DEGRADATION AND LIFE EXPECTANCY TESTS FOR BF3 DETECTORS

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ABSTRACT

Degradation and life expectancy tests for BF3 detectors were conducted at AECL's Chalk River Laboratories. This paper provides the test objectives and results for twelve detectors from four manufacturers. The results confirmed that there is wide difference in the performance of detectors from different manufacturers. Based on the test results, the plausible cause of detector failure at the stations and the solutions are suggested, the detector life specification is clarified and the symptoms of a typical failed detector are summarized. Recommendations are presented on preferred detectors for CANDU®[1] stations, detector qualification test, and improving detector testing and assessment methods. Pretreatment of the detectors made through special techniques is proposed to rid them of transient degradation.

1. INTRODUCTION

Degradation and life expectancy tests for Boron Trifluoride (BF3) startup instrumentation (SUI) detectors were conducted because of recent high failure rates of this type of detector at a CANDU station. The purposes of the tests were:

1. To reduce the station operation and maintenance (O&M) cost.

   The O&M costs associated with the failure of BF3 SUI detectors in CANDU stations include the cost of BF3 detectors, and the person-hours required to diagnose the problem, carry out the procurement and replacement of the detectors and to adjust the monitoring system. Moreover, the neutron monitoring capability of the safety channel is unavailable during the repair.

2. To answer questions/concerns on BF3 detector degradation and life expectancy.

   The test was intended to determine the cause of detector failure and to find ways to reduce the failure rate. Experience of station staff shows that sometimes these detectors degrade quickly. This is particularly true for the Pickering Nuclear Generating Station (PNGS) A, where part of the ion chamber access tube is not shielded. The detectors at those locations are exposed to strong gamma fields, and the detector failure rate has been high. It is not clear whether the detector failures were caused by detector quality problems or by exposure to strong gamma fields.

3. To clarify the manufacturers' specification for BF3 detectors.

   Different manufacturers have different specifications for the life expectancy of their BF3 detectors. For example, one specification is "> 1E10 counts", whereas others specify the life expectancy to be 1E18 nvt or 1E19 nvt (nvt is a unit of flux * time). It is not clear how to interpret some of these specifications because they seem to differ so widely. Calls to manufacturers for assistance made it clear that some manufacturers do not have the technical expertise to provide this kind of advice. One of the objectives of the test is to evaluate the specifications provided by the manufacturers.

4. To compare quality consistency and performance of BF3 detectors from the same manufacturer and to compare the quality and performance of detectors from different manufacturers.

   Some manufacturers claim that they apply proprietary techniques to achieve quality and performance that is superior to that achieved by their competitors. These claims need to be tested by an objective comparison of

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[1] CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).

BF3 detectors from different manufacturers. CANDU stations are concerned about the quality and consistency of BF3 detectors obtained from their current supplier. To resolve these concerns, sample detectors were solicited from manufacturers, and these detectors were tested under the same conditions.

5. To compare BF3 detector performance when exposed to relatively high gamma fields.

   Gamma-rays play an important role in detector degradation. Some manufacturers claim they have adopted special techniques to tackle the problem. From the specifications we obtained from different manufacturers, it seems there is a wide difference between the maximum gamma exposure that these detectors are designed to withstand without significant reduction in their performance. Degradation and life expectancy tests involving a neutron source and a gamma source were done to evaluate the detector performance under strong gamma fields.

6. To assist CANDU stations in making purchasing decisions.

   CANDU station staff expressed interest in obtaining this kind of evaluation to assist them in making purchasing decisions. The test was also welcomed by the manufacturers. They were interested in knowing the strong and weak points of their own products so that they can improve the quality of their product and increase the competitiveness of their products in the world market.

7. To secure multi-source suppliers of high-quality BF3 detectors for CANDU stations.

   From the operational reliability point of view it would be desirable to have more than a single supplier of BF3 detectors for CANDU stations. The test results would help develop a preferred supplier list for SUI detectors.

Although BF3 detectors have been produced for about half a century, the manufacturing process does not seem to be as reliable as it should be. Of the manufacturers who agreed to supply sample detectors, only one delivered sample detectors without reporting any manufacturing failures. One manufacturer delivered only two detectors the first time, having rejected one in in-house testing. It took another one-and-a-half months to remake the other one. Another manufacturer failed the first and second attempts to prepare the filling gas for the detectors and took a total of five months to deliver the 3 sample detectors. The difficulties encountered in manufacturing BF3 detectors casts some doubt on the quality consistency of the detectors produced by the existing processes.

2. SCOPE

This paper presents the results obtained during the period of October 1995 to February 1996 for tests on a total of twelve detectors of four models from various manufacturers (one model was a prototype made jointly by two manufacturers). The following tests were conducted: high voltage plateau measurement, rise time and pulse height measurement, gas multiplication factor measurement, degradation and life expectancy tests in a neutron beam, and degradation and life expectancy tests in gamma field.

The most notable results were obtained in the degradation and life expectancy tests with laboratory neutron and gamma sources and with the neutron beam facilities at the NRU research reactor. Therefore, those results are highlighted, whereas the general measurements of high voltage plateau, rise time and pulse height, and gas multiplication factor are omitted from this paper. Participants in the COG R&D program interested in obtaining more detail may access the COG report [1]. Please note that these tests are not sufficient to certify these detectors for use in CANDU reactors. The BF3 detectors tested, the SUI equipment and the radioactive source facilities used in the tests are described in Section 3. The degradation and life expectancy tests with neutron and gamma sources are presented in Section 4 and 5, and the findings of these tests and recommendations are provided in Section 6.

3. TEST SPECIMENS AND EQUIPMENT

The BF3 detectors tested were chosen according to the CANDU specification [2] for these detectors, particularly, the size and thermal neutron sensitivity requirements. The detectors have a thermal neutron sensitivity of about 4 cps/nv and overall dimensions of about 2.5-cm (1.0 inch) diameter and 30-cm (12 inch) length. The gas pressure inside the detector is 40 cm Hg. For ease of reference, the detectors were designated as Ax, Bx, Cx and Dx where "A", "B", "C" and "D" refer to different models and "x" is specimen number (1, 2 or 3). The startup instrumentation electronics along with the monitoring equipment used in the tests is not listed to save space.

The neutron beams from the N5 and L3 spectrometers at the NRU research reactor were used to test the degradation and life expectancy of BF3 detectors under a thermal neutron flux. The two spectrometers have structures similar to that illustrated in Figure 1. The neutrons from the moderator in the reactor core hit the crystal monochromator placed at an angle to the incident neutron beam. Only the neutrons of a certain wavelength can diffract from the crystal, thus forming the desired beam. The arrangement of the neutron beam facility and the sample detectors are shown in Figure 1. Three removable Lucite absorbers that can be inserted between the detectors and the incident neutron beam were used during the test for achieving the desired count rate and for reducing the neutron flux temporarily when collecting spectra in a multichannel analyzer (MCA).

Gamma irradiations were done using an Ir-192 source with a half life of 74 d. A weak neutron field in the presence of a very strong gamma field was used to test the degrading effects of gamma on the spectra. The neutron source was so weak that no degrading effects occurred from neutrons. At the start of the Batch-1 gamma test, the activity of the gamma source was about 50 Ci. By the end of the Batch-3 test, the source activity had decayed to about 23 Ci. The energy spectrum of Ir-192 lies, for the most part, above 100 KeV and below 1 MeV. In this energy range, the interaction of gamma-rays is primarily photoelectric absorption and Compton scattering. A polyethylene block was machined to place the specimen detectors around the neutron and the gamma sources symmetrically. The Ir-192 was in a C-340 radiographic pigtail capsule assembly, for use with an Iriditron Model 520 Radiographic Exposure Device (RED). With the RED, the gamma source can be inserted to the normal irradiating location, or be withdrawn into the shielding flask. Information about the radioactive sources (neutron and gamma) used for the gamma tests is given in Table 1.

4. DEGRADATION AND LIFE EXPECTANCY TESTS IN NRU

Batch-1 neutron

The Batch-1 neutron tests were conducted on the N5 spectrometer at NRU in 1995 November for detectors A1, A2, B1 and B2. The tests were done in four stages under different conditions. These stages and conditions are listed in Table 2.

