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Most current radiation portal monitors (RPMs) use neutron detectors based upon ^{3}He-filled gas proportional counters. ^{3}He is in short supply in the world and continues to decline in availability. Concurrent with the decline in gas is a disproportionate increase in the cost of available gas. It is therefore desirable to find substitutes for the ^{3}He with technologies that will effect minimal changes to currently deployed systems and provide equivalent effectiveness in neutron detection. This project investigates the feasibility of BF_3 as a substitute for the ^{3}He in configurations that can be readily installed in currently deployed systems.

In response to this ^{3}He shortage, the U.S. Department of Homeland Security's (DHS), Domestic Nuclear Detection Office (DNDO), Product Acquisition and Deployment Directorate (PADD) commissioned Brookhaven National Laboratory (BNL) to construct and test a boron tri-fluoride (BF_3) based neutron detection module (NDM). The NDM was required to meet specific criteria as outlined in a DNDO Functional Requirements Document (FRD) [1]. The detector was to be built utilizing (as much as practicable) off the shelf components and have the same exterior dimensions as current NDMs so that they can fit into existing portal monitor enclosures.

The module was mounted in the standard Radiation Portal Monitor (RPM) NEMA enclosure inside the standard steel shroud, and shipped to the Nevada National Security Site (NNSS) for testing. Concurrently, a full-scale surrogate "BF_3 detector", fabricated with air replacing the BF_3, was constructed for the purpose of evaluating the ability of the design to survive being dropped from a height that would be typical when performing a field replacement of an NDM on the tallest portal monitor configuration. This height corresponds to a condition such that the bottom of the NDM is at an elevation of 15 feet, or 457 cm, above ground level.

This paper will discuss the design features of the detector system, mitigation techniques developed to ameliorate the hazards posed by the BF_3 gas, drop test results, and discussion of neutron detection efficiency for the constructed detector system. BF_3 detectors potentially have direct applications to international safeguards where ^{3}He neutron detectors are typically deployed.

Background

In September 2010, the U.S. Department of Homeland Security's (DHS), Domestic Nuclear Detection Office (DNDO), Product Acquisition and Deployment Directorate (PADD) commissioned Brookhaven National Laboratory (BNL) to construct and test a boron tri-fluoride (BF_3) neutron detector. The detector was designed to meet the specific criteria outlined in a DHS / DNDO Functional Requirements Document (FRD).

The module was then mounted in the standard RPM NEMA enclosure inside a standard steel shroud, and shipped to the Nevada National Security Site (NNSS) for testing (Note: NNSS is the United States Department of Energy reservation located in southeastern, Nevada, approximately 65 miles northwest of Las Vegas, formerly known as the Nevada Test Site).

This paper is a compilation of the work performed in the execution of the DHS project and the results of the BNL efforts to build and test a neutron detector that has significant potential applications in the safeguards and security arena as a substitute for ^3He.

The following tasks were performed for this project:

Task 1. Design of the BF_3 detector-based NDM

Los Alamos National Laboratory (LANL) and Brookhaven National Laboratory collaborated on developing the design of the BF_3 detector-based NDM. The NDM design requirements were specified in a DNDO FRD [1]. The primary design requirements were that

1. the NDM should have an absolute detection efficiency greater than 2.5 cps/ng of ^{252}Cf at 2 meters,
2. the NDM should fit into existing envelope dimensions (5 inches thick by 12.5inches wide by 85 inches tall),
3. the NDM should contain hazard mitigation for BF_3, and
4. a passive indicator for BF3 leak annunciation.

MCNP [2] simulations were performed to develop and optimize the NDM design. Many different tube sizes and configurations were modeled and compared. In the final analysis the simplest design meeting the sensitivity criteria was selected in order to minimize cost and increase reliability.

The final design incorporated three (3) stainless steel BF_3 tubes, filled to a pressure of one atmosphere, with BF_3 enriched to 96% ^{10}B. The tube dimensions were 5.08 cm. in diameter, by 183 cm active length. The thicknesses of the front, back and sides of the high-density polyethylene (HDPE) moderator cavity were optimized within the constraints of the specified envelope dimensions. Details of the design development and optimization are discussed in reference 3..

