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Publication Date

2009

LLNL-CONF-414017

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June 18, 2009

NCSD 2009 Topical
Richland, WA, United States
September 13, 2009 through September 17, 2009

ROCKY FLATS CAAS SYSTEM RECALIBRATED, RETESTED, AND ANALYZED TO INSTALL IN THE CRITICALITY EXPERIMENTS FACILITY AT THE NEVADA TEST SITE

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ABSTRACT

Neutron detectors and control panels transferred from the Rocky Flats Plant (RFP) were recalibrated and retested for redeployment to the CEF. Testing and calibration were successful with no failure to any equipment. Detector sensitivity was tested at a TRIGA reactor, and the response to thermal neutron flux was satisfactory. MCNP calculated minimum fission yield (~ 2×10^{15} fissions) was applied to determine the thermal flux at selected detector positions at the CEF. Thermal flux levels were greater than 6.39×10^{6} (n/cm^2-sec), which was about four orders of magnitude greater than the minimum alarm flux. Calculations of detector survivable distances indicate that, to be out of lethal area, a detector needs to be placed greater than 15 ft away from a maximum credible source. MCNP calculated flux/dose results were independently verified by COG. CAAS calibration and the testing confirmed that the RFP CAAS system is performing its functions as expected. New criteria for the CAAS detector placement and 12-rad zone boundaries at the CEF are established. All of the CAAS related documents and hardware have been transferred from LLNL to NSTec for installation at the CEF high bay areas.

I. INTRODUCTION

Plans are underway to install the RFP Criticality Accident Alarm System (CAAS) at the Criticality Experiments Facility (CEF) located inside the Nevada Test Site (NTS). Prior to the Rocky Flats Plant (RFP) shutdown, more than 200 neutron detectors and 10 control panels were removed from service and shipped to LLNL for potential future use. The RFP CAAS system was in operation for more than a decade before transferred to LLNL. Transfer of the RFP CAAS system to LLNL, and then, to National Security Technologies (NSTec) is a great example of the cooperative effort of the Criticality Safety Enduser Group under the sponsorship of the DOE Nuclear Criticality Safety Program. The redeployment of the RFP CAAS to the CEF represents a substantial cost saving to the government.

II. CALIBRATION AND TESTING

The CAAS system transferred to LLNL is an ANSI/ANS-8.3 compliant system. Rigorous testing and calibration program at the RFP included detector sensitivity testing at a TRIGA reactor, detector survivability testing at the Sandia National Laboratory (SNL) SPR III facility, seismic qualification tests, and electromagnetic interference testing (Ref. 1).

The CAAS neutron detector is sensitive to thermal neutrons. The detector contains LiF, which produces an alpha particle and a triton as a result of neutron interaction with Li-6. These particles are detected by the silicon diffused junction detector. The lithium fluoride has a nominal Li-6 enrichment of 95.63 wt% and Li-7 enrichment of 4.37 wt%. A preamplifier located inside the aluminum box amplifies and shapes pulses from the sensor, and passes them through a discriminator, and counting circuit to provide the alarm signal output (Ref. 1). The electronics are designed so that sixteen counts recorded in any one second time interval fires a silicon controlled rectifier, which latches a D.C. line to a low voltage condition. This condition is sensed at a central control panel. Any two such signals will generate an immediate evacuation alarm. The neutron detectors are set to alarm at 16 counts per second.

To confirm the system performance, two control panels along with 21 detectors were selected to calibrate and test at the LLNL electronic shop. Electronic calibration for the detector includes: 1) Precalibration, 2) Backup Battery Power Supply Check, 3) Amplifier Gain Adjustment, 4) Discriminator Setpoint Adjustment, and 5) Time base Generator Adjustment. Testing and electronic calibration were successful with no failure to any equipment.

Detector sensitivity is determined by TRIGA reactor testing and is verified annually. The thermal flux is measured using gold foils with/without cadmium jacket, and the corresponding counts are recorded to a detector of the reactor facility. The CAAS neutron detector is then placed at the same location, and a ratio of counts between the neutron detector and the facility detector is calculated to estimate the thermal flux equivalent to producing 16 counts per second. In the annual detector calibration, the required minimum thermal flux to alarm is 500 n/cm^2-sec.

