LABORATORY TESTS OF A MODIFIED ^{3}He DETECTOR FOR USE WITH STARTUP INSTRUMENTATION[1]

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ABSTRACT

Boron trifluoride (BF_3) detectors are currently used in all CANDU®[4] stations as startup instrumentation (SUI) detectors for monitoring neutron flux during extended outages and startups. Experience at some CANDU stations has shown that some models of BF_3 detectors degrade quickly, even in moderate neutron and gamma fields.

Degradation and life expectancy tests for five models of BF_3 detectors from different manufacturers were performed at Chalk River Laboratories (CRL) to investigate the problem. The test results reveal that most BF_3 detectors have low neutron and gamma durability, and some exhibit an undesirable time-dependent degradation followed by recovery. As a result of this finding, other detector options including a modified helium (^{3}He) detector described herein were investigated. Modified ^{3}He detectors were procured from an established supplier and were found to perform without degradation in neutron and gamma fields.

1. INTRODUCTION

Degradation during use and short operational life of BF_3 detectors have long been recognized as a potential problem by researchers in the area of neutron detection [1-5]. BF_3 detectors are currently used in all CANDU stations as startup instrumentation (SUI) detectors. Experience at some CANDU stations and subsequent laboratory tests at AECL's Chalk River Laboratories have shown that some models of BF_3 detectors degrade quickly, even in moderate neutron and gamma fields [6].

The test results [6] reveal that most BF_3 detectors have low neutron and gamma durability, and some exhibit an undesirable degradation/recovery phenomenon. As a result of this finding, other detector options including a modified helium (^{3}He) detector described herein were investigated.

Regular ^{3}He detectors have been used in CANDU SUI only on rare occasions of fresh-fuel conditions or very long outages when the greater neutron sensitivity of regular ^{3}He detectors is needed to obtain adequate count rates. For normal outages and startups, neutron fields are much higher. Consequently, the high neutron sensitivity of regular ^{3}He detectors leads to count rates that are too high for the detector and the electronics to handle. Also, typical ^{3}He detectors are more sensitive to gamma radiation than BF_3 detectors. This makes it difficult to separate gammas from neutrons when gamma fields are high. As a result of these operational disadvantages of regular ^{3}He detectors, only some CANDU stations have them on hand and no station uses them routinely [7].

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[1] AECL-11873, COG-97-436-I

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

Based on the physics of ^{3}He detectors, it was predicted that, by modifying the isotopic and chemical composition of the filling gas of a regular ^{3}He detector, a reduced neutron sensitivity, equivalent to that of a normal BF_3 SUI detector, can be achieved. It was also predicted that, because ^{3}He gas is far more stable than the BF_3 gas, ^{3}He detectors would suffer less from degradation in neutron and gamma fields.

To assess the accuracy of these predictions, modified ^{3}He detectors were procured from an established ^{3}He detector supplier and tested in neutron and gamma fields. This paper discusses these tests and presents ^{3}He detector test results and, for comparison, some of the results of similar tests for BF_3 detectors.

In Section 2 we review the characteristics of ^{3}He and BF_3 neutron detectors presently used in CANDU SUI. Section 3 summarizes the tests conducted and Sections 4 and 5 describe the test facility and test procedures, respectively. Section 6 presents test results for modified ^{3}He detectors, and compares them with those for the BF_3 detectors. Section 7 discusses and analyzes the test results and Section 8 concludes the paper.

2. CANDU SUI DETECTORS

Two types of neutron detectors have been used in CANDU SUI systems: the BF_3 detector and the ^{3}He detector. Table 1 lists the relative advantages and disadvantages of these two types of detectors.

The neutron sensitivity of an SUI detector is specified by the number of counts per second per neutron flux (cps/nv). The BF_3 detectors currently used in CANDU stations achieve a neutron sensitivity of about 4 cps/nv with an overall length of 30 cm (12") and a diameter of 2.5 cm (1"). The neutron sensitivity of regular ^{3}He detectors used in CANDU can be as high as 110 cps/nv. This high sensitivity can be a problem, because of the maximum count rate the electronics can cope with. The modified ^{3}He detectors were specified with different composition in the filling gas to achieve a neutron sensitivity comparable to that of BF_3 detectors.

