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UF_6 Enrichment Monitor: Operating Procedures Manual

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UF_6 ENRICHMENT MONITOR: OPERATING PROCEDURES MANUAL

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T. D. Reilly, E. R. Martin,
and J. L. Parker

ABSTRACT

This manual describes the construction and operation of a UF_6 Enrichment Monitor for the continuous measurement of percent ^{235}U and percent ^{234}U in a liquid UF_6 stream. The system uses a gamma enrichment meter to measure ^{235}U and ^{3}He neutron detectors to measure ^{234}U. It is presently installed at the Goodyear Atomic Corporation gaseous diffusion plant in Piketon, Ohio.

I. GENERAL DESCRIPTION

The UF_6 enrichment monitor is a system to continuously measure percent ^{235}U and ^{234}U in the UF_6 product of a gaseous diffusion plant; the measurements are made on liquid UF_6 prior to withdrawal into product cylinders. The percent ^{235}U is measured with a gamma enrichment meter, and the percent ^{234}U is measured with a neutron detector counting (α, n) neutrons from the UF_6. Figure 1 is a picture of the system prior to installation.

The major gamma radiation from ^{235}U is at 185.7 keV. For a sample of constant volume the intensity of this radiation is proportional to ^{235}U enrichment. This system uses a NaI scintillation detector to detect the 185-keV gamma rays. The detector consists of a NaI crystal coupled to a photomultiplier tube. A gamma ray interacts with the crystal producing a short light pulse with an intensity proportional to the gamma energy. This is converted into an electrical pulse by the photomultiplier tube. Two single-channel analyzers are then used to strip the 185-keV events from the background.

There are two major components of the neutron signal from UF_6. Alpha particles from uranium (mostly ^{234}U) react with fluorine to produce fast neutrons,

$$^{19}F(\alpha, n)^{22}Na.$$

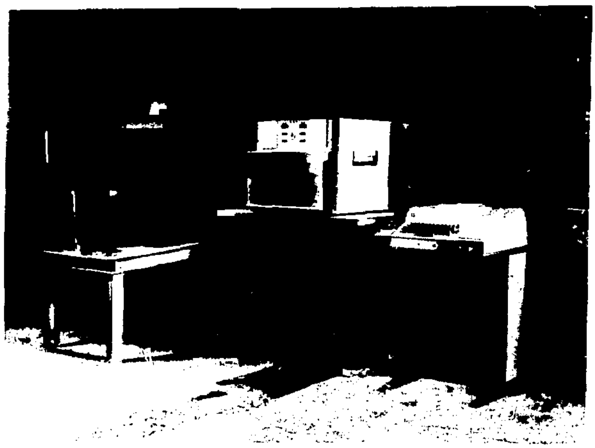

Fig. 1. UF_6 enrichment monitor; detector assembly, electronics cabinet, and teletype.

For a fixed mass of UF_6 this signal is proportional to percent ^{234}U. The other neutron source is ^{238}U, through spontaneous fission and (α, n) reactions. The ^{238}U signal is about equal to the ^{234}U (α, n) signal in normally enriched UF_6. This represents a background to the ^{234}U enrichment measurement. For low enriched uranium (2-5% ^{235}U) the ratio, $^{235}U/^{234}U$, is nearly constant, so the instrument can be calibrated to measure ^{235}U indirectly. The neutron detector consists of sixteen ^3He proportional counters in a polyethylene moderator. Fast neutrons from UF_6 are thermalized in the polyethylene. They then react with ^3He, $^3He(n, p)^3H$; the reaction energy, 765 keV, is shared between the proton and the triton.which then ionize some of the gas in the counter and produce an electrical discharge which is proportional to the reaction energy.

Figure 2 gives a block diagram of the system. The sample chambers and detectors are located in the Extended Range Product (ERP) withdrawal station at Goodyear (see Fig. 1; this is the assembly on the far left). This assembly is connected to the existing withdrawal line and a control valve is added to direct the UF_6 flow through the instrument line. An elevated vapor bypass is added to provide a low resistance path for vapor bubbles which may form in the UF_6. The level sensors are small, shielded Geiger tubes which measure whether or not a given pipe is full of UF_6. The vapor bypass should normally be empty and the measurement loop must be full in order to get a meaningful answer. Although not indicated in this figure, sufficient valves and vent lines have been added so that the instrument loop can be isolated from the rest of the system without interfering with product withdrawal.

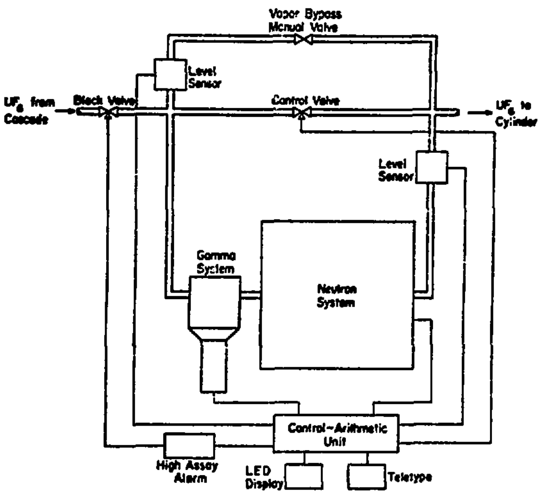

Fig. 2. UF_6 enrichment monitor block diagram.

The system electronics are explained in detail in later sections. The gain of the gamma system is stabilized with an external ^{241}Am source and an automatic gain control amplifier locked onto the 60-keV gamma ray from the source. This corrects for changes in system gain due to aging and varying environmental conditions. Pulses from the gamma and neutron detectors are amplified and fed to the control-arithmetic unit. The unit scales these pulses for a set time period. At the end of each count period, it computes the percent ^{235}U and percent ^{234}U from the accumulated count and predetermined calibration constants. Scaler counts, time-of-day, and the computed enrichments are displayed on the front panel and printed as a continuous record on the teletype. The gamma and neutron sections are electrically separate but contained in one chassis.

If the computed assay goes above or below preset limits, the control unit issues a high or low alarm. These alarms are front panel lights and rear panel switch closures to drive other warning systems and operate valves (e. g., the block valve would be closed on high alarm to stop UF_6 withdrawal).

A physical description of the system is best given in Figs. 3 through 6, showing the sample chambers and detector assemblies.

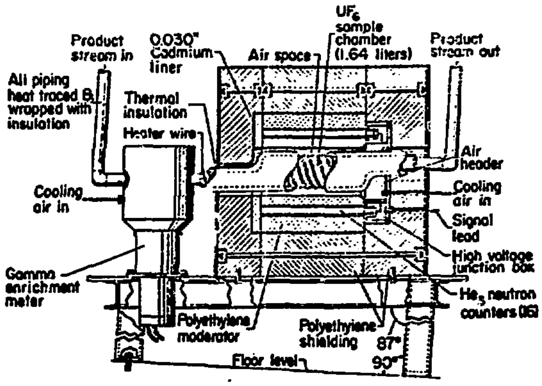

Fig. 3. UF_6 neutron counter and gamma enrichment meter assembly.

