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## **Fast-Neutron Coincidence-Counter Manual**

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by

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## ABSTRACT

The fast neutron counter (FNC) described in this report is a computer-based assay system employing fast-pulse counting instrumentation. It is installed below a glove box in the metal electrorefining area of the Los Alamos National Laboratory Plutonium Processing Facility. The instrument was designed to assay plutonium salts and residues from this process and to verify the mass of electrorefined metal. Los Alamos National Laboratory Groups Q-1, Q-3, and CMB-11 carried out a joint test and evaluation plan of this instrument between May 1978 and May 1979. The results of that evaluation, a description of the FNC, and operating instructions for further use are given in this report.

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## I. INTRODUCTION

During the past several years the Los Alamos National Laboratory Plutonium Processing Facility has received a large amount of nondestructive assay (NDA) equipment as part of the dynamic materials accountability (DYMAC) safeguards program. In the metal electrorefining area, there was a need for an instrument that could assay the plutonium salts and fluoride residues produced in the electrorefining process and that could verify the impure metal input and the pure metal output of this process. It appeared that the Los Alamos-designed random driver might be appropriate for this problem. This instrument contains two strong AmLi random neutron sources that can induce fissions in the sample. When the sources are removed, the instrument passively measures coincidence neutrons from the spontaneous fission of the even isotopes of plutonium. If the plutonium is in the form of fluorides or other compounds with high  $(\alpha, n)$  cross sections, these neutrons may induce fissions that contribute to the coincidence signal. Then it is desirable to introduce the random neutron sources and actively interrogate the odd isotopes of plutonium. The net active-minus-passive coincidence response is proportional to the mass of  $^{239}\text{Pu}$  and (hopefully) independent of chemical impurities.

For these reasons the fast neutron counter (FNC) consists of a random driver chassis with two AmLi neutron sources that can be moved in and out under computer control. The chassis contains three plastic scintillators to provide neutron multiplicity information on large multiplying samples. Lead shielding is used to reduce the flux of fission gamma rays to the scintillators. Fast-pulse processing circuits are used to reduce the background of accidental coincidences from the neutron sources and from impure samples and to further reduce the gamma-ray response. A Digital Equipment Corp. (DEC) PDP-11/04 computer is provided for assay control, source motion, and data analysis.

The FNC was installed in the metal electrorefining area in May 1978 for a 1-yr test and evaluation period. The Safeguards Assay Group (Q-1) was responsible for installation, checkout, calibration, maintenance, and documentation. Group Q-3 assisted with these activities and provided a cognizant scientist to train operators, help carry out assays, and maintain a record of system performance. Group CMB-11 performed a series of assays of electrorefining residues and plutonium metal, including daily background and normalization checks. CMB-11 also provided (through CMB-1) information on the isotopic composition of all samples and a complete destructive analysis of six residue samples.

Section II of this report describes the results of the test and evaluation of the FNC. Sections III, IV, and V describe the FNC chassis, electronics, and software. Instructions for tune-up, operation, and maintenance are given in Secs. VI, VII, and VIII.

## II. TEST AND EVALUATION RESULTS

### A. Instrument Performance

During the test and evaluation period, the FNC functioned well, with only a few days lost to equipment repair or replacement. In particular, the mechanism for moving the AmLi interrogation sources into place for active assays was reliable. In the year following the test and evaluation period, failures of individual channels of the 4-, 8-, or 12-channel nuclear instrument modules (NIM) were more frequent. Exchange and repair of the affected modules resulted in several weeks of lost time. Some repair of computer peripherals and motor controllers and microswitches was also required. Part of this damage was the result of improper handling by plant workmen engaged in other duties.

The temperature correction originally applied to the data was deleted because of the stable plant environment. A correction for moderation of interrogation neutrons by the sample—as measured by the flux of thermal neutrons recorded in two  $^3\text{He}$  detectors—was also found to be unnecessary for the small sample sizes encountered in practice. Both the temperature correction and the flux correction were replaced by alarm limits. A correction for sample fill height also was not needed, because the integrated response of the instrument is uniform to within several per cent over the range of sample sizes.

Sample assays were corrected only for background, detector efficiency, and self-multiplication within the sample. Coincidence background rates ranged between 3 and 10 counts/s, depending on the amount of material in the vicinity. The detector efficiency (whose absolute value is about 17%) was stable to  $\pm 1\%$  of the nominal value for 1-wk periods and has been stable to  $\pm 2\%$  since installation. This stability is somewhat better than that reported for earlier random drivers and is presumably due to the stable temperature in the plant. The correction for self-multiplication is based on the ratio of triple to double coincidences, as described in Sec.V.B. The formulas described there also provide for samples that emit neutrons produced in ( $\alpha,n$ ) reactions.

### B. Calibration

After the FNC was installed in the plant, a variety of well-known plutonium metal, oxide, and fluoride samples were run in the FNC to provide data for calibration curves. When measurements of process material began, some adjustments of the calibration curves and correction factors were required. At present, the instrument is calibrated for five classes of material: oxides, fluorides, pure electrorefined metal, impure metal from oxide reduction, and electrorefining residues. All calibration curves are of the form  $\text{Mass} = A(\text{Response})/[1 + B(\text{Response})]$ . The curves are nearly linear ( $B$  is small) because of the self-multiplication correction. One self-multiplication correction is used for all passive assays, another for all active assays.

The oxide calibration was based on oxide standards measured after installation. Two curves were provided, one for passive assays (Fig. 2-1) and one for active assays (Fig. 2-2). An active assay is automatically carried out by the computer if the passive assay indicates that the sample may be impure [that is, unusually high singles count rate resulting from  $(\alpha, n)$  reactions]. Because impurities can only increase the measured response, the computer then selects the minimum result as the final assay. On the basis of the calibration, the FNC should provide oxide assays of about 2% accuracy, but no oxides have been assayed yet.

For plutonium fluorides, only a passive calibration (not illustrated) was provided. This should provide assays of pure  $\text{PuF}_4$  to ~5% accuracy, but so far no fluorides have been assayed. An active calibration was not available at the time of the evaluation because of a saturation problem in the electronics. This problem has now been diagnosed as an imbalance between the double and accidental double coincidence circuits. The imbalance has been removed by the addition of clipping lines to define the gate lengths precisely. It should now be possible to calibrate the FNC for active assays of  $\text{PuF}_4$  up to about 800 g. However, the high count rate observed with this material (about 1000 counts/s-g) will limit the active assay precision for such large samples to about 10% in a 1000-s counting time.

Figure 2-3 shows the FNC calibration curve for electrorefined metal (>99.9% purity). Pure metal required only a passive measurement. The calibration curve is the same, within statistical errors, as the passive oxide calibration curve. The metal consisted of irregular curved pieces stacked in a small can. As a consequence of the self-multiplication correction, the response was nearly independent of the geometrical configuration. Each data point was measured with ~1% statistical precision. The actual scatter of 2.5% (1  $\sigma$ ) is attributed primarily to the approximations inherent in the self-multiplication correction.

Figure 2-4 shows the FNC calibration for impure metal, which required an active assay. This material consisted of 600-g metal buttons, derived from oxide reduction, which contained 10 to 20 g of impurities and 1 to 2 g of magnesium or calcium salts acquired during reduction. Induced fissions from  $(\alpha, n)$  reactions in the salts make the passive assay high by 100 to 200 g. The active assay is more accurate, but is subject to 3% statistics resulting from the active-minus-passive difference measurement. The active metal and active oxide calibrations both curve downward with increasing mass and are not the same within statistical errors. Probably this is due to absorption of interrogating neutrons by the samples.

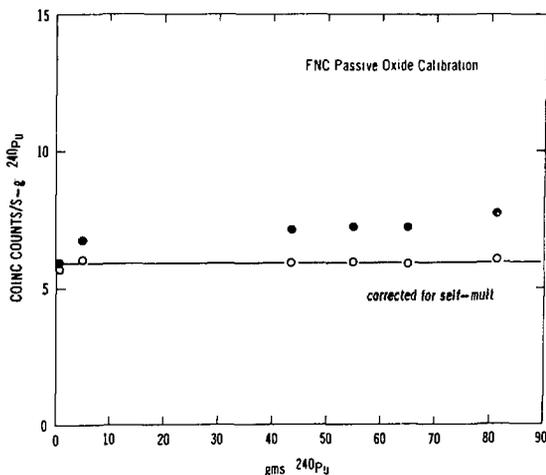


Fig. 2-1.

Data used for FNC passive oxide calibration. The calibration was based on the self-multiplication-corrected values.

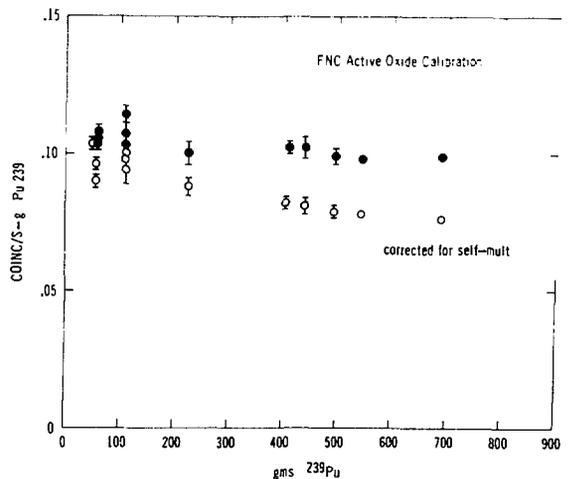


Fig. 2-2.

Data used for FNC active oxide calibration. The calibration was based on the self-multiplication-corrected values.

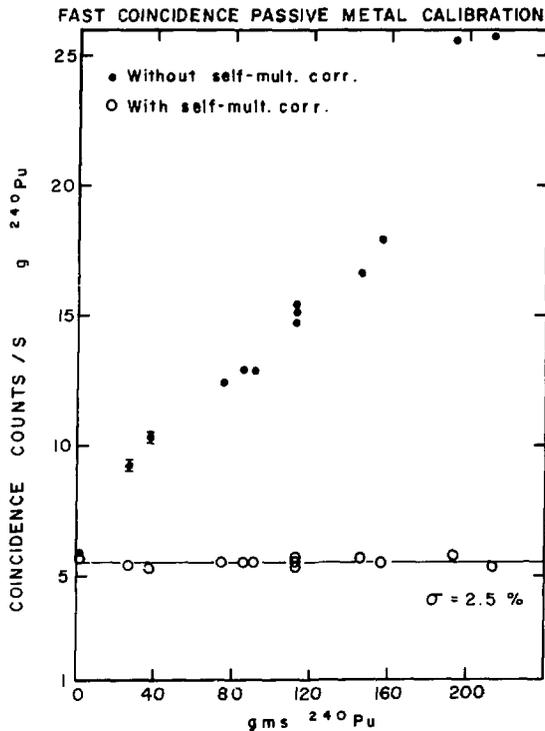


Fig. 2-3.

Data used for FNC pure metal calibration (passive only).

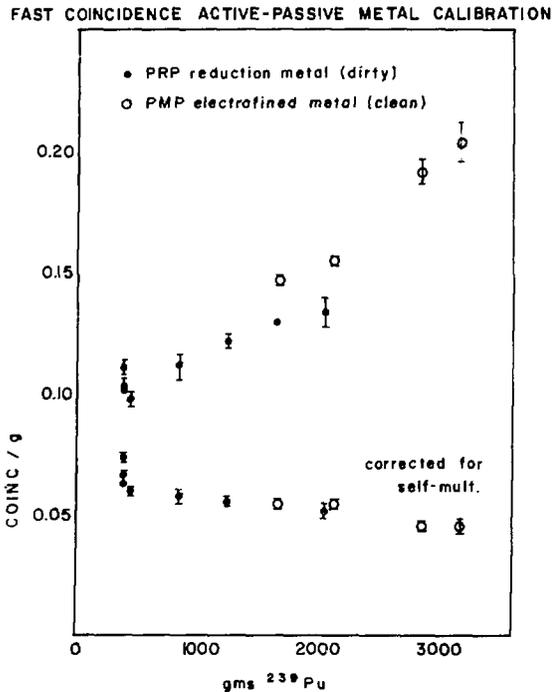


Fig. 2-4.

Data used for FNC impure metal calibration (active only). Both impure metal and electrorefined metal data were used, because both should show the same response to active interrogation.

For the electrorefining residues, the active and passive oxide calibration curves (Figs. 2-1 and 2-2) were used.

### C. Assay Results for Metal

Table II-1 summarizes the results of the test and evaluation period for the five categories of material for which the FNC was calibrated. As mentioned earlier, no oxide or fluoride samples were assayed after calibration. For pure electrorefined metal, the FNC provided a verification with a random error of 3.5% of the measured weight. The assays were 3.1% high (average), calling for some adjustment of the calibration curve. The statistical precision of each assay was about 1% in a 500-s counting time, but the self-multiplication correction factor was 2 to 3. Because of the magnitude of this approximate correction, the observed precision was worse than the statistical precision. Also, the error obtained at the time of the assay was somewhat worse than 3 to 4% because the operator usually did not know the isotopic composition of the sample. The actual effective <sup>240</sup>Pu was typically 1 to 2% different from the nominal value of 6%.

For impure metal obtained from oxide reduction, the FNC provided a verification with a random error of 3.7% of the by-difference value. This error is due almost entirely to the 3 to 4% statistical precision of the active assay (500-s counting time). The FNC assays averaged 5.2% lower than the measured weight of the sample. After allowance for the impurities in the metal, these assays averaged 2.2% lower than the by-difference values. Again, an adjustment to the calibration curve would eliminate this bias.

**TABLE II-1**  
**TEST AND EVALUATION RESULTS**

Sample Category	Assay Type	Source of Calibration	Number of Samples Since Calibration	Systematic Error (with respect to by-diff) %	Random Error ( $1\sigma$ ) %
oxide	passive (active)	oxide standards	none		
fluoride	passive	PuF <sub>4</sub> powder	none		
electrorefined metal	passive	metal weight	10	+ 3.1	3.5
impure metal	active	active assay of electrorefined metal	44	- 2.2	3.7
residues	active	oxide standards	24	0	15.0
	(passive)		24	+ 36.0	37.0

For pure metal, the FNC assay was less accurate than the electronic balance measurement. For impure metal, the FNC assay accuracy was comparable to (but not better than) the 3% difference between the measured and by-difference weight. Thus for both categories of metal, the FNC assays do not replace traditional accounting values, but do provide a verification of the amount of special nuclear material present.

#### D. Assay Results for Residues

The residues of the electrorefining process contain 30 g of PuF<sub>3</sub> (the converted catalyst), 1400 g of KCl and NaCl electrolytes, and small beads of impure plutonium. These electrorefining salts are strong ( $\alpha, n$ ) neutron emitters, and contain enough plutonium to be self-shielding with respect to gamma radiation and self-multiplying with respect to neutrons. The total mass of plutonium in the residues assayed by the FNC varied between 40 and 600 g. (The three samples with values between 40 and 60 g represent abortive electrorefining runs that occurred during plant start-up.) To assay these residues, the active and passive oxide calibration curves were used.