The thermal neutron detection mechanism in SUI detectors depends on neutron capture interactions to convert the neutron to charged particles, followed by the subsequent detection of the charged particles. Of prime importance here is the Q-value of the reaction, which is a measure of the energy liberated following neutron capture. The higher the Q-value, the greater the energy given to the charged particles, and the easier will be the task of discriminating against gamma-ray events using simple amplitude discrimination. The (n,p) reaction for ^{3}He and the (n, α) reaction for BF_3 detectors are given below in equations (1) and (2), respectively [8]:

$$n + {}^3\text{He} \rightarrow {}^3\text{H} + p + 0.765 \text{ MeV} \tag{1}$$

$$\begin{aligned} n + {}^{10}\text{B} \rightarrow {}^7\text{Li}^* + \alpha \rightarrow {}^7\text{Li} + \alpha \\ + 0.48 \text{ MeV } \gamma\text{-ray} + 2.31 \text{ MeV } (94\%) \\ \rightarrow {}^7\text{Li} + \alpha + 2.79\text{MeV}(6\%) \end{aligned} \tag{2}$$

The Q-value for the ^{3}He reaction induced by thermal neutrons is 0.765 MeV. The detection of neutrons in BF_3 is based on ^{10}B (n, α) reaction, which produces a reaction product of ^{7}Li either in the excited state with a Q-value of 2.31 MeV, or in the ground state with a Q-value of 2.79 MeV. The excited state ^{7}Li* quickly decays (half-life of $\sim 10^{-13}$ s) to its ground state with the emission of a 0.48 MeV gamma ray.

The Q-values in (1) and (2) are indicated by the peak locations in the spectra of ^{3}He and BF_3 detectors as seen by a multi-channel analyzer (MCA). Figure 1 shows the representative MCA spectra for a ^{3}He detector and a BF_3 detector. The distance between the spectrum peak and the gamma tail also depends on the absolute gamma sensitivity of the detector.

Figure 2 shows three typical spectra for a good, a degraded and a failed BF_3 detector. Note that as the detector degrades, the peak in the spectrum reduces in height, broadens, shifts to the left and eventually disappears altogether.

3. TESTS CONDUCTED

Tests were conducted at CRL on five models of BF_3 detectors (referred to as A, B, C, D, E), and one model of modified ^3He detectors. For each model, three specimens were tested to achieve statistically valid results. This paper presents mainly the test results for the modified ^3He detectors. Some of the test results for BF_3 detectors are also included for comparison purposes.

Three phases of tests were conducted for each model. The first phase was the general measurement of the high-voltage plateau, tail pulse rise-time, pulse height and gas multiplication. The second phase was the neutron test and the third phase was the gamma test. Most notable results were obtained in the neutron and gamma tests. Therefore, only those results are presented in this paper.

4. TEST FACILITY

In the neutron tests, the thermal neutron beam from the N5 and E3 spectrometers at the NRU research reactor at CRL was used to test the degradation and life expectancy of the detectors under a thermal neutron flux. A schematic of the spectrometer setup is provided in Figure 3. 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 thermal neutron beam. The detectors to be tested are placed in the thermal neutron beam in four locations. Removable absorbers between the detectors and the incident neutron beam were used to achieve the desired count rate, and to reduce the neutron flux temporarily when collecting spectra in an MCA.

In the gamma tests, the gamma irradiations were done using an Ir-192 source with a half life of 74 d (see Figure 4). A weak neutron source was used to produce the spectra. The neutron source was so weak that no degrading effects occurred due to this source. 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 was conveniently withdrawn into the shielding flask, allowing the spectra from the weak neutron source to be collected before and after gamma irradiation.

Standard SUI electronics modules were used in the neutron and gamma tests. They included four preamplifiers, four shaping amplifiers, four high voltage power supplies, one single channel analyzer (SCA) and one rate meter. A multi-channel analyzer was used to capture the pulse height spectra for the detectors.

5. TEST PROCEDURE

The neutron tests were conducted in two stages: Stage 1 neutron flux produced a neutron count rate in the detector in the order of 30 kHz. Stage 1 lasted 3 ~ 4 days to yield a cumulative count for each detector in excess of 10^{10}. The 10^{10} counts which is equivalent to about two months exposure time in a reactor at a count rate of 2000 counts per second, is specified as the lower limit of life expectancy for the BF3 detectors by one manufacturer. Other manufacturers quote longer life expectancies. Stage 2 neutron flux produced a much higher neutron count rate in the detectors (calculated to be in the order of 300 kHz). Stage 2 tests also lasted one to two days achieving cumulative counts in excess of 1.2E10. Throughout the neutron tests, spectra for each detector were collected once a day, with the absorbers temporarily inserted to reduce the count rate to a few kHz.

The gamma tests were conducted in a gamma field in the order of a few kR/h, with gradually increasing exposure time to give a total cumulative gamma exposure of about 100 ~ 500 kR.

6. TEST RESULTS

Detailed test results for all the five models of BF_3 detectors and one model of ^3He detector were contained in CANDU Owners Group (COG) reports [6, 9]. Highlights of the results have also been published [10, 11]. In the following, the results for the ^3He detector tests are presented and compared with some of the results of BF_3 detector tests.

6.1 Neutron Test Results

The spectra of the modified ^3He detector before and after the stage 1 neutron tests (cumulative counts in excess of 10^{10}) are shown overlapped in Figure 5. There is very little change in the spectrum shape. Figure 6 shows the spectrum of a ^3He detector at the end of stage 2 (cumulative counts in excess of 1.2E10) overlapped with the spectrum taken at the beginning of neutron tests. Still, there is very little change in spectrum shape indicating almost no degradation at all.