These sensitivities were independently verified by TRIGA reactor testing at McClellan Nuclear Radiation Center, Sacramento, California in February 2008. Detector testing setup designed for thermal flux exposure is shown in Figure 1. An aluminum track was positioned at 20 degrees upward away from the reactor. Three pieces of 1 mm-thick boral attached to aluminum were used to cut down the thermal flux in the beam. Two pieces of 4”-thick polyethylene were used to thermalize the epithermal in the beam. A stand was placed for detector placement at 2 feet from the polyethylene plate. Bare and cadmium-covered gold foils were placed and centered on the aluminum stand to make flux measurements. The measurements give 3,400 n/cm^2-sec thermal neutron flux per 1,000 kW operating power while the online BF_3 proportional chamber gave an average reading of 640 cpm. To reach the desired flux level, the reactor power was reduced to 140 kW and that is corresponding to a flux level of 475 n/cm^2-sec and BF_3 counter reading of average 90 cpm. Twenty one detectors were tested, and all passed except two; one detector failed in testing and one detector was excessively sensitive to neutrons.

III. CAAS DETECTOR PLACEMENT AND 12-RAD ZONE ANALYSES

III.A. Minimum Accident of Concern`

ANSI/ANS-8.3-1997 states that a minimum accident of concern is a criticality accident in which a total absorbed dose of 20 rad at a distance of 2 m in air occurs in 60 sec. The number of fissions necessary to produce this minimum accident of concern was calculated, in which eigenvalue (KCODE) calculations were performed to determine the size of a critical metal sphere. It was assumed that Pu is composed of 95.5 wt% Pu-239 and 4.5 wt% Pu-240 with a density of 19.7 g/cm^3. It is the typical enrichment and is one of the data set described in

LA-10860-MS (Ref. 2). Criticality calculations were performed to determine 1) leakage fractions of neutrons and gamma rays from the source, 2) ν, the average number of neutrons produced per fission, and 3) energy distributions of neutrons and gamma rays.

Fig. 1. Detector Testing Setup at the MNRC TRIGA Reactor.

Configurations of the fissionable material and/or radiation test object (RTO) used in the CEF depend on the types of experiments to be performed. Because a spherical configuration is most reactive, critical configuration was modeled as a sphere. A spherical source was defined using the minimum critical mass and dimension for the Pu metal system, and the critical configuration was fine-tuned by a series of MCNP (Ref. 3) calculations to make the system critical. KCODE calculations showed that a bare sphere containing Pu has the critical radius of 5.04 cm for a Pu metal system. Leakage fractions of neutrons and gamma rays were 0.674 and 0.202, respectively. These leakage fractions were used to convert the spherical source to a point source in the subsequent MCNP calculations. Similar criticality calculations were performed for a uranium metal system, and water moderated U and Pu systems to select the lowest fission yield.

Fixed source calculations were then performed to calculate neutron and gamma ray air doses at a distance of 2 m, which determines the total fissions that produces 20 rad in one minute. The steps taken are:1) perform coupled neutron/photon fixed source calculations for neutrons and secondary gamma ray doses, 2) perform photon only fixed-source calculation for prompt gamma ray dose, and 3) estimated delayed gamma ray dose.

MCNP point detector (tally 5) was used for flux/dose calculations. For the neutron absorbed dose in air (rad-air), MCNP results are given in units of energy deposition per unit atom in air per source neutron (in MeV-b/atom-cm^2-source neutron). To convert the MCNP results to rad-air, the following conversion factor (C) was used for the Pu metal source:

$$\frac{MeV-b}{atom-cm^{2}-sn}\,x\,5.070\ x10^{-5}(atoms/b-cm)\,x\,\frac{cm^{3}}{1.225\ x10^{-3}\,grams-air}\,x\,\frac{1.602\ x10^{-6}\,erg}{MeV}\,x$$

$$\frac{rad-air-g}{100\ erg}\,x\,\frac{3.158\,neutrons}{fission}\,x\,0.674 = 1.411\times10^{-9}\ \text{(rad-air/fission).}$$

Similarly, for the neutron-induced secondary gamma ray dose, MCNP tally results are also given in units of energy deposition per unit atom in air per source neutron (in MeV-b/atom-cm^2-source neutron). The same conversion factor, 1.411×10^{-9}, was used for flux to rad conversion. For the prompt gamma ray conversion factor, the conversion factor for neutrons was multiplied by a gamma ray-to-neutron leakage ratio to account for the relative fraction of gamma rays leaking out of the fission source.