The design specifications also required the inclusion of several layers of mitigation to ameliorate the potential hazards presented by the BF_3, which is a hazardous corrosive gas. The tubes themselves were constructed of high quality stainless steel, subjected to rigorous cleaning, manufacture, and quality control by the vendor (LND, Inc.), who has decades of experience making BF_3 tubes. The HDPE moderator cavity was fabricated from one monolithic billet of HDPE, with an O-ring sealed cover. Sealed electrical feed-throughs were incorporated in the design (Figure 1). These features provide a robust barrier to leakage of gas. Typical cavities are built from a number of flat slabs, with no regard to hermetic sealing. As an additional barrier to leakage, the entire moderator cavity was placed inside a welded stainless steel “envelope” with a sealed cover.

A “gettering” material (alumina) was distributed in the interstitial spaces between the BF_3 tubes to react with the BF_3, preventing its migration outside the moderator cavity. Alumina (Al_2O_3) beads were mixed with HDPE beads which provide some additional neutron moderation and increase the efficiency of the detector.

Figure 1: This is a photograph of the full assembly, showing the machined one-piece cavity with o-ring seal, the tubes with electronics modules, and the alumina and poly bead blend, just prior to assembly. The top cover can be seen leaning against the wall.

Given the short timeframe of the project, commercial neutron detector electronics were ordered and incorporated in the design. These electronics modules will most probably not be used in any final production device since it is envisioned that the electronics will need to be more tightly integrated into the current overall electronics design of the RPM.

Task 2. Drop tests to validate the primary and secondary containment function with surrogate gas and/or BF_3 within the detector assembly.

A full-up surrogate "BF_3 detector" was constructed for the purpose of evaluating the ability of the design to survive being dropped from a height that would be typical when performing a field replacement of an NDM on the tallest portal configuration. This height corresponds to a condition such that the bottom of the NDM is at an elevation of 15 feet, or 457 cm, above ground level. The criterion for success in this test was not that the detector remain functional, but rather that there is no release of BF_3 gas to the environment. The drop test surrogate was constructed precisely as the actual NDMs were constructed, except for the following details. The three tubes used in the drop test surrogate were manufactured by the BF_3 tube vendor precisely as if they were going to be filled with BF_3, except that they were equipped with valves where they would have had sealed pinch-offs, and they were filled with air to one atmosphere. In addition, the blend of polyethylene and alumina beads that was used in the actual NDM was replaced by polyethylene beads only.

The drop test was performed in a "high bay" laboratory space equipped with an overhead crane. A layer of solid concrete blocks was arranged on the concrete floor underneath the impact area, primarily to protect the floor tiles from impact damage. The drop test surrogate was also equipped with a lifting eye bolted into the top of the detector such that when suspended from the crane, the detector hung vertically, with the bottom face parallel to the floor. A "special effects" quick release device was used between the surrogate detector and the crane to initiate a free-fall drop of the surrogate from the test elevation of 15 feet above the floor. The drop test surrogate was observed to bounce upward after impact with the concrete floor, to a height of about 29 inches, estimated from video taken during the drop test. The calculated velocity at impact ($v=\text{sqrt}(2gd)$, where $g= -9.8\ m/sec^2$) is -9.47 m/sec, or -21.1mph. Measurements made by scaling the displacement of the detector in progressive frames of video resulted in measurements of velocity ranging from -18.5 to -21 mph. After impact, visible deformation of the outer stainless steel envelope is evident at the lower edge, as can be seen in Figure 2. Upon inspection, no breach of the stainless steel envelope was detected. The drop test surrogate actually bounced on its end twice before falling over on its side.

Figure 2: This photograph (after impact) depicts the damage to the concrete bricks and the damage to the stainless steel case for the detector assembly. The stainless steel case was not breached.

