RADIATION DETECTION CHALLENGES

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ABSTRACT

Most ground-based radioxenon nuclear detonation detection systems rely on a combination of detectors to measure beta-gamma signatures for treaty monitoring (Hayes et al., 1999; Bowyer et al., 1999). The detection packages often use a plastic scintillator to detect the beta or conversion electron particle and a crystal scintillator such as NaI or CsI to detect the gamma- or x-ray. While these detection systems work well, there was a need to simplify the setup, calibration and improve robustness. The redesign, which led to using CsI(Na) well detectors, sought to achieve higher detection efficiency, better shock resistance, and less temperature dependence (Cooper et al., 2007), as shown in Figure 1. Preliminary testing showed excellent characteristics. After further study two issues were discovered that need to be overcome. First, there is potential for a dead layer, due to the manufacturer handling of the crystal, to be present on both the CsI and NaI crystals. The second issue is an energy drift caused by incorrect mating of PMT and PMT base to the crystal. These two issues cause adverse effects on the measurement of radioxenon or any other radiological measurement. It is clear that additional handling and inspection procedures are necessary during the manufacturing process. This paper will discuss the matter in more detail and give evidence of the presence of these issues in PNNL purchased crystals. The paper will also propose procedures for handling and testing of high-quality CsI and NaI crystals that get delivered on future purchases.

OBJECTIVES

The objective of this paper is to discuss apparent causes of low detection efficiency and detector gain drifts. These two issues have recently been identified with purchased components which points out the need for performance confirmation testing prior to incorporation of parts into a system.

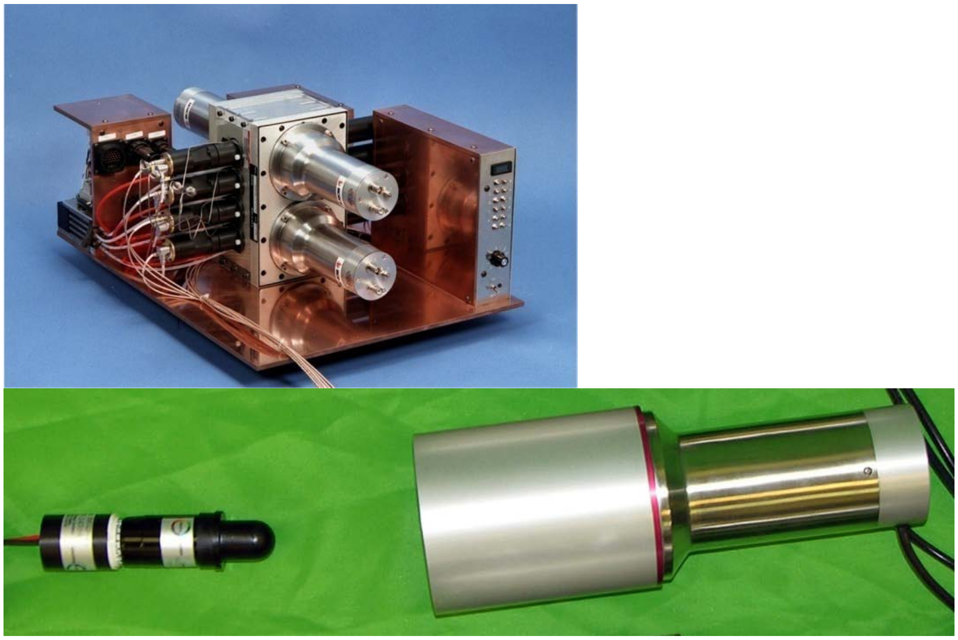

Figure 1. The top figure shows an older beta-gamma detector style that relies on multiple PMTs to determine both the beta and gamma energies. The bottom figure shows a portion of the replacement detector in a semi-complete stage.

The first issue is a low detection efficiency for the 31 keV x-ray from ^{133}Xe. Low detection efficiency is caused by additional material present between the sample and the active crystal. The additional material causes some of the x-rays to partially (sometimes completely) deposit their energy before reaching the active detector. This effect causes a broadening of the peak (poor energy resolution) and in the worst case it can cause a drop in detection efficiency. This is the most likely cause of the low detection efficiency in the CsI.