MCNP cannot calculate dose from fission product gamma rays unless detailed gamma spectrum from fission is provided. The total number of fission product gamma rays generated during 45 seconds after fission is 3.3, while the total number of the prompt gamma rays is 7.7 (Ref. 4). It was therefore, conservatively assumed that the dose from the fission product gamma rays in the first minute is the same as the prompt gamma ray dose in determining the minimum fission yield calculations.

For the absorbed dose of 20 rad at a distance of 2 m in air in 60 sec, the number of fissions for the minimum criticality accident was calculated from the formula:

$$20\ \text{(rad)} = f\ \text{(fissions)} \times \Sigma\, [y_i\ \text{(rad/fission)}]$$

where f = total fissions, y_i = doses from neutrons, secondary gamma rays, prompt gamma rays, and delayed gamma rays

Table 1 summarizes the calculated minimum fission yields of the metal and the moderated U and Pu systems.

TABLE 1. Calculated Doses at 2 m and Minimum Fission Yields.

System Type	Neutron Dose (rad/fission)	Secondary Gamma Dose (rad/fission)	Prompt Gamma Dose (rad/fission)	Fission Product Gamma Dose (rad/fission)	Total (rad/fission)	Minimum FissionYield (fissions)
Pu Metal	1.822×10^{-15}	1.633×10^{-18}	6.703×10^{-16}	6.703×10^{-16}	3.164×10^{-15}	6.321×10^{15}
U Metal	1.092×10^{-15}	8.633×10^{-19}	3.810×10^{-16}	3.810×10^{-16}	1.855×10^{-15}	1.078×10^{16}
Pu Moderated	7.260×10^{-16}	1.151×10^{-18}	5.117×10^{-15}	5.117×10^{-15}	1.096×10^{-14}	1.825×10^{15}
U Moderated	5.729×10^{-16}	1.078×10^{-18}	4.008×10^{-15}	4.008×10^{-15}	8.590×10^{-15}	2.328×10^{15}

Based on above, the lowest value of 1.825×10^{15} from the moderated plutonium source was used as the number of fissions for the minimum accident of concern. This value will conservatively envelop both moderated and metal systems. The neutron and gamma ray spectra are therefore based on those of the moderated Pu system.

III.A.1. Calculated Thermal Flux Spectrum and Thermal Flux

Using MCNP, the CEF high bay areas were modeled. Since specific concrete composition was not available for the CEF, preliminary calculations were performed using ORNL Concrete, Los Alamos Concrete, and Magnuson's Concrete to model with the least reflective concrete. Thermal flux results were lowest with the ORNL Concrete. Flux results from Los Alamos Concrete and Magnuson's Concrete were close to each other. Concrete walls were, therefore, modeled using ORNL Concrete. The accident source was positioned at the northwest corner of the room to maximize the distance between the source and the detector. Four detectors were placed at the north, south, west, and east walls.

Note that the detector is sensitive to thermal neutrons. Because the thermal flux was measured from the gold activation analysis, average thermal flux for neutron energy range from 0 to 0.4 eV (cadmium cut-off energy) was tallied for detector response. Thermal spectra of the four detector positions were calculated, and compared to the Maxwellian thermal spectrum (Ref. 5). Figure 2 compares the thermal flux spectrum against the Maxwellian at one of the four detector positions (D1). The calculated spectrum was slightly harder near the cutoff energy of 0.4 eV, but very close to the Maxwellian. Other three spectra showed the similar results.

