CAAS-3S Radiation Testing for Y-12 and UPF with Godiva-IV

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ABSTRACT

The Y-12 National Security Complex and the Uranium Processing Facility (UPF) selected the Mirion CAAS-3S as the Criticality Accident Alarm System for UPF and for Y-12 facilities replacing their legacy CAAS as part of efforts to extend the facility lifespans. As part of this process, the CAAS-3S system was exposed to a high radiation dose and dose rate during reactor testing with the Godiva-IV fast burst reactor. The reactor testing was designed around preliminary analyses that determined Y-12 and UPF requirements, and simulations of the radiation field within the reactor facility were used to determine reactor operating parameters, CAAS equipment locations, and the design of a neutron shield wall. This paper presents the design and results of the testing, and discusses how the test results were interpreted by criticality safety engineers at Y-12 and UPF.

Key Words: CAAS, Godiva, Burst Testing, NCS

1 INTRODUCTION

The Uranium Processing Facility (UPF) and the Y-12 National Security Complex are installing a new Criticality Accident Alarm System (CAAS) and replacing older CAAS, respectively, to support future site operations. The Mirion CAAS-3S was selected as the uniform CAAS for UPF and for the Y-12 replacement systems. The preliminary design for the UPF CAAS identified a number of system requirements for the qualification of the CAAS, shown in Table 1. These requirements applied to every component of the system, including the probes and electronics cabinets.

Table I. UPF System Requirements

Requirement
Fluence: 1 MeV equivalent neutron fluence of at least 6.0 x 10^9 n/cm^2.
Dose: neutron dose of at least 0.5 rad(Si) and photon dose of at least 25 rad(Si).
Dose Rate: neutron dose rate of at least 4.0 x 10^2 rad(Si)/s and photon dose rate of at least 2.4 x 10^4 rad(Si/s)

These system requirements were higher than what had been previously demonstrated for the system, resulting in a need for reactor testing of the system. Y-12 did not set a specific system requirement, but the need for reactor testing became apparent during the design of the replacement CAAS for one of the legacy facilities. Notable features of the UPF system requirements are that the criteria are in units relevant to radiation effects on electronics, and that the dose is dominated by the photon contribution. These requirements are similar to requirements that could be derived from preliminary calculations performed for the Y-12 installation. Because Y-12 and UPF would equally benefit from the reactor testing, Y-12 and UPF decided to collaborate on the testing campaign.

The reactor testing with the Godiva-IV reactor was performed during January 2021 at the National Criticality Experiments Research Center (NCERC). Godiva-IV is a well-characterized burst reactor using highly enriched uranium alloy fuel, and is reasonably representative of the radiation spectra anticipated during unshielded accident conditions at Y-12 and UPF. A detailed description of Godiva-IV is contained in HEU-MET-FAST-086. For all CAAS analyses, Y-12 and UPF use a set of standardized sources. A representative source was used in conjunction with a MCNP model of the facility to locate equipment for irradiations. Because of differences between NCERC and the proposed installation, a high density polyethylene (HDPE) shield wall was constructed to decrease the neutron dose and thus increase the relative contribution of photon dose.

This paper represents the efforts of Y-12 and UPF personnel, and their interpretation of the test results.

A secondary goal of the measurement campaign was to determine whether Y-12's MCNP shielding validation, which uses a variety of dose responses but explicitly not the electronics-relevant responses, could be extended to rad(Si). The MCNP shielding validation recommends a minimum safety margin of two due to uncertainties in the materials of construction, nuclear data, and responses. Results consistent with a factor of two safety margin support the use of the MCNP shielding validation, and actual safety basis calculations may use a higher margin of safety due to other considerations.