In contrast to the ^3He stability, two models of BF_3 detectors showed significant changes even during stage 1. Figures 7 and 8 show the spectra at the beginning and at the middle of stage 1 neutron tests for model C. Figures 9 and 10 show the same for model D. The degradation evident in these figures is so bad part way through Stage 1 that Stage 2 tests were not done for models C and D detectors.

Figure 11 shows the degradation of BF_3 detector model A, with three spectra overlapped showing the spectrum shape evolution at the beginning of stage 1, at the end of stage 1, and at the end of stage 2. Figure 12 shows the same for model B. As is evident from these figures the degradation due to neutron is not as bad for these two models but is still quite serious.

6.2 Gamma Test Results

Gamma test results show the most significant difference between the BF_3 and the modified ^3He detectors, and between different models of BF_3 detectors.

Figure 13 shows spectra of a ^3He detector at the beginning of the gamma test, after a cumulative exposure of 3.2 kR, and after a cumulative exposure of 12.6 kR. The spectra at the beginning and end of the gamma test when an exposure of 410 kR had been achieved are overlapped in Figure 14. Even for this extreme exposure there is no detectable degradation what so ever.

Figures 15 and 16 show spectra of model C BF_3 detector at the beginning of the tests and after initial gamma exposure. Figures 17 and 18 show the same for model D. As is evident from these figures, BF_3 detector models C and D that showed low neutron durability, even in stage 1 neutron tests, also failed shortly after exposure to gamma, and showed no sign of recovery with prolonged gamma exposure.

Figure 19 shows the overlapped spectra of model A BF_3 at the beginning of the gamma test and after a cumulative exposure of 1.6

kR. Figure 20 shows the same for model B. As is evident from these figures models A and B BF_3 detectors showed significant degradation after the initial gamma exposure. The most significant degradation was observed during the initial exposure with a cumulative exposure of less than 10 kR. Some gradual recovery with prolonged gamma exposure was also observed (not shown here).

Comparing ^3He spectra (Figures 13 and 14) with those of BF_3 detectors we can see the gamma tails in the spectra of the modified ^3He detector are further to the right than those in the BF_3 spectra (but similar to that of a regular ^3He). This indicates that ^3He detectors whether modified or not have a higher gamma sensitivity.

7. DISCUSSIONS AND ANALYSES

Throughout the tests, the modified ^3He detectors showed the same level of neutron count rate as the BF_3 detectors in the same radiation fields. This indicates that the modified ^3He detectors achieved the same level of neutron sensitivity as that of BF_3.

The ^3He detectors showed very stable performance throughout the neutron and gamma tests with almost no detectable degradation, and no degradation/recovery phenomenon as observed in some models of BF_3 detectors. This robust behavior makes the ^3He detector particularly suitable for use as a reliable removable SUI detector. This very stable ^3He detector is also a candidate for a possible new design of permanently installed CANDU SUI detectors.

The gamma sensitivity of the modified ^3He detector, like regular ^3He detector, is higher than that of BF_3 detector. However, this is not a serious limitation, the very stable spectrum of the modified ^3He detector in high neutron and gamma fields makes it possible to set the SCA threshold at a higher level than that used for BF_3 detectors. It is thus possible to provide sufficient discrimination against gamma radiation.

8. CONCLUSIONS

The neutron sensitivity of the modified ^3He detector is the same as that of BF_3 SUI detectors. The modified ^3He detectors showed superb stability during neutron and gamma tests compared to all models of BF_3 detectors, and a great potential for use as CANDU SUI detectors. The gamma sensitivity is somewhat higher than that of the BF_3 detectors. However, the very stable spectrum shape of the modified ^3He detectors, even in high neutron and gamma fields, makes it possible to set the SCA threshold at a higher level than that used for BF_3 detectors so as to discriminate against the gamma. The modified ^3He detector shows great potential for use as CANDU SUI detectors.

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REFERENCES

[1] R.K. Soberman and S.A. Korff, "Deterioration of Boron Trifluoride Counters Due to High Counting Rates", The Review of Scientific Instruments, Vol. 24, No. 11, 1953 Nov., pp. 1058-1060.

[2] A.J. Stokes, T.J. Meal and J.E. Myers, Jr., "Improved Performance of BF_3 Neutron Counters in High Gamma Fluxes", IEEE Trans. on Nucl. Sci., 1966 Feb, pp. 630-635.

[3] W. Abson, P.G. Salmon and S. Pyrah, "Boron Trifluoride Proportional Counters", The IEE, 1958 Jan, pp. 357-365.