Fig. 5. Gamma shield and sample chamber.

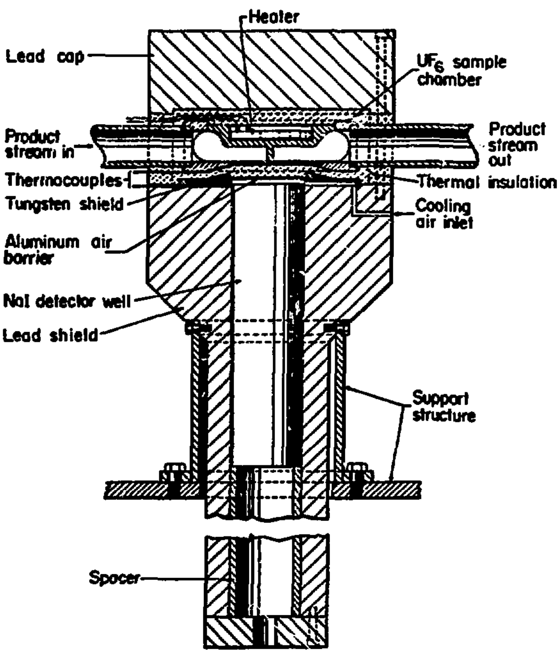

Fig. 4. Gamma enrichment meter.

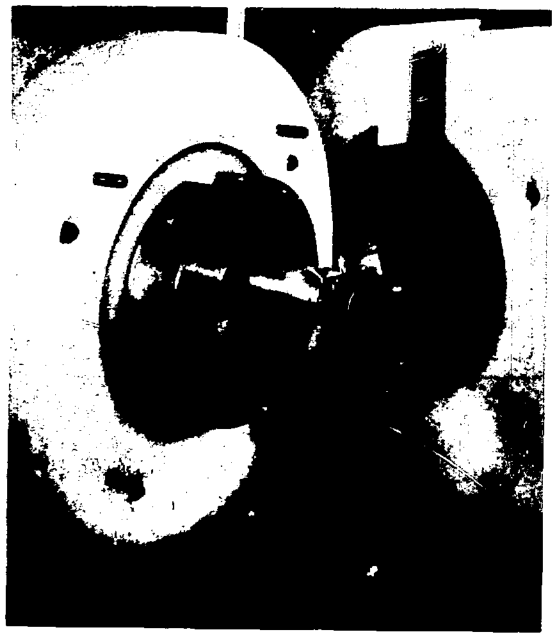

Fig. 6. Neutron detector assembly.

II. OPERATION OF ARITHMETIC-CONTROL UNIT

A. Connections to the Arithmetic Unit

All connections to the arithmetic-control unit are made via connectors on the rear panel. Most connections are self-explanatory, as indicated in Figs. 7 and 8. The purpose of this discussion is to make clear the various signal requirements and capabilities at each connector.

Consider each connector, from left to right (see Fig. 8):

1) TELETYPE: This four-pin connector provides a signal to start the teletype motor 300 msec before data are to be printed, and the signal current to drive the teletype printer. It is capable of providing 100 mA of signal drive current, sufficient to drive two teletypes in parallel through cable lengths up to a thousand feet.

2) L1-L2: These two BNC connectors provide signal inputs to the arithmetic unit from the UF_6 level monitors. Input impedance is 50 ohms, and inputs are 0 to +3.5 V pulses of 200-μsec duration; i.e., these inputs are designed to mate with the outputs of the level detector preamps through 50 ohm cables.

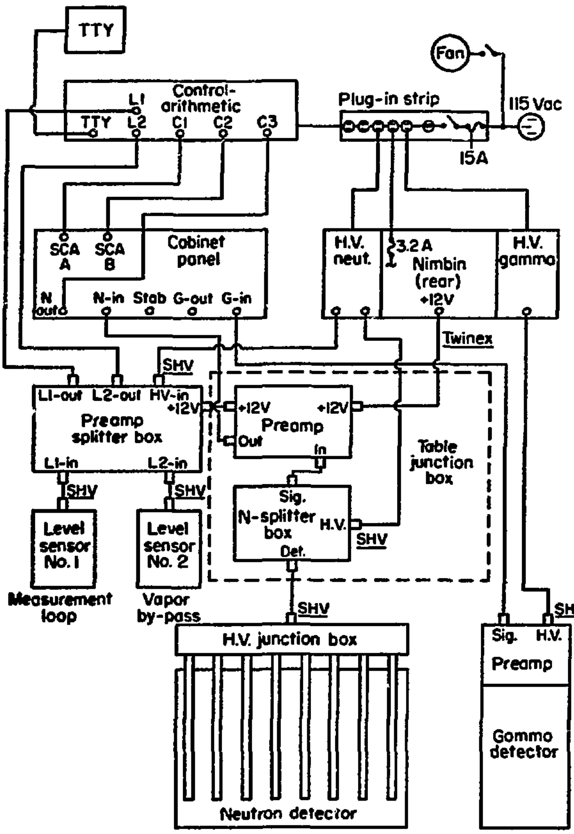

Fig. 7. Cabling diagram.

3) SCALERS C_1, C_2, and C_3: These are 50 ohm, internally terminated inputs which have triggering thresholds of +1.5 V independent of signal risetime. They require unipolar pulses of less than +6 V.

4) CONTROL VALVE: This connector is the output of a solid-state switch capable of handling 2.5 A at up to 240 V, ac. It energizes (i.e., contacts close) to close the control valve. The condition of this switch is indicated on the front of the unit by a green LED indicator labelled "VALVE" which lights when the valve is closed.

5) HIGH ALARM: This connector is again the output of a switch which closes on high alarm, and is capable of handling 2.5 A up to 240 V, ac or dc.[†]

6) BLOCK VALVE: This switch is closed in normal operation. When a high alarm condition exists, this switch opens. It is capable of handling 2.5 A up to 240 V, ac.[†]

7) LOW ALARM: This output is exactly the same as the high alarm, except that it actuates on low alarm.[†]

8) AC: This is the ac power cord connector for the arithmetic box.

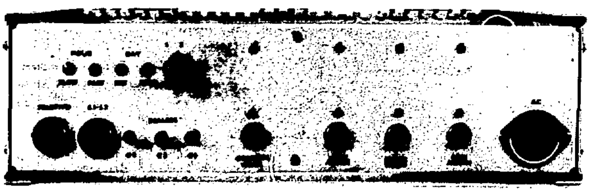

Fig. 8. Rear panel of arithmetic-control unit.

† Once an alarm condition has occurred, it will not reset until the "alarm reset" button on the front of the unit is pushed and the condition causing the alarm is changed.

B. Front Panel Controls (see Fig. 9)

There are four sets of five-digit thumbwheel switches and four sets of three-digit thumbwheel switches on the front panel. The five-digit switches are labelled A, B, D, and E, and have the function of setting the constants in the two equations:

$$A*C_1 - B*C_2 = \text{Gamma Enrichment}$$

$$D*C_3 - E = \text{Neutron Enrichment}$$

The gamma constants, A and B, are preceded by 0.0000 for a 10-min count interval. For example:

For $A = 6.085 \times 10^{-6}$ set 06085

$B = 1.217 \times 10^{-5}$ set 12170.