1.1 Mirion CAAS-3S system

The reactor testing used the Mirion CAAS-3S system. As tested, the system consists of at least one cluster of three detector probes, set to indicate alarm at 1V (roughly equivalent to 50 mrad/h), with a power supply, processing, and alarm cabinet. Two safety programmable logic controllers (Safety PLCs) are used to independently initiate an alarm signal. A photograph of the CAAS-3S cabinets is shown in Figure 1, with the leftmost (black) cabinet being the alarm cabinet, middle cabinet the power supply, and the rightmost cabinet the processing cabinet. The power supply cabinet is primarily a series of batteries, and was considered prior to irradiation to be relatively robust against radiation. The alarm cabinet is a series of electric switches, and similarly was considered to be robust against radiation prior to irradiation. The processing cabinet, however, contains computer components, and was anticipated to be the least radiation tolerant of the three cabinets prior to irradiation.

Figure 1. CAAS-3S cabinets.

Prior to any irradiations, the system behavior to be considered in analysis was determined. CAAS at Y-12 and UPF performs a variety of functions, including data-logging for dose reconstruction, remote reset, and ability to monitor radiation dose rates after an accident. Some of these functions were considered by the selection committee during system selection. For this testing campaign, system responses were grouped into two categories: safety function and secondary function. The safety function of the system is interpreted as the system alarming when at least two of three probes are exposed to a dose rate exceeding the alarm threshold. All other functions are considered secondary. As a system, secondary functions are required to be operational to reset from an alarm and prior to an accident, but can fail during the performance of the safety function.

1.2 Simulation-Driven Design

UPF and Y-12 will use MCNP, with ADVANTG variance reduction, to design the CAAS installation and develop the safety basis documentation for the systems. These calculations will use standardized assumptions, especially with regards to materials and accident characteristics. Any assumptions, approximations, and biases in the safety basis analysis methodology need to be quantified and addressed. By using the same simulation methodology in the design of the reactor testing, the effects of the assumptions, approximations, and biases can be consistent between the various analyses and directly compared against the measured data during the burst testing.

The sources used in the Y-12 and UPF CAAS placement and maximum accident calculations are unreflected HEU-water critical systems, with moderation ranging from 15 gU/l to pure metal, and spherical geometry. To represent Godiva-IV, a metal HEU accident was used. Because of the difference in geometric buckling between the the accident and a simplified Godiva-IV geometry, the modeled accident is anticipated to have ~70% of the leakage of Godiva-IV, and would be anticipated to lead to a negative bias in the calculation, which was not accounted for in the calculation.

CAAS shielding analysts used cabinet masses, layout, and construction from Mirion to generate MCNP models of the cabinets, with a number of tally locations per cabinet, shown in Table II. Tally locations included cabinet exterior and interior locations, with "front" referring to the face furthest from the reactor, and "rear" referring to the face nearest the reactor. Tallies included a number of representations of the dose, including kerma (air, tissue, and Si), dose equivalent, and silicon damage.

Table II. Cabinet Tally Locations

Cabinet	Designation	Location
Power Supply	PS	cabinet interior lower
		cabinet interior upper
		tally front
		tally rear
Processing	PC	cabinet interior
		tally front
		tally rear
Alarm	AC	cabinet interior lower
		cabinet interior upper
		tally front
		tally rear

The cabinets were aligned on a curve in an ante-room adjacent to the reactor room, with each cabinet centered between 28 and 30 ft from Godiva. Preliminary calculations indicated that the gamma-neutron ratio could be lower than 10, depending on cabinet location, significantly lower than the ratio set in the system qualifications (50). A 2 inch thick high-density polyethylene (HDPE) wall was modeled and constructed between the reactor and the cabinets, with preliminary calculations that this would decrease the neutron dose (rad(Si)) sufficiently to shift the gamma/neutron ratio to 20-25. The HDPE shield wall was constructed from six one inch thick, four feet wide, 8 feet tall panels. As-installed, there were small gaps between the panels, which were not modeled because the gaps were staggered and there were no direct streaming paths. The layout of the cabinets and shield wall within the anteroom are shown in Figure 1. In Figure 1, AC corresponds to the alarm cabinet, PC the processing cabinet, and PS the power supply.