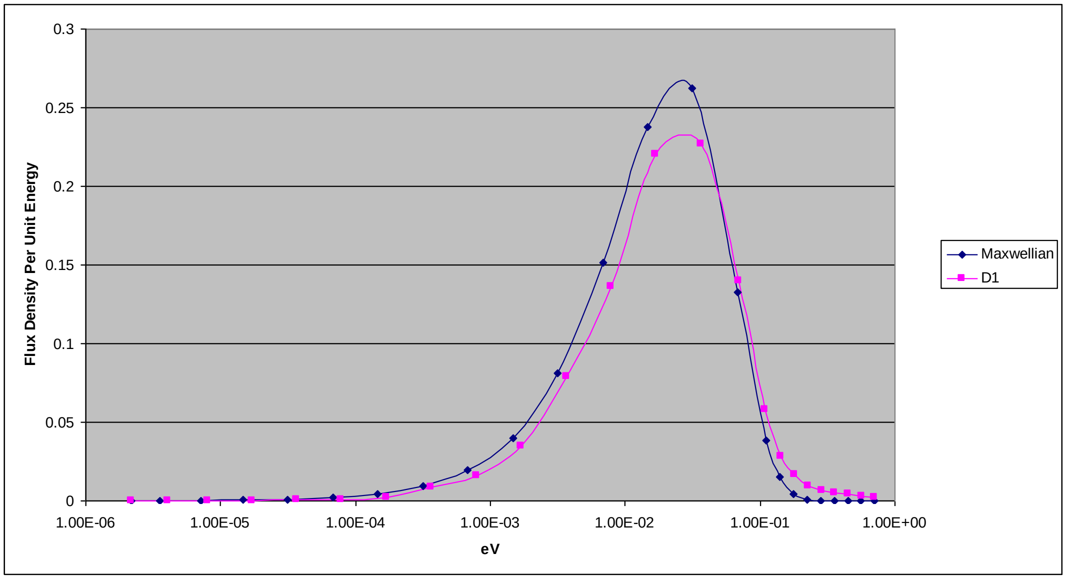

Fig. 2. Thermal Flux Spectrum Compared with the Maxwellian Thermal Spectrum.

For the minimum accident of concern, MCNP fixed-source calculations were performed to calculate the thermal neutron flux for detector positions inside a CEF high bay. Table 2 summarizes MCNP results for the four detector positions.

TABLE 2. Thermal Neutron Flux at the Detector Location.

Detector ID	Distance Between Source and Detector (ft)	Thermal Neutron Flux (n/cm^2-sec) ± 1σ	Alarm
D1	16.1	$(2.16 \pm 0.02) \times 10^7$	Yes
D2	42.2	$(1.11 \pm 0.03) \times 10^7$	Yes
D3	30.6	$(1.09 \pm 0.02) \times 10^7$	Yes
D4	65.7	$(6.39 \pm 0.2) \times 10^6$	Yes

MCNP results indicate that sufficient thermal neutrons are detected at each of the four detector positions to alarm the CAAS. Note that the minimum thermal flux to alarm is 500 n/cm^2-sec. Estimated thermal flux at each detector position is at least four orders of magnitude greater than the minimum alarm flux. Thermal neutrons for varying distance from the source was independently calculated (see Figure 3) using COG (Ref. 6) in which one metal and two solution cases were considered for a fission yield of 10^{15}. These COG results, an independent code system, supports the conclusion that the MCNP calculations can be relied upon.