Table II-1 and Fig. 2-5 summarize the results obtained for the active and passive residue assays. As expected, the passive assays were high and very inaccurate because of ( $\alpha, n$ )-induced fissions. This is why the active neutron technique was chosen. However, the active assay results were also disappointing. Although there is no systematic bias relative to the oxide standards, the 1-std-dev scatter between the active assays and the plant by-difference values was 15%. The statistical precision of the assays was 3 to 5% for most of the residues, but was as large as 15% for the smallest samples. The accuracy of the plant by-difference values is not exactly known, but has been estimated from the values obtained when the residues were totally dissolved. Six residues were analyzed by CMB-1 as part of the test and evaluation

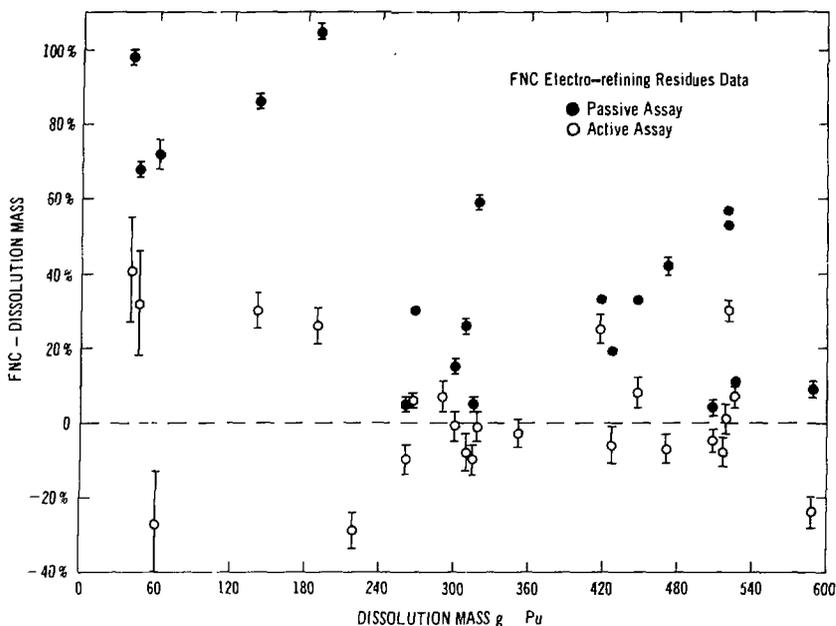


Fig. 2-5.  
Comparison of FNC assays of electrorefining residues with dissolution values for the plutonium mass.

plan, and 10 others were reprocessed by CMB-11 during the past year. The average deviation between the original by-difference and the final dissolution value is 10%. However, this deviation is not responsible for the scatter in the FNC assays. As shown in Fig. 2-5, the deviation between the FNC assays and the final dissolution values is still large and is still roughly 15%.

One residue assay, which yielded a value of  $333 \pm 14$ g, has been excluded from the above comparisons. The plant by-difference value was 189 g. Because of the large discrepancy, this sample was submitted to CMB-1 for complete destructive analysis, with a result of 349 g. After this result was obtained, a check of the plant by-difference calculation showed that an incorrect impurity factor had been used in the calculation. Thus the FNC residue assays are able to detect large discrepancies in the by-difference values, although the average accuracy is only about 15%.

In an attempt to improve this accuracy, the residue data were reanalyzed in several different ways. The dissolution value (when available) or the plant by-difference value was taken to be the true mass. The goal was to find a correction that would make the observed active coincidence response/g of  $^{239}\text{Pu}$  nearly constant from sample to sample. The following observations were made.

1. There is no correlation between the active double coincidence response/g and the passive triple/double coincidence ratio. The triples/doubles ratio is used to estimate and correct for sample self-multiplication. The lack of correlation implies that the self-multiplication correction is not effective for this material. This appears to be due to the large variation in the ratio of  $(\alpha, n)$  neutrons to spontaneous-fission neutrons. This ratio, which is 0 for metal and roughly 0.6 for oxide, varied between 0.3 and 9.8 for normal residues. For the three residues from the aborted electrorefining runs, the ratio was 30 to 33. These three residues consisted almost entirely of  $\text{PuF}_4$  and the electrolytic salts.
2. There is no correlation between the active double coincidence response/g and the passive singles response/g. The passive singles response provides a means for estimating the ratio of  $(\alpha, n)$  neutrons to spontaneous-fission neutrons. The lack of correlation again makes it difficult to apply a

self-multiplication correction to the data. It does seem, however, that appreciable self-multiplication is taking place in the residues. Most samples that show a high active coincidence response/g also have either a high triples/doubles ratio or a high singles response/g. The self-multiplication correction available at this time, however, only reduces the observed scatter from 20% to 15%.

3. There is some evidence that the gamma sensitivity of the plastic scintillators is affecting the assay accuracy. Table II-2 summarizes the passive FNC response to four oxide standards. STD-2 and STD-10 are pure oxide, and STD-5 and STD-7 contain MgO. The double coincidence response/g is enhanced whenever the singles response/g is high. The triples response/g is unaffected within statistical errors. One explanation for these results is the presence of ( $\alpha, n$ -gamma) or ( $\alpha, p$ -gamma) reactions, where the neutron or proton and the gamma ray can be detected in coincidence. The reaction gamma rays are typically 1-2 MeV in energy and have transmission factors of about 12% through the lead shielding (including downscattering effects). An examination of  $\text{PuF}_4$  and  $\text{PuO}_2$  (with MgO) standards with a germanium detector revealed the presence of 1275-keV gamma rays from the  $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$  reaction and 1779-keV gamma rays from the  $^{25}\text{Mg}(\alpha, n)^{28}\text{Si}$  reaction, respectively. The magnitude of the gamma-ray response was of the right order to explain the results in Table II-2. Although reaction gamma rays do not affect the active assay, they affect the calculation of the active self-multiplication correction, which is based on the passive singles, doubles, and triples response. Consequently, some attempts were made to adjust the self-multiplication correction to allow for the gamma response of the FNC. These attempts have not been successful yet. Because the gamma emission rate of the residues depends on the impurity composition and is subject to severe attenuation effects, it may be too variable to permit a successful correction.

Thus the present accuracy of the FNC for the residue samples is still 15%. This accuracy is thought to be limited by the gamma response of the scintillators. Future attempts to obtain better assays of electrorefining residues might include the following.

1. Assay a new series of residues with the present instrument for 1- to 3-h counting times. This would eliminate statistical precision as a factor influencing the evaluation of the assay accuracy. This new series of assays should include only residues from completed production runs for which final dissolution values are obtained. This would eliminate unusual electrorefining runs and errors in plant by-difference values as factors influencing the evaluation. These steps probably would yield accuracies better than 15%, but not better than 5%.
2. Base the assay on the passive triple coincidence response to reduce the effect of reaction gamma rays. This attempt would require some increase in the FNC sensitivity to get better statistical precision. Also, a multiplication correction would still be needed, and this correction would still require meaningful single and double coincidence data.
3. Increase the amount of lead between the sample well and the plastic scintillators from 2 in. to 3 in. or more to reduce the effect of reaction gamma rays. This would require rebuilding the FNC chassis.

TABLE II-2  
OXIDE STANDARDS IN FNC

Sample	Mass	Singles/g	Doubles/g	Triples/g
STD-2	5	356 ± 56	6.74 ± 0.18	0.082 ± 0.018
STD-5	60	1429 ± 36	12.23 ± 0.04	0.065 ± 0.003
STD-10	60	318 ± 3	6.72 ± 0.03	0.074 ± 0.005
STD-7	120	1039 ± 16	10.40 ± 0.16	0.073 ± 0.002

4. Assay a series of residues with a thermal neutron counter to evaluate its suitability for this category of material. Although electronic deadtime and induced-fission self-multiplication effects are known to be severe, the insensitivity of the  $^3\text{He}$  tubes to gamma rays may be more important. Eight of the residues analyzed for this report were also assayed with a thermal neutron counter. The results (Table II-3) were of comparable accuracy with the FNC assays, implying that this technique deserves further study.
5. Initiate research on improved self-multiplication corrections or on a fast detector that is insensitive to gamma rays (such as a liquid scintillator with pulse shape discrimination circuitry). Such research might lead to more accurate assays at some future time.
6. Lastly, it should be noted that good assays of residues have been obtained with calorimetry *if* the Americium content is well known and that good results have been obtained with segmented gamma scanning techniques *if* the residues are pulverized and do not contain many beads of metal.<sup>1</sup>

### III. MECHANICAL DESCRIPTION

#### A. Chassis

Figure 3-1 is a top view of the FNC chassis. This chassis is mounted beneath a glove box, as illustrated in Fig. 3-2. The chassis can be separated into two parts along the dashed line in Fig. 3-1. The front part of the chassis is a U-shaped assembly consisting of three plastic scintillators that are surrounded by 2 in. of lead on the interior and 1 in. elsewhere. The interior of the U is a 6-mm boral-lined cavity that surrounds the sample well protruding from underneath the glove box. The boral hardens the neutron spectrum, and the lead shielding reduces the gamma background in the scintillators. The front assembly is mounted on four large caster wheels. It can be rolled into place beneath the glove box and bolted to the steel back support frame.

This back support frame is permanently bolted to the floor. It supports the steel and nickel neutron source reflectors, the neutron source cable mechanism, and two 8-in. active-length  $^3\text{He}$  tubes, which can be used as thermal neutron monitors. For active assays, the AmLi neutron source is raised from beneath the floor by a Teleflex cable, pulleys, and a dc motor. The motor is visible in Fig. 3-2 to the right of the

TABLE II-3

#### FIRST RESIDUES DATA

Sample ID	By-Diff Mass	Destructive Analysis	FNC Active	TNC Passive
XBL-300	422	426.0	402 + 20	464
301	474	448.0	482 ± 18	479 ± 14
100	268	267.0	284 ± 4	263 ± 32
302	557	526.0	562 ± 20	542 ± 27
101	42	40.4	57 ± 8	
102	50	44.0	58 ± 8	16 ± 22
303	466	416.0	518 ± 19	516 ± 35
304	300	---	298 ± 13	283 ± 28
103	53	60.0	44 ± 6	77 ± 26

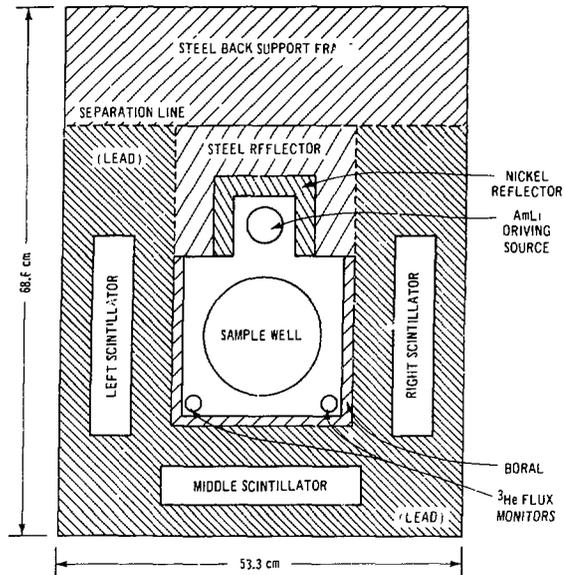


Fig. 3-1.  
Top view of the FNC detector chassis.



Fig. 3-2.  
Location of the FNC detector chassis beneath a transfer glove box (drop box) in the Los Alamos Plutonium Processing Facility.

chassis. It is a Bodine NSH-34Rd right-angle drive motor with 142 lb-inches of torque, identical to those used for the thermal neutron counters elsewhere in the plant. Both parts of the FNC chassis together are about 54 by 69 by 90 cm high and weigh about 1400 kg.

The three plastic scintillators are 5- by 25- by 60-cm rectangular slabs of Pilot F (Nuclear Enterprises, San Carlos, California) encased in aluminum. Pilot F has a long light-attenuation length (300 cm) and a large light output (64% of anthracene), making it suitable for this application. Each scintillator is viewed by two RCA 8575 photomultiplier tubes (PMTs), optically coupled with DOW Corning Corp. 20-057 optical coupling compound. Each phototube is coupled to an Ortec Inc. 265 base.

The two AmLi neutron sources were obtained from Monsanto Research Corp. MRC-65 has a strength of  $4.93 \times 10^5$  n/s, and MRC-66 has a strength of  $4.87 \times 10^5$  n/s ( $\pm 3\%$ ). Each source contains about 2.4 g of AmO<sub>2</sub> and 19 g of LiH<sub>2</sub> and emits 8.1 Ci of radiation. The sources are doubly encapsulated in stainless steel by the manufacturer. At Los Alamos, a 3/8-in.-thick tungsten shield was added, which reduces the dose caused by 60-keV gamma rays from americium by roughly 2 orders of magnitude.

When the two neutron sources are not in use, they are kept about 4 ft below the chassis in a shielded cask that is mounted to the ceiling of the room below. The cask surrounds the sources with 3/4 in. of lead and 2 in. of polyethylene lined with cadmium on the outside. This additional shielding reduces the dose at the surface of the container to 1.5 mrad/h. A microswitch inside this shielded cask allows the computer to determine when the sources are inside.

When the two neutron sources are in use, they are up against a second microswitch located at the top of the back support frame. The sources are centered with respect to the scintillators. The center line is 9 3/4 in. below the microswitch, and 16 3/4 in. below the bottom of the glove box. The centers of the sources are 10 3/8 in. apart. With the sources in these positions, the integrated active response is constant to within 2% for either 4-in.- or 11-in.-high sample cans, provided they are at least half full. A similar statement holds true for the passive response of the detector, so that no fill-height correction is necessary.

## B. Sample Holder

Figure 3-3 shows the holder that is used to load samples into the FNC from the glove box above. The floor of the sample holder is 4 1/2 in. below the scintillator and neutron source center line. The holder is tall enough to accommodate 11 3/8 in.-high residue cans. When 4-in.-high cans with buttons are assayed, a 3-in. spacer is used to center the sample. Above the sample cavity, the holder contains about 4 in. of aluminum and steel reflector material and a small Bodine KYC-22T5, Model No. 765, 3-rpm motor. This motor slowly rotates the sample during the assay. The entire sample holder mechanism is raised and lowered by another Bodine NSH-34Rd right-angle drive motor mounted above the glove box. As can be seen in Fig. 3-3, both the power cord for the rotator motor and the cable connection to the lifting motor can be disconnected from the sample holder if this glove box area is needed for other work.

Los Alamos Group Q-1 has the original assembly and detail drawings for the FNC chassis.

## IV. ELECTRONICS

Table IV-1 is a list of the electronic components for this instrument. The layout and interconnection of these components are described in this section. Tune-up instructions are given in Sec. VI.