[4] T. Tomoda, and S. Fukakusa, "Deterioration and Recovery of BF_3 Counters Due to Operation in Intense Radiation Fields", Nucl. Instr. and Methods in Physics Research, 224 (1984), 557-565.

[5] T. Tomoda, S. Fukakusa, S. Yamashita, and K. Akita, "Development of Long-life BF_3 Counters", J. of Nucl. Sci. and Tech., 22[2], (1985 February), 120-128.

[6] T. Qian, N. Keller, P. Tonner, "Degradation and Life Expectancy Tests for BF_3 Startup Instrumentation Detectors", COG-96-142 (Rev. 0), 1996 March.

[7] T. Qian, A. Lopez, "Survey of Startup Instrumentation in Domestic CANDU Stations", COG-95-117 (Rev. 0), 1995 May.

[8] G.F. Knoll, Radiation Detection and Measurement, John Wiley & Sons, 1989.

[9] T. Qian, P. Tonner, N. Keller, "Tests for a Model of BF_3 and a Modified Model of ^3He Detectors", COG-97-nnn-P1, 1997 April.

[10] T. Qian, N. Keller, P. Tonner, "Degradation and Life Expectancy Tests for BF_3 Detectors, " Proc. of the 17th Annual CNS Conf., 1996 June 9-12, Fredericton, NB, Canada.

[11] T. Qian, P. Tonner, N. Keller, W. Buyers, "Degradation of Boron Trifluoride and Helium Detectors in Neutron and Gamma Fields", Proc. of the 1997 IEEE Nucl. Sci. Symp. and Medical Imaging Conf., Albuquerque, NM, 1997 Nov 9-15.

Table 1. Comparison of BF_3 and ^3He as SUI detectors

Detector type	BF_3	^3He	Modified ^3He
Cost range (CND$)	700-2200	~2100	~1100
Neutron sensitivity (cps/nv)	4	110	4
γ sensitivity	lower	higher	same as ^3He
γ discrimination	better	poorer	same as ^3He
Q-value	2.31 MeV (94%) 2.79 MeV (6%)	0.765 MeV	same as ^3He
Stability of filling gas in neutron and gamma fields	less stable	stable	stable