The second issue is detector gain drifts. Gain drifts are continuous shifts in the energy calibration of a detector. Gain shifts and drifts are often be caused by instability in photo-multiplier tube (PMT) high voltage (HV), incorrect selection of PMT, instability in data acquisition electronics or potentially software bugs in the data analysis code. Figure 2 has a many 10 minute spectra taken over approximately 16 hours. These spectra used a ^{137}Cs source inserted into the detector and left there over the entire 16 hours. A color scale is used to represent the counts in each spectrum with the highest counts being in red. Figure 2 shows the observed drift is still occurring even after 16 hours, although it has slowed significantly. Gain drifts and shifts can cause misinterpretation of data and can be very difficult to discern.

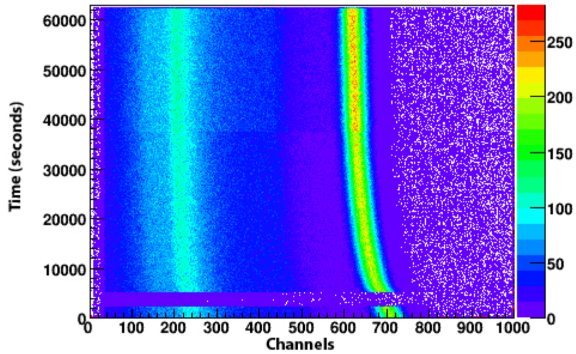

Figure 2. A contour plot showing a 13% gain drift over a ~16 hour period. The ^{137}Cs spectra were accumulated in 10 minute increments. The line originating at channel 700 represents the shifting 661.7 keV Cs-137 gamma-ray.

RESEARCH ACCOMPLISHED

Low Detection Efficiency

Low x-ray detection efficiency was observed during initial characterization of the detector system, however it came as a surprise since the prototype detectors did not have a similar low efficiency. The most probable cause for the drop in x-ray efficiency is a dead layer on the crystal surface. This effect would increase the number of interactions outside the active crystal (undetected events). A. Gleyzer (see Acknowledgements) also noted that CsI(Na) crystals are likely to have a dead layer caused by hydration and may be due to poor handling during fabrication. This affect has been long known (Reeder 2004), but was unexpected. To understand the efficiency of the detector a Monte Carlo simulation was performed (Keillor 2009) in addition to extensive testing of the detectors.

The Monte Carlo simulation was performed using PStudy (Brown et al., 2004) to generate a series of Monte Carlo Neutral Particle (MCNP5) simulations (Booth et al., 2003). An unexpected finding from this study is a correlation between the dead layer thickness and the intensity of the 31 keV x-ray. When simulating the presence of ^{133}Xe in the well detector, there is an 80 keV gamma-ray and a 31 keV x-ray. As the dead layer increases, the intensity of the full energy peak (FEP) at 80 keV decreases in intensity while the 31 keV peak increases in intensity. Under normal circumstances, additional material between the source and the detector will decrease the intensity of the lower energy peak more than the higher energy peak. Figure 3 shows simulated spectra corresponding to dead layers of 0 mm and 0.21 mm thick.

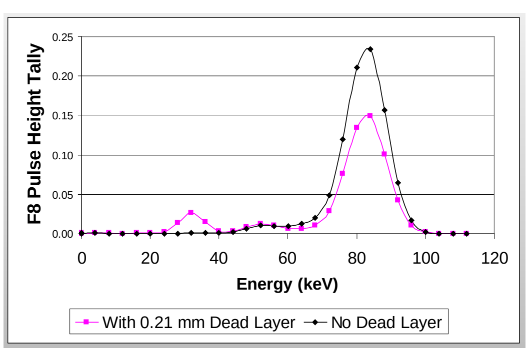

Figure 3. MCNP5 simulation of ^{133}Xe within a CsI well detector.

To confirm the presence of a dead layer in the purchased CsI detector, several sample detectors were selected. The selected detectors include a NaI(Tl), CsI(Na) (proto-type) and CsI(Na) which exhibited the low efficiency. Two experiments were run against all three detectors. Initially a ^{241}Am source with a 59.5 keV gamma-ray was used, however it also has two lower energy gamma-rays at 26.34 and 21.00 keV as well as several x-rays that are near the ~31 keV energy of interest. Because the ^{241}Am has these low energy gamma- and x-rays it turns out to be more complicated than originally hoped for (see Figure 4).