During stage 1 a minimum of 1.2E10 counts were accumulated at a rate of 36 kHz. The minimum accumulated counts were calculated based on the lowest count rate recorded for the four detectors, some detectors accumulated more counts. During stage 2 a minimum of an additional 6.8E10 counts were accumulated at a rate of 840 kHz and bringing the total minimum to 8.1E10. As in stage 1, the lowest count rate recorded for the four detectors was used for the calculation. The purpose of stage 2 was to observe the detector performance after accumulating more than 1E10 counts and during exposure to a higher flux. During stage 3 the same test conditions as stage 2 for the neutron beam applied, however, the two front row detectors (B1, A2) were disconnected from the HV supply and terminated with 50-ohm terminators. The purpose of stage 3 was to observe the effect of terminating the detectors while exposing them to a high neutron flux. Stage 4 was performed with the neutron beam shut off to observe if there would be any appreciable recovery over the period of one day.

Throughout these four stages, the reactor power were monitored with a computer (W. Buyers, unpublished data). Spectra were collected once a day for each of the detectors with three absorbers temporarily inserted to reduce the count rate to a few thousand Hz. The region of interest (ROI) in the spectrum was set at 3.0 V to 8.2 V. The dates the spectra were taken, the detector location, the name of the recorded spectrum data file along with recorded count rate, gross counts in the ROI, the spectral peak location and the cumulative counts for detectors are listed in Table 3. Note that cumulative counts are calculated using count rate shown in Table 3 multiplied by the combined attenuation factor of the absorbers and by the time duration.

A few spectra are shown in Figures 2 to 9, with the date and time when the spectrum was taken indicated on the top line. "GROUP Q1" shown on the second line indicates the spectrum was stored in memory location Q1, the first quarter of the memory available. "VS: 2K" indicates the vertical scale is 2000 counts.

The spectra collected for the two type B detectors at the end of stage 1, when more than 1.2E10 counts were accumulated, are plotted in Figure 2. Their peak heights are about the same as they were at the start of the test. The spectra for the two type A detectors are shown in Figure 3. The peak heights for A1 and A2 are about the same but A2 has a much broader peak shifted to the left. The peak heights, compared with the start of test, have reduced to about half for A2 and two-thirds for A1.

By the end of stage 2 the detectors had been exposed to an additional one day of high neutron dose rate (bring the minimum to a total of 8.1E10 counts). The spectra all showed significant (B1, somewhat less) degradation as indicated by broadened lower peaks in the spectra. Spectra for each detector at the start of stage 1, at the end of stage 1, and at the end of stage 2 show the evolution of the detector degradation, as indicated by the peak shifting leftwards and flattening (Figures 4 to 7).

In stage 3, the HV to the two front row detectors (B1, A2) was turned off and the detectors were terminated with 50-ohm BNC terminators. The four detectors were all exposed to a high neutron dose for another day (bringing the minimum total to 1.5E11 counts). The two terminated detectors showed a significant degree of recovery from their previous degradation. Their spectra at the end of stage 3, together with their spectra at the start of stage 1, are shown in Figures 8 and 9.

Batch-2 neutron

The Batch-2 neutron tests were conducted in 1996 February for detectors D1, D2, A3, and C3. A He3 detector from the Neutron Scattering and Condensed Matter Branch at CRL was also tested along with the four BF3 detectors. Detector A3 was used as a basis for comparison with the Batch-1 tests. The L3 spectrometer at NRU was used for the Batch-2 tests. Because of the difference in setting of the monochromator angle, a lower neutron flux was obtained in Batch-2 and, consequently, fewer neutron counts were accumulated during the tests. Despite this, much more serious degradation in spectral resolution was observed in some of the detectors than in the Batch-1 neutron tests. The Batch-2 test conditions are listed in Table 4.

During stage 1 a minimum of 2.1E9 counts was accumulated at a rate of 35 kHz. During stage 2 a minimum of 4.6E9 counts was accumulated at a rate of 14 kHz, bringing the total minimum to 6.7E9 counts. During stage 3, the same test conditions as stage 2 for the neutron beam applied. However, the HV for detector D2 was reversed for ten min and a spectrum was taken afterwards. Then the three detectors (D1, D2, C3) that had shown serious deterioration in spectral resolution were terminated with 50-ohm terminators, whereas the other one (A3) was still powered with the HV. After one day spectra were taken. Some of the spectra are shown in Figures 10 to 13, and spectra data are summarized in Table 5.

Type D detectors (D1, D2) showed serious degradation in resolution in stage 1 and showed further degradation afterwards. At the end of stage 3, the count rate readings from type D detectors reduced to 2/3 of their starting values. The spectra for D1 at the start of stage 1 and end of stage 3, after an accumulated dose of 9.9E9, are plotted in Figure 10. The spectra for D2 are almost the same and are not shown here.

Type C detector (C3) showed significant degradation in spectral resolution by the end of stage 1 after a dose of 3.2E9 counts, but very little degradation afterwards. The neutron count rate readings from that detector were quite stable despite the degradation in spectra shape. The spectra for C3 at the start and end of stage 1 are plotted in Figure 11. The spectra for C3 at the end of stage 1 and at the end of stage 3 are plotted in Figure 12.

In striking contrast to other detectors, detector A3 showed very little degradation throughout the batch-2 neutron test and other tests (detector A3 had undergone a gamma test but was fully recovered before the neutron test). The spectra for A3 at the start of stage 1 and the end of stage 3 are plotted in Figure 13. This detector was not terminated with a 50-ohm resistor during the recovery test because it showed very little degradation.

The degradation behaviors were quite different for type D and C detectors. When deteriorated, the spectrum of type D detectors showed no normal peak at all with only monotonically decreasing height (see Figure 10), whereas the spectra of the type C detector showed a plateau-like peak (Figure 11). Also the count rate readings from type D detectors reduced to 2/3 of their starting values, whereas the type C detector count rate remained nearly constant. Therefore, the type C detectors outperformed type D detectors in this test, though they both performed poorly compared with the type A detector in Batch-2 tests and type A and B detectors in Batch-1 tests.

The neutron flux for the Batch-2 tests was much lower than that in the Batch-1 tests; it corresponds to 35 kHz in stage 1 and about 14 kHz afterwards. The minimum cumulative neutron counts of 8.0E9 were also lower than that in the Batch-1 tests. Since these detectors (D1, D2 and C3) had already exhibited serious degradation in the test before the total accumulated counts reached 1E10, the specification of the total accumulated counts of "1E10" is not met by type C and D detectors.

Reversing the voltage on type D detector D2 appears to have no effects on its spectrum. Also, unlike the Batch-1 result for type A and B detectors, terminating the detectors with 50-ohm resistors appears to have no effect on type C and D detectors.

5. DEGRADATION AND LIFE EXPECTANCY TEST WITH GAMMAS

A weak neutron field in the presence of a very strong gamma field was used to test the degrading effects of gammas on the detectors. The neutron source was so weak that no degrading effects resulting from neutron would occur. Because of the closeness of the Ir-192 gamma source to the detectors a high gamma flux level was obtained. By integrating the flux along the detector length, the average radiation field at the detector was estimated to be about 3.4 kR/hr without considering the Taylor buildup factor at the start of the test [4]. Because of the high gamma flux, it was not possible to collect spectra from the detectors when the gamma source was in the normal irradiation location. Every time a spectrum was taken during the test, the gamma source was temporarily retracted into the flask to leave only the neutron source irradiating the detectors. Spectra were also taken with the gamma source partially out of the flask to see the effect of gamma-rays on the neutron spectrum.

Batch-1 gamma

The Batch-1 gamma tests were conducted in 1995 December for detectors A2, A3 and B1, B3. The gains of the amplifiers were set so that the initial spectral peaks were located at channel 800 in the spectrum. The test date, test condition, spectra designation numbers and cumulative gamma exposure are summarized in Table 6. Table 7 provides the date and time, the detector location, the spectrum file name along with the count rate, the spectral peak location and the cumulative gamma exposure for selected spectra.