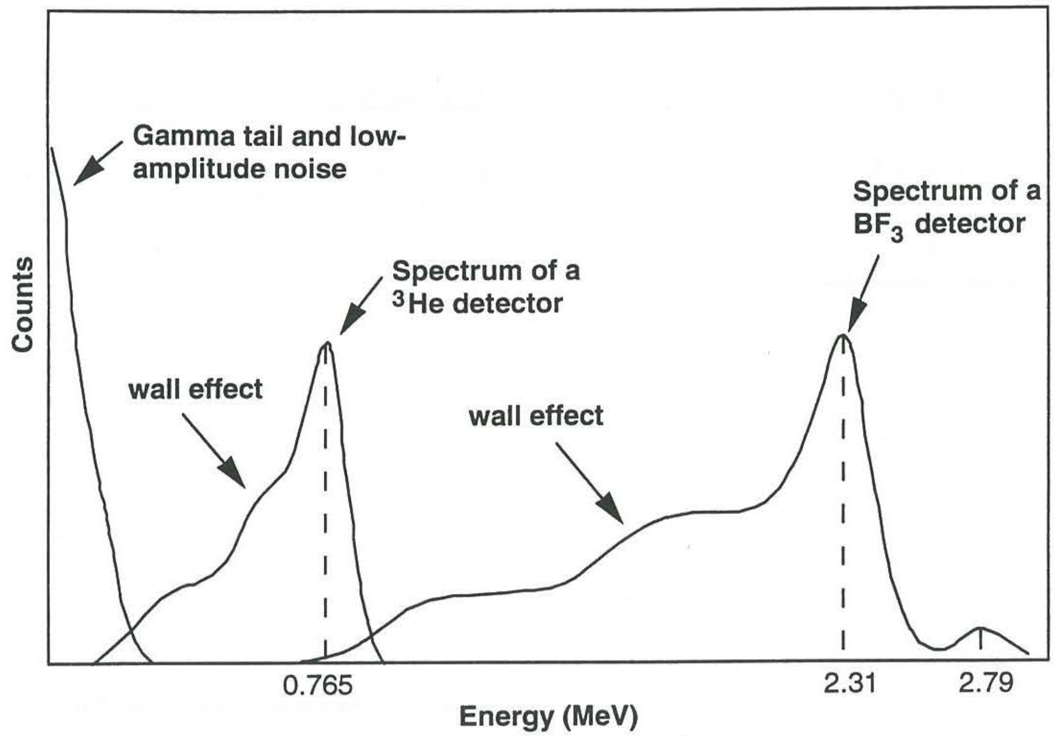

Figure 1. Typical spectra of BF_3 and ^3He detectors

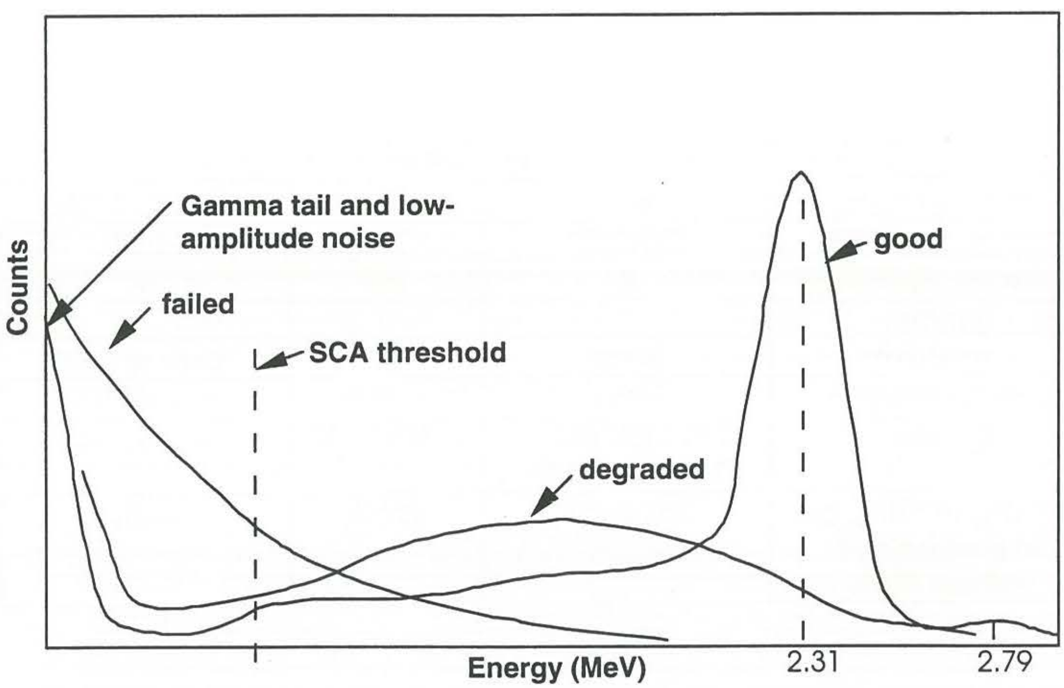

Figure 2. Typical spectra for a good, degraded, and failed BF_3 detector

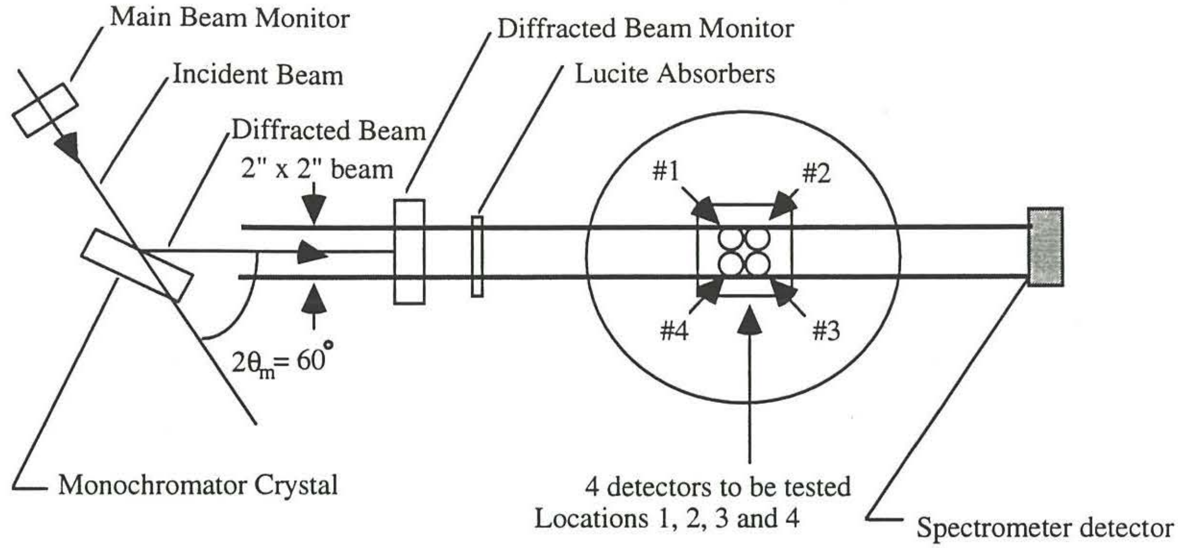

Figure 3. Neutron test facility of spectrometer at NRU reactor

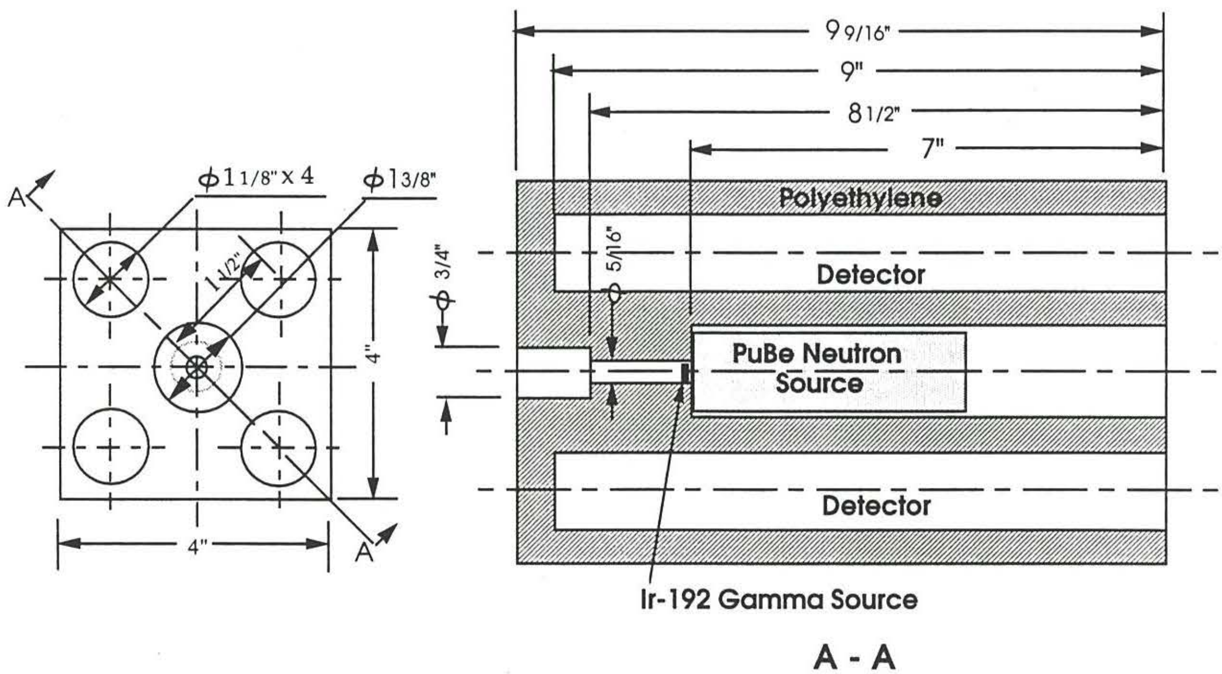