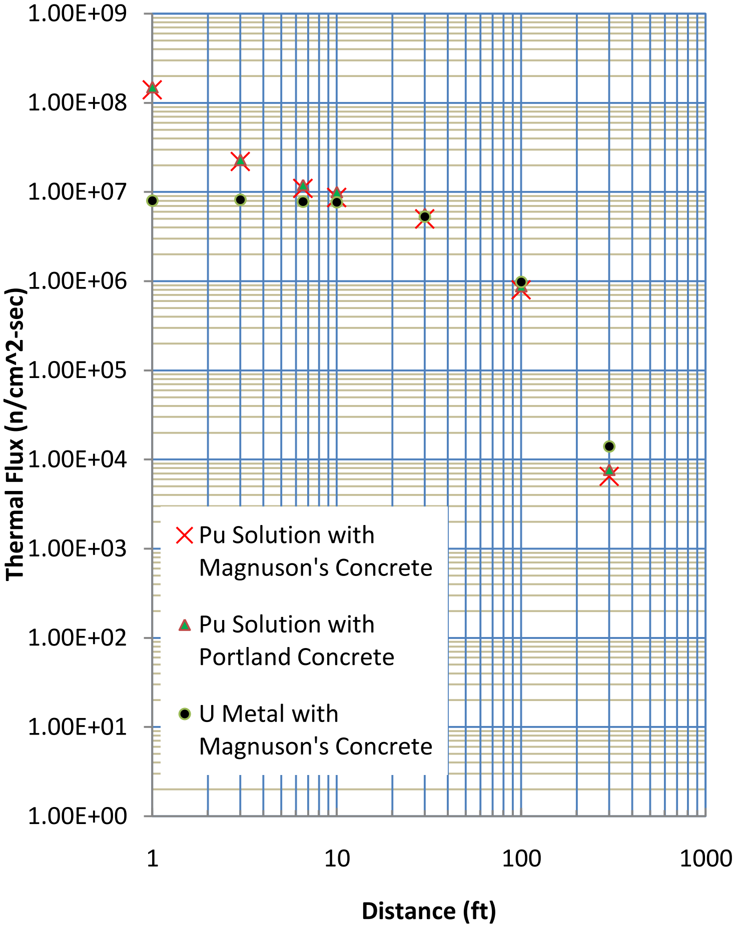

Fig. 3. COG Results for 10^{15} fissions.

III.B. Detector Survivability

Fifteen detectors were tested at the SNL SPR III reactor in January 1991 to determine detector response to the maximum design basis criticality accident level (Ref. 1). Five detectors were placed 18" from the core centerline, and were exposed to fast neutrons that correspond to 2×10^{17} fissions for a 90 µs pulse width. All five were destroyed. Another five detectors were placed at the same position, and exposed to 6×10^{16} fissions for a 400 µs pulse. All five detectors successfully counted and alarmed. The last five detectors were placed at 109" from the core centerline. At this distance, all detectors counted and alarmed for both a 400 µs 6×10^{16} fission pulse and 80 µs 1×10^{17} fission pulse. Based on the tests, the maximum survivable neutron fluence of the detector was determined to be approximately 6.0×10^{12} (n/cm^2), and a maximum dose rate of 3×10^8 rads (Si)/sec. Each of these criteria is analyzed for a maximum accident for the CEF building environments.

The primary fissionable materials handled at the CEF will be plutonium and high enriched uranium in the form of metal alloys, and oxides. Historical excursions for moderated and reflected solids and the basis for the total fission yield are discussed in the DOE Handbook, DOE-HDBK-3010-94 (Ref. 7). According to the handbook, "Given the types of situations encountered in DOE facilities where it is difficult to accumulate the quantity of materials required, contain the material and moderator, and assume any shape that would be unfavorable, a reference value of 1.0×10^{18} fission in a single burst is assessed to be bounding reference value and is believed to be very conservative." "This configuration covers reflected bulk metal and metal pieces or solid fines, such as powders, that are moderated and reflected." Therefore, a maximum fission yield of 1.0×10^{18} was assumed in the maximum neutron fluence calculations.

Using the Pu metal source, neutron fluence at the selected detector positions were calculated to determine the survivable distance between the source and the detector. The survivable neutron fluence for the neutron detector was reported as 6×10^{12} n/cm^2. Using the maximum fission yield of 1×10^{18} fissions, neutron fluence at the detector positions were calculated to determine the distance between the source and the detector which makes the fluence less than 6×10^{12} n/cm^2. Figure 4 summarizes the results. Four different directions were considered in moving the critical source in the survival distance calculations. 'NS' represents the source movement along the south direction from the north detector. 'NW' represents source movement along the west direction from the north detector. For this movement, the distance between the source and the north wall was kept constant (5 ft). 'ED' represents the diagonal northwest direction from the east detector. 'WE' represents the source movement along the east direction from the west detector. Calculated results indicate that the detector survival distance is 15 ft.