Of the four detectors in the Batch-1 tests, three of them (A3, B3, A2) showed significant degradation in resolution (see Figures 14 to 17) after a cumulative exposure of only 1.6 kR. However, after a period of irradiation, the detectors all showed continued improvement in resolution and stabilized. At the end of the Batch-1 gamma tests after a cumulative exposure of about 496 kR, the four detectors were fully recovered. Their spectra at the start and the end of the Batch-1 test are plotted in Figures 18 to 21.

Batch-2 gamma

The Batch-2 gamma tests were conducted in 1996 January for detectors C1, C2, A1 and B2. The amplifier gains for the two type C detectors were set so that the initial spectral peaks were located at channel 800. The same two channels of electronics were used for the other two detectors as were used in the neutron test. Their amplifier gains were set at the same values as at the beginning of the neutron life test at NRU. Therefore the spectral peaks of these two detectors were not located at channel 800 at the start of this test. Experimental conditions and spectra data are given in Tables 8 and 9.

When type C detectors were exposed to gammas they showed immediate significant degradation in their spectral resolution. The neutron count rates of the detectors also dropped to about half of their initial values. In the following five days, the neutron count rate dropped further to about 40% of their initial values and the spectral resolution further deteriorated a little. The resolution showed no sign of recovery even with periods of "no gamma" and with one detector shorted for 2 d and 16 h. The spectra at the start and end of the Batch-2 gamma tests are plotted in Figures 22 and Figure 23 for C1 and C2, respectively.

The initial spectrum for detector A1 was close to that at the end of the Batch-1 neutron tests. When exposed to a gamma field, the resolution of this detector showed continued improvement and then stabilized after an exposure of about 72 kR. The spectrum at the end of the Batch-2 gamma tests looked like that of a new detector. The peak location of the spectrum was at 799, close to the location at the start of the Batch-1 neutron tests. The spectra at the start and the end of the Batch-2 gamma tests are plotted in Figure 24.

The initial spectrum for detector B2 was close to that at the end of the Batch-1 neutron tests. When it was exposed to gamma exposure of about 8.3 kR, the spectrum showed significant degradation. With continued exposure its resolution recovered and deteriorated a few times and after 72 kR continued to improve and stabilize. The spectra for B2 at the start and the end of the Batch-2 gamma tests are plotted in Figure 25.

Batch-3 gamma

The Batch-3 gamma tests were conducted in 1996 February for detectors C3, D1, D2 and D3. The amplifier gain for detector D3 was set so that the initial spectral peak was located at channel 800. The amplifier gains for the three detectors were set at the same values at the beginning of the neutron tests at NRU. The experimental condition and spectra data are given in Tables 10 and 11.

It appears that type D detectors (D1, D2, D3) and type C detector (C3) are extremely sensitive to gamma-rays. Note that three of these detectors (D1, D2 and C3) had just finished Batch-2 neutron tests on NRU. Therefore their initial spectra already showed different degrees of degradation. When the four detectors received a gamma exposure of only 6.2 kR, they showed immediate serious degradation. In the following days all four detectors showed a little further degradation in resolution and decline in count rate. After an exposure of about 51 kR the detector performance stabilized but did not improve. Shorting the detectors for 24 h did not yield any recovery. The spectra at the start and the end of the Batch-3 gamma tests are plotted in Figures 26 to 29.

6. CONCLUSIONS AND RECOMMENDATIONS

General

There is noticeable difference in the initial (as delivered) detector resolution for detectors from different manufacturers. Type C detectors were the best, followed by type A and type B, with type D detectors the worst in this respect. The consistency in detector resolution varies from good (A) to fair (C). Significant differences in detector resolution after exposure to neutron and gamma fields were observed, as summarized below and in Table 12.

The neutron tests

1. Below cumulative counts of 1E10 accumulated at a rate of 36 kHz, the resolution deterioration is small for type A and B detectors and is serious for type D detectors and less serious for type C detectors. The requirement for good operation for a total accumulated counts of "1E10" is not met by type D and type C detectors.
2. For accumulated counts exceeding 1.2E10 and when exposed to a higher flux level (a rate of about 843 kHz), type A and B detectors showed significant deterioration in resolution. It is not clear whether this deterioration was caused by the 8 times higher cumulated counts or by the 23 times higher flux level. Type C and type D detectors were not tested for exposure to higher cumulative counts and higher flux level because they had already deteriorated seriously at lower cumulative counts and lower flux level.
3. Termination with 50-ohm resistors during neutron irradiation resulted in significant recovery for type A and B detectors but had no effect on type C and D detectors.
4. At the end of the neutron test after 8.0E9 cumulative counts, the count rate readings for type D detectors had reduced to 2/3 of their starting values, whereas all other types of detectors had quite stable reading.
5. The performance of the type A detector (A3) in the Batch-2 neutron tests was much better than that for type C and D. Detector A3 showed very little degradation throughout the Batch-2 neutron tests with cumulative counts of 8.9E9 compared with type D and type C detectors that degraded after only about 3.0E9 cumulative counts.
6. The degradation mode was quite different for type C and D detectors. The spectrum of type D detectors, when deteriorated, showed no normal peak at all with only monotonically decreasing height, whereas the spectrum of the type C detector showed a plateau-like flat-top peak. Also the count rate readings for type D detectors reduced to 2/3 of their initial values at the end of the test, whereas the type C detector kept a quite constant reading. Therefore, the type C detector outperformed type D detectors in this test, though both C and D types performed poorly compared with the type A and type B detectors.
7. Reversing the voltage on the type D detector (D2) appeared to have no effect on its spectrum.

The gamma tests

1. Detector B1 remained quite stable during the gamma tests. Detector A1 tested after the neutron test showed only improvement in spectral resolution after its previous degradation. All other type A and B detectors showed significant initial degradation in their spectra. Detector B3 had the most serious degradation in spectral

resolution at a time after a cumulative exposure of 13 kR. Its count rate had also dropped to 74% of its initial count rate at that time, whereas other types A and B detectors kept quite a constant count rate.

2. All type A and B detectors were fully recovered at the end of the gamma tests. This is true even for the degradation incurred during the neutron tests. Some detectors had a spectrum that was almost the same (or better) as the one at the start of gamma tests.
3. The consistency of gamma dynamics of type A detectors is better than that of type B detectors.
4. Type C and D detectors appear to be extremely sensitive to gamma-rays. Though the gamma activity had decayed to a lower level (2.4 kR/hr and 1.9 kR/hr) when testing type C and D detectors than it was when testing type A and B detectors (3.4 kR/hr and 2.4 kR/hr), the degradation was much more severe than that for type A and B detectors.
5. Type C and D detectors showed the "failure symptoms" (see below) with no sign of recovery.
6. Terminating the type A and B detectors appeared to have a little effect on spectral shape (not as dramatic as in the neutron tests).
7. Terminating the type C and D detectors had no effect on these detectors.

Special techniques used in detector manufacturing

Remarkable results were found for different detectors in the gamma tests. The recovery after an initial deterioration in resolution for type A and B detectors is counter to the expected continued degradation caused by chemical changes, which occur inside these detectors [3]. Communications with the manufacturers confirmed that various proprietary techniques were applied to type A and B detectors that resulted in the recovery of those detectors after prolonged gamma exposure.

Detector life specification

Type C and D detectors showed serious degradation before reaching 1E10 total accumulated counts in a neutron flux. Therefore, this specification was not met by type C and D detectors.

Detector failure symptoms

The failure symptoms that can be used to tell if a detector is "dead" are (i) a significant drop in count rate with a constant neutron source, and (ii) a monotonically decreasing spectrum shape. Type A and B detectors (with the exception of B3) have in the gamma test all had spectra shapes that were degraded but not to the point of monotonically decreasing as was found in type C and D detectors.

A detector with a poor spectrum shape may still be usable for neutron counting and may have a chance of recovery provided that its spectrum shape is not monotonically decreasing and its count rate has not dropped significantly. This has been observed for type A and B detectors that are processed with proprietary technologies to enhance their gamma durability and recovery.

Preferred detectors to be used in the SUI

Type A and B detectors with their excellent performance in both neutron and gamma durability, compared to type C and D detectors, are preferred for use in the CANDU SUI systems.