### A. Chassis Area

The high-voltage (HV) distribution box for the PMTs is mounted on the left side of the FNC chassis (Fig. 3-2). This box contains six 300 k $\Omega$  10-turn potentiometers that receive high voltage on cable 7 from

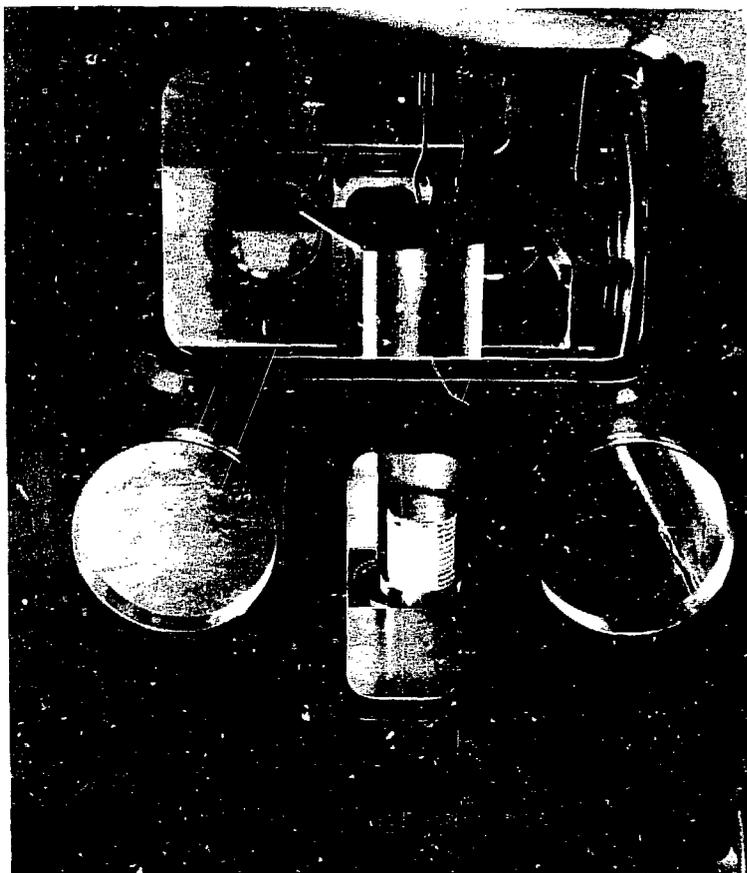


Fig. 3-3.  
Sample holder mechanism visible through the glove box window.

the Power Designs HV supply. The potentiometers are used to form six voltage divider circuits that supply high voltage to the PMTs on cables 1 through 6. In this way the PMT gains can be individually adjusted to give equal magnitude output signals.

The junction box and preamplifier box for the  $^3\text{He}$  tube flux monitor circuit are mounted behind and below the HV distribution box. Figure 4-1 traces the signal path from the tubes to the CAMAC scaler. Figure 4-2 is a schematic of the Los Alamos-designed preamplifier.<sup>3</sup> With a tube high voltage of +1500 V, the preamplifier output is typically 100-300 mV, 70-80  $\mu\text{s}$  time constant. It is customary to adjust the amplifier gain (on the order of 50) to obtain 0- to 6-V unipolar output pulses.

Helium-3 detectors also detect (gamma,e) reactions in the gas, but the lower  $dE/dx$  of the electrons means that these pulses will be wider in time. A relatively fast amplifier time constant of 0.5  $\mu\text{s}$  or less is used to clip pulses caused by (gamma,e) reactions so they appear in the noise. With this time constant, the total width of the amplifier output pulses is 2 to 4  $\mu\text{s}$ . The single-channel analyzer (SCA) discriminator is set to 3 V to reject noise pulses. The SCA output is +5 V, 500 ns wide. The transistor to transistor logic (TTL)-to-NIM converter will convert this output to NIM standard pulses (-800 mV).

Also mounted near the counter chassis is the request assay box. This is visible in Fig. 3-2 directly below the glove-box floor and to the left of the chassis. Just below and to the left of the request assay box is the Minarik motor controller for the sample-holder mechanism. Behind this Minarik controller is a

**TABLE IV-1**  
**FNC ELECTRONICS LIST**

**A. Chassis**

- High-voltage distribution box
- <sup>3</sup>He tube junction box
- <sup>3</sup>He tube preamplifier box
- 6 RCA 8575 photomultiplier tubes
- 6 Ortec Inc. 265 tube bases
- Request assay box
- Minarik motor controller for AmLi neutron sources
- 2 YSI No. 44211 thermilinear components

**B. Texas Instruments Inc. 743 desktop hardcopy terminal**

**C. Electronics cabinet (Fig. 4-3)**

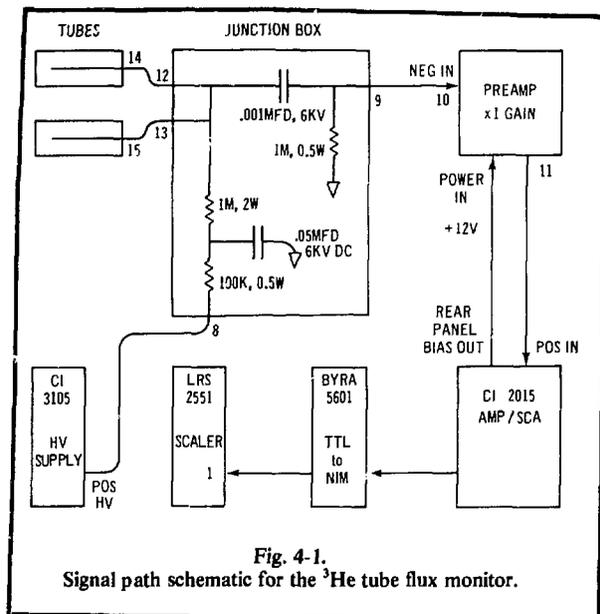
- DEC RX-11 dual floppy disk and controller
- Patch panel
- SEC 1510 CAMAC crate
- DEC PDP-11/04 MC computer
- DEC dc11A-8F unibus cable
- 2 YSI No. 44211 thermilinear components
- Power Designs 3K-40 HV supply
- Variac 1592 automatic voltage regulator
- High-speed fan/blower

second Minarik box used to control the source drive motor. Because the source drive motor controller and the request assay box are interfaced to the CAMAC assay LRS control module, their electronic schematics are given in Sec. IV.C.

**B. CAMAC Crate Modules**

Figure 4-3 shows the layout of the electronics cabinet. The CAMAC crate is located just below the patch panel. Table IV-2 lists the modules located in the CAMAC crate in the order of their slot addresses. The first 14 addresses are used by 7 commercial NIM modules to avoid the use of a separate NIM bin. The NIM modules receive their power from the CAMAC crate through seven Nuclear Electronics, Inc. Model 7092 NIM-to-CAMAC adapters. One of the NIM modules, the LRS 365 AL logic unit, also requires +0.8 and -5.0 V, which it receives from an internal power supply that operates on 120 Vac. However, the CAMAC crate does not supply ac power to this module. For this reason a separate ac power cord has been added to the rear of this module. Addresses 16 to 21 are used by five commercial CAMAC modules. Addresses 22 and 23 are used by a Los Alamos-designed assay control module, which is described in Sec. IV.C.

The first five NIM modules constitute the fast timing circuits that generate single, double, and triple events. Fig. 4-4 is a diagram of this circuit, including the final outputs to the 12-channel CAMAC scaler. The six inputs to the LRS 612 12-channel PMT amplifier are the negative timing anode signals (50 Ω dc-coupled) from the Ortec 265 PMT bases. After amplification (x10) these signals are up to several volts in magnitude and 10 to 20 ns wide (see Fig. 6-1). The LRS 623 octal discriminator rejects PMT noise pulses, and after discrimination the pulses are set to 10-ns width, NIM level (-800 mV).



## PROPORTIONAL COUNTER PREAMPLIFIER

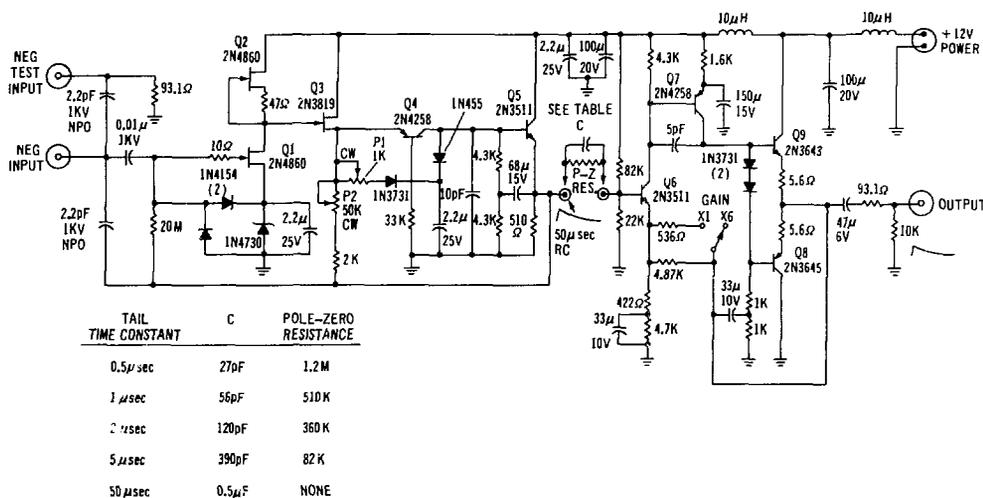


Fig. 4-2.

Schematic of Los Alamos-designed proportional counter preamplifier used for the  $^3\text{He}$  tube flux monitor.

An LRS 622 quad coincidence unit is used to AND together the two PMT signals from each scintillator. This further reduces the amount of PMT noise entering the coincidence circuit and reduces the measured singles rate by roughly 50%. It is also helpful to set the output pulse width of these AND circuits to more than 50 ns to eliminate the spurious coincidence background produced by phototube afterpulsing caused by light returning from the anode region to the photocathode. However, for this particular coincidence circuitry, it is important not to set the AND gates to lengths between 50 and 300 ns. Such a choice would permit accidental coincidences to occur within a scintillator and between scintillators, whereas real coincidences (which occur within 50 and 100 ns) could occur only between scintillators. To prevent an imbalance in the circuitry that would yield negative assays, the AND gates are presently set to yield 400-ns output pulse widths. These pulses are then clipped to 5 ns and ORED together by the LRS 365 AL dual fourfold logic unit.

Two autocorrelation circuits analyze these pulses (Fig. 4-5). The triple O.P. that defines time = 0 for double coincidence events is the bottom half of the LRS dual fourfold logic unit referred to in the preceding paragraph. Additional LRS 622 coincidence units are then used to generate double coincidences (actually real plus accidental events) and accidental double coincidences. These data are sent to the CAMAC scalars, and the data analysis program computes the net real coincidences as the difference between the double and the accidental double coincidence response. To balance the circuit at high count rates, the outputs of the one-shots that define the coincidences are clipped to 38.4 ns and 38.8 ns for double and accidental double coincidences, respectively. The second autocorrelation circuit is used for triple coincidences. The output of the double coincidence module is sent to the upper half of the fourfold logic unit to define time = 0 for triple events. Thus, the triple events are actually generated by looking for pairs of double events. For the triples circuit, count rates are so low that it is not necessary to define the lengths of the one-shots with clipping lines.

The above circuitry processes both neutrons and gamma rays that are detected by the plastic scintillators. The octal discriminator thresholds of  $-100$  mV are equivalent to 95 keV of electron energy deposition.<sup>4</sup> This energy corresponds to 220-keV gamma rays and 650-keV neutrons. Although these thresholds imply that the AmLi neutron source 60-keV gamma rays and 300- to 500-keV neutrons will not be detected, it is possible for the neutrons to be detected by means of the  $n + p \rightarrow d + \text{gamma} + 2.2$  MeV reaction.

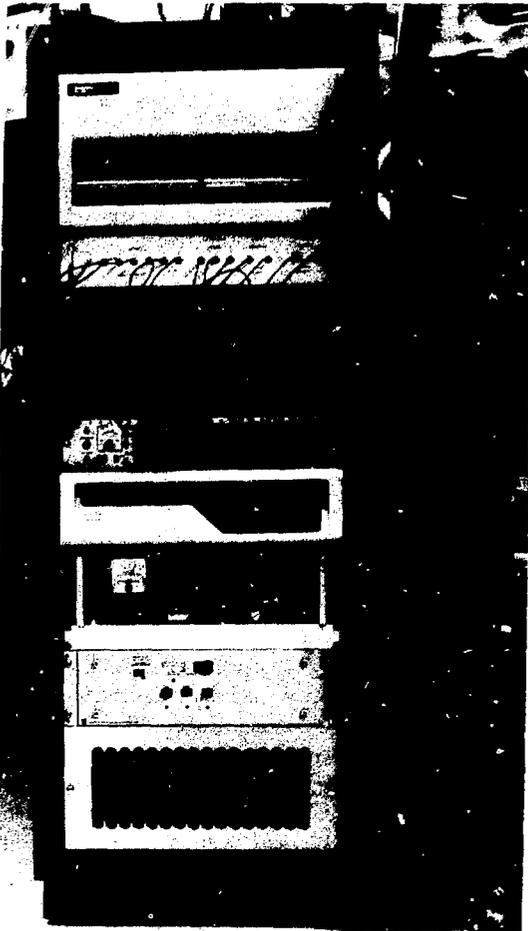


Fig. 4-3.  
Electronics cabinet used for FNC.

As illustrated in Fig. 4-6, (n,n), (n,gamma), and (gamma,gamma) coincidences are possible. The time difference between both events is a function of the size and shape of the detector cavity and the neutron energy spectrum. Figure 4-6 shows the approximate time difference spectrum present in the FNC with 5 cm of lead between the cavity and the scintillators.<sup>4</sup> (Gamma,gamma) events are largely rejected by the LRS 365 AL fourfold logic unit, which has a pulse-pair resolution of 5 ns. Because the gates (one-shots) are set to about 40 ns, the FNC accepts roughly 72% (n,n) and 28% (n,gamma) events in the time interval 5 to 45 ns (Fig. 4-6).

The following list of modifications to the SEC DC-11 crate controller were done by Atwell.\* These crate controller modifications eliminate the problem of sending an unwanted DATIP CAMAC command on a computer MOV instruction. These changes are incorporated into later DC-11 models.

- (1) Cut connector between pin 4 (H9) and pin 10 (E8). This disconnects NOREAD bit so it is not used.
- (2) Connect pin 4 (H9) to pin 1 (H3). This connects SIFF and DMAOP output.

\*T. L. Atwell, one of the authors of this report.

TABLE IV-2

CAMAC CRATE EQUIPMENT LIST

Address	Module
1,2	LRS 612 12-channel PMT amplifier
3,4	LRS 623 octal discriminator
5,6	LRS 622 quad coincidence
7,8	LRS 365 Al 4-fold logic unit
9,10	LRS 622 quad coincidence
11,12	Canberra 2015 amp/SCA
13,14	Canberra 3105 HV power supply
15	Unused
16	ByRa 5601 TTL-NIM converter
17	KS 3290 Dataway display
18	LRS 2551 12-channel scaler
19,20	KS 3552 ADC
21	KS 3530 relay multiplexer
22,23	Assay control module
24,25	SEC DC-11 crate controller

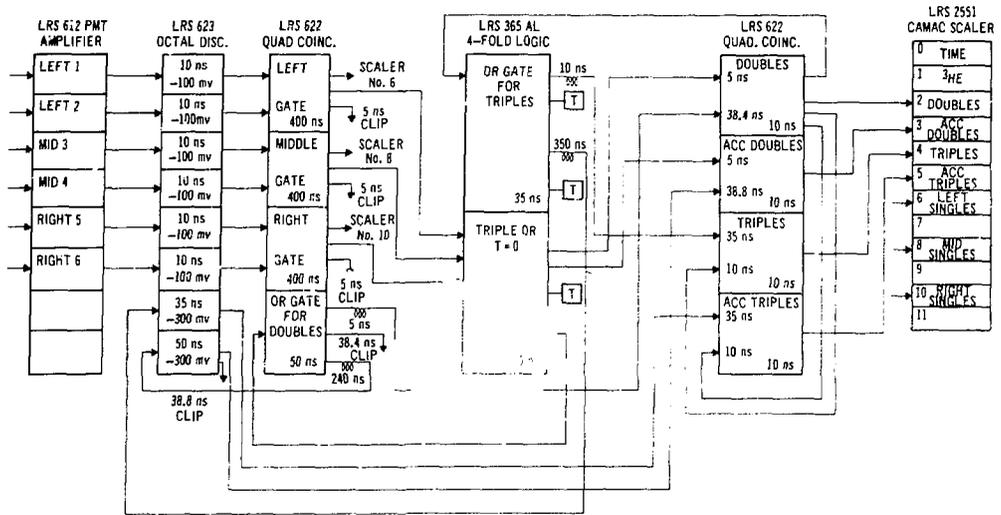


Fig. 4-4.  
FNC fast-timing circuit diagram.