The neutron constants, D and E, are tied in with the rear panel switch, D. P. In position 1 (^{234}U computation), D is preceded by 0.000000 and E by 0.0. For example:

For $D = 4.17 \times 10^{-7}$ set 41700

$E = 5.24 \times 10^{-3}$ set 05240.

In position 2 (^{235}U computation), D is preceded by 0.0000 and E has a decimal point implied between the first and second digits. For example:

For $D = 5.35 \times 10^{-5}$ set 53500

$E = 0.712$ set 07120.

The three-digit thumbwheel switches on the left set the alarm levels for the gamma enrichment meter. A decimal point is to be assumed following the second thumbwheel switch, so that the maximum setting for these switches is 99.9. At the end of each interval measurement, a comparison is made between the calculated enrichment and the values set into these switches. If the calculated value exceeds the high level, the gamma high alarm is actuated; if the enrichment is less than the low level, the low alarm is actuated. The two LED indicators directly above the gamma enrichment LED readout will light accordingly: the red indicator lights on high assay, and the amber lights on low assay. These lights remain lit until ALARM RESET is pressed. If the condition causing the alarm is not removed, then they will light again at the end of the next assay interval. These front-panel indicators will always light on alarm condition, but the toggle switch labelled ALARM DISABLE can be used to prevent either the gamma assay or the neutron assay from triggering the alarm contacts on the back panel. The switch does not permit the operator to remove both assay instruments simultaneously from the alarm contacts.

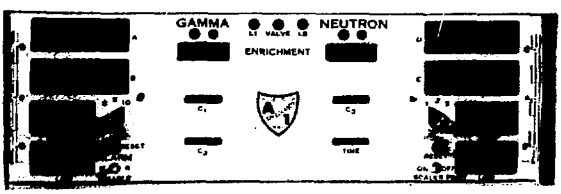

Fig. 9. Front panel of arithmetic-control unit.

The three-position switch labelled TIMER controls the timing interval of both assay instruments, and allows the selection of 2-, 5-, or 10-min assay intervals. Note that when this interval is changed, the calibration constants must be changed accordingly in order for the enrichment results to track. That is, if the interval is changed from 2 to 10 min, the constants set into thumbwheel switches A, B, and D must be divided by five. The constant E is independent of count interval.

The three-digit switches on the neutron side of the instrument have the same function in setting the alarm levels for the neutron counter as their gamma counterparts, with the exception that the neutron counter is capable of being calibrated to measure either ^{234}U or ^{235}U enrichment. With D. P. in position 1 (^{234}U) the decimal point is assumed at the front of the number (maximum setting 0.999); in position 2 (^{235}U) it is assumed after the second digit (maximum setting 99.9).

The SCALER PRINT toggle switch is provided to allow the operator to suppress the printing of the raw scaler values if desired. In the OFF position, the teletype printout will not include C_1, C_2, or C_3.

The three-position MODE switch provides the following functions: In position 1, the instrument will make continuous measurements of UF_6 enrichment at intervals selected by the timer setting, and the control valve will be continuously open. In position 2, continuous measurements of enrichment are made as before, but the control valve is closed. In position 3, the control valve is cycled in synchronization with the interval of enrichment measurement. The control valve is closed for about 10 min (scaler digits blank during this time) with the instruments not counting; then the control valve opens and after a 1-min delay the assay instruments start counting. They count for the interval selected by the timer setting, the control valve closes, and the cycle is repeated. The system will normally be operated in MODE 2. Note that in each mode the vapor bypass is to be controlled manually so that it may be open or closed in any of the three modes.

The RESET pushbutton on the right side of the instrument resets all scalers and restarts the timing interval. In MODE 3 the interval starts with a 10-min wait period. RESET must be pushed after any change in the calibration constants, since the arithmetic is being done continuously during the counting interval.

The front panel indicators are self-explanatory. The count contained in each of the three scalers is indicated on the small displays, along with the time of day. The two large displays indicate the results of the previous counting interval and display the enrichment directly, providing the constant switches have been properly set.

The "VALVE" LED indicator at the top of the unit lights when the control valve is energized.

C. Teletype Printout Format

Each counting interval results in a two-line teletype printout (see Figure 10), which is separated from previous printouts by two line feeds. The printout begins with the day of the year, a dash, the time of day (24-h reckoning), and then the gamma enrichment. This is followed

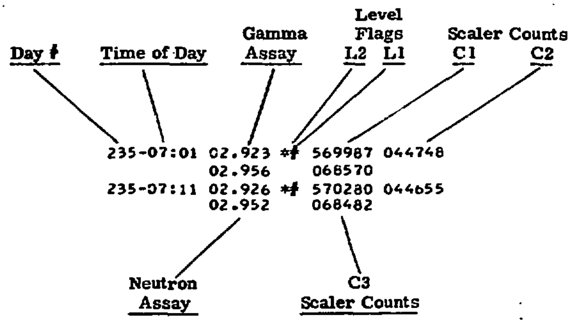

Fig. 10. Teletype format.

by a space in which either an asterisk or a sharp sign may be present. These flags indicate the condition of UF_6 levels as measured by the level detectors (* = L2, # = L1). When conditions are as expected, i.e., the top detector empty and the bottom detector full, no flags will appear on the printout. Next the scalers C_1 and C_2 will be printed, providing the SCALER PRINT switch is in the ON position. The next line of type will have the neutron enrichment printed directly below the gamma enrichment, and the contents of scaler C_3 directly below C_1 unless the scaler print is suppressed.

D. Back Panel Controls

As one views the arithmetic unit from the back (Fig. 8) there are five controls on the left side of the rear panel. The first two pushbuttons are used to set the time-of-day clock. The SLOW button advances the minute indication at the rate of 1 min/sec, and the FAST pushbutton advances the hours indication at the rate of 1 h/sec. The DAY SET pushbutton advances the day counter one day each time it is pushed. The DAY ZERO pushbutton returns the day counter to zero. The first teletype printout following a manual change in the day counter will probably contain the wrong leading digit in the day number (the second and third digits will be correct). On all subsequent printing the day number will be printed correctly.

The two-position switch to the right of the DAY ZERO pushbutton is used to change the position of the decimal point in the neutron assay. In position 1, the decimal point in the neutron enrichment display and printout is at the front of the numeral (maximum number therefore is .99999). This position is used when the neutron assay is set to measure ^{234}U enrichment. In position 2, the decimal point is positioned after the first two digits (maximum number 99.999). This is used when ^{235}U enrichment is being measured.

E. Summary

Assuming the cables are connected as shown in Figure 7, the unit is placed into operation in the following manner:

1) The calibration constants are set into thumbwheel switches A, B, D, and E.

2) The four three-digit thumbwheel switches are set at the desired alarm levels.

3) The ALARM DISABLE toggle switch is placed in the center position (neither instrument alarm disabled).

4) The TIMER switch is set to the desired timing interval.