Figure 4. Polyethylene block for holding the sources and the detectors

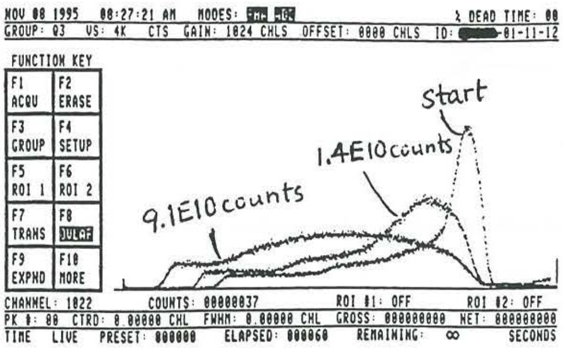

Figure 11. Model A BF_3 in neutron tests at start, after stage 1 and after stage 2

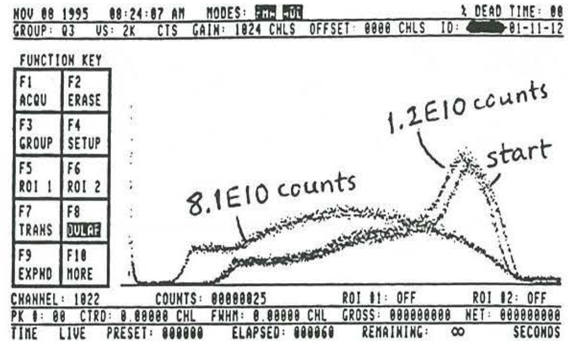

Figure 12. Model B BF_3 in neutron tests at start, after stage 1 and after stage 2