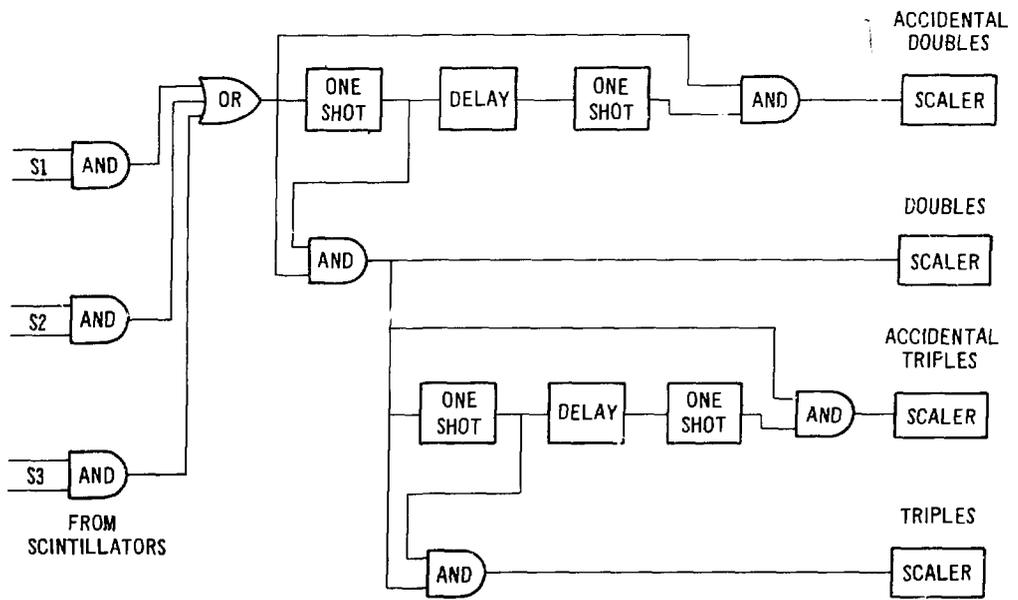


Fig. 4-5.  
Autocorrelation circuits used to generate fast double and triple coincidences.

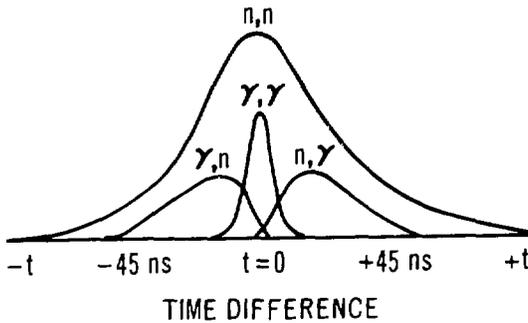
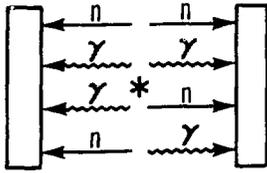


Fig. 4-6. Idealized timing distributions for the FNC. The various possible coincidence distributions are drawn approximately to scale.

### CONTRIBUTIONS OF VARIOUS COINCIDENCES FOR DIFFERENT COINCIDENCE GATES

Coincidence Gate (ns)	Coincidence Type (%)		
	$n-n$	$n-\gamma$	$\gamma-\gamma$
0 to 5	54	21	25
5 to 45	72	28	0
0 to 45	65	25	10

- (3) Cut connection between pin 5 (H9) and pin 4 (G1). This disconnects inverter on  $\overline{\text{DATIP}}$ .
- (4) Connect pin 3 (G1) to pin 5 (H9). This connects DATIP to pin 5 (H9).
- (5) Cut connection between pin 6 (H9) and pin 9 (G9). This disconnects the output of the NAND gate (H9) from BUSYFF.
- (6) Tie pin 9 (G9) to +5 Vdc (input not used).
- (7) Cut connection between pin 2 (H4) and pin 12 (H3). This disconnects inverter (H4).
- (8) Connect pin 12 (H3) to pin 6 (H9). This NANDS  $\overline{\text{DATIP}}$  with SIFF and  $\overline{\text{DMAOP}}$  to prevent HDR from clocking on DATIP cycles.

### C. Assay Control Module

This module was designed and built by T. Atwell, B. Tippens, K. Henneke, K. Johnson, and T. Van Lyssel to interface assay control, temperature read-out, and source drive motor control to the computer.

The module is a CAMAC module with slot address 22. The custom circuitry is wire-wrapped on an SEC WW-04 double-width CAMAC prototype module. The prototype module has an 86-pin connector, which provides dc power and all signals from the dataway. Circuitry is provided to decode CAMAC functions (F), subaddresses (A), slot address (N), and all strobe timing and gating signals, busy, inhibit, look-at-me (LAM), and clear commands (S1, S2, C, Z, B, I, L, X, Q). A 36-pin rear panel connector is provided for external inputs or outputs. Table IV-3 lists the present allocation of pin locations on this connector, and Fig. 4-7 is a schematic of the custom wire-wrap circuitry on the module.

TABLE IV-3

ASSAY CONTROL MODULE REAR-PANEL CONNECTOR LAYOUT

Pin No.	Function	Cable	Destination	Pin No.
1	thermistor No. 3	green	photomultiplier tubes	
1R	thermistor No. 1	green	top of cabinet	
2	thermistor No. 3	red		
2R	thermistor No. 1	red		
3	thermistor No. 3	brown		
3R	thermistor No. 1	brown		
4	thermistor No. 4	green	HV power supply	
4R	thermistor No. 2	green	CAMAC crate	
5	thermistor No. 4	red		
5R	thermistor No. 2	red		
6	thermistor No. 4	brown		
6R	thermistor No. 2	brown		
7	temperature No. 1 data gnd	coax	relay multiplexer	15
7R	temperature out	coax	relay multiplexer	15R
8	temperature No. 2 data gnd	coax	relay multiplexer	14
8R	temperature out	coax	relay multiplexer	14R
9	temperature No. 3 data gnd	coax	relay multiplexer	13
9R	temperature out	coax	relay multiplexer	13R
10	temperature No. 4 data gnd	coax	relay multiplexer	12
10R	temperature out	coax	relay multiplexer	12R
11	solid state relay -gnd	black	request assay box	A
11R	solid state relay +5 V	brown	request assay box	B
12	in process LED (green)	red	request assay box	C
12R	requested LED (yellow)	yellow	request assay box	D
13	request assay button	blue	request assay box	E
13R	ready LED (red)	green	request assay box	F
14	preamp power +12 V	coax center	unused	
14R	brake relay	blue-green	Minarik controller	E
15	ground	black	encoder, limit switch	B
15R	+5 V		request assay box, Minarik, encoder	
16	down relay	yellow-white	Minarik controller	D
16R	up relay	brown-red	Minarik controller	B
17	down limit switch	white	source holder	
17R	up limit switch	black	source holder	
18	signal A	blue-green	optical encoder	D
18R	signal B	brown-red	optical encoder	E

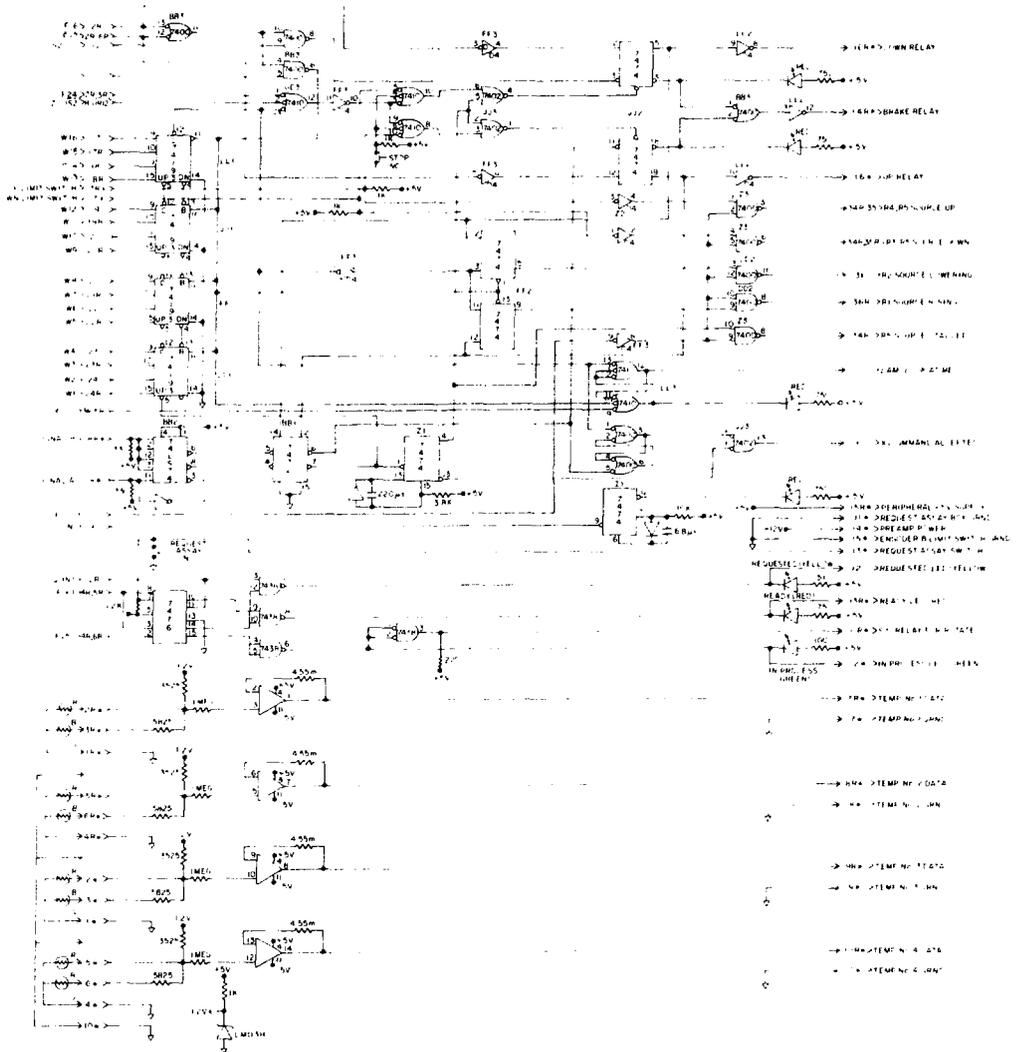


Fig. 4-7.  
Assay control module wire-wrapped circuitry.

The assay control circuitry is shown in the center of Fig. 4-7. It consists of three light emitting diodes (LEDs) that indicate assay status: FNC ready for a new assay (red), assay in process (green), new assay requested (yellow), and a request assay button. If the FNC is ready for a new assay (red LED on), pushing the request assay button will set the yellow LED and signal the computer that a new assay has been requested. The computer will have been waiting for the status variable S to become = 0; this is accomplished by returning Q = 1 and X = 1 from the assay control module. (For additional details on this sequence, refer to the DYMAL3 and the NAFD software listings.) The above assay control circuitry is replicated in the request assay box mounted underneath the glove box containing the FNC chassis, so the operator does not have to walk over to the electronics cabinet. The request assay box also contains an on-off switch for the sample holder rotator. If the rotator is not on, the request assay button on this box

is disabled. The schematic of this box is given in Fig. 4-8, and the electrical connections are included in Table IV-3. Neither request assay location has a button to stop an assay in progress. This is done using the software by typing CONTROL-C and GO TO 1000.

Four YSI 44211 thermistors, accurate to  $\pm 1^\circ\text{C}$  or better, are used to supply room, PMT, HV power supply, and CAMAC crate temperatures to the computer. With this information a temperature correction can be applied to the observed coincidence response. The thermistor signals are amplified by a factor of 4.55 by four LM 224 operational amplifiers. These circuits are included in the assay control module and are shown on the lower portion of Fig. 4-7. The amplifier outputs are sent to the KS 3530 relay multiplexer and then converted to a digital signal by the KS 3552 optically isolated 12-bit analog-to-digital converter (ADC). The ADC is operated with a gain of one that covers a range of 0 to 5.12 V.

The remaining circuitry in the assay control module is used to control the AmLi neutron source drive motor. This circuitry is shown in the upper half of Fig. 4-7. Information on the position of the source is obtained from up and down limit switches and from an optical rotation encoder mounted on the dc motor shaft used to drive the Teleflex cable. The encoder is a Trimstep model that supplies 50 pulses per revolution without a marker pulse. The pulses are complementary square waves obtained from TTL active pull-up. These pulses enter the circuit as signals A and  $\bar{B}$  and are used to increment C74193 up-down counters. The computer uses the CAMAC write lines to set a specified number of pulses in these counters.

Source motion is initiated automatically by the computer by a CAMAC F(16) command (down) or an F(17) command (up). These commands activate the down or up relays added to the modified Minarik motor controller (Fig. 4-9). A third relay has been added to this controller to act as a positive brake. The up and down relays are opened, and the brake relay is activated (1) when the up or down limit switch is set, (2) when the number of optical encoder pulses received by the up-down counters equals the number set on the write lines, (3) when encoder pulses are not being received but the up or down relay is activated, indicating that the source is stalled, or (4) when the manual stop button on the front panel of the assay control module is pushed. A computer request for source motion is indicated by a brief flash of the N (crate address) LED on the assay control module. When source motion is complete, the look-at-me (LAM) LED will come on until the computer responds to the module. The relay and limit switch connections between the assay control module and the modified Minarik motor controller are included in Table IV-3. Additional details on computer control of the source drive are given in Sec. V (software).

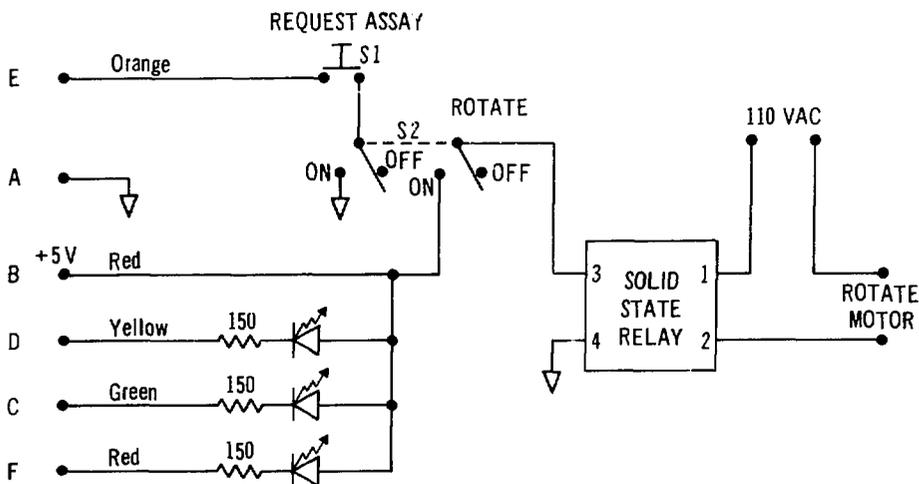


Fig. 4-8.  
Request assay box schematic.