5) The MODE switch is set to the desired mode (usually position 2).

6) The time of day and day of the year are set, using the rear-panel pushbutton switches.

7) The rear-panel D. P. (decimal point) switch is set.

8) The scaler print switch is set in the desired position.

9) ALARM RESET is pressed.

10) RESET is pressed, and the unit commences operation.

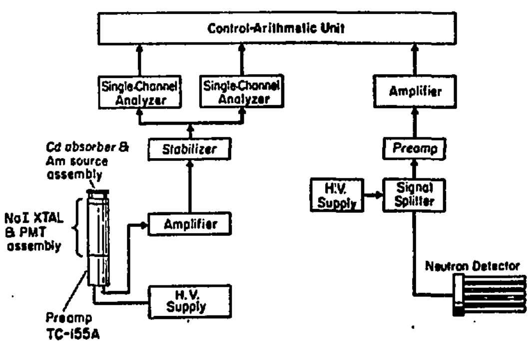

Fig. 11. System electronics block diagram.

III. GAMMA-RAY ELECTRONICS

A. General

Figure 11 is a block diagram of the system electronics. Manufacturers' manuals have been provided for all commercial electronics. These should be consulted for specific details on individual instruments. The purpose of this discussion is to briefly describe the components of the system and their operation. Sufficient pulse shapes are shown to enable the operator to check the proper operation of the system and perform elementary trouble shooting. Figure 12 shows the system electronics and most of the important controls. These modules are powered by a Nimbin located in the electronics cabinet. A panel has been placed over the controls to minimize accidental adjustments. The cable connections within the electronics cabinet are shown in Fig. 13. The cabinet has a small ventilation fan; this should be left on at all times.

B. Recommended Control Settings

The following are recommended control settings; they should require minimal further adjustment. The amplifier fine gain may be adjusted periodically to keep the stabilizer operating in the desired range.

1. Main Amplifier (TC 202-BLR)
   a. All time constant switches on 0.53 μsec (these are internal)
   b. BLR Switch - OUT
   c. Shaping Switch - BIPOLAR
   d. Rate Switch - HIGH
   e. Coarse Gain Switch - 50
   f. Fine Gain Control - ~ 8.25
   g. Polarity Switch - DIRECT
2. High Voltage Power (Power Designs--AEC Model 315-B)
   a. Voltage Setting Switches - Set for 1000 V
   b. Polarity - POSITIVE (Rear Panel Switch)
3. Stabilizer (Harshaw NA-22)
   a. Range Switch - 100%
   b. E Control - 1.00

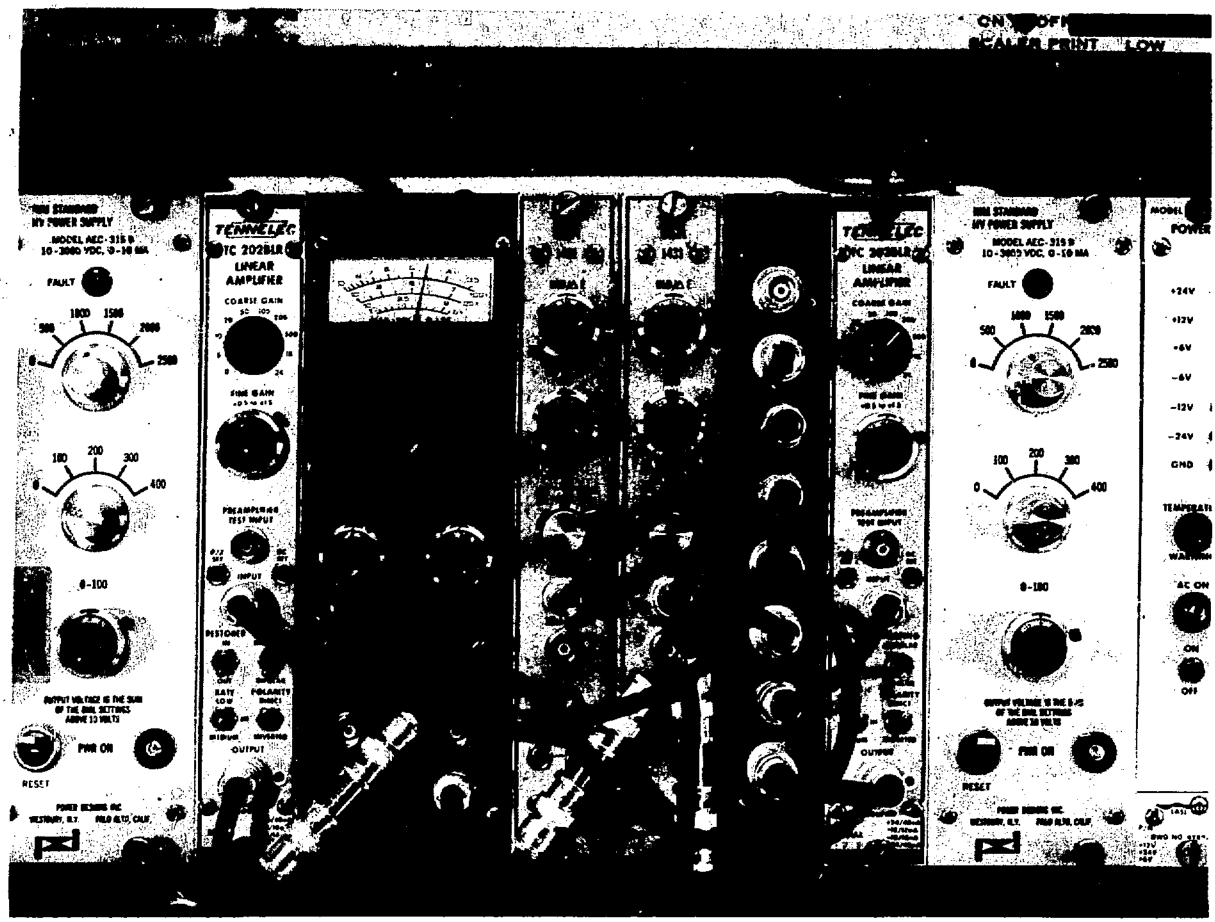

Fig. 12. System electronics showing major controls and module interconnection. Gamma electronics are to left of patch panel, neutron electronics to right.

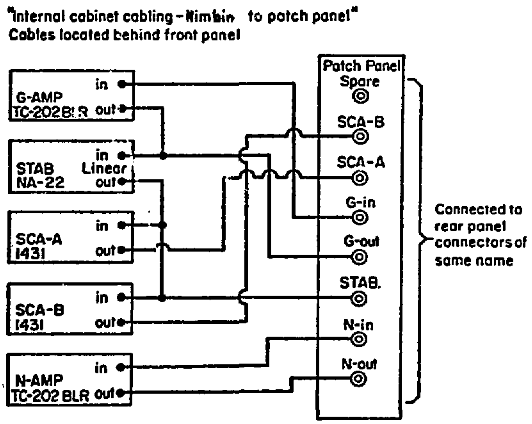

Fig. 13. Electronics cabinet cabling diagram.

c. ΔE Control - 0.35

d. Track/Disable Switch - TRACK

e. Sensitivity Switches -
1 x 16 during operation
16 x 16 for setup

f. For best results, it is suggested that the Amplifier fine gain be adjusted periodically so that meter indication on the 100% scale is between 4.5 and 3.5 (i.e., between gain ~ 2.2 and gain ~ 2.9).