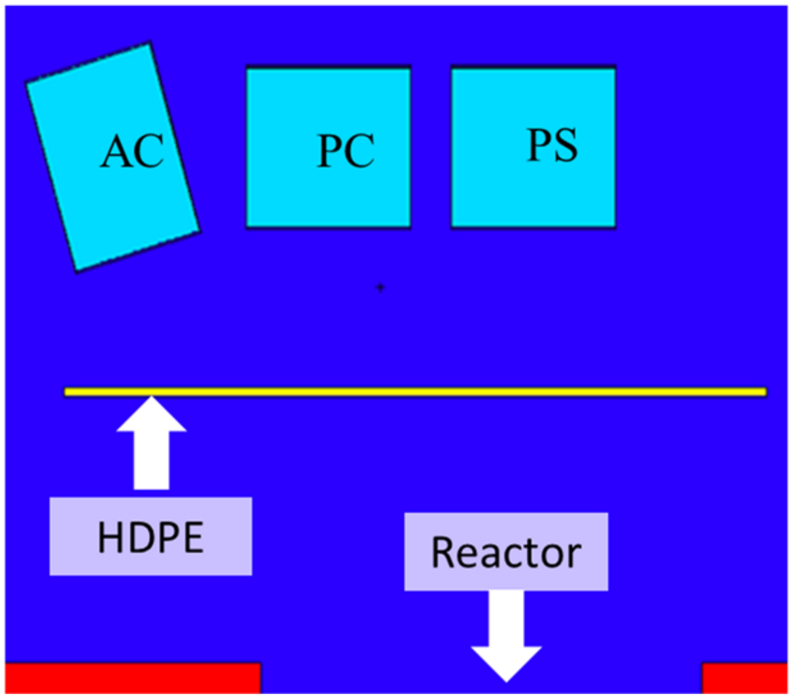

Figure 1. CAAS-3S cabinet Layout in Simulation.

1.3 Reactor Irradiations

Five irradiations were performed over four days, three of which were burst operations, two of which were steady-state operations. A summary of the irradiations is presented in Table III. In addition to the five irradiations, a number of low-power delayed critical operations were performed prior to each irradiation as part of normal reactor operations, but did not represent significant doses or dose rates.

Table II. Godiva-IV Operating Parameters

Burst						
Irradiation	Date	Type	Pulse #	Temperature Rise (°C)	FWHM (μs)	Fissions
1	1/11/2021	Burst	2055	71.6	149	1.10E+16
4	1/13/2021	Burst	2056	133	55	2.00E+16
5	1/14/2021	Burst	2057	250	36	4.00E+16
Steady State						
Irradiation	Date	Type	Pulse #	Temperature Rise (amp-sec)	Length (min)	Fissions
2	1/12/2021	Steady State	n/a	1.24E-03	41	8.68E+15
3	1/13/2021	Steady State	n/a	5.65E-03	28	3.96E+16
Total						1.19E+17

Irradiation five represents an accident approximately 1.1E+21 fissions/s, similar to the intensity of the maximum accident (1E+21 fissions/s) used in CAAS analysis at Y-12 and UPF. This irradiation became the basis for the dose rate qualification. The integrated fissions is significantly lower than the magnitude of the maximum accident (1E+18 fissions). Because the system behavior was consistent between all irradiations, the integrated dose and dosimetry was used as the basis for the dose qualification. Due to the short width of irradiations 1, 4, and 5, any change in system status was characterized as immediate.

