA data and switch control.

Fig. 14. Scan table signal receivers.

Table I shows the connections between the interface unit and the Northern Scientific pulse height analyzer. Table II shows the connections from the table to the interface unit, and Table III gives the layout of the cable and connector between the interface and computer. These connectors on the interface unit are readily identified by the number of pins each contains. The PHA connector is a 37-pin subminiature D Cannon connector, the table requires a 25-pin subminiature D Cannon connector, and the computer cable uses a 50-pin subminiature D Cannon connector. It is wise to use twisted pair cables for interconnecting the units, since these are quite free from noise and pickup.

TABLE I

Interface Connector	Function	PHA Connector
1	A ₀	D
2	A ₁	N
3	A ₂	X
4	A ₃	$\bar{g}$
5	A ₄	$\bar{q}$
6	A ₅	$\bar{y}$
7	A ₆	AH
8	A ₇	AS
9	A ₈	BA
10	A ₉	BK
11	A ₁₀	BU
12	A ₁₁	CC
13	R	Z
14	P ₀	$\bar{S}$
15	A-R	AU

A₀ RETURN

21	A ₁	"	CS
22	A ₂	"	CS
23	A ₃	"	CS
24	A ₄	"	CS
25	A ₅	"	CS
26	A ₆	"	CS
27	A ₇	"	CS
28	A ₈	"	CS
29	A ₉	"	CS
30	A ₁₀	"	CS
31	A ₁₁	"	CS
32	R	"	CS
33	P ₀	"	CS
34	A-R	"	CS
35			
36			
37			

TABLE II

Interface Connector	Function
1	+ CONT-SEG
2	+ ROT
3	+ STRT
4	+ STOP
5	+ END
6	
7	
8	
9	
10	
11	
12	
13	
14	- CONT-SEG
15	- ROT
16	- STRT
17	- STOP
18	- END
19	
20	
21	
22	
23	
24	
25	

TABLE III

Interface Connector	Function	Computer Connector
1	GRND	A, AF, all numbers
2	CLR	K
7	DATA 4	$\bar{v}$
8	DATA 5	$\bar{f}$
9	DATA 6	AE
10	DATA 7	$\bar{n}$
11	DATA 8	$\bar{u}$
12	DATA 9	$\bar{x}$
13	DATA 10	AC
14	DATA 11	$\bar{s}$
15	DATA 12	$\bar{t}$
16	DATA 13	$\bar{y}$
17	DATA 14	$\bar{p}$
18	DATA 15	AA
19	DATIA	F
32	DSO	X
33	DS1	v
34	DS2	U
35	DS3	H
36	DS4	S
37	DS5	T
40	INTR	$\bar{t}$
42	IORST	W
45	RQENB	$\bar{m}$
46	SELB	$\bar{a}$
49	PWR ON	B
50	GND	A, AF, all numbers

IV. SYSTEM SOFTWARE

The computer has a single 8K word memory board of which the present gamma scan program system, including error analysis, occupies about 3.5K words (7250₈). The remaining 4.5K words of core are available for future expansion or time-sharing with other assay instrumentation.

The actual program listing in machine language is available in Group A-1. We shall here attempt to explain the software philosophy rather than a detailed description of the machine-language implementation.

Since this minicomputer is not equipped with hardware floating point equipment, floating point calculations must be software implemented. There are basically two general methods of accomplishing this. One approach is simply to write separate subroutines for each floating point operation needed, e.g. multiply, divide, exponentiation, square root, etc., and then call these subroutines whenever the operation is needed. This suffers the disadvantage of laborious argument passing between the calling routine and the called subroutine. Since all floating point operations are at least two words per argument in length, this calling procedure usually involves address passing for the arguments, slowing down the operation as well as making coding more tedious. The alternative is to use an interpretive method where floating point instructions are "interpreted" by the assembler as calls to a general system subroutine which performs the operations in a more user-transparent manner. In this system the coder has only to enter the interpretive mode of coding, perform the desired operation, and exit the interpretive mode. All argument passing is left to the interpreter, which makes for more efficient code as well as greater simplicity in coding. This latter approach was used in the present gamma scan codes, and all calculations are done in single precision floating point format. This limits the accuracy to 23 binary bits for the mantissa, 1 bit for sign, and 8 bits for

the characteristic. The accuracy is therefore roughly six hexadecimal digits or about seven decimal digits. The range is roughly 10^{-73} to 10^{+72} . As can be seen from Fig. 3, the output is F-format which requires less accuracy than this in every case.

The main program breaks rather naturally into the following main subgroups (1) Interrupt service routines, (2) Data sort routine, (3) Teletype-user conversation routines, (4) Analysis routines, and (5) Error calculation routines. The interrupt service routines include codes to determine the interrupting device, and to perform the necessary servicing of each of the external devices requesting service. It should be noted that the realtime clock, internal to the computer, is also an interrupting device, and a rather important one, since in the present configuration, it determines the scan time for each segment and reinitializes the address of buffer storage within the computer for the data from each segment scan. This section of code also includes subroutines to output data to the teletype, to fetch information from the teletype, to convert ASCII numbers to internal binary data, and to perform each of the functions listed for the pushbutton switches.