4. Peak Count SCA (CI 1431)

a. E Control - 2.30

b. ΔE Control - 1.70

c. Mode Switch - 100% ΔE

5. Background Count SCA (CI 1431)

a. E Control - 4.30

b. ΔE Control - 1.70

c. Mode Switch - 100% ΔE

C. Cd Absorber and ^{241}Am Source Assembly

This assembly fits into the lead shield and rests on the face of the NaI detector. It is a 0.090-in.-thick cadmium absorber with four 1-μCi ^{241}Am sources glued underneath with RTV rubber. Each source is encapsulated in a stainless steel button about 1/4-in. diam. and 1/8 in. thick. The 60-keV gamma rays from the americium provide a constant rate spectral peak for gain stabilization. The cadmium suppresses the undesirable low energy x-ray portion of the uranium spectrum.

D. Detector and Preamplifier Assembly

The detector is a stainless steel jacketed Harshaw Integral Line unit consisting of a 2-in.-diam by 1/2-in.-thick NaI crystal scintillator coupled to an RCA 8053 photomultiplier tube (PMT). The system employs a Tennelec TC 155-A plug-on preamplifier which combines the PMT socket voltage divider chain, and preamplifier in one package. The preamplifier derives its power from the same high voltage supply which drives the PMT, thus eliminating the necessity for a separate low voltage supply. The preamplifier output which is presented to the amplifier resembles a very irregular sawtooth. Figure 14 shows the preamplifier output with the ^{241}Am and a uranium sample in place.

Fig. 14. Preamplifier output with the americium source and a uranium sample in place. Horizontal scale: 100 μsec/cm. The amplitude range is a few tenths of a volt.

Fig. 15. Main amplifier output.
Horizontal: 1 μsec/cm.
Vertical: 1 V/cm.

E. Main Amplifier

The main amplifier (a Tennelec TC 202-BLR) picks off the sharp vertical steps (which are proportional to the energy deposited in the detector crystal) from the preamp output and forms the smooth bipolar pulses seen in Figure 15.

F. Stabilizer

The stabilizer (Harshaw NA-22) is used to maintain a constant system gain. The Harshaw operating manual should be consulted for a description of its function and operation. With the recommended settings the stabilizer will operate at gains between ~ 2 and ~ 3. Figure 16 shows the

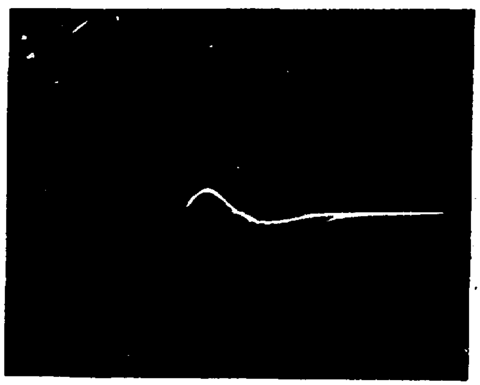

Fig. 16. Stabilizer output to SCA's.
Horizontal: 1 μsec/cm.
Vertical: 2 V/cm.

output of the stabilizer as it is presented to the SCA's. It is a faithful reproduction of the amplifier pulse except for an increment in gain and a harmless ringing in the negative lobe. The bright band at ~ 1.15 V is caused by 60-keV events from the ^{241}Am source. The band at ~ 3.25 V includes the 185-keV events from ^{235}U on which the enrichment measurement is based. The weaker band at ~ 0.6 V is from ^{241}Am and is of no importance. If the system is set up as recommended and is viewing a uranium sample, the stabilizer output should be virtually identical to Fig. 16.

G. Single-Channel Analyzers

The single-channel analyzers (SCA) are Canberra CI 1431's. One SCA window is set over the 185-keV spectrum peak, and the other is set above this peak to provide a correction for higher energy Compton background. The SCA outputs are the usual square logic pulses and are connected to scaler inputs of the processor unit. The scaler inputs are terminated internally with 50 ohms, causing the input pulses to appear as the upper trace in Fig. 17. If one views the SCA output without terminating the cable, there is a ringing as shown in the lower trace of Fig. 17.

The SCA outputs can be used to trigger an oscilloscope monitoring the stabilizer output as a means of qualitatively setting and/or checking the stabilizer and SCA windows. Because of delays in the SCA's, only the negative lobes of the pulses within the window are displayed. Figure 18 shows the stabilizer output gated by the stabilizer window, the ^{235}U peak window, and the ^{235}U background window.

H. Rates and Characteristics of the Gamma-Ray Spectrum

It is informative to examine the multichannel analyzer spectrum of the stabilizer output. Figure 19 shows the multichannel analyzer (MCA) spectrum of the stabilizer output as it enters the SCA's. It is superimposed on a spectrum gated by the SCA's showing precisely the location of peak and background windows with the recommended settings. In this spectrum the sample is of ~ 4% enrichment. The prominent peaks are 26 keV and 60 keV from ^{241}Am and 185 keV from ^{235}U. The ^{241}Am peaks are a constant feature of the spectrum while the magnitude of the ^{235}U peak will vary with the enrichment. This variation is illustrated in Fig. 20, which shows the ^{235}U portion of the spectrum for enrichments of 0.3%, 1.0%, and 4.0%.

The gross rate from the americium source is close to 6100 pulses/sec. Rough tests indicate

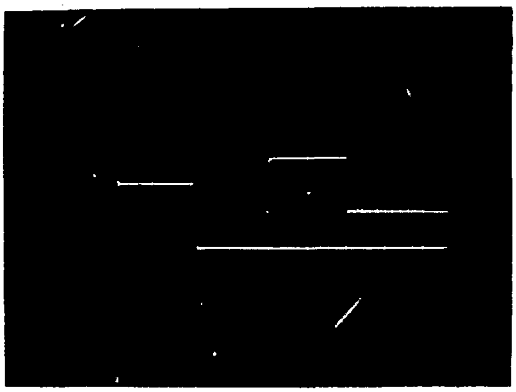

Fig. 17. Single-channel analyzer outputs. Upper is terminated into the scaler inputs. Lower trace is unterminated. Horizontal: 1 μsec/cm. Vertical: 5 V/cm.

