LOCKHEED MARTIN

**PORTSMOUTH
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PLANT**

**Determination of the Response
Function for the
Portsmouth Gaseous Diffusion
Plant Criticality Accident
Alarm System Neutron
Detectors**

By
Robert W. Tayloe
Angela S. Brown
M. Christian Dobelbower
Jeffrey E. Woollard

March 1997

LOCKHEED MARTIN UTILITY SERVICES, INC.
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By
Robert W. Tayloe, Jr.
Angela S. Brown
M. Christian Dobelbower
Jeffrey E. Woollard

Battelle
Columbus, Ohio

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LOCKHEED MARTIN UTILITY SERVICES, INC.
Portsmouth Gaseous Diffusion Plant
P.O. Box 628 Piketon, Ohio 45661

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1.0 INTRODUCTION

Neutron-sensitive radiation detectors are used in the Portsmouth Gaseous Diffusion Plant's (PORTS) criticality accident alarm system (CAAS). The CAAS is composed of numerous detectors, electronics, and logic units. It uses a telemetry system to sound building evacuation horns and to provide remote alarm status in a central control facility.

The ANSI Standard for a CAAS [Am86] uses a free-in-air dose rate to define the detection criteria for a minimum accident-of-concern. Previously, the free-in-air absorbed dose rate from neutrons [He93] was used for determining the areal coverage of criticality detection within PORTS buildings handling fissile materials. However, the free-in-air dose rate does not accurately reflect the response of the neutron detectors in use at PORTS.

Because the cost of placing additional CAAS detectors in areas of questionable coverage (based on a free-in-air absorbed dose rate) is high, the actual response function for the CAAS neutron detectors was determined. This report, which is organized into three major sections, discusses how the actual response function for the PORTS CAAS neutron detectors was determined. The CAAS neutron detectors are described in Section 2. The model of the detector system developed to facilitate calculation of the response function is discussed in Section 3. The results of the calculations, including confirmatory measurements with neutron sources, are given in Section 4.

2.0 DESCRIPTION OF THE DETECTOR

All detectors in the PORTS CAAS are of the neutron scintillation type. They consist of a lithium fluoride [LiF], silver-activated zinc sulfide [ZnS(Ag)], and polyethylene mixture coated on a lucite substrate. This assembly is known as the scintillator crystal. The lithium on the scintillator crystal is enriched to 95 weight percent Li^6 . The Li^6 absorbs mostly thermal energy neutrons and emits ionizing particles. The reaction of interest is $\text{Li}^6 (n, \alpha) \text{H}^3$. The ionizing particles react with the zinc sulfide to produce photons in the visible range. The visible photons or "flashes of light" pass through the lucite substrate and are converted to electronic pulses by a photomultiplier tube. The electronic pulses are shaped and counted within the CAAS.

Two types of scintillator crystals are in use at PORTS. Both types are approximately 2 inches (5 cm) in diameter, use the same scintillating material mixture, and have a grooved surface. One crystal, however, has 6 grooved rings, whereas the other has 9 grooved rings. The different effective detection surfaces of the two types of crystals necessitated an evaluation of their respective response functions. Figure 1 is a micrograph of the cross-section of a scintillator crystal. The scintillating material is approximately 0.06 inches thick.

Several scintillator crystals in use at PORTS were examined. The crystals, of varying age, all had yellowish tints.¹ The yellowish tint of the crystals may decrease photon transport to the photomultiplier tubes, thereby decreasing detection efficiency. However, the effect of yellowing was not analyzed.

¹ Possible causes of this yellowing might be repeated exposure to environments of elevated temperatures for extended time periods or repeated exposure to intense radiation sources during calibration.

Figure 1 Cross-sectional Micrographic View of Scintillator Crystal

The scintillator crystals and the photomultiplier tubes are encased in cylindrical Mu metal² shells which act as magnetic shields. The bottom of each Mu metal shell is surrounded by a plastic Delrin® (an acetyl homopolymer plastic) spacer ring. The scintillator crystal and the photomultiplier tube within the Mu metal shell, along with photomultiplier-associated electronics, are encased in a cylindrical aluminum case that measures approximately 9 inches (23 cm) in height and slightly more than 2 inches (5 cm) in diameter. The resulting unit is referred to as the detector.