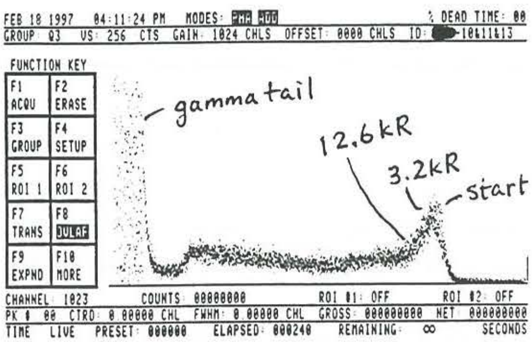

Figure 13. ^3He after initial gamma exposure

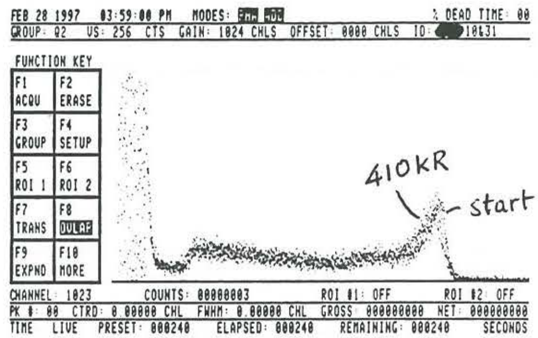

Figure 14. ^3He at the beginning and end of gamma tests

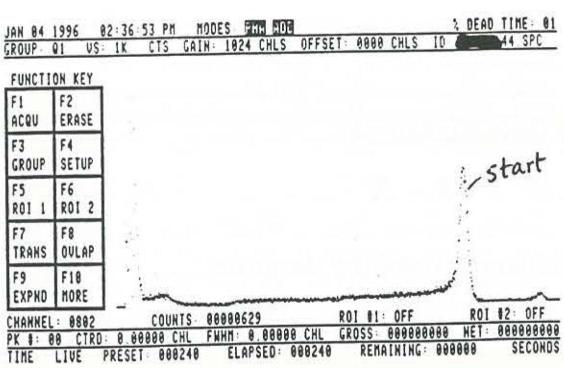

Figure 15. Model C BF_3 at the beginning of gamma tests

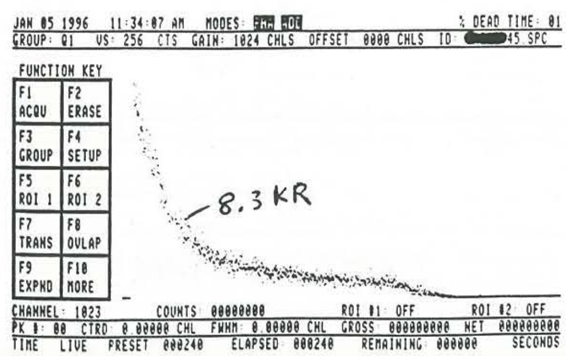

Figure 16. Model C BF_3 after initial gamma exposure

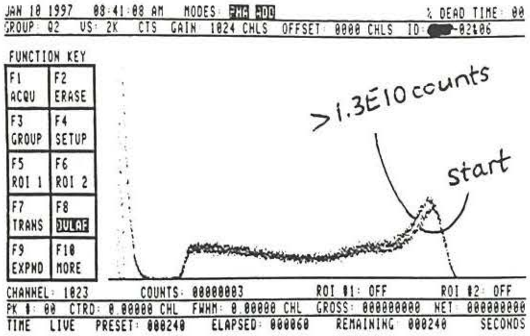

Figure 5. ^{3}He before and after stage 1 neutron tests

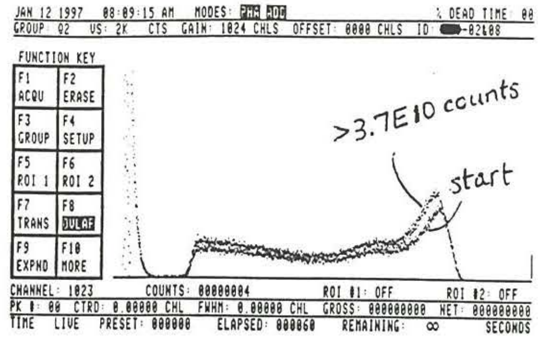

Figure 6. ^{3}He before stage 1 and after stage 2 neutron tests

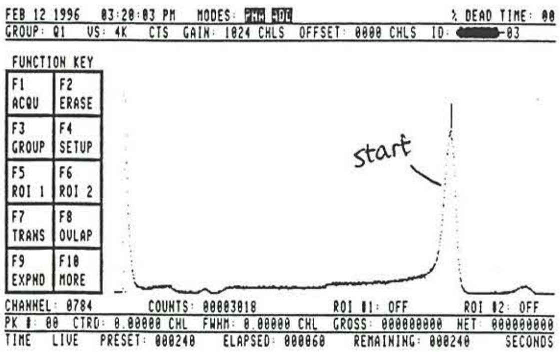

Figure 7. Model C BF_3 at the beginning of stage 1 neutron tests