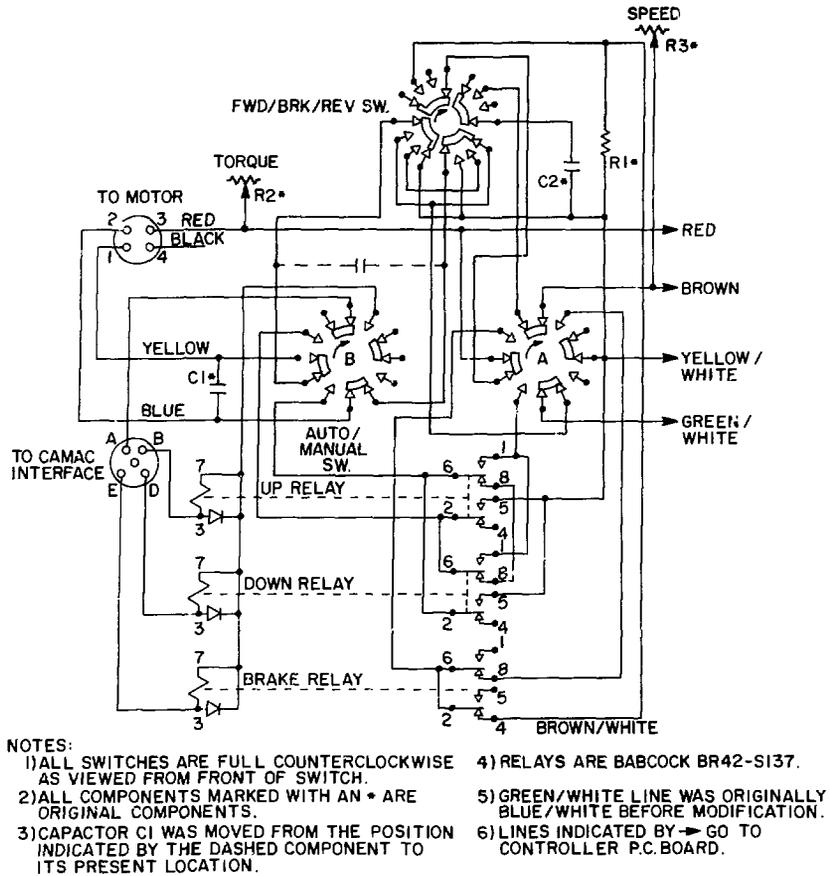


Fig. 4-9.  
Modified Minarik motor controller schematic.

#### D. Computer Configuration

The FNC uses a DEC PDP 11/04-MC computer that requires 115 V (47-63 Hz). The chassis is 5-1/4 in. high and contains nine Hex (full-width) slots. Table IV-4 lists the boards mounted inside the chassis. The central processing unit (CPU) is ferrite core based, and the computer has 28-K words of usable core memory. Core memory was selected for this computer so provision could be made in the future for recovery from a power failure in the production plant. An undesirable feature of this choice is that only 8 A of +5 V are available for additional boards. Because of this limitation, a second terminal *cannot* be added to the computer although slot space is available for the additional serial line interface.

### V. SOFTWARE

#### A. Introduction

The operating system for the DEC 11/04 computer is RT-11 Version 1. The programming language used up to the present time is Multi User-BASIC (MUBASIC). RT-11 and MUBASIC use up a little

TABLE IV-4

## PDP-11/04-MC CONFIGURATION

Component	Board Number	Description	+5 V dc A Required
M7263	M7263	CPU	
MM11-DP		16-K bytes core memory	
MM11-DP		16-K bytes core memory	
M9301-YB	M9301-YB	Bootstrap/emulator	
KY11-LB	M7859	Console register	3
RX11-WB	M7846	Dual floppy disk controller	1.5
DL11-WB	M7856	Serial line interface and line frequency clock	2
M9302	M9302	Unibus terminator	
			6.5 A <sup>a</sup>

<sup>a</sup>Warning: This number must not exceed 8 A.

more than half of the 32-K memory, leaving 14-15 K for programming. The FNC program is called DYM3 and uses about 7 K of memory. Thus additional computer memory is available, although, as mentioned in Sec. IV.G, the computer does not have enough dc power for an additional terminal interface board.

A typical floppy disk should contain the following programs:

MONTR.SYS	46	19-OCT-77
DX.SYS	2	19-OCT-77
TT.SYS	2	19-OCT-77
LP.SYS	2	19-OCT-77
PR.SYS	2	19-OCT-77
PP.SYS	2	19-OCT-77
SYSMAC.SML	18	19-OCT-77
MACRO.SAV	31	19-OCT-77
LINK.SAV	25	19-OCT-77
PIP.SAV	14	19-OCT-77
EDIT.SAV	19	19-OCT-77
EXIT.boo	1	19-OCT-77
MUBASC.SAV	66	19-OCT-77
INIT.boo	1	19-OCT-77
1UR.DOO	2	19-OCT-77
2UNR.DOO	2	19-OCT-77
BYE.boo	1	19-OCT-77
DIRECT.BAS	6	19-OCT-77
RESEQ.BAS	4	19-OCT-77
DELETE.BAS	4	19-OCT-77
LSQFIT.BAS	14	19-OCT-77
LSQDA1.DAS	16	19-OCT-77

LSQDA2.DAS	16 19-OCT-77
DYMAC3.BAS	25 16-NOV-78
RDINIT.DO1	1 23-JUN-78

MONITR.SYS is the RT-11 system. MUBASC.SAV is the MUBASIC language. The C refers to CAMAC handlers written by T. L. Atwell that are described in Sec. IV. 1UR.DOO is the one-user configuration file required by MUBASC.SAV. DIRECT.BAS, RESEQ.BAS, and DELETE.BAS are three BASIC programs written by T. L. Atwell to facilitate programming. DIRECT can be called to provide a floppy disk directory without exiting from MUBASIC. RESEQ can be used to resequence or renumber BASIC programs. DELETE can delete sections of coding from other programs. These three programs print self-explanatory operating instructions when called. LSQFIT.BAS is the nonlinear least squares fitting routine used to generate calibration constants from the assay of known samples. LSQDA1.DAS and LSQDA2.DAS are data files used by this program. Section E describes LSQFIT. DYMAC3.BAS is the FNC operating program. Calibration constants and measurement control parameters are stored in RDINIT.DO1. Section IV B, C, and D describe DYMAC3.

## B. DYMAC3 Program Description

This program is used to carry out passive or active-minus-passive assays. It handles communication with the operator, the floppy disk files, and the CAMAC crate: operation of the source-control motor; all data reduction and print-out; and some measurement control functions. The following assay decisions are made by the program.

- 1) The assay time is fixed at 500 s for passive measurement and 500 s for active measurement. Improved assay precision can be obtained by using the autocyte feature and averaging the results by hand.
- 2) After the operator selects the material type, the program decides whether an active measurement should be made (lines 1070-1125).
- 3) Oxide assays are usually passive but, if the singles/doubles ratio is above 70 (implying that the oxide is impure), the program initiates an active assay (lines 2050-2060).
- 4) If the plutonium content of an unknown sample has been determined by both a passive and an active-minus-passive assay, the program chooses (within statistical errors) the smaller value as the final assay result (lines 3030-3050). Passive assays are inherently more precise but always overestimate the plutonium content if (α,n) reactions are present.

### Line-by-Line Program Description

10-670	Initialization.
40	A = SYS(5,80) sets line length to 80 characters.
110-200	These functions are described following line 6000.
500-520	If floppy disk is available, read stored parameters from VF1 into V(100).
530-560	Inspection or alteration of V(100) using subroutine 5200. This is optional if floppy disk is available, mandatory if it is not.
570-600	If elements of V(100) have been changed, these lines can be used to replace the elements in VF1.
610-670	Transfer stored parameters from V(100) to specific named variables.

1000 Start assay (or sequence of assays) routine.  
If initialization described above is still valid, program can be restarted by typing GO TO 1000.

1000 Go to subroutine 5400 and make sure source is down. When it is down print R.D. AVAILABLE.

1020 Wait loop until request assay button is pushed.

1030-1040 Ask operator if sample is loaded and rotating. If so, go to subroutine 5500 and start passive assay. (Active assay is optional, but passive always comes first.) Operator now has about 8 min to answer the questions that follow. Answering <CR> will skip to the next question. Answering B will return to the preceding question.

1060-1130 Assay type (background, normalization) or material type (oxide, fluoride, electrorefined metal, oxide reduction metal, or residue) must be specified. Twelve is set accordingly.

1150-1170 If sample weight, diameter, and fill height are supplied, material and plutonium densities will be calculated.

1180-1200 If enrichment is supplied, an assay in total grams plutonium will be given. Otherwise, only  $^{240}\text{Pu}$  (and maybe  $^{239}\text{Pu}$ ) will be given. The variables E2 and E8 are available to calculate  $^{240}\text{Pu}$  effective in the future. For the weapons-grade material zssayed so far, effective  $^{240}\text{Pu}$  is close to 1.02 times actual  $^{240}\text{Pu}$ , so this factor is being used.

1210-1230 Operator can enter NO to get one run, <CR> to get one run, or YES to get 100 runs; or he can enter a number to get a specific number of runs.

1240 Go to Sec. 2000, read temperature, and wait for passive assay to finish.

2000 Passive assay routine.

2000 If a sequence of runs is in process, start next passive assay here. Go to subroutine 5400 and lower source, then go to subroutine 5500 and start passive assay.

2010 When passive assay is in progress, go to subroutine 5000 and read temperature, then go to subroutine 5600 and wait for end of run.

2020 When run finishes, go to subroutine 4000 and do passive ( $J = 0$ ) data reduction.

2030 If the enrichment has been specified, convert assay to grams of total plutonium.

2040 For background, normalization, metal, and residues, go to active assay routine.

2050-2060 If the singles/doubles ratio is higher than that expected for clean oxide, go to active assay routine.

3000 Active assay routine.

3000 Go to subroutine 5400 and raise source. Go to subroutine 5500 and start assay.

3010 Go to subroutine 5000 and read temperature; then go to subroutine 5600 and wait for end of run.

3020 When run finishes, go to subroutine 4000 and do active ( $J = 2$ ) data reduction.

- 3030-3040 If the enrichment has been specified, convert active assay to grams of total plutonium. Use the active assay as the final result only if the passive assay is larger than the active assay by more than 1-std-dev.
- 3050 For electrorefined metal use passive assay. Active is done only to help calibration of reduction metal.
- 3100-3120 If the enrichment has been specified, and if the assay was not a background or normalization run, print the final result in grams of total plutonium. This final result may be based on the passive or on the active-passive assay.
- 3130 Increment run number. Start next assay in cycle or go to 1000 and wait for new input.
- 4000 Active or passive data reduction routine.
- 4010 Determine length of run in seconds.
- 4020-4060 Read scalars. Transfer <sup>3</sup>He and singles data to named variables. If all singles data were 0, repeat read-out up to 10 times if necessary. Print warning if read-out still 0.
- 4070-4100 Print scaler data.
- 4110-4140 Evaluate real double and triple coincidence rates and total singles rates. Compute associated statistical errors.
- 4150-4170 Check that left, middle, and right scintillator counts are equal within 50%. Print warning if not.
- 4180-4200 Calculate temperature correction for double coincidences. The actual correction for this driver has not been measured. The slope  $\alpha = -0.00137/^{\circ}\text{C}$  and the offset temperature  $T = 35.75^{\circ}\text{C}$  were determined for the Oak Ridge National Laboratory random driver. The temperature correction is of the form

$$\text{true response} = \frac{\text{measured response}}{1 + \alpha(T - T_0)}$$

T is now taken to be the mean of the crate, HV supply, and PMT temperatures. The error in the correction is based on an estimated 20% error in the determination of  $\alpha$ . Do not apply correction to data, but print warning if calculated correction is outside range 1.00-1.03.

- 4210-4220 Subtract background (as determined during background update) from double and triple coincidences.
- 4230-4240 If this was an active assay, subtract the passive (background corrected) assay to get the net active-minus-passive assay.
- 4250-4300 Calculate the flux correction (active assay only). Subtract passive <sup>3</sup>He flux rate, then divide active-passive flux rate by reference rate determined during active background update. This is the flux ratio. Then

$$\text{true response} = \frac{\text{measured response}}{1 + 0.217 * (\text{flux ratio} - 1)}$$

The coefficient 0.217 was determined in laboratory tests before installation of the FNC in the plant. In practice a flux correction greater than 1% was never encountered. Thus the correction is not applied to the data, but a warning is printed if it ever exceeds 1%.

4310-4330

Calculate self-multiplication correction. This correction is based on triple coincidence/double coincidence ratios. Let

$$r = \frac{T_{\text{meas}}/D_{\text{meas}}}{T_{\text{ref}}/D_{\text{ref}}} = \frac{M(4)}{M(J)} .$$

$T_{\text{ref}}/D_{\text{ref}}$  was estimated at 0.007 for both active and passive assays on the basis of data taken earlier with this instrument. Then subroutine 5300 is called to calculate the correction.

4350

Select appropriate set of calibration constants. Use oxide calibration for background, and normalization runs.

4360

Apply passive or active normalization (as determined during normalization update) to corrected double coincidence rate.

4370

Assay in grams of  $^{240}\text{Pu}$  (passive assay) or  $^{239}\text{Pu}$  (active-passive assay) is given by

$$\text{mass} = \frac{A * \text{response}}{1 + B * \text{response}} .$$

To determine A and B, it is necessary to do the LSQFIT of calibration standards in this form also, although in the case of calibration standards, it is really the response that is the dependent variable.

4375-4380

The error is given by the square root of

$$\frac{A^2 \sigma_R^2}{(1 + BR)^4} + \frac{R^2 \sigma_A^2}{(1 + BR)^2} + \frac{A^2 R^4 \sigma_B^2}{(1 + BR)^4} - \frac{2AR^3 \text{cov}(A,B)}{(1 + BR)^3} ,$$

where R is the corrected, normalized double coincidence response.

4390-4460

Compute material density if sample weight, diameter, and fill height were supplied. Compute plutonium density if enrichment was supplied. For metals and residues, sample diameter and fill height are assumed known.

4500-4690

Print results of preceding data reduction routine.

4700-4710

Prepare for background or normalization update if this assay was a BKG or NOR run. Open floppy disk file if disk is available.

4720-4770

Background update routine. Check AmLi source strength on active background run. Store measured backgrounds and  $^3\text{He}$  flux rate. Update floppy disk if it is available.

4800-4890

Normalization update routine. Use passive corrected coincidence rate obtained with normalization standard to set both passive and active normalization if response has changed by more than 2 std dev. Currently standard is STD-9, corrected coincidence response = 232 counts/s. If the normalization is more than 10% away from one, raise or lower the high voltage as needed and repeat calibration. Update the floppy disk if it is available.