The aluminum casing around the detector is inserted about 2 inches into a polyethylene moderator (cup). The polyethylene cup thermalizes the faster neutrons, thereby increasing

² Mu metal is a high permeability alloy that reduces electromagnetic effects on the photomultiplier tube operation.

Figure 2 Disassembled CAAS Detector

detection efficiency. The cup itself is about 1 inch (2.5 cm) thick on the sides and 2 inches (5 cm) thick on the bottom. A disassembled CAAS detector is shown in Figure 2. A scale diagram of a PORTS CAAS detector is shown in Figure 3.

In normal usage, three CAAS detectors are enclosed in a steel box. This group of three detectors in the box is called a CAAS cluster. In addition to the detectors, the cluster also contains electronics associated with shaping, counting, and logically evaluating the pulses from the photomultiplier, and batteries to provide backup power. The cluster box is about 25.5 inches (65 cm) long, 24.5 inches (62 cm) high, and 12 inches (31 cm) wide. The entire unit weighs about 90 pounds (40 kg). When the door to the box is open, as shown in Figure 4, the three detectors are easily seen. The batteries that supply backup power are located above the detectors. On the door, in front of the detectors, is most of the electronic hardware used in the pulse shaping, counting, and logic for determining trouble or alarm status. A schematic view of the back of the cluster is shown in Figure 5.

NOTE: A thin Al sheet is located immediately to the left of the LiF-ZnS-Poly Mix.
 Also a thin red plastic end cap is not shown.
 Geometry is cylindrical around detector centerline (dashed line).

Figure 3 Scale Diagram of CAAS Detector

Figure 4 Inner View of a CAAS Cluster

Within a cluster, each detector has a light emitting diode (LED) near its scintillator crystal. The LED provides a constant source of light pulses or "live background." If the live background for a single detector falls below a predetermined rate, a trouble indication is given. This trouble indication is also given if a detector functions outside of other predetermined parameters, such as count rate. However, if two of the three detectors in a cluster malfunction or have a count rate above the set point, the CAAS alarms [Op85].

Figure 5 Schematic View of the Back of a CAAS Cluster

The alarm set-point is checked and, if necessary, adjusted during periodic calibration of each CAAS cluster. During the calibration procedure, the cluster is exposed to a Cf^{252} neutron source at a fixed distance. The CAAS detectors are calibrated to alarm at or slightly below a count rate of 60,000 counts per minute [Ca96]. A detector response unit (DRU) is equivalent to a CAAS detector count rate of 60,000 counts per minute. A calculated detector response greater than or equal to 1 DRU indicates that the CAAS is expected to alarm.

3.0 ANALYSIS

The Monte Carlo N-Particle (MCNP) code [Br93] was used to perform the radiation transport analysis of the detectors. The MCNP uses the Monte Carlo method to track particle histories, thereby simulating the behavior of these neutrons in scattering and absorbing media. For individual histories, the likelihood of scattering or absorption is based on physical laws and parameters derived from theory and empirical data. The Monte Carlo simulation uses statistical methods to calculate the results. For this analysis, results correspond to detector response.

Complex three-dimensional models of physical objects were created with the MCNP by representing the surfaces of objects using surface equation parameters. The surfaces were combined using Boolean logic to describe volumetric regions. Each region was assigned element or mixture properties and respective densities. From these material descriptions, macroscopic cross sections were calculated by the MCNP for each region. Point-wise cross sections, derived from evaluated nuclear data files (ENDF/B-V) and supplied with the MCNP, were used [Mc94]. Thus, the CAAS scintillator crystal, detector, and cluster unit were precisely described.³

The model of the detector geometry used in the MCNP is shown in Figure 6. This cut-away view of the detector was created with the SABRINA code [Va93] to show the polyethylene moderator, the scintillator crystal, and other detector components. The lines leading into the polyethylene moderator represent neutron "tracks." The scattered neutron tracks are clearly distinguishable in the polyethylene. This small number of tracks (several hundred) was produced to illustrate the geometry model and the history tracking used in the MCNP. In the actual evaluation, several million histories are tracked. The count rate of the detector is proportional to the rate at which neutrons are absorbed by the Li^6 in the scintillator crystal. This count rate is the parameter used in the MCNP calculational results.

³The scintillator crystal with nine concentric grooves was explicitly included in the geometry model.

Figure 6 SABRINA Representation of CAAS Detector and Neutron Particle Tracks

The materials of construction of the PORTS CAAS detectors, as used in the calculation of the response function, are given in Table 1. The photomultiplier was assumed to be an aluminum right circular cylinder with a density of 0.13 grams per cubic centimeter.