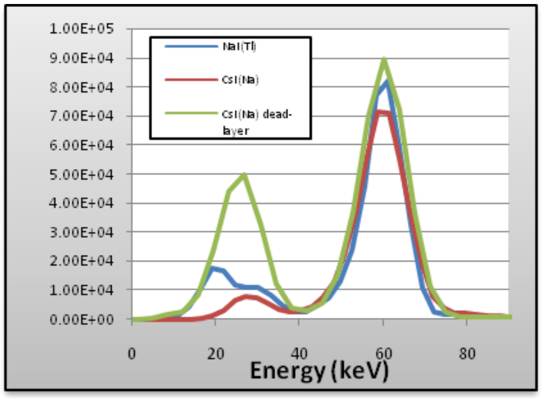

Figure 4. Spectra from three detectors: NaI, CsI and CsI (dead-layer) using a ^{241}Am source.

After analyzing the ^{241}Am spectra and noting the increase in the 30 keV peak as well as the complex features seen in the NaI spectrum, a simpler analysis was sought. Using a ^{57}Co source avoids most of the problems inherent in the ^{214}Am spectra. A comparison of the ^{57}Co spectra (Figure 5) from the same three detector set (NaI, CsI and CsI with dead layer), demonstrates that the dead layer of the newer CsI(Na) introduces a ~31 keV peak in the spectrum, while the other two detectors did not display this feature. All 3 spectra display the 122 and 136 keV unresolved peak, as well as an x-ray escape peak on the low energy side of the main peak.

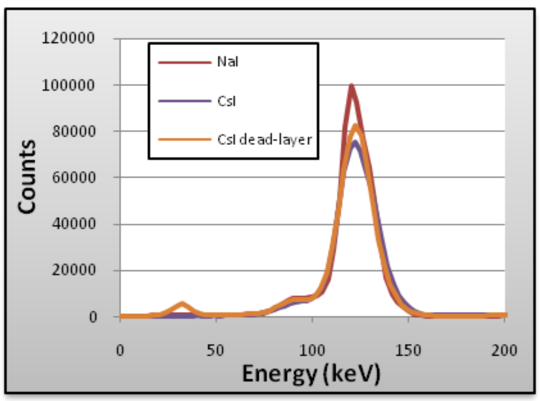

Figure 5. Co-57 spectra for three different well detectors showing the various levels of dead layer present.

Gain Drifts

Gain shifts and drifts are often observed in detection systems. The first step for eliminating a gain drift is, obviously, to recognize it is occurring. The second step is to discover what component is causing the behavior and fixing it. However, if it is not possible to fix the gain drift it is important to actively correct for the drifting.

In this particular case there are two factors playing a role. First there is a brief drift observed during system startup, which is due to the high voltage powering on and settling into a particular voltage setting. This is observed over several minutes time and has two components. The first component is due to a voltage monitoring loop that is built into the high voltage circuit. This voltage monitor can take several minutes to settle into the appropriate voltage setting upon which it no longer causes drifting. The second component is due to thermal loads on the circuit. As the circuit warms up there are slight changes to the characteristics of the circuit which translates into small gain drifts while the circuit reaches an equilibrium temperature. These two effects amount to approximately a 5% shift, the majority of which is during the first hour (Figure 6).

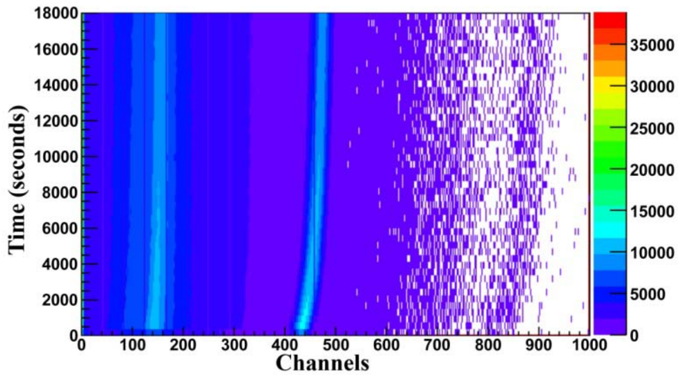

Figure 6. A contour plot showing a ~5% gain drift over a ~5 hour period. The ^{137}Cs spectra were accumulated in 10 minute increments. The line originating at channel 410 represents the shifting 661.7 keV ^{137}Cs gamma-ray.