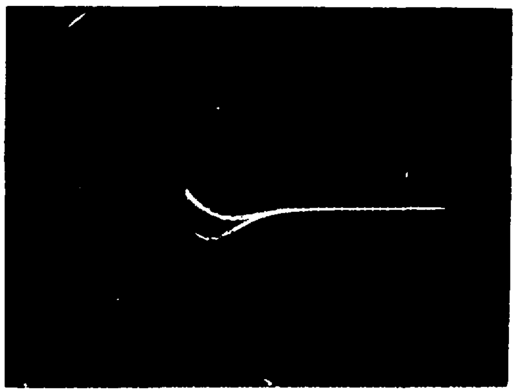

Fig. 18. Stabilizer output as gated by the various SCA windows illustrating how the windows may be set and/or checked. Horizontal: 1 μsec/cm. Vertical: 2 V/cm.

that the rate added by the uranium in the sample chamber will be roughly 270 pulses/sec-% enrichment. Thus UF_6 of 20% enrichment should produce an overall rate of ≤ 12000 pulses/sec. This will create problems with pile-up and deadtime at about the 1% level, which may probably be ignored. For enrichments above 20% appropriate corrections may be required. Alternatively the sample-detector distance could be increased to reduce the overall count rate remembering that this would also change the calibration.

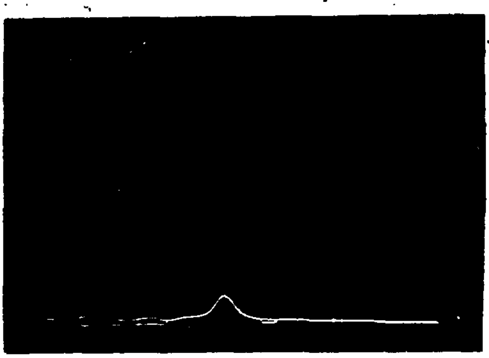

Fig. 19. Multichannel analyzer spectrum of the stabilizer as it enters the single-channel analyzers. It is superimposed on a spectrum gated by the single-channel analyzers showing precisely the location of peak and background windows with the recommended settings. The prominent peaks are, from left to right, 26 keV and 60 keV from ^{241}Am and 185 keV from ^{235}U. This spectrum corresponds to UF_6 of about 4% enrichment.

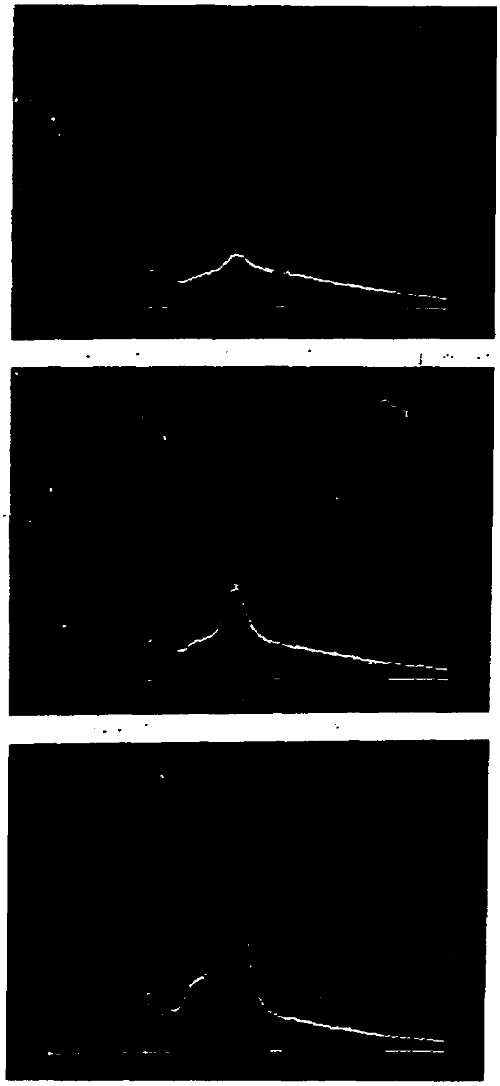

Fig. 20. Spectra of samples having enrichments of 0.3%, 1.0%, and 4.0%. Each also has superimposed a window gated spectrum. The vertical scale is expanded by a factor of 16 over Fig. 19.

IV. NEUTRON ELECTRONICS

Figure 11 shows a block diagram of the neutron system. The detector consists of sixteen ^3He proportional counters (10-in. active length, 4-atm gas pressure) supplied by Reuter-Stokes. The tubes are connected in parallel through a hermetically sealed junction box. The high voltage power supply is a Power Designs AEC-315-B. The signal splitter is located at the detector table and involves a capacitive pick off for the signal pulse. This signal goes to a proportional counter preamp of LASL design. The preamp is located at the detector table also. Figure 21 shows typical preamp output signals as seen on an oscilloscope; note that the pulses have a fast rise and slow decay. This signal goes to a TC 202-BLR amplifier in the electronics cabinet. Figure 22 shows typical amplifier output signals. The bright band just over 4 V is the neutron peak corresponding to the deposition of 765 keV from the $^3He(n,p)^3H$ reaction in the detector tube. The lower bright band is electronic noise. The amplifier output is fed directly to the scaler input, C_3, of the arithmetic unit. This input is terminated in 50 ohms, which causes the amplifier output to saturate at 5 V. This input goes to an integral discriminator with a threshold fixed at about 1.5 V. Any pulse over this threshold adds one count to scaler C_3.

The following are the recommended control settings for the neutron electronics:

1. High Voltage Power Supply
   a. HV - 1400 V
   b. Polarity - POSITIVE (Rear Panel Switch)
2. Preamplifier
   Gain - x5
3. Amplifier
   a. Coarse Gain - 200
   b. Fine Gain - 7.50
   c. BLR - OUT
   d. Shape - UNIPOLAR
   e. Rate - LOW
   f. Polarity - DIRECT

The following signals are available for examination on the rear of the electronics cabinet. These include all of the pictured signals in this and the previous section.

G IN	gamma preamp output
G OUT	gamma amplifier output
STAB	gamma stabilizer output
SCA A	single channel analyzer output, peak
SCA B	single channel analyzer output, background
N IN	neutron preamp output
N OUT	neutron amplifier output

These allow the operator to perform elementary trouble shooting without opening the electronics cabinet.

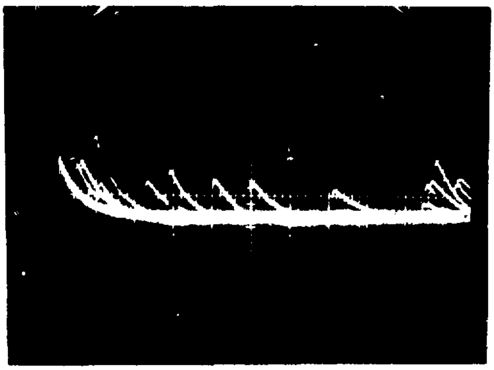

Fig. 21. Output of neutron preamp. .1 V/div., 200 μsec/div.

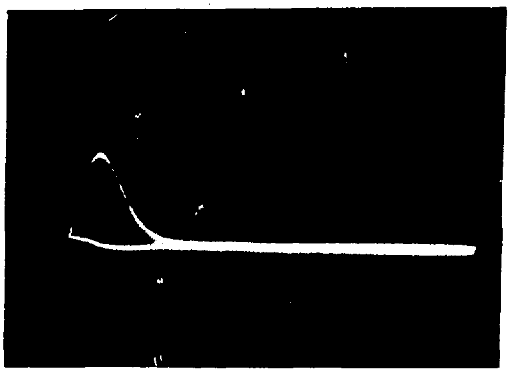

Fig. 22. Output of neutron amplifier. 2 V/div., 5 μsec/div.