Table 1 CAAS Detector Materials of Construction

Substance	Molecular Formula	Molecular Weight	Density (g cm ⁻³)	Elemental Constituents	Weight Percent	Atom Density (atoms cm ⁻¹ barn ⁻¹)
Aluminum	Al	27.0	2.70	Al	100	0.060
Polyethylene	CH ₂	14.0	0.92	C	86	0.040
				H	14	0.079
Lucite	C ₅ H ₈ O ₂	100.0	1.18	C	60	0.036
				H	8	0.057
				O	32	0.014
Mu Metal		58.2	8.5			
				Cr	2	0.065
				Fe	18	0.016
				Ni	75	0.004
	Cu			Cu	5	0.002
Delrin® (Black Plastic)	CH ₂ O	30.0	1.42	C	40	0.029
				H	7	0.057
				O	53	0.029
CRYSTAL MIX*			2.3			
63 wt %	ZnS**	97.5		Zn	42	0.009
				S	21	0.009
21 wt %	LiF	25.1		Li ⁶	5	0.011
				Li ⁷	0.3	0.001
				F	16	0.011
16 wt %	CH ₂	14.0		C	14	0.016
				H	2	0.032

* Scintillation coating of the detector crystal is a homogenous mix of 3 substances.

** Zinc sulfide is silver activated. However, the quantity of silver is insignificant to the transport of neutrons and was not included in the model of the CAAS detector.

First, the response function of a single detector was calculated. Then, the model of a CAAS cluster unit was developed. The steel box was modeled with height, width, and depth of 61.0, 61.2, and 25.4 centimeters, respectively. The steel box was assumed to be iron with a density of 7.92 grams per cubic centimeter. Although the actual thickness of the box is less than 1.0 cm, the thickness was modeled as 1.0 cm. The relative transparency of steel to higher energy neutrons makes this difference relatively unimportant.

Three detectors and objects representing a battery box and the electronics were included within the cluster unit. The three detectors were spaced 18.5 centimeters center-to-center. The far right detector, as viewed from the rear of the cluster, is designated the first detector and is 11.2 centimeters from the right most inner surface of the steel box.

The three batteries were modeled as a single unit having a height, width, and depth of 21.0, 54.0, and 18.4 centimeters, respectively. The battery unit is positioned above the detectors in the back upper right corner of the steel box, as viewed from the rear of the unit. The battery unit was assumed to have a density of 1.34 grams per cubic centimeter and was represented by a water and lead mixture. The weight fractions for the elements hydrogen, oxygen, and lead were 0.08, 0.54, and 0.28 centimeters, respectively.

Lastly, the electronics were modeled as being a rectangular box of copper with a density of 2.24 grams per cubic centimeter. The height, width, and depth of the electronics were 3, 33, and 53 centimeters, respectively. The electronics were located in the front of the detectors, flush with the inner steel surface. The bottom of the electronics parallelepiped corresponded to the bottom of the inside of the steel box. The electronics were centered within the steel box.

The CAAS detector response function was determined by calculating the number of Li^6 reactions occurring within the scintillator volume of a single detector from a monoenergetic neutron source using a track length tally estimator. This calculation was performed for monoenergetic neutron sources of energy ranging from 1×10^{-9} MeV to 20 MeV. The number of detector counts is directly proportional to the number of $\text{Li}^6(n, \alpha)\text{H}^3$ reactions occurring within the crystal. The proportionality constant, or calibration factor, was determined experimentally with a Cf^{252} neutron source. The MCNP calculation for the determination of the calibration factor and confirmatory measurement used a geometric model of the CAAS cluster.

A supplemental analysis was performed to examine the effect of changing the thickness of the cylindrical polyethylene moderator surrounding each detector. The cylindrical wall thickness was varied from 0 to 2 inches (0 to 5 cm), at which point the moderator for the three detectors would touch. In this analysis, the CAAS detectors' responses to a spherical shell source, centered around the scintillation crystal of the center detector was calculated. The response to three neutron source spectra, Cf^{252} [Co90], the Godiva critical assembly leakage spectrum [Co78], and the SHEBA critical assembly neutron spectrum measured at 69 meters [Fi83], was calculated.