Plausible cause of detector failure at CANDU stations and solutions

From the performance observed during the neutron and gamma tests (the immediate serious degradation when exposed to gamma-rays and the low durability in a neutron flux) for the detectors currently used in CANDU stations, it is recognized that both neutron and gamma radiation exposure is likely the cause of detector failure in most cases with the gamma exposure effects being the most serious. The solutions to the problem are (i) to use better performing detectors such as type A and B detectors, (ii) to apply detector qualification tests with improved detector testing and assessment methods (see below), and (iii) avoid unnecessary exposure of the detectors to high gamma fields.

Detector qualification tests with improved testing and assessment methods

It is recommended that the SUI detectors undergo a neutron and gamma qualification test on some samples of detectors before putting them into service.

A way for testing and assessing all detectors, including the kind of detectors with enhanced gamma durability is to discern if the "deadly" detector failure symptoms are there, i.e., (1) observe the detector spectrum shape to see if it has become one of monotonically decreasing height in a gamma exposure exceeding 6 kR, and (2) check the detector count rate with a constant neutron source to see if the count rate has dropped significantly. To do this, one needs a neutron source with a fixed counting geometry and one needs to compare the neutron count rate of the detector with that source before and after the gamma exposure. Combining these two measures we can better tell, especially for those kinds of detectors processed with special techniques, if a detector is really "dead" or if it is still usable for neutron counting but under close monitoring of its performance. This is prompted by the fact that during the Batch-1 gamma tests, when the detectors were initially exposed to gammas, three detectors (B3, A2 and A3) showed significant initial deterioration in spectrum resolution that would normally have been judged as "dead" in station operations. However, the count rate of these detectors in a neutron flux was quite stable (except for B3, its count rate dropped from 115 to 85 in its early stage of gamma exposure). That means their counting efficiency had not been changed after exposure to gammas despite the dramatic change in their spectrum shape. After a period of gamma irradiation, these detectors fully recovered from their initial degradation in resolution.

This indicates that the current practice of judging the "goodness" of the detector by only looking at the spectrum shape may be a bit overly restrictive. However, in power plant operation, pulling a doubtful detector and testing it is quite involved and costly. It may be cheaper to simply replace any detectors showing doubtful spectra.

<u>Pretreatment of detectors to rid them of transient degradation</u>

The gamma tests suggest that it might be favorable to pre-treat the detectors processed with proprietary technologies to enhance their gamma durability before putting them in service. The pre-treatment here refers to a process similar to the one in our gamma tests to rid these detectors of their initial degradation when first exposed to gamma irradiation. If the pre-treatment process can achieve that result then it certainly will be favored by the users of these detectors. More detailed studies are needed to get a better understanding of the phenomenon and how long the beneficial effects of the pretreatment would last.

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TABLE 1. RADIOACTIVE SOURCES FOR THE TESTS

Source	PuBe 3.906 g	PuBe 1.3 g	Ir-192
Parameter	57-10-1	95-10-16	54 Ci, Model C340, Serial No. A959

TABLE 2. CONDITIONS FOR BATCH-1 NEUTRON TESTS AT NRU

STAGE	DURATION	TEST CONDITION	MINIMUM CUMULATIVE COUNTS
1	Nov 03 afternoon - Nov 07 morning	With 1/4" and 5/16" absorbers	1.2E10
2	Nov 07 morning - Nov 08 morning	No absorbers	8.1E10
3	Nov 08 morning - Nov 09 morning	No absorbers. HV to detectors #1 and #4 turned off and detectors terminated with 50-ohm terminators. Detectors #2 and #3 HV were on.	1.5E11
4	Nov 09 morning - Nov 10 morning	The neutron beam was turned off. All HV powers to detectors were turned off.	1.5E11

TABLE 3. SELECTED SPECTRA FILES AND DATA FOR BATCH-1 NEUTRON TESTS

DATE & TIME	LOCA-TION	FILE NAME	COUNT RATE (Hz)	GROSS COUNTS IN ROI	PEAK CHANNEL	CUMULATIVE COUNTS FOR DETECTORS
Nov 03 PM (start of Stage 1)	1	B1-01.SPC	6380	356702	820	3.8E5
	2	A1-01.SPC	6037	347732	820	7.2E5
	3	B2-01.SPC	5424	313033	820	9.8E5
	4	A2-01.SPC	8004	462275	820	1.9E6
Nov 07 AM (end of Stage 1)	1	B1-11.SPC	6800	394239	812	1.5E10
	2	A1-11.SPC	6400	377364	779	1.4E10
	3	B2-11.SPC	5700	336446	792	1.2E10
	4	A2-11.SPC	8600	489672	727	1.8E10
Nov 08 AM (end of Stage 2)	1	B1-12.SPC	7400	414045	752	9.7E10
	2	A1-12.SPC	6900	384150	649	9.1E10
	3	B2-12.SPC	6100	328799	523	8.1E10
	4	A2-12.SPC	9200	478605	551	1.2E11
Nov 09 AM (end of Stage 3)	1	B1-14.SPC	7900	454925	830	1.8E11
	2	A1-14.SPC	7300	402705	607	1.7E11
	3	B2-14.SPC	6700	380468	701	1.5E11
	4	A2-14.SPC	10000	593745	803	2.3E11

TABLE 4. TEST CONDITIONS FOR BATCH-2 NEUTRON TESTS AT NRU

STAGE	DURATION	TEST CONDITION	MINIMUM CUMULATIVE COUNTS
1	Feb 12 afternoon - Feb 13 morning	With 1/8" absorber	2.1E9
2	Feb 13 morning - Feb 16 morning	With 1/4" absorber	6.7E9
3	Feb 16 morning - Feb 17 morning	With 1/4" absorber. HV to detector #3 was reversed for 10 minutes and a spectrum was taken. Then detectors #1, #3 and #4 were terminated with 50-ohm terminators. Detector #2 HV was on.	8.0E9
4	Feb 17 morning -	The neutron beam was turned off. All HV powers to detectors were turned off.	8.0E9

TABLE 5. SELECTED SPECTRA FILES AND DATA FOR BATCH-2 NEUTRON TESTS

DATE & TIME	LOCATION	FILE NAME	COUNT RATE (Hz)	GROSS COUNTS IN ROI	PEAK CHANNEL	CUMULATIVE COUNTS FOR DETECTORS
Feb 12 PM (start of Stage 1)	1	D1-03.SPC	3000	158934	760	1.8E5
	2	A3-03.SPC	2300	127956	792	2.8E5
	3	D2-03.SPC	2500	135398	774	4.5E5
	4	C3-03.SPC	3500	186012	784	8.4E5
Feb 13 AM (end of Stage 1)	1	D1-04.SPC	2800	79012	214	2.8E9
	2	A3-04.SPC	2300	127270	780	2.1E9
	3	D2-04.SPC	2300	65440	230	2.3E9
	4	C3-04.SPC	3200	161298	679	3.2E9
Feb 17 AM (end of Stage 3)	1	D1-09.SPC	2100	47204	No Peak	9.9E9
	2	A3-09.SPC	2300	129211	776	8.9E9
	3	D2-09.SPC	1650	36770	No Peak	8.0E9
	4	C3-09.SPC	3400	142658	610 (flat)	1.3E10

TABLE 6. TEST CONDITIONS FOR BATCH-1 GAMMA TESTS

Date	Test Condition	Spectra #	Cumulative γ Exposure (kR)
Dec 05	Set up test with spectral peak at channel 800 for each detector.	N/A	0
Dec 06	Collected the first spectrum. Started collecting spectra regularly at 0.5-h interval.	17 19-22	6.4
	4 d + 17 h, no HV, no gamma.		
Dec 11	Collected spectra regularly at 1-h interval (X3) and 2-h interval (X1).	23-27	22.4
	16 h, HV on, no gamma.		
Dec 12	Collected spectra regularly at 2-h interval (X2) and 3-h interval (X1).	28-31	44.8
	16 h, HV on, no gamma.		
Dec 13	Collected spectra at 8-h interval (X1).	32-33	70.4
	16 h, HV on and with gamma.		
Dec 14-15	Collected spectra at 32-h interval (X1).	34-35	224.0
Dec 15	Collected spectrum with gamma partially inserted.	36	
	2 d + 16 h, HV on and with gamma.		
Dec 18	Collected spectrum in the morning.	37	428.8
	24 h, HV on, no gamma.		
Dec 19	Collected spectrum in the morning.	38	428.8
	24 h, HV off, detector shorted, no gamma.		
Dec 20	Collected spectrum in the morning.	39	428.8
	20 h, HV off, detector shorted, with gamma.		
Dec 21	Collected spectrum in the morning.	40	496.0
Dec 21	Collected spectrum with some gamma present.	41	
	12 d, HV off, no gamma.		
Jan 02	Collected spectrum in the morning.	42	496.0