During every irradiation, the CAAS-3S system alarmed immediately when exposed to a dose rate exceeding the alarm threshold. The low-power delayed critical operations prior to each irradiation exceeded the alarm threshold for the probes. During each low-power delayed critical operation, the CAAS-3S system immediately alarmed when the dose rate at the probes exceeded the alarm threshold. Immediately after irradiation 1, the computer component of the processing cabinet entered a fault state, and secondary functions were lost. The system continued to alarm, and did not cease until the computer was manually reset, at which point the system returned to normal operation. One lasting effect of the irradiation was that one of the two alarm lights on the processing cabinet was no longer functional, indicating that safety PLC A had failed, but that the system could operate on safety PLC B alone. The system was still capable of performing its safety function, and the decision was made to continue testing. After 41 minutes of alarm during irradiation 2, the processing cabinet PC component shut down, and the irradiation was terminated. The system continued to alarm until the alarm was manually terminated. Eleven minutes into irradiation 3, the computer component of the processing cabinet shut itself down, and the irradiation was continued until the planned integrated fissions was completed. Prior to this irradiation, the only confirmation of an alarm was audio, and there was no visual confirmation of strobe actuation, during which it was determined that the strobes were not actuating. Post-test diagnostics indicated that there was a wiring error preventing strobe actuation, which was demonstrated after reconnecting the strobes to the alarm cabinet. No differences in system response were seen between Irradiation 1 and Irradiation 4.

During the low-power excursion prior to Irradiation 5, the system immediately alarmed, and the processing cabinet PC component entered a fault state, and could not be remotely reset. After performing an auto-run out to shut down Godiva, personnel reentered the ante-room to reset the PC. A second establishment of delayed critical was performed, with the reactor power kept sufficiently low during this criticality so as to not initiate an alarm. Then, the burst was performed. The CAAS-3S system alarmed immediately after the pulse as confirmed by the horns alarming and visual confirmation of the strobes alarming. The PC component of the system shut down after the pulse, and could not be remotely reset.

1.4 System Qualification

A variety of dosimeters were used during the testing campaign to provide different interpretations of the radiation field. Dosimetry was provided by LANL, LLNL, SNL, and NNSS, and was mounted and interpreted using standard dosimetry methods. The dosimeters used, and what aspect of the radiation field it represents, is shown in Table IV. Each dosimeter was used during every irradiation, and most equipment had at least one of every type of dosimeter. Notably, the CaF_2 was on every component of the CAAS-3S (cabinets, horns/strobes, probes), as well as the TLD. No single dosimeter provided all of the information needed to meet the system requirements provided by UPF. However, γ, Gy (Si) is represented, as well as n, kerma (air), and a variety of representations for comparison against calculations.

Table IV. Dosimeters Used in Measurement Campaign

Dosimeter	Particle Type	Unit
PIC	γrad(air)	rad(air)
Sandia CaF_2	γ	Gy (Si)
LLNL NAD	n	rad(tissue)
TLD	γ γ n n	rem kerma (air) rem kerma, (air)
MSTS Combo	γ n	rem rem
Cr-39	fast n	rem

Using the integrated dose from all of the measurements and the dose values from Irradiation 5, the dosimetry-based component qualification is shown in Table V. The rad(si), g results are from the Sandia CaF_2 dosimeters, and the rad(air), n results are from the TLD. Dose rate qualification was determined by dividing the Irradiation 5 dosimetry by the pulse width. One limitation in using the dosimetry results is that not all dosimeters met the limit for detectability in each irradiation, and the uncertainty in the lower dose dosimetry was fairly high. For example, the $CaF_2$was below the lower detectability limit for Irradiation 1 for the horns/strobes.

Table V. Qualified Component Dose and Dose Rates Without Margin, Dosimetry-Based

Component	Rad(si), g	Rad(air), n	Rad(si)/s, g	Rad(air)/s, n
Processing	3.01E+01	2.52E+01	3.22E+05	2.72E+05
Power Supply	3.10E+01	2.67E+01	3.31E+05	2.69E+05
Alarm	2.00E+01	1.53E+01	2.09E+05	1.47E+05
Probes	1.20E+02	1.29E+02	1.40E+06	1.71E+06
Horns/Strobes	4.58E+00		5.22E+04	

The dose and dose rate qualifications are used in the safety analysis using the same calculation methods and data as the burst testing design. Additionally, rad(air) is not an ideal representation of the neutron field when applied to radiation effects on electronics. For the calculation-based qualification, Irradiation 5 was used for the dose and dose rate. The calculated gamma-ray component of the radiation dose, in rad(si), is shown in Table VI. The results indicate that the C/E ranges from 0.59 to 0.72 for this response, and that a minimum safety margin of two is appropriate for the safety basis calculations.