Numbered cables run between the electronics cabinet and the detector assembly. The present cable assignments are listed below.

Cable #	Description
1	Neutron HV
2	Gamma HV
3	Level Detector HV
4	L2 - Vapor Bypass
5	L1 - Instrument Loop
6	Neutron Signal
7	Gamma Signal

V. CALIBRATION

A. General

The assay of the UF_6 in the instrument loop must be accurately known in order to calibrate this system; direct access to these data is difficult. The most readily available calibration data are from the on-line mass spectrometer and the routine laboratory samples; the evidence is that the latter is the more reliable of the two sources. Both of these measurements are made on the gas stream ahead of the condenser and the in-line UF_6 monitor. If the assay of the withdrawal stream is changing, there will be a time delay between the change at the gas withdrawal points and the change at the instrument loop and cylinder pigtail. This delay is a function of the volume of material between the two points and the flow rate; it can be as large as 30-60 minutes. In view of this it is best to pick calibration points when the withdrawal assay is running relatively constant so that the gas samples can be expected to accurately reflect the assay of material in the instrument loop.

B. Gamma

The gamma system is assumed to follow the equation

$$\%\ ^{235}U = A*C1 - B*C2 \qquad (1)$$

where C1 and C2 are the measured peak and background counts, and A and B are constants determined by the calibration procedure (these are set on front panel switches). The most reliable procedure for determining A and B is to perform a least-squares fit of a large number of accurately measured calibration points to the expression above. The equations and description of this procedure are beyond the scope of this manual so only a brief discussion of results is included here.

To accurately determine A and B 20 calibration points were measured over a 3-wk period (August 11 to September 2, 1973). Each point involved three numbers, the ^{235}U assay as determined by the laboratory analysis of a routine UF_6 sample and values of C1 and C2 taken as the average of six 10-min counts immediately following the withdrawal of the laboratory sample. These points were least-squares fit to the assay equation to determine the best estimates of the parameters A and B. These values are

$$A = 6.005 \times 10^{-6} \pm 0.015 \times 10^{-6} \quad (06005)$$
$$B = 11.464 \times 10^{-6} \pm 0.199 \times 10^{-6} \quad (11464)$$

where the quoted errors are one standard deviation and the numbers in parentheses are the corresponding thumbwheel settings. Using these parameters the fractional standard deviation (FSD) between the gamma assay (% ^{235}U) and the laboratory sample analysis for all 67 samples in this 3-wk period is

$$FSD \left(\frac{\text{gamma-sample}}{\text{sample}}\right) = 0.0024$$

or about 0.25%. This indicates very good agreement between the gamma enrichment meter and the laboratory sample analysis. Figure 23 shows a graph of gamma enrichment versus laboratory sample for a 6-day period. Gamma measurements are plotted every 3 h for legibility; measurements are taken every 10 min. This illustrates the excellent agreement between the two measurements.

The present calibration indicates a net ^{235}U signal of approximately 277 counts/sec/% ^{235}U. The background is approximately 160 counts/sec but is variable. Most of this background comes from a plating of nonvolatile ^{238}U daughter products (mostly ^{234}Th; 24.1 d) on the

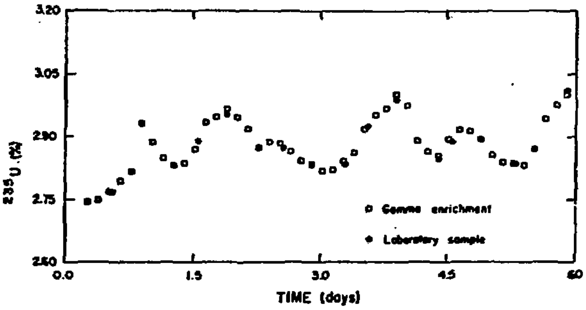

Fig. 23. Comparison of gamma enrichment measurements with percent ^{235}U as determined from routine laboratory samples. The points which appear as black squares indicate the two measurements overlap.

walls of the gamma chamber. The UF_6 alone presents a very clean signal for analysis since most of the daughter products have been removed in the diffusion process. The background is fairly large and varies with time. In particular, it increases significantly whenever the withdrawal stops and a UF_6 freezeout occurs in the instrument loop (some freezeout seems to occur whenever the UF_6 flow is stopped). This daughter product plating occurs on all system piping. It represents a minute amount of material, about 10^{-9} grams ^{234}Th per month. The background gamma activity comes from ^{234m}Pa, the decay product of ^{234}Th. Initially the background count rate rose from less than 10 counts/sec to an equilibrium value of about 160 counts/sec during the first 3 months of operation (this time scale is determined by the 24 d of ^{234}Th). While it may increase considerably during periods of interrupted flow, it returns to the equilibrium value when flow is resumed.

The gamma calibration should only require occasional adjustments whenever the gamma assay deviates consistently from the percent ^{235}U determined from the laboratory sample analysis. The following procedure should be used for this recalibration. Assume the ratio of the calibration parameters is constant, B/A = 1.909. Obtain data for several calibration points (minimum five) when the assay is running relatively constant. For each point use the percent ^{235}U determined from a laboratory sample and the average C1 and C2 obtained from six gamma measurements immediately following the sample withdrawal. For each calibration point compute A from

$$A = \frac{\% \, ^{235}U}{C1 - 1.909 * C2} .$$

Then compute the average A for all calibration points. Compute B from

$$B = 1.909 * A .$$

Set these values on the front panel switches and the instrument is calibrated. Consider the following example.

The data for six calibration points are listed in the table below. These include the % ^{235}U as determined from the laboratory sample and the average counts, C1 and C2, from six 10-min count periods immediately following sample withdrawal. For each calibration point the parameter A has been computed and listed in the fourth column of the table. These values are then averaged to give the calibration parameter A. As indicated in this example, the spread in A for the individual calibration points should be small.

Assay	C1	C2	A
2.862	541646	34643	6.019×10^{-6}
2.744	529304	37360	5.991
2.898	566293	43943	6.007
3.176	628116	51814	6.001
3.066	604505	49693	6.016
3.190	627812	50811	6.010
		mean =	6.007×10^{-6} = A

$$B = 1.909 * A = 11.468 \times 10^{-6}$$

The instrument should be recalibrated, as explained above, whenever the gamma assay deviates consistently from the laboratory sample analysis. It must be recalibrated whenever any of the electronic components are replaced or reset. Any change in the detector or sample chamber position will require recalibration. The instrument should operate stably for long periods with minimal recalibration. Large (1% or greater) unexplained changes in the calibration parameters may indicate electronic failures in the system and should be checked carefully. A complete multipoint calibration should be performed occasionally to check for changes in the parameter B/A. Appropriate data can be sent to LASL for this analysis.