TABLE 7. SELECTED SPECTRAL DATA FOR BATCH-1 GAMMA TESTS

Date & Time	System	File Name	Count Rate	Peak Channel	Cumulative γ Exposure (kR)
Dec 06, 10:12 am	1	B1-17.SPC	110	709	0.0
	2	A3-17.SPC	130	802	0.0
	3	B3-17.SPC	115	726	0.0
	4	A2-17.SPC	135	792	0.0
Dec 06, 1:20 pm	1	B1-19.SPC	115	667	1.6
	2	A3-19.SPC	125	522	1.6
	3	B3-19.SPC	110	440	1.6
	4	A2-19.SPC	130	501	1.6
Jan 02, 8:23 am	1	B1-42.SPC	115	884	496.0
	2	A3-42.SPC	130	807	496.0
	3	B3-42.SPC	115	872	496.0
	4	A2-42.SPC	130	821	496.0

TABLE 8. TEST CONDITION FOR BATCH-2 GAMMA TESTS

Date	Test Condition	Spectra #	Cumulative γ Exposure (kR)
Jan 04	Set up test with spectrum peak at channel 800 for new detectors.	44	0.0
Jan 05	Started gamma irradiation. Collected spectrum at noon and at the end of the working day.	45, 46	17.8
	2 d + 16 h, HV on, no gamma.		
Jan 08	Collected spectrum in four-hr interval (X2).	47, 48, 49	34.4
	16 h, HV on, with gamma.		
	Jan 09-12, with gamma and HV on all day long.		
Jan 09	Collected spectrum in the morning and at the end of the working day.	50, 51	91.4
Jan 10	Collected spectrum at the end of the working day.	52	148.4
Jan 11	Collected spectrum at the end of the working day.	53	205.4
Jan 12	Collected spectrum at the end of the working day.	54	262.4
	2 d +16 h, no gamma, #1 shorted, others with HV on.		
	Jan 15-17, with gamma during the working day and without gamma overnight.		
Jan 15	Collected spectrum in the morning and at the end of the working day.	55, 56	280.2
Jan 16	Collected spectrum in the morning and at the end of the working day.	57, 58	298.0
Jan 17	Collected spectrum in the morning and at the end of the working day.	59, 60	315.8
Jan 18	Collected spectrum in the morning.	61	315.8

TABLE 9. SELECTED SPECTRA DATA FOR BATCH-2 GAMMA TESTS

Date & Time	System	File Name	Count Rate	Peak Channel	Cumulative γ Exposure (kR)
Jan 04, 2:36 pm	1	C1-44.SPC	140	802	0.0
	2	A1-44.SPC	130	635	0.0
	3	B2-44.SPC	105	737	0.0
	4	C2-44.SPC	140	802	0.0
Jan 18, 7:59 am	1	C1-61.SPC	50	No Peak	315.8
	2	A1-61.SPC	130	813	315.8
	3	B2-61.SPC	110	723	315.8
	4	C2-61.SPC	55	No Peak	315.8

TABLE 10. TEST CONDITION FOR BATCH-3 GAMMA TESTS

Date	Test Condition	Spectra #	Cumulative γ Exposure (kR)
Feb 19 noon	Set up test. Collected spectra. Started gamma irradiation.	10	0.0
Feb 19	Collected spectrum at the end of the working day.	11	6.2
	Feb 19 - 23, with gamma during working day and without gamma overnight.		
Feb 20	Collected spectrum in the morning and at the end of the working day.	12, 13	21.4
Feb 21	Collected spectrum in the morning and at the end of the working day.	14, 15	35.7
Feb 22	Collected spectrum in the morning and at the end of the working day.	16, 17	51.0
Feb 23	Collected spectrum in the morning and at the end of the working day.	18, 19	65.3
	2 d + 16 h, HV on, no gamma.		
Feb 26	Collected spectrum in the morning and at the end of the working day.	20, 21	78.6
	16 h, HV on, no gamma		
Feb 27	Collected spectrum in the morning and at the end of the working day.	22, 23	91.9
	No gamma, detectors were shorted.		
Feb 28	Collected spectrum in the morning and at the end of the working day.	24	91.9

TABLE 11. SELECTED SPECTRA DATA FOR BATCH-3 GAMMA TESTS

Date & Time	System	File Name	Count Rate	Peak Channel	Cumulative γ Exposure (kR)
Feb 19, noon	1	D1-10.SPC	90	No Peak	0.0
	2	D3-10.SPC	135	800	0.0
	3	D2-10.SPC	90	No Peak	0.0
	4	C3-10.SPC	135	612 (flat)	0.0
Feb 28, pm	1	D1-24.SPC	28	No Peak	91.9
	2	D3-24.SPC	28	No Peak	91.9
	3	D2-24.SPC	25	No Peak	91.9
	4	C3-24.SPC	62	No Peak	91.9

TABLE 12. SUMMARY OF DETECTOR PERFORMANCE IN NEUTRON AND GAMMA TESTS

TESTS	PERFORMANCE CHARACTERISTIC	DETECTOR PERFORMANCE A	B	C	D
PRE-TEST	Resolution	good	fair	good	fair
	Resolution consistency	good	fair	fair	good
NEUTRON TESTS	Resolution deterioration below cumulative counts of 1E10	minor	minor	significant	serious
	Effect of terminating detectors	significant recovery	significant recovery	no effect	no effect
	Count rate readings	stable	stable	stable	reduced to 2/3
	degradation in neutron	minor	minor	significant	serious
	Failure symptoms appeared	no	no	no	yes
GAMMA TESTS	Count rate readings	stable	stable (except B3 in a short period)	reduced to 40% of starting value	reduced to 20% of starting value
	Recovery in gamma	yes	yes	no	no
	Failure symptoms appeared	no	no (except B3 in a short period)	yes	yes