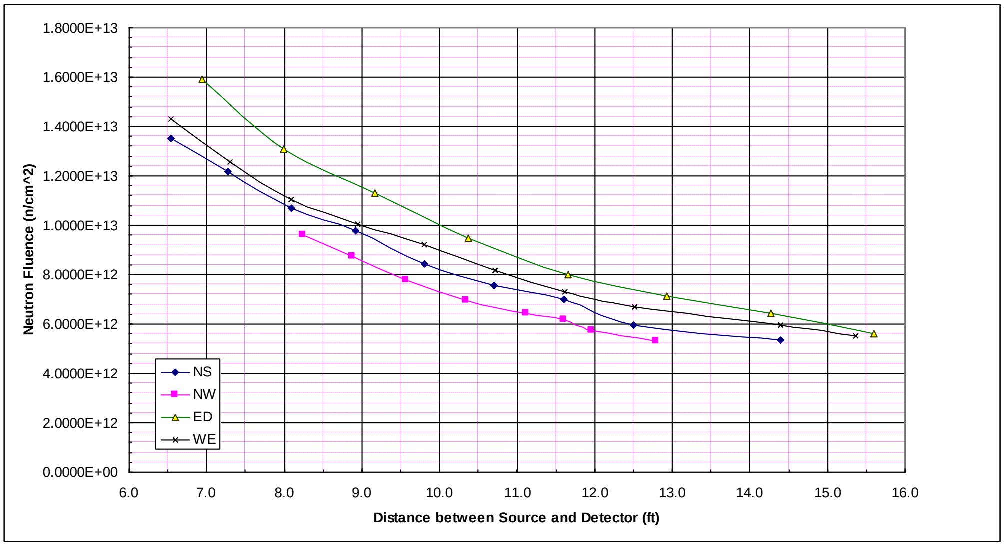

Fig. 4. Neutron Fluence vs. Source Distance from Detector.

The second criterion for survivability was also analyzed. The maximum survivable dose rate of the detectors was reported to be 3×10^8 rads/sec in silicon. As shown in Figure 4, for the distance between 14 and 15 ft, the highest neutron fluence among the three data points is 6.44×10^{12} n/cm^2 for the east detector . Calculated total dose rate for this fluence was 1.0156×10^{-15} (rad/fissions). The limiting fission rate (fissions/sec) is then calculated as:

$$3 \times 10^8 \text{ (rad/sec)} \div 1.0156 \times 10^{-15} \text{ (rad/fission)} = 2.9539 \times 10^{23} \text{ (fissions/sec).}$$

This result indicates that the detector can survive up to 2.9539×10^{23} fissions/sec. Note that the maximum fission rate of the SNL SPR III generated pulses was 2.2×10^{21} fissions/sec. The calculated maximum fission rate of the 6.2 kg Pu sphere involved in the 1945 and 1946 LANL accidents was 10^{19} fissions/sec (Ref. 8). LANL's Lady Godiva created about 10^{16} fissions in 100 μs, which is equivalent to 10^{20} fissions/sec. Results of kinetic calculations for the FRAN Prompt burst machine (Ref. 9) indicate that for 1.64×10^{18} fissions, the maximum fission rate is 1.29×10^{23} fissions/sec, which is lower than the detector limiting fission rate.

Based on above, as long as the distance between the source and the detector is greater than 15 ft, the detector will survive the maximum criticality accident of 1×10^{18} fissions with the neutron fluence less than 6×10^{12} n/cm^2, and the maximum dose rate less than 3×10^8 rad/sec in silicon.

To summarize, detectors should be placed at least 30 ft apart from each other to ensure loss of only one detector in the maximum criticality accident. The criticality alarm requires that two out of N signals be detected. If a total of three detectors are placed with 30 ft separation, one detector may be within the lethal area (less than 15 ft from accident locator), but the other two detectors will survive (2 out of 3). The minimum number of detectors required is three. It would be recommended to have at least four detectors, which provides one detector redundancy. Thus, a trouble signal in any one detector will not cause the system to be inoperable.

III.C. 12-Rad Zone Boundary Analysis

The 12-rad zone analysis was performed for the immediate evacuation zone and CAAS coverage for planned CEF operations. The bounding fission yield of 1.0×10^{18} was assumed. Volume tally (f4) was also used to check the point detector (f5) results for consistency. Buildings at the CEF were modeled, a hypothetical critical accident was assumed to occur in each of the high bays/assembly bays. Doses at varying distance from the accident source were calculated, and the 12-rad zone boundaries were defined.

VI. SUMMARY

New CAAS calibration and testing confirmed that the RFP CAAS system is performing its functions as expected. Criteria for the CAAS detector placement and the 12-rad zone boundaries at the CEF are established. All of the CAAS related documents and hardware have been transferred from LLNL to NSTec for installation at the CEF high bay areas.

ACKNOWLEDGMENTS

Special acknowledgment is given to Dave Tichota who provided valuable information about the RFP CAAS system and made significant contribution to the CAAS calibration and detector testing. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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