- 5000-5060 Subroutine to read temperature. The conversion from ADC reading (X9) through temporary variable V(k), to temperature U1, 2, 3, 4 is done using T. Van Lyssel's\* calibration data of 3/31/78.
- 5100-5150 Subroutine to read ADC for temperature. Wait 1 s, start ADC conversion, and read value into X9. Do this 11 times, and repeat if difference between highest and lowest reading is more than 20. If not, discard highest and lowest reading, and return the average of the other nine as the ADC result (X9).
- 5200-5220 Subroutine to check or change contents of VF1(100) = RDIT.DO1, as represented by V(100). As each variable is typed out, the operator can enter a new value, enter B to backspace, or leave the current value unaltered by typing <CR> or O<CR>.
- 5300 Self-multiplication correction subroutine.
- 5305-5310 Select value of  $\alpha$  = number of ( $\alpha, n$ ) neutrons/number of spontaneous-fission neutrons appropriate for each material category;  $\alpha = 21$  for PuF<sub>4</sub> was an empirical choice that is no longer correct.
- 5315-5320 Set correction factor = 1 for background runs.
- 5325 Set correction factor = 1.217 for (STD-9) normalization runs.
- 5330-5345 Solve a quadratic for the net leakage multiplication M
- $$[4.709 + 3.735\alpha]M^2 - [0.369r + 6.510 + 4.980\alpha]M + [0.17r + 2 + 1.245\alpha] = 0$$
- 5350-5355 If this value of M is within 2 std dev of unity, set M = 1. The statistical error in M is given by an approximate formula.
- 5360-5365 The self-multiplication correction factor is
- $$M(8) = 0.8547M(2.17M - 1) + 1.282\alpha(M - 1)(3M - 1)$$
- The statistical error in M(8) is again given by an approximate formula.
- 5370 For active assays of the normalization standard, the self-multiplication correction factor is 1.117. M is the same as before.
- 5375-5380 For other active assays, the net leakage multiplication M derived during the passive assay is again used. But the equation for the correction factor is modified by replacing the spontaneous-fission multiplicity  $v_s = 2.17$  by an induced fission multiplicity  $v_i = 3$  and dropping the ( $\alpha, n$ ) term. The result is

$$M(8) = 0.5(3M - 1)(M)$$

The above equations are approximate equations that were used to apply self-multiplication corrections to the FNC data

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\*T. Van Lyssel, one of the authors of this report.

during the test and evaluation (1978-1979) of the instrument. The equation for M is based on a derivation similar to one previously published.<sup>5</sup> The correction factor is

$$\frac{Mv_s(Mv_s - 1)(1 + \beta)}{v_s(v_s - 1)}$$

where  $\beta$  is defined in the above paper.

A better correction factor, which is based on a summation of fission chains through all orders, is now available for passive assays. It should be incorporated into the software for any future assay campaigns. A derivation of the new correction factor has not yet been published. However, the correction is available in the following BASIC routine.

```

let R2 = r = M(4)/M(J)
let A1 =  $\alpha$  = L(I2)
64 P=-(1.738+2.128*A1+.140135*R2+.140135*R2*A1)/(1+A1)
66 Q=(.914534+1.38*A1+.141163*R2+.195816*R2*A1)/(1+A1)
68 S=-(.135948+.252*A1+.041614*R4+.055681*R2*A1)/(1+A1)
70 A=Q-P*P/3
72 B=.074074*F3-P*Q/3+S
74 W=B2/4+A3/27 IF W<0 GO TO 90
76 A=(-B/2+SQR(W))(1/3) B=(-B/2-SQR(W))(1/3)
78 X=A+B GO TO 110
90 T=SQR(-4*A3/(27*B2)-1) F=ATN(T)
100 X=2*SQR(-A/3)*COS(F/3)
110 M=X-P/3
115 C1=3.4528*(1+A1)*M2-(3.4781+4.8247*A1)*M+1.0253+1.3719*A1
M = net leakage multiplication = M(6).

```

C1 = self-multiplication correction factor = M(8).

For active assays a similar correction could be derived, but this has not been done yet.

- 5400 Subroutine to check or change AmLi source position.
- 5410 Initial number of steps to motor will be 410, which should be the full length of travel required from one microswitch to the other. Total number of steps traveled so far = 0.
- 5420 Check status of microswitches.
- 5430 If the source is at the upper limit, and if this is the desired position, return.
- 5440 If the source is at the lower limit, and if this is the desired position, return.
- 5450 If the source is stalled, announce this and proceed.
- 5460 If the motor has been asked to move more than 424 steps by this time (and the proper limit switch has still not been set), give up.
- 5470 If the source has already been moved (and the proper limit switch has not been set), set the number of steps for the next command to the motor at 5.
- 5480 Send command to motor, wait for source to move, increment record of total travel, and return to start of subroutine to check limit switches.

5500	Subroutine to start assay.
5510	Set crate inhibit, no read bit.
5530	Clear scalers.
5540	Remove inhibit (this starts scalers). Start timer routine for 30 000 cycles or 500 s. To actually measure the time interval, save the starting time in Z0§.
5550	Turn on assay in process light.
5600	Subroutine to stop assay.
5600	Wait for timer function to time out (X8 goes to +1 from -1). Set crate inhibit (this stops scalers). Record stopping time in Z1§.
5610	Turn off assay in process light, turn on ready light.

### C. DYMAC3 Variable List

A(0)	passive daily normalization	D(3)	error
A(1)	error	D(4)	passive net dbls, bkg corr.
A(2)	active daily normalization	D(5)	error
A(3)	error	D(6)	active net dbls, bkg corr.
A(4)		D(7)	error
A(5)		D(8)	passive/active corrected doubles
A(6)		D(9)	error
A(7)		D	sample diameter
B(0)	passive net doubles bkg	D§	flag for floppy disk availability
B(1)	error	E	effective <sup>240</sup> Pu enrichment
B(2)	active net doubles bkg	E0	per cent <sup>240</sup> Pu
B(3)	error	E2	per cent <sup>242</sup> Pu
B(4)	passive net triples bkg	E8	per cent <sup>238</sup> Pu
B(5)	error	E§	+/- symbol
B(6)	active net triples bkg	F0	temperature correction
B(7)	error	F1	error
B(8)	passive totals bkg	G	ADC gain 1 = 5.12 V F.S. 2 = 512 mV F.S. 3 = 51.2 mV F.S.
B(9)	error	H	sample fill height
B(10)	active totals bkg	i	index
B(11)	error	I2	sample type 1 = oxd 4 = PRP 2 = flu 5 = res 3 = PMP 12 = norm.
C(I,0)	passive calib A	J	assay type 0 = passive 2 = active
C(I,I)	error 6A	K	index
C(I,2)	active calib A	K(0)	passive <sup>3</sup> He flux rate
C(I,3)	error 6A	K(1)	error
C(I,4)	passive B	K(2)	active <sup>3</sup> He flux rate
C(I,5)	error	K(3)	error
C(I,6)	active B	K(4)	passive bkg reference flux rate
C(I,7)	error	K(5)	error
C(I,8)	passive covariance	K(6)	active bkg reference flux rate
C(I,9)	active covariance	K(7)	error
D(0)	passive/active net doubles, uncorrected		
D(1)	error		
D(2)	passive/active temp. corr. dbls		

K(8)	passive/active flux ratio	S(9)	middle singles overflow
K(9)	error	S(10)	right singles scaler
K(10)	passive/active flux correction	S(11)	right singles overflow
K(11)	error	T	count time
L(12)	$\alpha = N_{an}/N_{SF}$	T(0)	passive/active net triples, uncorrected
L2	temporary variable for quad. formula	T(1)	error
L3	temporary variable for quad. formula	T(2)	passive/active temp. corr. triples
L4	temporary variable for quad. formula	T(3)	error
M(0)	passive triples/doubles reference	T(4)	passive net triples, bkdg. corr.
M(1)	error	T(5)	error
M(2)	active triples/doubles reference	T(6)	active net triples, bkg. corr.
M(3)	error	T(7)	error
M(4)	passive/active measured triples/doubles	T(8)	passive/active corrected triples
M(5)	error	T(9)	error
M(6)	passive/active leakage mult.	U1	room temperature
M(7)	error	U2	crate temperature
M(8)	passive/active self-mult. corr. factor	U3	PMT temperature
M(9)	error	U4	HV supply temperature
N	current or available run number	V	sample volume
N0	total runs in cycle	V(100)	virtual file temporary storage
N1	assay type 0 = passive only 1 = active OK 2 = active required	W	sample weight
N2	not used	X	temporary variable
N3	source position 0 = down desired 1 = up desired	X(0)	passive left totals
N4	limit switch status 16 = stall 20 = down 24 = up	X(1)	error
N5	number of steps sent to motor	X(2)	active left totals
N6	total number of steps travelled	X(3)	error
0		X(4)	active-passive left totals
0§	one blank space	X(5)	error
P1	material density	X8	run timer
P2	plutonium density	X9	ADC reading
S	CAMAC status word	Y	temporary variable
S(0)	time scaler/passive singles	Y(0)	passive middle totals
S(1)	<sup>3</sup> He scaler/error	Y(1)	error
S(2)	dbl. coinc. scaler/active singles	Y(2)	active middle totals
S(3)	acc. dbls. scaler/error	Y(3)	error
S(4)	trip. coinc. scaler/active-passive sg.	Y(4)	active-passive middle totals
S(5)	acc. trip. scaler error	Y(5)	error
S(6)	left singles scaler	Z1	ADC lowest reading
S(7)	left singles overflow	Z2	ADC highest reading
S(8)	middle singles scaler	Z(0)	passive right totals
		Z(1)	error
		Z(2)	active right totals
		Z(3)	error
		Z(4)	active-passive right totals
		Z(5)	error
		Z§	time string variable

D. Calibration Constants for DYMAC3, as Stored in File RDINIT.DO1

VF1()	variable	meaning	value	
1	C(1,0)	oxide	passive A	0.1775 (11/16/78)
2	C(1,1)		error	0.0015
3	C(1,2)		active A	9.87
4	C(1,3)		error	0.11
5	C(1,4)		passive B	$8.4 \times 10^{-5}$
6	C(1,5)		error	$2.2 \times 10^{-5}$
7	C(1,6)		active B	$-3.05 \times 10^{-3}$
8	C(1,7)		error	$2.3 \times 10^{-4}$
9	C(1,8)		passive covariance	$3.0 \times 10^{-8}$
10	C(1,9)		active covariance	$2.25 \times 10^{-5}$
11	C(2,0)	fluoride	passive A	0.0738 (10/4/78)
12	C(2,1)		error	0.0007
13	C(2,2)		active A	0
14	C(2,3)		error	0
15	C(2,4)		passive B	$4.1 \times 10^{-3}$
16	C(2,5)		error	$1.3 \times 10^{-4}$
17	C(2,6)		active B	0
18	C(2,7)		error	0
19	C(2,8)		passive covariance	$7.8 \times 10^{-8}$
20	C(2,9)		active covariance	0
21	C(3,0)	PMP	passive A	0.1812 (1/3/79)
22	C(3,1)		error	0.0012
23	C(3,2)		active A	14.14
24	C(3,3)		error	0.16
25	C(3,4)		passive B	$1.82 \times 10^{-5}$
26	C(3,5)		error	$1.20 \times 10^{-5}$
27	C(3,6)		active B	$-1.63 \times 10^{-3}$
28	C(3,7)		error	$9.4 \times 10^{-5}$
29	C(3,8)		passive covariance	$1.67 \times 10^{-8}$
30	C(3,9)		active covariance	$1.36 \times 10^{-5}$
31	C(4,0)	PRP	passive A	0.1812 (1/3/79)
32	C(4,1)		error	0.0012
33	C(4,2)		active A	14.14
34	C(4,3)		error	0.16
35	C(4,4)		passive B	$1.82 \times 10^{-5}$
36	C(4,5)		error	$1.20 \times 10^{-5}$
37	C(4,6)		active B	$-1.63 \times 10^{-3}$
38	C(4,7)		error	$9.4 \times 10^{-5}$
39	C(4,8)		passive covariance	$1.67 \times 10^{-8}$
40	C(4,9)		active covariance	$1.36 \times 10^{-5}$
41	C(5,0)	residue	passive A	0.1775 (11/16/78)
42	C(5,1)	(same as oxide)	error	0.0015
43	C(5,2)		active A	9.87
44	C(5,3)		error	0.11
45	C(5,4)		passive B	$8.4 \times 10^{-5}$

46	C(5,5)		error	$2.2 \times 10^{-5}$
47	C(5,6)		active B	$-3.05 \times 10^{-3}$
48	C(5,7)		error	$2.3 \times 10^{-4}$
49	C(5,8)		passive covariance	$3.0 \times 10^{-8}$
50	C(5,9)		active covariance	$2.25 \times 10^{-5}$
51	C(6,0)	unused	passive A	
52	C(6,1)		error	
53	C(6,2)		active A	
54	C(6,3)		error	
55	C(6,4)		passive B	
56	C(6,5)		error	
57	C(6,6)		active B	
58	C(6,7)		error	
59	C(6,8)		passive covariance	
60	C(6,9)		active covariance	
61	A(0)		passive daily normalization	
62	A(1)		error	
63	A(2)		active daily normalization	
64	A(3)		error	
65	B(0)		passive net doubles bkg	
66	B(1)		error	
67	B(2)		active net doubles bkg	
68	B(3)		error	
69	B(4)		passive net triples bkg	
70	B(5)		error	
71	B(6)		active net triples bkg	
72	B(7)		error	
73	B(8)		passive totals bkg	
74	B(9)		error	
75	B(10)		active totals bkg	
76	B(11)		error	
77			reference temp $T_0$	
78			reference temp slope $\alpha$	
79	K(4)		flux rate during passive bkg	
80	K(5)		error	
81	K(6)		flux rate during active bkg	
82	K(7)		error	
83	M(0)		trps/dbls passive reference	0.007
84	M(1)		error	0
85	M(2)		trps/dbls active reference	0.007
86	M(3)		error	0
87	N		next run number to be used	

## E. Documentation for Least Squares Fit Program (LSQFIT)

This program is used to fit a set of standard cans run in the FNC to the functions

$$\text{response (counts/sec)} = \frac{a(\text{mass})}{1 + b(\text{mass})} ,$$

$$\text{mass} = \frac{a(\text{response})}{1 + b(\text{response})} , \text{ or}$$

$$\text{response (counts/sec)} = a(\text{mass}) + b .$$

Because the first two functions are nonlinear, the fit is carried out by iteration. For reasons of program compactness the last function is also fit by the same iterative routine, although an exact solution is possible in this case.

Lines 520 to 660 are used to initialize the program and open the files containing the values and names of the data points. These files are LSQDA1.DAS and LSQDA2.DAS for VF1 and VF2§.

The program then prints its name and the list of allowed commands. The statements immediately below this list of commands will cause the program to branch to the desired subroutine and should be referred to by the reader to help locate the routines described below.

The command L-LIST DATA SET should be invoked first to look at the two data files that have just been opened (one for name strings and one for data points). For the purposes of this program the 2 data files are mixed together, but the combined file is treated as 10 separate data sets (1-10) that may contain up to 50 points each. The L command is used to review the contents of these by typing 1 to 10. Typing 11 calls up the data selected for fit described below. Typing 0 will cause a return to the list of commands.

The command C-CREATE DATA SET is used to enter data into one of the 10 available data sets. In response to the questions, choose the desired data set, the number of the point to be entered, and the title of that data point. Answering 0 will cause a return to the next higher level of command. Typing <CR> as a title will cause a zero data point. This is the only way to zero data but it should be sufficient because data points can be selected or overwritten as desired.

The command S-SELECT DATA FOR FIT is used to assemble an array of 50 or fewer data points for the least squares fitting. In response to the questions, choose the desired data set and then the first and last point. For example, to choose points 1, 3, 4, 5, 6, 8, 9, 10, enter the successive commands, 1,1; 4,6; and 8,10. To exit or to select from another data set, type 0,0.

The command A-FIT TO A ONLY IN  $Y = AX/(1 + BX)$  will cause the program to request that B be entered. Subroutine 9000 is then called to help select a starting value  $A_0$  from the data set selected by S. The program will then proceed to the iterative fitting routine.

The command B-FIT TO B ONLY IN  $Y = AX/(1 + BX)$  causes a similar response to that described above for A.

The command F-FIT TO A AND B IN  $Y = AX/(1 + BX)$  will cause the program to select starting values  $A_0$  and  $B_0$  and then proceed to the iterative fit.