The second factor leading to gain drifts in this detection system is dependent upon detection rate. This long-term drift can be seen in Figure 2 and was far more difficult to determine. It is observed by inserting a 5 mCi ^{137}Cs source into the detector. The drift occurs when going from background detection rates to high count rates, but the effect can be moderated by gradually increasing the count rate rather than have large jumps in the count rate. Attempts to see the gain drift on an oscilloscope proved to be too challenging, even with some averaging tools to check pulse heights.

A duplicate detector system was established to investigate the drifts on an independent system. Identical hardware and software were used in the test system, although, the test detectors used were of similar geometry but from a different manufacturer. Attempts to re-create the drifts in the electronics using a pulser and detector proved unsuccessful. This suggested that the effect is either within the detector or there may have been internal components in the electronics that were not identical. A change of some of the internal electronics components (DACQ cards and HV cards) did not fix the drift problem, which left the detector as the most likely cause. Since the drift was only observed on the gamma detectors, these were targeted. After swapping each of the well detectors in the system, testing commenced. Repeat test were performed using the 5 mCi ^{137}Cs source. Figure 7 shows no gain drift is observed with rate changes after the detector change was made. This can be seen by the straight vertical red line (661.7 keV ^{137}Cs) gamma-ray line that is centered at channel 250 in the figure.

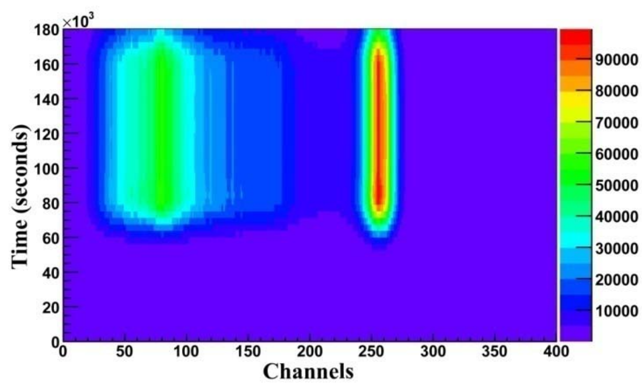

Figure 7. A contour plot showing no gain drift over a 24 hour period. The ^{137}Cs spectra were accumulated in 10 minute increments. The line at channel 255 represents the shifting 661.7 keV Cs-137 gamma-ray.

CONCLUSIONS AND RECOMMENDATIONS

This paper draws attention to the need for rigorous testing of nuclear detectors prior to use in detection systems, even when previous generations of the detectors have not shown any adverse characteristics. The potential for a detector dead-layer to complicate the analysis of xenon measurement data when CsI(Na) scintillators are used has been observed and will become a standard characteristic to check in initial testing. The presence of cesium in the detector crystal allows x-rays to be generated which interfere with xenon x-rays when there is partial energy capture. The Iodine x-rays cause a similar problem in resolving the xenon x-rays. Further, the presence of an inactive dead layer on the crystal increases the chance of detecting only partial energy from the event (seeing only the 30 keV from Cs or I). CsI(Na) crystals can be produced without this dead layer effect, so they are not necessarily unsuitable for xenon measurement applications. Detector buyers interested in low energy events should consider specifying the acceptable dead layer thickness, perhaps by specifying the acceptable ratio of counts in the 122 keV and 30 keV peaks from measurement of a ^{57}Co check source.

Another issue that should be checked during initial detector testing is gain drifts. The testing should use equipment that is known to be stable and not have gain shifting or drifting present. Currently it is believed that poor matching between the PMT and base is the cause of the drift. This hypothesis will be tested once manufacturer specified PMT bases arrive. It should be noted that the drifting (5%) due to system start up in no way effects data quality for system results, but does affect the quality assurance/quality control method (Cooper et al., 2007). However, the gain drift associated with the PMT bases mismatch does impact data quality. This drives home the necessity of detector component matching.

The challenges illustrated in this work show why considerable care is critical when designing and building a high-performance detection system. Steps both early and late in the process can have dramatics impact in the final system.

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