The drop test surrogate was recovered and disassembled. The deformation of the outer stainless steel envelope was mild enough that the envelope could still be slid off of the sealed polyethylene cavity by having two people pull in opposite directions. The polyethylene cavity can be seen in figure 3. When the screws were removed from the polyethylene cover, it was observed that several of the brass threaded inserts installed in the plastic had been slightly lifted out of the plastic. This was not sufficient to allow any of the polyethylene beads inside the cavity to fall out. Inspection of the three surrogate tubes revealed that differing amounts of damage had occurred. Tube number one suffered almost no discernible damage. Tube number two suffered some mushrooming distortion near the bottom end, similar a the bare-tube drop test conducted earlier. Tube three suffered similar damage, but slightly larger in magnitude. The tubes can be seen in figure 4. Each of the tubes from the drop-test surrogate were evacuated to roughing pump vacuum and then valved off for periods of time ranging from 24 to 72 hours. None of the three tubes that were used in the drop test surrogate experienced any change in pressure over the time that they were evacuated, indicating that none of the tubes had been breached.

Figure 3: The polyethylene cavity after being slid out of the stainless steel envelope.

Figure 4: A close-up view of the most damaged tube from the drop test mock-up. While wrinkled, the tube has not been breached. The tube is being held above its installed position in the mockup for this photo.

Task 3. Assemble a "Full-Up" BF_3 Detector

Besides optimizing the neutron sensitivity, the detector was fabricated in order to incorporate several BF_3 leak mitigation strategies. The polyethylene moderator cavity was fabricated by machining the recess which the BF_3 tubes occupy, out of a solid billet of plastic. This was done to minimize the number of seams and joints that the cavity would have, all of which would be potential leak paths. The cover for this cavity was sealed to the cavity by an O-ring installed in a machined groove in the top edge of the cavity. The cover was screwed to the cavity, compressing the O-ring, by an array of stainless steel screws that threaded into brass inserts that were installed in the cavity. The brass inserts provided a higher quality thread for attachment as opposed to threading directly into the plastic. The thickness of the back of the cavity, behind the tubes, was 5.08 cm (2 inches). The depth of the recess in which the tubes were installed was also 5.08 cm (2 inches). The thickness of the front polyethylene cover was 1.9 cm (0.75 inch).

Three stainless steel BF_3 tubes were installed into the cavity. The tubes were manufactured by LND Inc., and were filled with BF_3 at 96% ^{10}B enrichment, to one atmosphere. The tubes have a 5.08 cm (2 inches) diameter, and a 183 cm (72 inches) active length. In order to minimize the risk associated with developing custom electronics at this time, commercial-off-the-shelf electronics were used. Compact neutron electronics modules were obtained from Precision Data Technology. These modules provided tube bias voltage and signal conditioning in one small package that could be mounted directly onto the BF_3 tubes' HN fittings. The modules from each tube were connected in daisy chain fashion and provided a TTL pulse train with one pulse corresponding to one neutron event in the aggregate detector. The modules only require 12VDC power to operate.

After the tubes were installed in the cavity, the interstitial space was filled with a blend of poly and alumina (Al_2O_3) beads. (Figure 1) The alumina provided another level of mitigation for the BF_3 hazard. The alumina reacts irreversibly with the BF_3 and sequesters it, so it is not freely released to the environment. A 3mm bead size was decided on for the materials as a compromise between providing a large bed surface area and still allowing flow of gas to permeate the bed without requiring significant driving pressure. The alumina and poly beads were mixed 50/50% by weight, and the space between the tubes was completely filled with the blend. The poly beads added slightly to the neutron moderation, and were taken into account in the MCNPX modeling.

As a final layer of mitigation, the entire detector was installed inside a stainless steel envelope. This was fabricated from 16-gauge type 304 stainless steel. All seams were welded over their full length. The detector slides into the envelope from one end and a stainless steel cover is then sealed with silicone, and screwed in place. Two sealed bulkhead penetrations exit the top of the detector, and provide connections for 12 VDC input, and the TTL pulse output.