C. Neutron

For normal UF_6 the major components of the neutron signal are approximately

$$^{234}U(\alpha, n) \sim 50\%$$

$$^{238}U(\alpha, n) \sim 20\%$$

$$^{238}U(SF) \sim 30\%$$

At higher assays $^{234}U(\alpha, n)$ becomes the dominant process. The neutron yield of UF_6 can be approximated by the expression

$$n/sec\text{-}gU = 4.68 * I_4 + 0.0245$$

where I_4 is the percent ^{234}U. The neutron counter is assumed to follow the expression

$$\%^{234}U = D * C3 - E$$

where C3 is the neutron count and D and E are constants. The constant E represents the small ambient background plus the background from ^{238}U in the sample chamber. This expression ignores any multiplication effects in the counter. The magnitude of this was estimated using a Monte Carlo neutron transport code. This analysis gave the ratio of neutron counts from 5% (^{235}U) material to that from 1% material as 5.33 ± 0.06. This shows the magnitude of the error made by assuming a linear equation for percent ^{234}U. This effect can be reduced by adding a thin sheet of cadmium between the detector and the neutron sample chamber.

The parameters D and E should be determined by least-squares fitting a number of accurately determined calibration points to the assay equation. No ^{234}U data have been available so this calibration has not been possible.

For low enriched material (2 to 5% ^{235}U) it is reasonably accurate to assume the %^{235}U is directly proportional to the %^{234}U. The assumption is not strictly correct as the ratio $^{235}U/^{234}U$ will vary several percent as the operating parameters of the cascade change. This assumption allows the percent ^{235}U to be calculated from the expression

$$\%^{235}U = D * C3 - E$$

where D and E are larger by the ratio $^{235}U/^{234}U$. The instrument measures %^{234}U directly and this is the best mode of operation. However, the indirect %^{235}U measurement seems the most probable mode of operation.

The assay equation can be rewritten

$$\%^{235}U = D * (C3 - E/D).$$

E/D represents the ambient room background and the background from ^{238}U in the chamber. This number is independent of ^{234}U and should remain constant except for a variation in the ambient background with cylinder fill weight. In the present location the detector is about 3 ft from the filling product cylinder which represents the major source of ambient background. As the cylinder fills, the background varies from approximately 650 to 1750 counts per 10 min. This variation represents an uncertainty in the neutron assay of approximately ± 0.03% ^{235}U. The total neutron signal from 3% enriched material is approximately 70,000 counts in 10 min.

Over 100 calibration points were determined during a 4-wk period in June and July 1973. These points and selected subsets thereof were least-squares fit to the assay equation to determine values of D and E. It was assumed that the large number of points included measurements at all stages of cylinder filling so that the fit gave an average over variations in the ambient background. The values obtained from this procedure were

$$D = 5.32 \times 10^{-5} \quad (53200)$$

$$E = 0.878 \quad (08780)$$

$$E/D = (1.65 \pm 0.16) \times 10^{4} \ .$$

The values for D and E are not important since they vary continually with the changing $^{235}U/^{234}U$ ratio. E/D, however, is constant and is used in the calibration procedure explained below.

The calibration of the neutron system is very similar to the gamma system. Assume the ratio of the calibration parameters is constant,

$$E/D = 1.65 \times 10^{4} \ .$$

Obtain data for several calibration points (minimum five) when the assay is running relatively constant. These points should cover a complete cylinder filling to average the background variations due to cylinder weight. For each point use the % ^{235}U determined from a laboratory sample and the average C3 obtained from six neutron measurements immediately following the sample withdrawal. For each calibration point compute D from

$$D = \frac{\%\,^{235}U}{C3 - 16500} \ .$$

Then compute the average D for all calibration points. Compute E from

$$E = 16500 * D.$$

Set these values on the front panel switches and the instrument is calibrated. Consider the following example.

Data for six calibration points are listed below. C3 is the average of six 10-min count periods immediately following the sample withdrawal. The points are from a 3-day period covering one cylinder filling. For each calibration point the parameter D has been computed and listed in the third column of the table. These values are then averaged and the results set in the front panel switches.

% ^{235}U	C3	D
3.101	68804	5.929 x 10^{-5}
3.096	68870	5.912
3.082	69045	5.865
3.098	69147	5.884
3.099	69032	5.899
3.074	68946	5.861
		mean = 5.892 x 10^{-5}

$$B = 16500 * 5.892 \times 10^{-5} = 0.972$$

The calibration of the neutron system should be checked often as the $^{235}U/^{234}U$ ratio is changing continuously causing the calibration to drift. The instrument should be recalibrated whenever the neutron assay deviates consistently from the laboratory sample. It should be recalibrated whenever there is a significant change in the assay (>1% ^{235}U) since multiplication effects will be noticeable. Over a period of 1 month the $^{235}U/^{234}U$ ratio was observed to drift over a range of 7%. Based on available information, even larger changes can be expected. For short periods the variability is considerably less. For periods of the order of 1 wk the fractional standard deviation between the neutron assay and the laboratory sample analysis was observed to be about

$$FSD\left(\frac{\text{neutron-sample}}{\text{sample}}\right) = 0.013$$

or about 1.3%. This shows reasonably good agreement between the two measurements. For periods when the $^{235}U/^{234}U$ ratio is constant, the deviation between neutron assay and laboratory sample can be expected to approach the limit set by counting statistics and the variability of the ambient background (~1.1%). If the calibration is not checked weekly, the deviation can be as large as 5% or greater.

D. Alarm Limits

If the measured assay goes above or below preset limits, an alarm condition is registered as explained in section II. These alarm limits are set on front panel switches and are set independently for the neutron and gamma systems. When calibrated properly the measurements will be distributed about the true percent ^{235}U, but single measurements will deviate from the true answer according to statistical laws. There is a small, but finite, probability that fairly large deviations will occur. Such deviations can produce false alarms, if they fall outside the preset limits. The measurements are assumed to be distributed about the true assay according to a Gaussian distribution with a standard deviation σ. The table below lists the probability of occurrence for a deviation outside a given limit expressed as a number (n) of standard deviations. If m is the true answer, column two lists the probability of a statistical deviation resulting in a measurement falling outside the interval $m \pm n\sigma$. The third and fourth columns list the number of false alarms per day and per week assuming a 10-min count period (144 measurements per day). This table should be used as a guide in setting the alarm levels. The levels should be set at $\pm 4\sigma$ or greater in order to minimize the number of false alarms. The standard deviation (σ) of the gamma system is of the order of 0.25%. If the alarm levels are to be set at 5σ (1.25%) and the target assay is 3.0%, the levels should be 2.96 and 3.04%. The neutron system has a larger standard deviation, 1.3% (if the calibration is checked routinely, otherwise larger), so the same alarm conditions (5σ = 6.5%) would require levels at 2.80 and 3.20%. When the alarm levels are set close to the target assay (as in the above examples), the calibrations should be checked carefully to reduce the possibility of false alarms.

n	Probability of Occurrence	False Alarms Per Day	False Alarms Per Week
1	0.3173	45.7	
2	0.0455	6.6	
3	0.0027	0.39	2.7
4	6.34×10^{-5}	0.009	0.064
5	5.73×10^{-7}	8.3×10^{-5}	5.8×10^{-4}
6	2.0×10^{-9}	2.9×10^{-7}	2.0×10^{-6}