Table VI. Rad(si), g, Calculation and Dosimetry Results and Comparison

Cabinet	Location	Calculated [rad(Si)]	CaF2 [rad(Si)]	Calc/Exp
Power Supply	front	8.08E+00	1.19E+01	6.79E-01
Power Supply	rear	2.94E+00	4.25E+00	6.91E-01
Processing	front	6.84E+00	1.16E+01	5.90E-01
Processing	rear	4.03E+00	5.56E+00	7.25E-01
Alarm	front	4.87E+00	7.52E+00	6.48E-01
Alarm	rear	2.66E+00	4.35E+00	6.11E-01

The calculated neutron component of the radiation dose, in rad(air), is shown in Table VII. The results indicate that the C/E ranges from 0.50 to 1.19 for this response, and that a minimum safety margin of two is appropriate for the safety basis calculations.

Table VII. Rad(air), n, Calculation and Dosimetry Results and Comparison

Cabinet	Location	Calculated [rad(air)]	TLD [rad(air)]	Calc/Exp
Power Supply	front	5.26	9.7	5.42E-01
Processing	front	4.90	9.8	5.00E-01
Processing	rear	2.61	2.2	1.19E+00
Alarm	front	3.61	5.3	6.80E-01

The interpretation of neutron effects on biologic material is complex and assumptions and methods can result in large differences between representations of the biologic response. The two biologic representations of neutron dose (rad(tissue) and rem) are shown in Table VIII. The rad(tissue) results strongly differ between the calculation and dosimetry, leading to the conclusion that, not only is rad(tissue) an inappropriate representation of the neutron dose for CAAS equipment, but that the implementation of rad(tissue) in the calculation likely differs from what was measured with the LLNL NAD.

Table VIII. Neutron Biologic Calculation and Dosimetry Results and Comparison

Cabinet	Location	Neutron Kerma, rad(tissue)	LLNL Nad rad(tissue)	Calc/Exp
Power Supply	front	1.21E+01	5.46E-01	2.22E+01
Processing	front	1.09E+01	6.08E-01	1.79E+01
Processing	rear	7.39E+00	2.56E-01	2.89E+01
Alarm	front	7.92E+00	4.70E-01	1.69E+01
		Neutron Dose Equivalent, mrem	MSTS n, (mrem)	Calc/Exp
Power Supply	front	1.93E+05	9.91E+04	1.95E+00
Processing	front	1.73E+05	7.87E+04	2.20E+00
Processing	rear	1.15E+05	4.16E+04	2.77E+00
Alarm	front	1.24E+05	5.03E+04	2.47E+00

Based on the rad(air),n results and the calculated gamma-ray results, it was determined that the calculated rad(si), n results would be acceptable. The calculation-based qualified equipment dose and dose rates are shown in Table IX.

Table IX. Qualified Equipment Dose and Dose Rates Without Margin, Calculation-Based

Equipment	Rad(si), g	Rad(si), n	Rad(si)/s, g	Rad(si)/s, n
Processing	2.04E+01	9.52E-01	1.90E+05	8.89E+03
Power Supply	2.40E+01	1.04E+00	2.24E+05	9.75E+03
Alarm	1.45E+01	7.07E-01	1.35E+05	6.60E+03

2 CONCLUSIONS

In January 2021, the Mirion CAAS-3S system was burst tested with the Godiva-IV reactor in order to qualify the system to a mixed radiation dose and dose rate for installation at Y-12 and UPF. The equipment placement, including the installation of a neutron shield to more accurately represent the radiation field anticipated during accident conditions at Y-12 and UPF, was driven by MCNP modeling of the planned measurement campaign. During each irradiation, the CAAS-3S system immediately alarmed and performed its safety function when the dose rate exceeded the alarm threshold, but during each irradiation the secondary functions of the system failed and the system became non-responsive. Two representations of radiation qualification, one dosimetry-based and the other calculation-based, were developed for use at Y-12 and UPF.

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