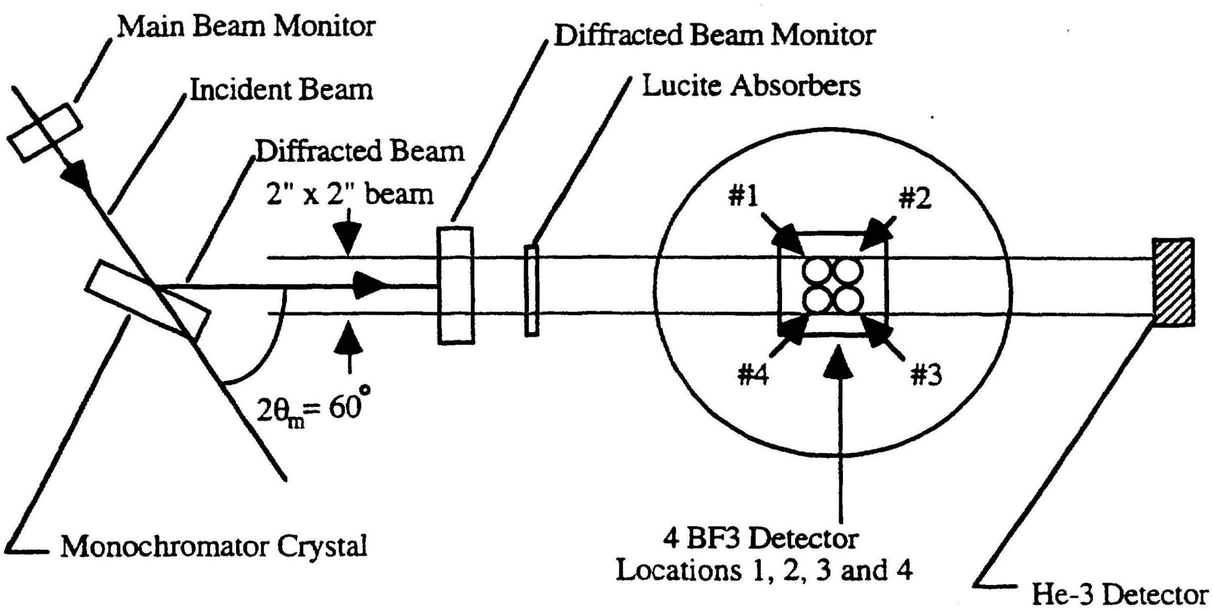

FIGURE 1. NEUTRON BEAM FACILITY AT NRU

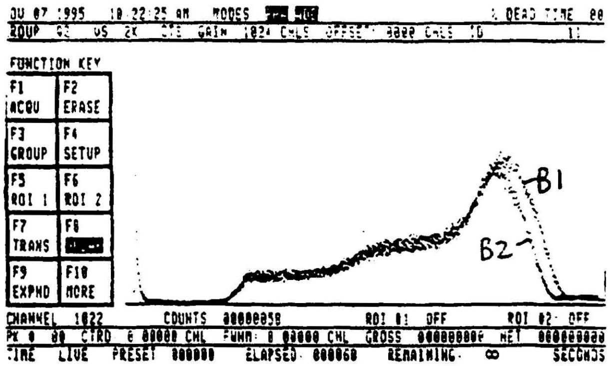

FIGURE 2. SPECTRA B1&B2-11 (Batch-1-N)

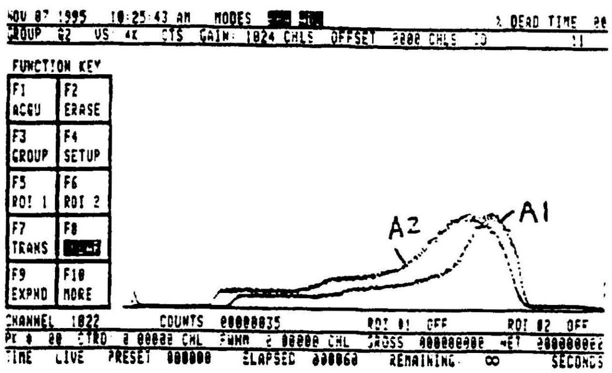

FIGURE 3. SPECTRA A1&A2-11 (Batch-1-N)

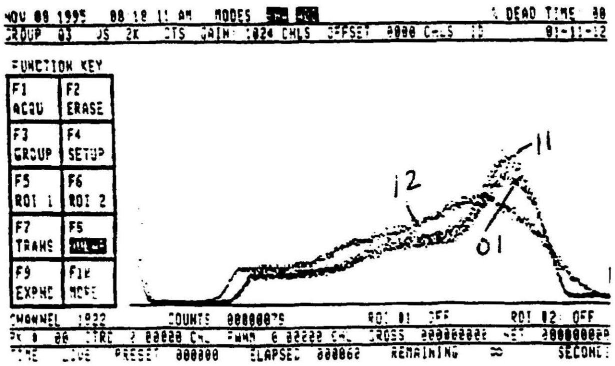

FIGURE 4. SPECTRA B1-01&11&12 (Batch-1-N)

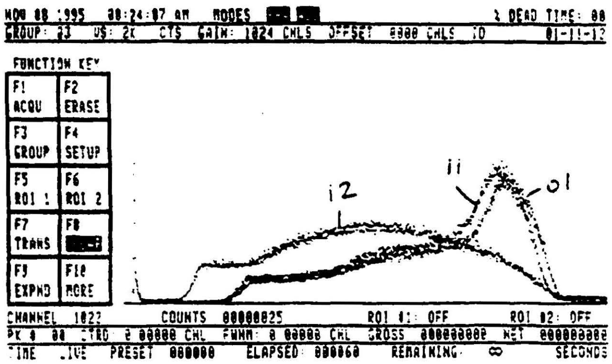

FIGURE 5. SPECTRA B2-01&11&12 (Batch-1-N)

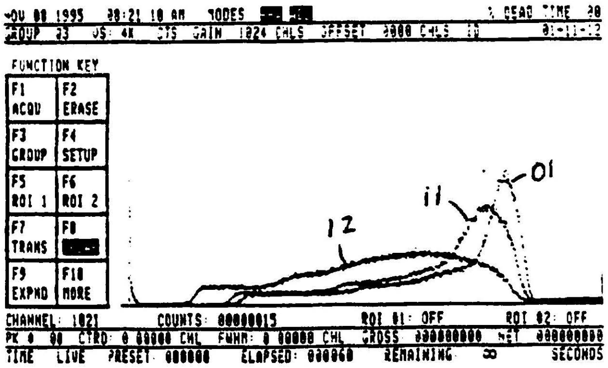

FIGURE 6. SPECTRA A1-01&11&12 (Batch-1-N)

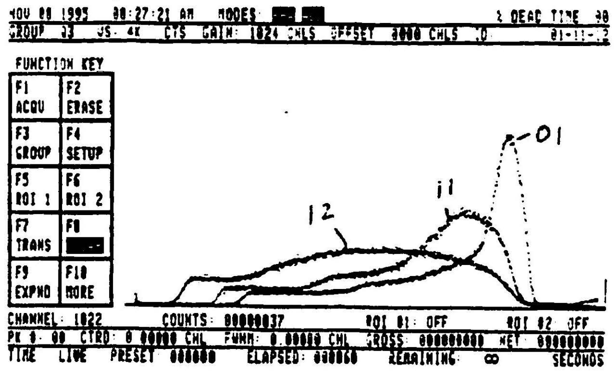

FIGURE 7. SPECTRA A2-01&11&12 (Batch-1-N)

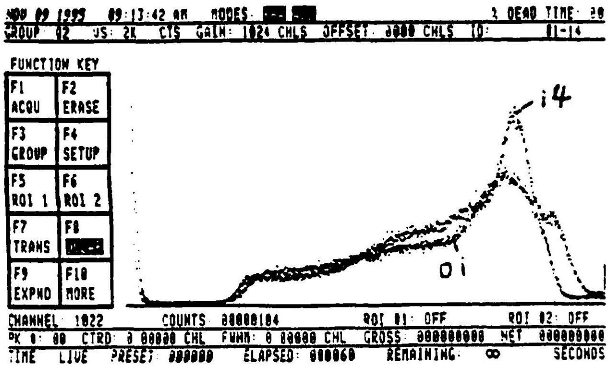

FIGURE 8. SPECTRA B1-01&14 (Batch-1-N)

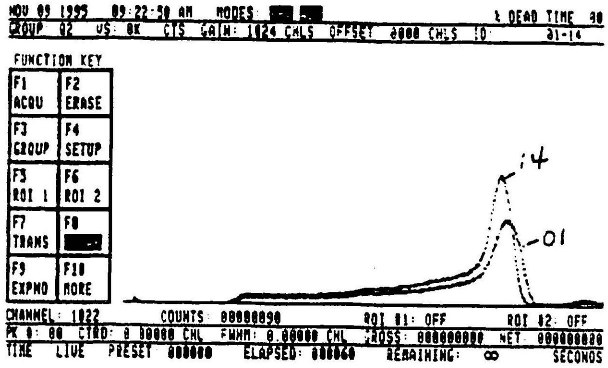

FIGURE 9. SPECTRA A2-01&14 (Batch-1-N)

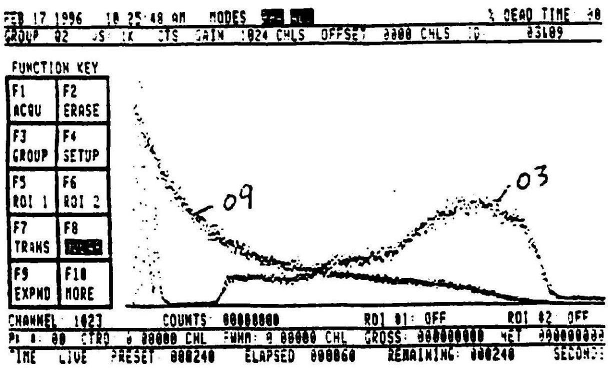

FIGURE 10. SPECTRUM D1-03&09 (Batch-2-N)