Task 4. Developmental tests of the BF_3 detector at BNL

Neutron detection sensitivity was evaluated at the site of BNL's, former RAdiation Detector Test and Evaluation Center (RADTEC) . This area provided a section of paved roadway along which concrete footings for mounting portal monitors were available for detector mounting. The module, without its stainless steel envelope, and not installed in its NEMA 4 enclosure or steel shroud, was mounted on a footing. DNDO Functional Requirements Document (FRD) For Radiation Portal Monitor System (RPMS) ^3He Neutron Detection Module (NDM) Replacement", delineates some performance criteria for the prototype NDM replacement. The neutron sources used for evaluation of this detector contain a mixture of ^{252}Cf and ^{250}Cf, and have a fair fraction of their neutron emission attributed to their ^{250}Cf content. The neutron flux of these sources is well understood. The sources used produced a neutron flux of 21,475 N/sec at the time of the testing. The current assumption of one nanogram of ^{252}Cf producing an emission rate of 2100 N/sec implies that the equivalent ^{252}Cf mass that our sources represent is 10.226 nanograms. Table 1 contains the results of the final testing of the NDM. The measurements indicate that the module's sensitivity to this source.

BF_3 NDM Replacement Neutron Sensitivity Test Data					
Measurement type	Time (sec)	Total Counts	Count rate (N/sec)	Net Count Rate (N/sec) (source – bkg)	Sensitivity (N/sec/ng of ^{252}Cf at 2 meters) Target = 2.5
background	4000	10,641	2.66	-	-
Cf source	300	8574	29.1	26.44	2.59
Cf source	300	8832	29.4	26.74	2.61
Cf source	300	8785	29.3	26.64	2.605
Sum of three	900	26,371	29.3	26.64	2.605

Table 1. BF_3 NDM Neutron Sensitivity Test Data

The insensitivity of the neutron detector to gamma ray-induced neutron counts was also evaluated. Requirement of the FRD states “The NDM shall not cause the RPMS to alarm on neutrons when exposed to gamma radiation at an exposure rate of up to 20 mR/h (threshold).” This behavior was evaluated in BNL’s Low Scatter Irradiation (LSI) facility, where a gamma source of an appropriate magnitude was available. Due to the presence of other neutron sources in the facility that cannot be removed, the neutron background reported is significantly higher than the background at the former RADTEC site. The module was moved into the LSI and placed horizontally on the remote controlled positioning stage such that the detector centerline was aligned with the “source-deployed” location. A 196 millicurie ^{137}Cs source was remotely deployed, and the detector position remotely adjusted to produce a 20 mR/hr field at the center of the detector face. Several sets of count rate data were collected. The ^{137}Cs source was retracted, and a set of “background” neutron count rate measurements was collected. Table 2 presents some of the data that was collected. There is no evidence of any increase in the measured neutron count rate when the detector was exposed to a gamma field of 20mR/hr from ^{137}Cs.

BF_3 NDM Replacement Module Gamma Insensitivity Test Data			
Measurement Type	Time (sec)	Counts	Count Rate (N/sec)
20 mR/hr ^{137}Cs	300	15,172	50.573
20 mR /hr ^{137}Cs	300	15,023	50.077
20 mR /hr ^{137}Cs	300	14,978	49.927
sum	900	45,173	50.192
LSI background	300	15,192	50.64
LSI background	300	15,073	50.24
LSI background	300	15,120	50.4
sum	900	45,385	50.428

Table 2. BF_3 NDM Module Gamma Insensitivity Test Data

Task 5. Performance tests

An assembly of the completed detector, a NEMA 4 enclosure, and a standard portal monitor steel shroud was shipped to the Nevada National Security Site (NNSS) for inclusion in a DNDO test of alternative neutron detection modules.

Results of Testing:

The BNL detector performed without mishap during the DNDO Test campaign in Nevada. It met all of the functional and dimensional requirements specified by DNDO; and is considered (by BNL) to be a viable alternative to ^{3}He for neutron detection.

Continuation Work at BNL:

After the independent Government Test Campaign and drop tests were completed, BNL was tasked (by DNDO) to re-evaluate the design using MCNP calculations to continue to optimize performance and cost. This optimization process for the BF_3 design was to encompass the following design considerations: the tube pressure, operating voltage, design of the indicator for the BF_3 leak detection on the secondary containment (if any), survivability in the drop test, reduce electronic costs, and location and amount of “Getter Material” to neutralize the gas within the secondary containment.

Unfortunately, the funding for these tasks was “zeroed out” by the funding agency with only a partial fulfillment of the tasks was able to be accomplished by BNL.

These additional data will be presented at a later time.

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References:

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