A least-squares fit program seeks to minimize the chi-square

$$\chi^2 = \sum_i \frac{[Y_i - F(a,b,x_i)]^2}{\sigma_i^2} = \sum_i Q_i^2 .$$

Expand  $X^2$  in a Taylor series about  $a = a_0 + \Delta a, b = b_0 + \Delta b$ :

$$X^2 \approx \sum Q^2|_0 + \frac{\Sigma \delta Q^2}{\delta a} |_0 \Delta a + \frac{\Sigma \delta Q^2}{\delta b} |_0 \Delta b + \dots$$

$$\approx \sum Q^2 + 2\Delta a \sum Q \frac{\delta Q}{\delta a} + 2\Delta b \sum Q \frac{\delta Q}{\delta b} + \dots$$

To minimize  $X^2$ , set the first order derivatives of  $X^2$ ,  $\delta X^2/\delta a$ , and  $\delta X^2/\delta b$ , equal to zero:

$$0 = \sum Q \frac{\delta Q}{\delta a} + \frac{\Delta a \Sigma \delta Q}{a} \frac{\delta Q}{a} + \frac{\Delta b \Sigma \delta}{a} \frac{\delta Q}{b}$$

$$0 = \sum Q \frac{\delta Q}{\delta b} + \frac{\Delta a \Sigma \delta Q}{\delta b} \frac{\delta Q}{\delta a} + \Delta \frac{\Sigma \delta Q}{\delta b} \frac{\delta Q}{\delta b}$$

Converting to the notation of the program.

$$0 = s_4 + a_3 s_1 + b_3 s_2$$

and

$$0 = s_4 + a_3 s_2 + b_3 s_3$$

In matrix notation, this is

$$\begin{pmatrix} -s_4 \\ -s_5 \end{pmatrix} = \begin{pmatrix} s_1 & s_2 \\ s_2 & s_3 \end{pmatrix} \begin{pmatrix} a_3 \\ b_3 \end{pmatrix}$$

or  $\bar{F} = \text{curvature matrix} \cdot \bar{a}$ . The solution that must be iterated is

$$a_3 = (s_2 s_5 - s_3 s_4) / D$$

$$b_3 = (s_2 s_4 - s_1 s_5) / D$$

$$D = s_1 s_3 - s_2 s_2$$

$$\text{The error matrix} = (\text{curvature matrix})^{-1} = \frac{1}{D} \begin{pmatrix} s_3 & -s_2 \\ -s_2 & s_1 \end{pmatrix}$$

From this we obtained (after convergence) the errors in the parameters

$$\delta a = \sqrt{s_3/D}, \quad \delta b = \sqrt{s_1/D}, \quad \text{cov}(a, b) = -s_2/D$$

Other program variables are A2 and B2, which determine whether A or B is varied, the variance in each data point,

$$G = \sigma_i = \sqrt{\sigma_y^2 + \frac{\delta f^2}{\delta x} \sigma_x^2}$$

and the chi-square-per-degree-of-freedom  $S_6$ . If the assigned errors  $\sigma_x(i), \sigma_y(i)$  correctly describe the variance in the data and if the choice of fitting function  $F$  is correct, the chi-square per degree of freedom will usually lie between 0.3 and 2.0 and thus provides a goodness-of-fit criterion. (Chi-square per degree of freedom will be 0 for a perfect fit, for example, a two-parameter fit to two data points). If the chi-square per degree of freedom is much larger than one, the errors have been underestimated. As a rough correction, increase  $\sigma_a$  and  $\sigma_b$  by the square root of chi-square per degree of freedom, and increase the covariance by the chi-square per degree of freedom.

After the above results are printed out, the data points used in the fit are listed. Next to each data point  $Y_i$ , the result  $F(x_i, a, b)$  is also calculated. This listing provides a direct qualitative confirmation of the validity (or nonvalidity) of the fit. The corresponding error in  $F$  is given by

$$\delta F = \sqrt{\left(\frac{\delta F}{\delta x}\right)^2 \sigma_x^2 + \left(\frac{\delta F}{\delta a}\right)^2 \sigma_a^2 + \left(\frac{\delta F}{\delta b}\right)^2 \sigma_b^2 - 2 \frac{\delta F}{\delta a} \frac{\delta F}{\delta b} \text{cov}(a, b)} .$$

Note that the functions to be fit appear only in the subroutine at 9040. To modify this program to fit other two-parameter functions, it is only necessary to insert new equations for  $G, Q, Q1, Q2, F,$  and  $F1$ .

## F. Additional Functions of MUBASIC

A series of assembly language routines have been written by T. L. Atwell and compiled with MUBASIC. The resulting file is MUBASC, and it must be called whenever MUBASIC is to be used to address the CAMAC crate. The assembly language routines themselves are stored in a file called ADDLFN.MAC, which is available on N. Ensslin's master system disks. The most important routine is NAFD, which is used to send data or instructions between the computer and the CAMAC crate.

## VI. FAST ELECTRONICS TUNE-UP

### A. Phototube Assembly

Examine each new tube to be sure its surface is clear and free of scratches. The interior of the tube should have a yellow tinge. If not, the gas has leaked out.

Push the tube gently onto the Ortec 265 base. Tape a 2-in.-wide piece of green felt around the center of the tube. This felt acts as a shock absorber and helps to maintain tube alignment.

Slide the tube into the mu-metal adapter and screw the adapter into place. Remove the outer cover from the tube base to expose the pots for gain adjustment.

### B. Phototube Gain Adjustment

Before installation in the FNC, each PMT should be adjusted on the bench. This tune-up consists of setting the three pots on the Ortec 265 tube base for maximum gain.

Couple the tube to a plastic scintillator and place a source nearby. Make sure there are no light leaks. If the tube is coupled to an LRS 612 PMT amplifier, set the high voltage to about -2100 V. RCA 8575 or Amperex XP-2230 tubes are suitable for the FNC. Because the Amperex tubes have about half of the gain of the RCA tubes, it is preferable to use six tubes of the same manufacture to make gain equalization easier to achieve.

Connect the fast timing anode signal to the LRS 612 PMT amplifier, and look at the output with a fast oscilloscope. The output should be about 1-2 V in magnitude (Fig. 6-1), with about 50 mV of noise. If there is an intense noise spectrum between 50 and 100 mV (about one in four tubes seems to exhibit this), the tube should be rejected.

On the phototube base, adjust the two bleeder string controls, Focus (R17) and Dynode (R15), for maximum output signal. Adjust the green pot (R16), which is the voltage on the last dynode, for maximum output signal without pulse shape distortion. The adjustment of all three pots may require some iteration, because they are somewhat interrelated. Finally, use the green pot (R26) as an attenuator to roughly equalize the gain from all six phototubes.

### C. Phototube Installation

Clean the face of the PMT and the mating surface on the plastic scintillator with Kleenex tissue dampened with ethanol. Other materials or solvents may damage the polished surfaces. Cover both cleaned surfaces with DOW DC-20-057 optical coupling compound. Screw the PMT assembly into place at the base of the scintillator. It is helpful to have someone else observe this procedure with a flashlight through the viewing ports at the top of the scintillator. The assembly should be tightened just enough to spread out the coupling compound, remove air bubbles, and give a clear view into the phototube. Both PMT assemblies on the same scintillator should be tightened together because pressure from one may loosen the other. When this is complete, tighten the lock nut on each assembly.

### D. Phototube Gain and Timing Adjustment

After amplification by the LRS 612 amplifier, the PMT pulses should be 10-20 ns wide and range in size from noise level to 1-2 V. A HV setting of  $-2100$  to  $-2200$  V will probably be required to obtain reasonable output pulses and reasonable coincidence response. This pulse spectrum is illustrated in Fig. 6-1. The final equalization of gain between the six tubes can be done now by displaying the pulse spectra two at a time on a fast oscilloscope. Overlap the two spectra very carefully, select NORMAL triggering, and then rapidly switch back and forth between them using the CHAN 1 and CHAN 2 display controls. The tube with the higher gain will show a more intense pulse spectrum. If adjustments need to be made, use the pots on the HV distribution box. Typically, several turns on the pots are required. If the range of the pots is not sufficient to equalize gains, readjust the green pots (R26) on the PMT bases or replace the weakest phototube.

Even if all cables from the PMTs to the circuit are of equal length, the output signals may not occur at exactly the same time because of variations in the transit times within the tubes (typically these times are



Fig. 6-1.  
Photomultiplier tube output pulse-height spectrum (20 ns/cm horizontal scale, 500 mV/cm vertical scale).

25 to 40 ns). For this reason it is necessary to check the relative timing of the phototubes. This is best done at the output of the discriminators because these pulses all have the same shape and are the ones used for the fast timing circuits that follow.

First set the LRS 623 discriminators to  $-100$  mV or whatever value has been chosen. This can be done using the test points on the front panel (output is  $10\times$  threshold). The settings can be checked conveniently by passing the amplifier output to the discriminator through the  $1\text{ M}\Omega$  scope input. Use the discriminator output as the trigger for the oscilloscope. Only those PMT pulses above the discriminator threshold will be visible on the scope. The discriminator output pulses should be  $10\text{ ns}$  wide,  $-800$  mV in size.

Now check the relative timing of the two PMTs on each scintillator. This procedure may be aided by putting a strong coincidence source like  $^{60}\text{Co}$  into the FNC cavity in addition to the random AmLi source already present, but this is not necessary. Pass the two discriminator outputs into one of the LRS 622 AND circuits through the  $1\text{ M}\Omega$  scope inputs. Use the AND output to trigger the scope. Because this trigger comes at the time of the later discriminator output, the leading edge of the earlier discriminator output will look fuzzy, and the leading edge of the later discriminator output will look sharp. For example, in Fig. 6-2 the upper discriminator output is about  $2\text{ ns}$  ahead of the lower. Adjust the cable lengths between the PMT assemblies and the amplifiers until both leading edges look about equally fuzzy, as illustrated in Fig. 6-3. This procedure may be facilitated by overlapping both scope traces and switching rapidly back and forth between them. It should be possible to equalize the timing of signals from the two PMTs on each scintillator to within  $0.5$  to  $1.0\text{ ns}$ .

The above procedure is more difficult to use to check the relative timing between the three scintillators. This timing was checked by setting a strong  $^{60}\text{Co}$  source on the corner between two scintillators and checking the two nearest PMTs. A more complex procedure involves the use of a time-to-amplitude converter (TAC), a multichannel analyzer (MCA), and a delay box. The TAC should be used to look at the time differences between two scintillators. The LRS 622 AND coincidence signals from the two phototubes on each scintillator should be connected to the TAC. The TAC output should go into the ADC in the MCA. Calibrate the MCA to  $1\text{ ns/channel}$  by varying the time delay to the TAC stop and then adjusting the range of the TAC or ADC as needed. Set time = 0 at the center of the MCA display by feeding one scintillator into two AND gates and then adjusting the time delay to the TAC stop or the MCA zero offset as needed. Now place a strong  $^{60}\text{Co}$  source midway between two of the scintillators and look at the time difference with the TAC and the MCA. If the central peak is not centered at  $t = 0$ , adjust both cable lengths from one scintillator relative to the other. Repeat this procedure with the other scintillator.

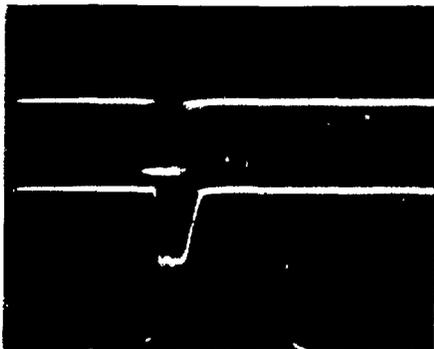


Fig. 6-2.  
Discriminator output of two PMTs on one scintillator. The upper trace is about  $2\text{ ns}$  ahead of the lower ( $10\text{ ns/cm}$  horizontal scale,  $500\text{ mV/cm}$  vertical scale).

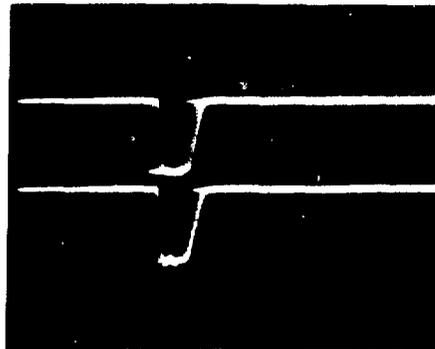


Fig. 6-3.  
Discriminator output of two PMTs on one scintillator. Both traces are simultaneous within  $0.5\text{ ns}$  ( $10\text{ ns/cm}$  horizontal scale,  $500\text{ mV/cm}$  vertical scale).

## E. Fast Timing Circuitry

Complete the wiring of the fast electronics, as illustrated in Fig. 4-4. Keep all cable lengths as short as possible and all cables of similar function of equal length. The double and accidental double coincidence signals are clipped to 38.4 ns and 38.8 ns, respectively. Other output pulse widths are given in Fig. 4-4. Terminators should be used where necessary to keep all output pulses at  $-800$  mV.

Check that immediately coincident events, such as (gamma,gamma) coincidences, will not be registered. The easiest way to do this is to feed only one scintillator into the triple OR and then check that the double coincidence module (top of the last LRS 622) has no output. Also, check the two inputs to the double coincidence module for correct amplitude, duration, and relative spacing. Correct timing is illustrated in Fig. 6-4.

A final confirmation of correct timing can be done by again using an MCA and a TAC connected between two scintillators. Use a strong source that emits gammas and neutrons in coincidence, and calibrate the MCA display as described earlier. Gate the input to the MCA with the double coincidence output of the fast electronics circuit. This makes it possible to check directly that the electronics accept only events separated in time by  $-45$  to  $-5$  ns or  $+5$  to  $+45$  ns. Within these windows the distribution of time differences will be similar to that illustrated in Fig. 4-6. If the windows are not set correctly, adjust gate and delay lengths as needed.

The above confirmation need not be carried out if the initial assays of background and random sources show that the real and accidental circuits are balanced at low and high rates, and if assays of fission sources show that the double and triple coincidence response is independent of background and linear with source strength.

## VII. OPERATING INSTRUCTIONS

### A. Sample Loading

The sample holder mechanism is raised and lowered by the front Minarik controller located to the left of the FNC chassis. For the 4 in. high recovery cans, use the 3 in. spacer to center the can with respect to the scintillators and the neutron sources. Make sure that no other large samples of plutonium are in the glove box. Start the sample rotator motor with the switch mounted on the request assay box. Note that the request assay button is inoperative unless the sample is rotating. If the FNC software is in the Random Driver Available mode, a valid assay request will cause the terminal to respond with IS SAMPLE LOADED AND ROTATING?

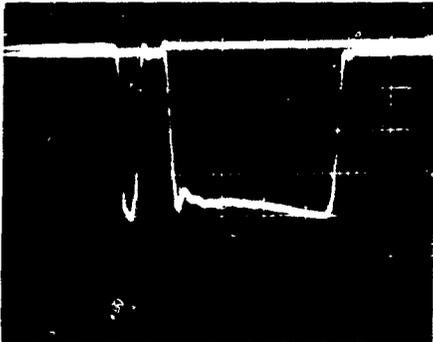


Fig. 6-4.

Correct timing at the input to the double coincidence module. One trace is a 5-ns-wide prompt signal; the other is a 40-ns-wide delayed signal (10 ns/cm horizontal scale, 200 mV/cm vertical scale).