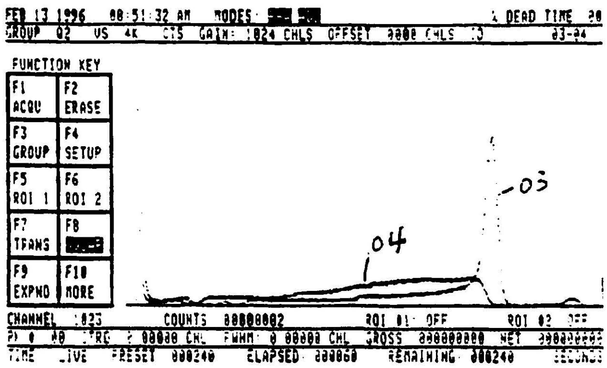

FIGURE 11. SPECTRA C3-03&04 (Batch-2-N)

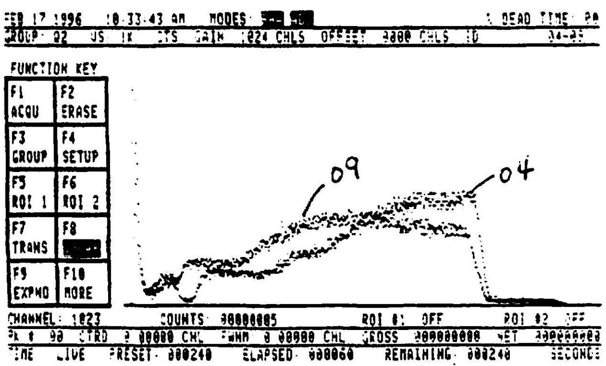

FIGURE 12. SPECTRA C3-04&09 (Batch-2-N)

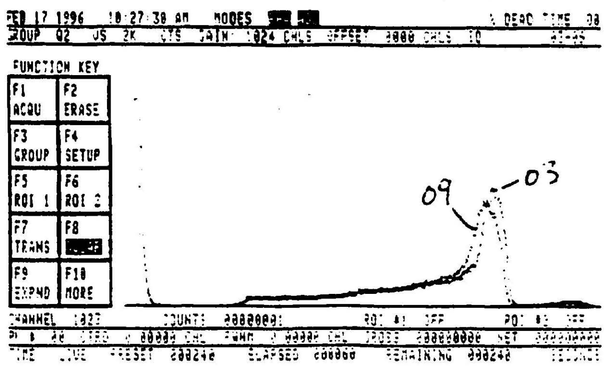

FIGURE 13. SPECTRA A3-03&09 (Batch-2-N)

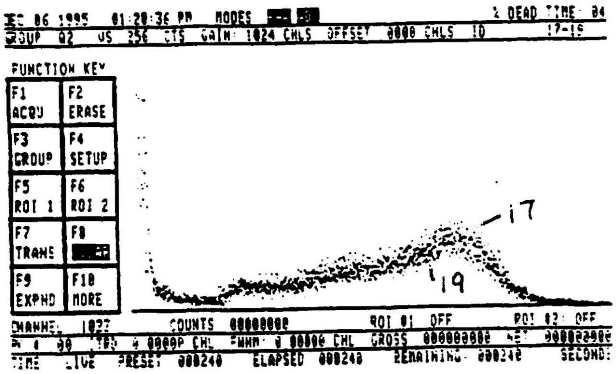

FIGURE 14. SPECTRA B1-17&19 (Batch-1-γ)

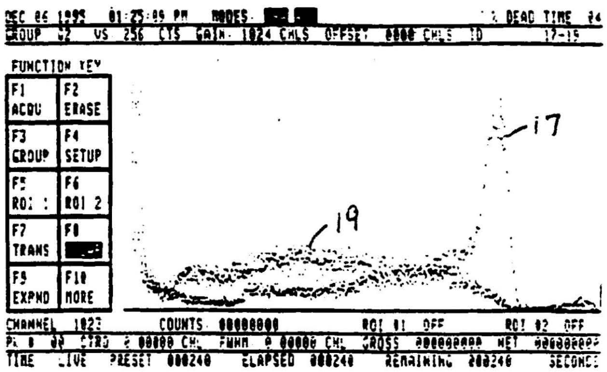

FIGURE 15. SPECTRA A3-17&19 (Batch-1-γ)

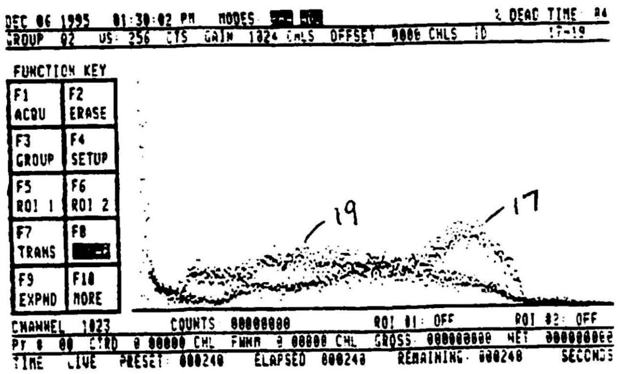

FIGURE 16. SPECTRA B3-17&19 (Batch-1-γ)

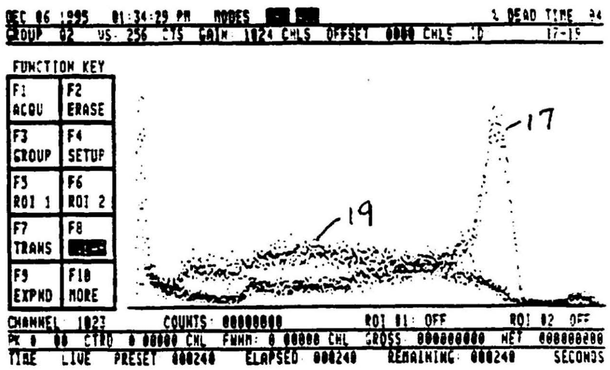

FIGURE 17. SPECTRA A2-17&19 (Batch-1-γ)

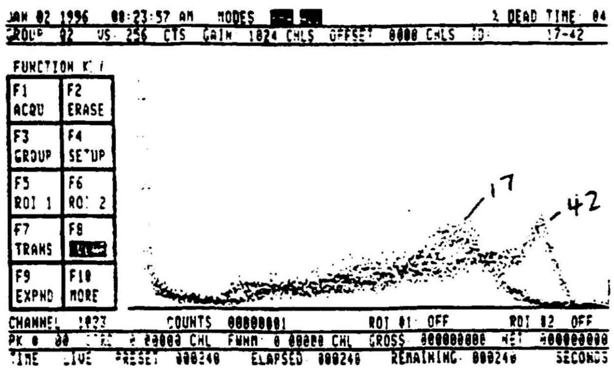

FIGURE 18. SPECTRA B1-17&42 (Batch-1-γ)

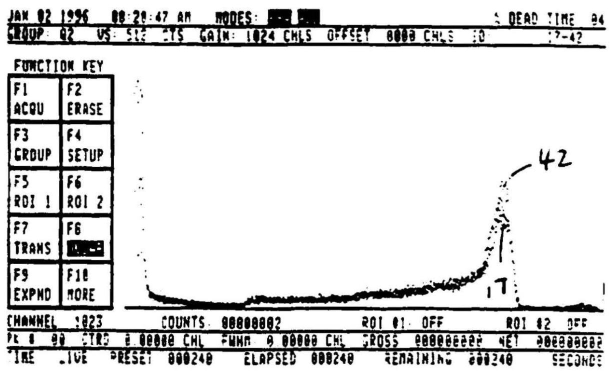

FIGURE 19. SPECTRA A3-17&42 (Batch-1-γ)