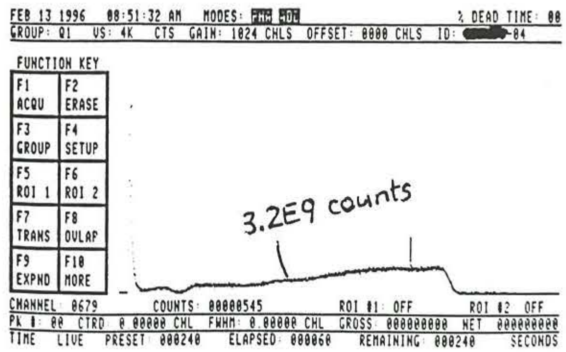

Figure 8. Model C BF_3 in the middle of stage 1 neutron tests

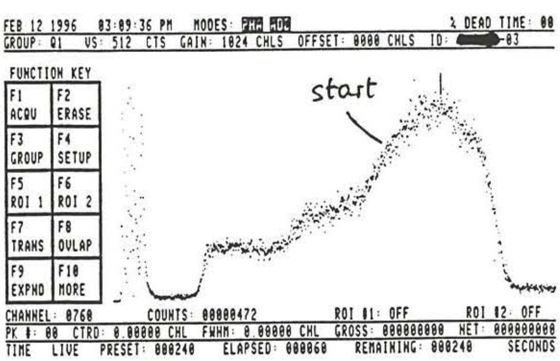

Figure 9. Model D BF_3 at the beginning of stage 1 neutron tests

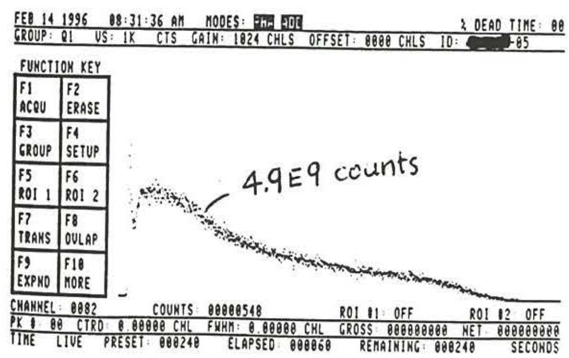

Figure 10. Model D BF_3 in the middle of stage 1 neutron tests

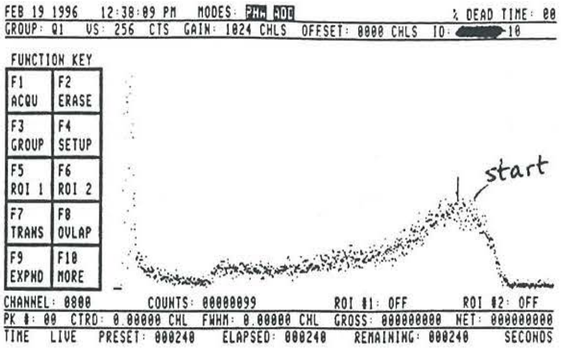

Figure 17. Model D BF_3 at the beginning of gamma tests

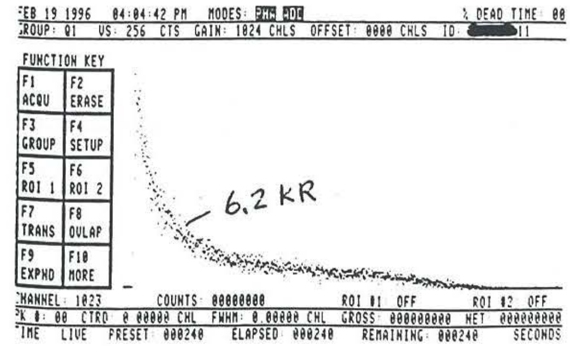

Figure 18. Model D BF_3 after initial gamma exposure

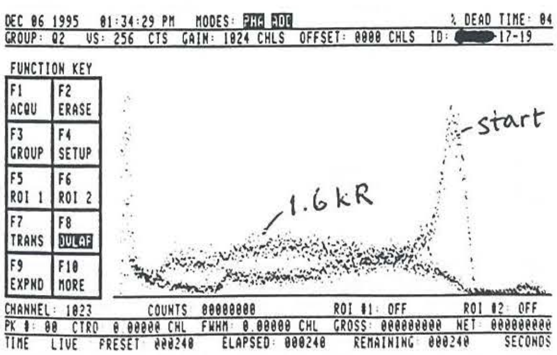

Figure 19. Model A BF_3 initial degradation

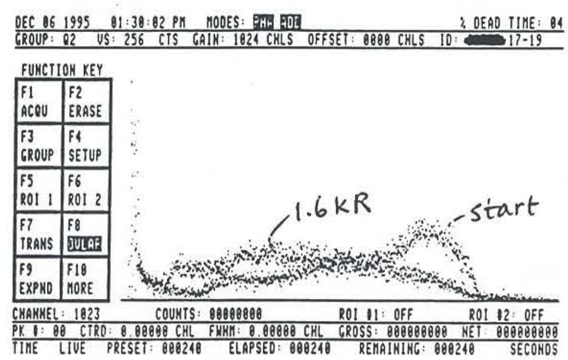

Figure 20. Model B BF_3 initial degradation