When the START pushbutton is pressed, the program determines whether this is to be a background or foreground run (determined by the toggle switch) and sets the appropriate flags. It then clears all data storage buffers. Note that there must be 440₈ data cells reserved, nine for each of 32 segments, for a total of 288, or 440₈. The realtime clock is started, and the PHA data interrupt system is released from the inhibit condition. When the run is complete (either STOP is pressed on the PHA or 32 segment scan times elapse), the data is analyzed automatically for entry into the live-time and transmission peaks in the case of background run, or simply stored in the case of an analysis run.

The sort subroutine accepts data from the PHA and filters it through a software grid to determine if it fits into any of the data windows previously entered by the operator. If it fits, the appropriate data cell is incremented; otherwise, it simply returns for more data.

The analysis routine prints out the data on a segment-by-segment basis. Referring to Fig. 3, one sees the data in F-format printed out under the appropriate headings. The live time for the i^{th} segment is simply LT_o/LT_i , where LT_o is determined from the background run, and LT_i is measured for the i^{th} segment. The transmission printed out is actually the live-time corrected transmission ratio $(T_i/T_o)(LT_o/LT_i)$, and represents a good measurement of the gamma attenuation through the container and sample. The peak value printed out is the background-corrected number of raw counts in the assay peak. The correction factor is given by Eq. (2), and is calculated on a segment-by-segment basis.

When the appropriate segment limits are given by the operator, the code then computes the corrected counts for those relevant segments and prints it out, along with the computed assay, and then enters the error correction routine.

V. ERROR ANALYSIS

The error analysis is a propagated error calculation on a segment-by-segment basis based on Poisson statistics on the individual peaks being counted. For the purposes of error calculation here, it is assumed that LT_o and T_o are known so well that their statistics do not significantly alter the error estimate. This is a reasonable assumption, since the background run can be made long enough to reduce its counting statistics effectively to negligible values compared with the assay runs. Also, it is assumed that the geometrical factor, A , and the attenuation constant ratio, K , are accurately known, since no estimate of error in these constants can be gleaned from the data available to the

computer at assay time. However, no assumptions are made about the relative errors involved in the three assayed peaks; the error from all of them is propagated through the calculation for each segment. Assuming Poisson statistics, the following equation is found for the deviation

$$\delta^2(CC_i) = \left(\frac{LT_o}{LT_i} \cdot CF_s(T_i') \cdot CF_{can} \right)^2 \delta^2(C_i) + \left(\frac{C_i \cdot LT_o \cdot CF_s(T_i') \cdot CF_{can}}{LT_i^2} \right)^2 \delta^2(LT_i) + \left(\frac{C_i \cdot LT_o \cdot CF_{can}}{LT_i} \right)^2 \delta^2(CF_s(T_i'))$$

$$\text{where } CF_{can} = \frac{1}{\sqrt{T_c}} \text{ and } CF_s(T_i') = \frac{-AK \ln T_i'}{1 - (T_i')^{AK}}$$

$$\text{and } T_i' = \frac{T_i}{T_o} \cdot \frac{LT_o}{LT_i} \cdot \frac{1}{T_c}$$

and where the individual deviations are given by:

$$\delta^2(T_i') = \frac{1}{T_c^2} \left\{ \left(\frac{LT_o}{T_o \cdot LT_i} \right)^2 \delta^2(T_i) + \left(\frac{T_i \cdot LT_o}{T_o \cdot LT_i^2} \right)^2 \delta^2(LT_i) \right\}$$

and

$$\delta^2(CF_s(T_i')) = \left\{ AK \left[\frac{(1 - T_i'^{AK}) + AK \cdot T_i'^{AK} \cdot \ln T_i'}{T_i' (1 - T_i'^{AK})^2} \right] \right\}^2 \cdot \delta^2(T_i')$$

and the individual peak error deviations are computed from

$$\delta^2(\text{peak}) = B + \left[\frac{\Delta B}{2\Delta A} \right]^2 A + \left[\frac{\Delta B}{2\Delta C} \right]^2 C$$

where A , B , C are the counts in a background window ΔA below the peak, in the window ΔB which contains the peak, and in a background window ΔC above the peak, respectively.

These equations are of course solved for each segment involved in the final analysis, and then the results added in quadrature and the square root taken. This final answer yields the deviation on the corrected counts and is divided by the counts-per-gram factor to give the estimated standard

deviation on the assay. This number represents a lower bound on the estimate of assay error, since systematic errors have not, and indeed, cannot, be taken into account by the computer data reduction code.

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