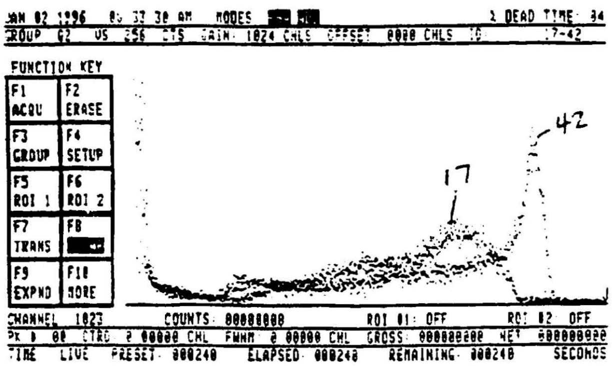

FIGURE 20. SPECTRA B3-17&42 (Batch-1-γ)

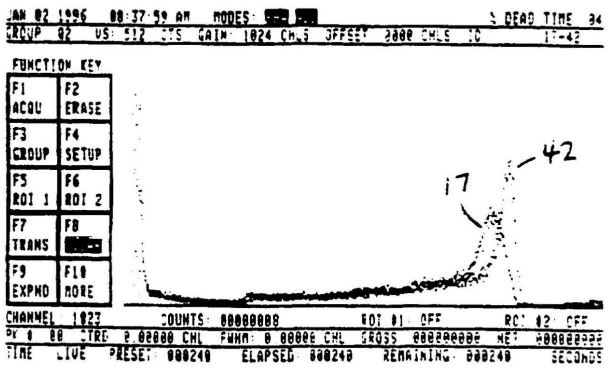

FIGURE 21. SPECTRA A2-17&42 (Batch-1-γ)

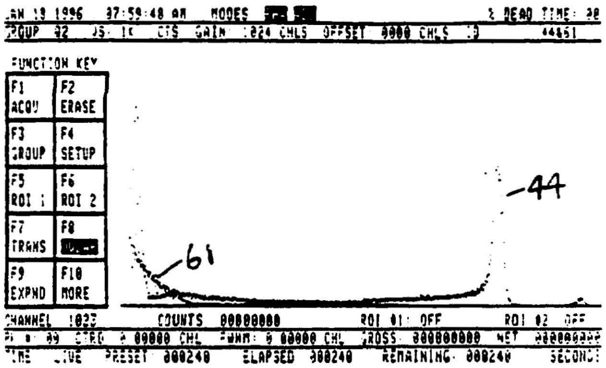

FIGURE 22. SPECTRA C1-44&61 (Batch-2-γ)

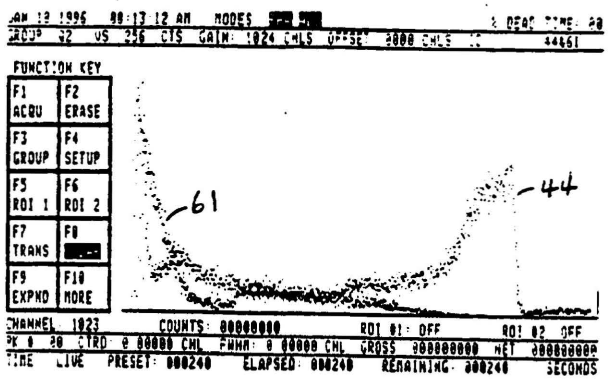

FIGURE 23. SPECTRA C2-44&61 (Batch-2-γ)

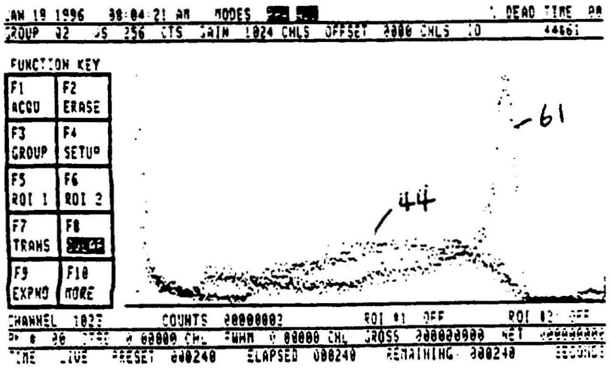

FIGURE 24. SPECTRA A1-44&61 (Batch-2-γ)

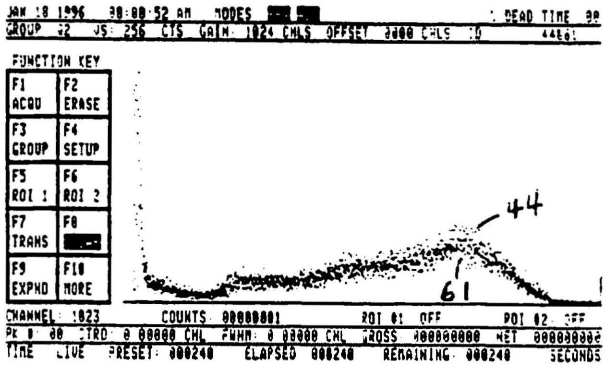

FIGURE 25. SPECTRA B2-44&61 (Batch-2-γ)

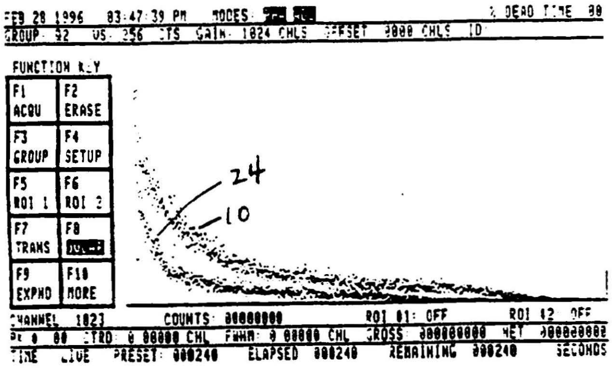

FIGURE 26. SPECTRA D1-10&24 (Batch-3-γ)

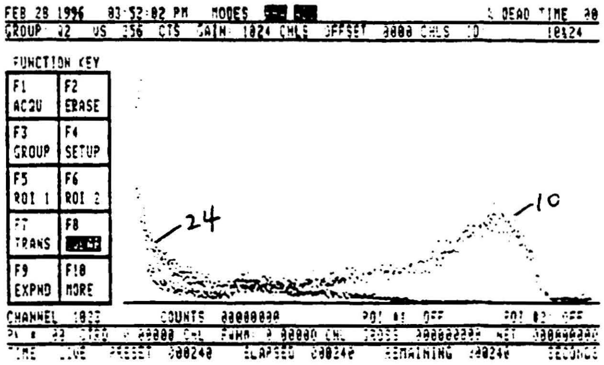

FIGURE 27. SPECTRA D3-10&24 (Batch-3-γ)

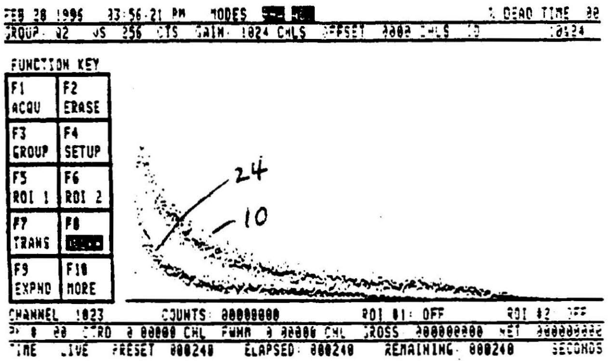

FIGURE 28. SPECTRA D2-10&24 (Batch-3-γ)

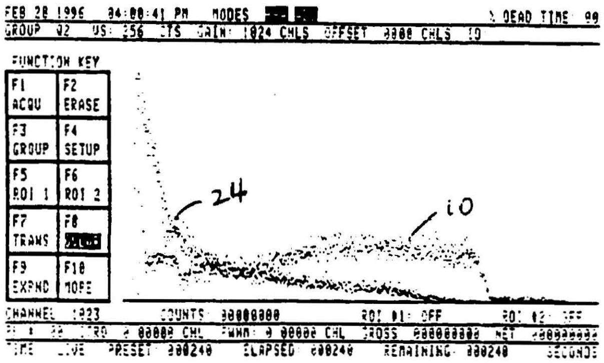

FIGURE 29. SPECTRA C3-10&24 (Batch-3-γ)