4.0 RESULTS

The response function of the CAAS detector for neutron energies between 1×10^{-9} and 20 MeV is shown graphically in Figure 7 and in tabular form in Table 2. The response functions for both the 6-ring and 9-ring scintillator crystals are given. Their responses show little difference. Subsequent analyses were performed using the detector with the 9-ring scintillator crystal only.

The shape of the response function is primarily affected by two factors, the $\text{Li}^6(n, \alpha)\text{H}^3$ reaction cross-section and the polyethylene moderator surrounding the detector. The polyethylene is thick enough to prevent most thermal neutrons from entering the crystal. The $\text{Li}^6(n, \alpha)\text{H}^3$ reaction cross-section is relatively small at high neutron energies.

Figure 7 CAAS Detector Neutron Response Function with 6-Ring and 9-Ring Scintillation Crystals

Table 2 Detector Response Function

Energy (MeV)	6-Ring Detector Response Function (detector counts neutron ⁻¹ cm ²)	9-Ring Detector Response Function (detector counts neutron ⁻¹ cm ²)
1.00E-09	0.49	0.46
1.00E-08	0.64	0.61
1.00E-07	1.24	1.20
5.00E-07	1.93	1.91
1.00E-06	2.13	2.17
5.00E-06	2.56	2.52
1.00E-05	2.66	2.62
5.00E-05	2.64	2.67
1.00E-04	2.66	2.53
5.00E-04	2.60	2.57
1.00E-03	2.66	2.53
5.00E-03	2.43	2.43
1.00E-02	2.34	2.36
2.00E-02	2.29	2.25
5.00E-02	2.23	2.24
1.00E-01	2.22	2.24
5.00E-01	1.91	1.91
1.00E+00	1.56	1.58
2.00E+00	1.12	1.13
5.00E+00	0.55	0.55
1.00E+01	0.25	0.25
2.00E+01	0.14	0.14

The response function was experimentally confirmed using Pu-Li and Pu-Be neutron sources. A Cf²⁵² [Co90] source was used to determine the ratio of predicted Li⁶(n,α)H³ reactions to physical detector counts, and a calibration factor of 1.47 was obtained. The results of the confirmatory measurements and the respective values calculated with the MCNP are given in Table 3.

Table 3 Experimental Versus Calculated Detector Response

Source	Source Neutron Activity (n sec ⁻¹)	Experimental Detector Counts	Calculated Detector Counts	Calculated to Experimental Ratio
Pu-Li	5.3x10 ⁵	26,200	23,600	0.90
Pu-Be	6.0x10 ⁶	18,600	20,000	1.08

Each measurement showed agreement within 10 percent with the values calculated using the MCNP. However, the Pu-Be source was not a well-characterized source. Variances in the values for the number of neutrons generated per second per Curie varied from 1×10^6 to 2.2×10^6 in the literature [An68, Pa91]. Because of this range, the calculated number of detector counts from the Pu-Be had a large range. However, the measured value was within this range.

The azimuthal angular dependency of the cluster was determined through calculations and confirmed by measurement. A Pu-Be neutron source, at 1 meter, was placed at various azimuthal angles relative to a CAAS cluster, as shown in Figure 8. The results of the calculation and measurement are given in Figure 9 and Table 4. The response is severely depressed in the center detector at an azimuthal angle of 90 degrees because the far left detector blocks the source from the center detector.

Figure 8 Azimuthal Angles for Determination of Angular Response of a CAAS Cluster

Figure 9 Experimental and Calculated Azimuthal Angular Detector Response to a Bu-Be Neutron Source Located 1 meter from the Center of Detector 2.

Table 4 Azimuthal Angle Detector Response

Azimuthal Angle (degrees)	Experimental Detector Counts			Calculated Detector Counts		
	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
0	15872	16491	17135	15763	18987	16479
45	11969	15159	20970	13685	18342	18808
90	4185	6764	25723	4156	8025	25113
135	13718	16305	19845	11177	16587	19775
180	15638	15962	16396	13255	13972	13506

The response of the CAAS to various neutron sources as a function of polyethylene moderator thickness is shown in Figure 10. The detectors have a 1-inch thick polyethylene moderator. The most probable neutron spectrum in a criticality accident is the SHEBA spectrum. For this spectrum, the detector response was at a maximum with a moderator thickness of 1.5 inches. However, the maximum response was only about 10 percent greater than expected with a 1-inch moderator.

Figure 10 CAAS Response as a Function of Polyethylene Moderator Thickness

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