## B. TI 743 Silent 700 Terminal Settings

HI SPEED  
FULL DUPLEX  
ON LINE  
NUM off

## C. Restarting Computer after Power Fail

1. On the front panel of the computer, push CONTROL-HALT (push HALT while holding down CONTROL). Then push CONTROL-BOOT. The terminal should respond by printing four numbers and a \$.
2. Type DX<CR> on the terminal. The terminal should respond with RT-11... and a . as a prompt.
3. Enter DAT DD-MON-YR<CR>.  
Enter TIM HH-MM-SS<CR>.
4. Type R MUBASC<CR>. The terminal should respond with MU-BASIC... ENTER CONFIGURATION FILE...?
5. Type (letter) O<CR>. The terminal should respond with FILE--?
6. Type 1UR<CR>. The terminal should respond with READY.

## D. Turning off Power on CAMAC Crate

If it is necessary to replace a module in the CAMAC crate without losing the computer memory, the following procedure should be followed.

1. Press CONTROL/HALT on computer.
2. Turn CAMAC crate offline.
3. Turn off crate power.
4. Loosen the screw at the bottom of the module and remove it.
5. Replace module, tighten screw with screwdriver.
6. Check to see that NIM - CAMAC adapter is all the way back into crate (NIM modules only).
7. Replace rear panel connectors (CAMAC modules only).
8. Turn on crate power.
9. Issue C and Z from crate controller by pressing INITIALIZE.
10. Turn crate online.
11. Press CONTROL/CONTINUE on computer.

This procedure will restore program operation, but of course the clock will not advance while the computer is halted.

## E. Loading the Operating Software

1. To start the assay program once MUBASIC is up (READY on terminal), type R DYMAC3.
2. The terminal will respond with IS FLOPPY DISK AVAILABLE FOR INITIALIZATION? Type YES <CR>.
3. The terminal will respond with DO YOU WISH TO CHECK OR CHANGE INITIALIZATION?  
If you wish to review or change some of the contents of the virtual file VF1 (100) that contains the calibration data, type YES <CR>. If not, type NO <CR>.
4. The terminal will respond with SOURCE IS DOWN, RANDOM DRIVER AVAILABLE.

## F. Assay Instructions

1. When the terminal has responded with RANDOM DRIVER AVAILABLE, and the sample is loaded and rotating, push the request assay button.
2. The terminal will respond with IS SAMPLE LOADED AND ROTATING? If so, answer YES <CR>.
3. The terminal will then request the desired counting time. Enter this in seconds.
4. The assay will now be started, and the assay number, date, and time will be printed. The remaining questions must be answered before the assay times out.
5. Enter operator's name.
6. Enter assay type. The operator response must be identical to one of the types listed. Some assay types will cause an active assay to be automatically performed.

<u>Initials</u>	<u>Material</u>	<u>Active Assay</u>
BKG	background run	yes
NOR	normalization standard	yes
OXD	oxide	maybe
FLU	fluoride	no
PMP	electrorefined metal	no
PRP	reduction metal (impure)	yes
RES	electrorefining residues	yes

7. Enter sample identification, weight, diameter, and fill height if called for. This information does not affect the calculated mass of the sample, although the choice of assay type (item 6 above) does.
8. Enter the enrichment (per cent  $^{240}\text{Pu}$ ) as accurately as possible because this value is used to compute the total mass of plutonium.
9. The AUTOCYCLE question may be answered NO<CR> (1 run will occur), YES <CR> (100 runs will occur), N >CR< (N runs will occur), or just <CR> (1 run will occur).
10. If a question has been answered incorrectly, answer "B" on the next question to backspace.
11. If a question has been answered with incorrect syntax, and the terminal responds with STOP AT LINE N, type GO TO N to repeat the question and continue.
12. To stop a run before it times out, type CONTROL/C. The terminal will respond with READY. Then type GO TO 1000. The terminal will respond with RANDOM DRIVER AVAILABLE.

## G. Interpretation of Assay Print-out

Table VII-1 illustrates the print-out obtained from the passive and active assay of PRP73, a sample of reduction metal. At that time the assay length was fixed at 500 s. In other respects the computer print-out is the same today.

TABLE VII-1

SAMPLE PRINT-OUT

RANDOM DRIVER AVAILABLE  
 IS SAMPLE LOADED AND ROTATING Y  
 PASSIVE ASSAY NO. 17  
 OPERATOR NAME DK  
 BKG,CAL,OXD,FLU,PMP,PRP,RES PRP  
 SAMPLE ID,COMMENTS PRP73  
 SAMPLE WGT (GMS) 600.7  
 SAMPLE DIAM (CM) 7.5  
 FILL HEIGHT (CM) 1.5  
 ENRICHMNT ( 240) 5.84  
 AUTOCYCLE N

TIME	HE3	DOUBLES	ACC DBL	TRIPLES	ACC TRP	LEFT	MIDD	RIGHT
500	212	204988	2083	5511	6	1.780+06	2.418+06	1.924+06
ROOM TEMP	BACKGROUND		SINGLES		TRIPLES		DOUBLES	
22.4	4.067		12245 ± 4.948		11.01 ± 0.14		405.81 ± 0.9101	
CRATE TEMP	TEMP CORR		FLUX RATIO		TRIPLES/DOUBLES		CORR.DOUBLES	
35.7	1.011		1 ± 0		0.026 ± 3.-04		232 ± 2.151	
PMT TEMP	MATL TEMP		FLUX CORR		LEAKAGE MULT		NORMALIZATION	
23.6	16.99		1 ± 0		1.22 ± 4.-03		0.977 ± 8.-03	
HV TEMP	PLUT DENS		ALPHA		SELF-MULT CORR ASSAY IN GMS PU240			
22.4	19.52		0 ± 0		1.73 ± 0.015		41.99 ± 0.57	

SOURCE IS UP  
 ACTIVE ASSAY NO. 17 STARTED AT 22/NOV/78-09:27

TIME	HE3	DOUBLES	ACC DBL	TRIPLES	ACC TRP	LEFT	MIDD	RIGHT
500	487	245901	13701	6354	6	4.972+06	5.734+06	5.273+06
ROOM TEMP	BACKGROUND		SINGLES		TRIPLES		DOUBLES	
22.6	5.9		31959 ± 7.994		12.69 ± 0.14		464.4 ± 1.019	
CRATE TEMP	TEMP CORR		FLUX RATIO		TRIPLES/DOUBLES		CORR.DOUBLES	
35.8	1.011		0.954 ± 0.10		0.029 ± 3.-03		34.72 ± 0.898	
PMT TEMP	MATL TEMP		FLUX CORR		LEAKAGE MULT		NORMALIZATION	
23.4	16.99		0.990 ± 0.02		1.22 ± 4.-03		0.977 ± 8.-03	
HV TEMP	PLUT DENS		ALPHA		SELF-MULT CORR ASSAY IN GMS PU240			
22.4	15.31		0 ± 0		1.63 ± 0.133		508.33 ± 15.37	

FINAL RESULT FOR TOTAL PLUTONIUM: 541.26 ± 16.36 GMS

SOURCE IS DOWN  
 RANDOM DRIVER AVAILABLE

The first line is the raw data received from the CAMAC scalers.

TIME	Assay length in seconds. This is the measured length, and may exceed the requested length by a few seconds.
HE3	Total neutron counts from <sup>3</sup> He tubes. The circuit is now turned off
DOUBLES	Counts from double coincidence circuit.
ACC DBLS	Counts from accidental double coincidence circuit.
TRIPLES	Counts from triple coincidence circuit.
ACC TRP	Counts from accidental triple coincidence circuits.
LEFT	Total counts from left scintillator AND circuit.
MIDD	Total counts from middle scintillator AND circuit.
RIGHT	Total counts from right scintillator AND circuit.
Below this line, the data are roughly organized in columns.	
ROOM TEMP	Temperature in °C at top of the electronics cabinet.
CRATE TEMP	Temperature in °C at back of the CAMAC crate.
PMT TEMP	Temperature in °C at base of one of the photomultiplier tubes.
HV TEMP	Temperature in °C at the top of the HV power supply.
BACKGROUND	Passive or active double coincidence background. These values are updated by each BKG run. The triple coincidence background values are also stored and updated, but are not printed out.
TEMP CORR	The temperature correction is calculated as described in Sec. V.B, but it is not applied to the data.
MATL DENS	Sample weight (pi × sample diameter × sample fill height), as supplied by the operator.
PLUT DENS	For passive assays, this is the grams of <sup>240</sup> Pu determined by the assay/(enrichment × sample volume). For active assays, this is the grams of <sup>239</sup> Pu determined by the assay/[(1 - enrichment) × sample volume].
SINGLES	(LEFT + MIDD + RIGHT)/TIME, total count rate.
FLUX RATIO	<sup>3</sup> He neutron count rate during active assay less <sup>3</sup> He neutron count rate during passive assay, divided by a reference rate determined during the last active background update.
FLUX CORR	A correction for neutron thermalization within the sample as determined by the flux ratio. The equation is given in Sec. V.B. This correction is not applied to the measured response.
ALPHA	The ratio of neutrons from (alpha,n) reactions to neutrons from spontaneous fission in the sample that was assumed for the self-multiplication correction applied to this assay.
TRIPLES	(TRIPLES - ACC TRP)/TIME, triples count rate.
TRIPLES/DOUBLES	Measured triples rate less triples background divided by measured doubles rate less doubles background.
LEAKAGE MULT	Net leakage multiplication within the sample as calculated by the self-multiplication correction.
SELF-MULT CORR	The self-multiplication correction applied to this assay. The correction is described in Sec. V.B.

DOUBLES	$(\text{DOUBLES} - \text{ACC DBL})/\text{TIME}$ , double coincidence rate.
CORR. DOUBLES	The above doubles rate less the doubles background, divided by the self-multiplication correction. For active assays, the passive doubles rate less its background is also subtracted before the self-multiplication correction is applied.
NORMALIZATION	The measured double coincidence response is adjusted by this factor, which is determined by counting standard No. 9 as a NORM run. The NORM run updates the passive and active normalization factors whenever it is performed.
ASSAY IN GMS PU240 (PU239)	The corrected double coincidence rate $\times$ the normalization constant is used to compute the mass from the relation $A \times \text{response} / (1 + B * \text{response})$ , where A and B are calibration constants.
FINAL RESULT FOR TOTAL PU	If the enrichment was specified, convert the passive (and active if done) assay to grams of total plutonium. Use the passive assay as the final result unless the active assay is smaller by more than 1 std dev.

## H. Measurement Control Procedures

It is strongly recommended that a BACKGROUND (BKG) (first) and a NORMALIZATION (NORM) run (second) be performed before unknown samples are assayed. This procedure should be carried out every day that the FNC is used. If the amount of nuclear material in the vicinity of the FNC changes appreciably during the day, a new BKG run should be done immediately. If there is any doubt about the proper operation of the instrument, the NORM run should be repeated.

The BKG run updates the passive and active double and triple coincidence backgrounds stored in the computer. The NORM run updates the passive and active double coincidence normalization factors. Both runs together allow the measured response to be corrected properly for room background variations and instrument drift. If these runs are not carried out regularly, the software can be modified to make them mandatory.

## I. Calibration Procedures

1. Complete the electrical tune-up and timing adjustment of all circuits (Sec. VI).
2. Carry out overnight BKG and NORM runs to ensure that the measured backgrounds and responses are of reasonable magnitude and are free of strong drifts and high voltage breakdowns.
3. Run a large, very hot sample to ensure that the circuitry is balanced at very high count rates.
4. If a self-multiplication correction is to be used as a correction factor or diagnostic check, assay a small (20 g or less) sample of pure electrorefined metal overnight to get good statistics. Perform long, careful BKG runs before and after. Determine the triples/doubles ratio from this "non-multiplying" sample and store it in the floppy disk file.

5. For each material category, assay a series of standards covering the desired range of sample sizes. Perform multiple assays to get good statistics and better reliability. Perform frequent BKG and NORM runs.
6. For each material category, carry out a least-squares fit of (double coincidence response less coincidence background) times normalization divided by self-multiplication correction (if desired) as a function of  $^{240}\text{Pu}$  effective mass and/or  $^{239}\text{Pu}$  effective mass. Load A,  $\sigma_A$ , B,  $\sigma_B$ , and the covariance values into the floppy disk file.

## VIII. MAINTENANCE

### A. List of Manuals Supplied

Table VIII-1 is a list of equipment manuals supplied with the FNC. These manuals cover all of the hardware except the Power Designs 3K-40 HV Power Supply.

TABLE VIII-1  
LIST OF MANUALS SUPPLIED

1. SEC 1510A/12	CAMAC power supply
2. SEC DCC-11	CAMAC crate controller
3. SEC WW-004	Prototype module
4. LRS 2551	12-channel scaler
5. KS 3290	Dataway display
6. KS 3530	Relay multiplexer
7. KS 3552-1	Optically isolated ADC
8. ByRa 5601	TTL-NIM converter
9. LRS 365 AL	Dual 4-fold logic
10. LRS 622	Quad 2-fold logic
11. LRS 623	Octal discriminator
12. LRS 612	12-channel PMT amplifier
13. Canberra 3105 HV power supply	
14. Canberra 2105 amplifier-SCA	
15. DEC RX01	Floppy disk
16. DEC RX01	Floppy disk engineering drawings
17. DEC PDP11/04	Engineering drawings
18. DEC DL11-W (M7856)	Serial line interface
19. DEC M9301	Bootstrap/terminator
20. DEC KY11-LB	Keyboard interface
21. TI 743	Printer
22. Variac 1592 ac regulator	
23. Minarik motor controller	
24. Bodine NSH-34RJ motor	
25. Ortec Inc. 265 PMT base	

## B. Routine Maintenance

1. The intake air filter on the electronics cabinet should be replaced every 6 months.
2. The TI 743 Printer should receive a new ribbon and lubrication every 6 to 12 months.
3. Every 12 months, the PMTs should be inspected to see if the optical coupling compound between the tube face and the scintillator has separated. The FNC chassis should be disconnected from its back frame and rolled forward. Remove the chassis cover and the black tape over the scintillators and look down at the phototubes. CAUTION: The PMT HV must be *off* when the scintillators are exposed to light.

## C. Troubleshooting

When unusual assay results or warning messages indicate equipment malfunction, it is usually possible to localize the area of trouble by looking at the data print-out.

1. If the trouble is in the fast electronics modules (which is often the case), it is easy to locate and replace the faulty module by using a fast oscilloscope to look at output signals.
2. If assay results are not reproducible or if the normalization factor varies significantly from day to day, the PMT HV power supply may be out of regulation. This can be checked by using a strip chart recorder to monitor the voltage.
3. Failure of a PMT or failure of a PMT to scintillator coupling is usually indicated by a decreasing response, an increasing normalization factor, an imbalance in the count rates between scintillators, and/or a decrease in assay precision due to a decrease in response from the affected scintillator.
4. Repeated messages of SOURCE IS STALLED usually indicate failure of the motor controller relays, damage to the microswitches, or that the sources have not reached their destination in the time allowed by the computer.

## D. Anticipated Problem Areas

The problem of providing a proper normalization for active assays is not yet solved. Because active assays have a lower statistical precision than passive assays, it is desirable to make the active normalization vary with the passive normalization. However, a large change in phototube high voltage or in the ratios of responses between scintillators seems to affect the active normalization more than the passive normalization. At present, the active normalization is set to be 90% of the passive normalization, but this ratio should be checked or changed whenever a large change in phototube response occurs.

## REFERENCES

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3. L. V. East and J. E. Swansen, "Charge Sensitive Preamplifier for Use with Large Proportional Counter Assays," Los Alamos Scientific Laboratory report LA-4972-MS (June 1972).
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