2010 CRITICALITY ACCIDENT ALARM SYSTEM BENCHMARK EXPERIMENTS AT THE CEA VALDUC SILENE FACILITY

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ABSTRACT

Several experiments were performed at the CEA Valduc SILENE reactor facility, which are intended to be published as evaluated benchmark experiments in the ICSBEP Handbook. These evaluated benchmarks will be useful for the verification and validation of radiation transport codes and evaluated nuclear data, particularly those that are used in the analysis of CAASs. During these experiments SILENE was operated in pulsed mode in order to be representative of a criticality accident, which is rare among shielding benchmarks. Measurements of the neutron flux were made with neutron activation foils and measurements of photon doses were made with TLDs. Also unique to these experiments was the presence of several detectors used in actual CAASs, which allowed for the observation of their behavior during an actual critical pulse. This paper presents the preliminary measurement data currently available from these experiments. Also presented are comparisons of preliminary computational results with Scale and TRIPOLI-4 to the preliminary measurement data.

Key Words: SILENE, CAAS, Benchmark, Neutron Activation, TLD

1 INTRODUCTION

In October 2010, several benchmark experiments were conducted at the CEA Valduc SILENE facility [1]. These experiments were a joint effort between the United States Department of Energy

(DOE) and the French Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA). The purpose of these experiments was to create three benchmarks for the verification and validation of radiation transport codes and evaluated nuclear data used in the analysis of criticality accident alarm systems (CAASs). Below is a discussion of the experiments, which will cover the source (SILENE), various detector types, shielding materials, and the configuration of the shielding materials and detectors around SILENE during all the experiments.

The data from these benchmark experiments is currently being evaluated for publication in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [2] as a shielding benchmark. All the preliminary measurement data currently available is presented below. Comparisons with preliminary computational results using Scale [3,4] and TRIPOLI-4®[1] [5] to the preliminary measurement data are also discussed.

2 EXPERIMENTAL DETAILS

The SILENE facility was selected for the benchmark experiments for a number of reasons: the size of the facility and ease with which detectors and shielding materials can be placed around the reactor, as well as the experience of the CEA staff with pulsed experiments and neutron activation analysis. Surrounding the reactor were a number of different shielding materials and detectors, which were arranged in three unique configurations. The remainder of this section provides more details about SILENE as the source for these experiments, the detectors used, the shielding materials used, and the three experimental configurations.

2.1 Source

SILENE was an excellent choice as a source for these experiments because it provides a neutron and photon source representative of a fissile solution criticality accident. Most shielding benchmarks use neutron sources that simulate steady state power (such as steady state research reactors, radioisotopes, or accelerators) so these experiments will represent a unique shielding benchmark that will be particularly interesting to facilities with CAASs.

SILENE is a uranyl nitrate pulsed reactor with an annular geometry. The uranyl nitrate solution is enriched to about 93 percent ^{235}U with a concentration around 71 grams of uranium per liter. A cadmium control rod in the central annular region of SILENE controls the mode of operation by varying the speed with which the control rod is removed from the fuel region. The three possible operation modes are a single pulse, multiple pulses (free evolution), and steady state. During the three experiments in this series SILENE was always operated with a single pulse. Before each pulse, but after all the detectors and shielding materials were arranged around the reactor, an approach to critical was performed to determine the critical solution height for the specific configuration. Once the final solution height was set for each pulse, additional solution above the critical height was added such that about 3 dollars of excess reactivity was inserted into the reactor. Finally, the control rod was ejected from the fuel region to be the critical excursion.

2.2 Detector Types

Four different types of "detectors" were used in this series of experiments. These include neutron activation foils, thermoluminescent dosimeters (TLDs), real CAAS detectors, and liquid scintillators. During each experiment there were a total of 65 detectors surrounding SILENE: 37 neutron activation foils, 19 TLDs, 7 CAAS detectors, and 2 liquid scintillators. For the purpose of the benchmark evaluation that will be published initially, the most important of these are the neutron activation foils and the TLDs.

[1] TRIPOLI® is a registered trademark of the CEA.

2.2.1 Neutron activation foils

The specific neutron activation foils used during these experiments were selected primarily based on the past experiences of the dosimetry staff at CEA Valduc. The foils produced a mixture of activation products sensitive to low energy neutrons and activation products resulting from reactions with high threshold energies (> 100 keV). Below in Table I is a list of the foils that were used, the activation reactions and activation products that were counted, the threshold energies of the reactions, and the half-lives of the reaction products. Note that the threshold energies are based on ENDF/B-VII cross section data [6], except for the indium inelastic scattering reaction, which is based on IRDF-2002 cross section data [7].

Table I. Neutron Activation Foils

Foil	Reaction	Threshold Energy (keV)	Reaction Product Half-life
Cobalt	$^{59}Co(n,\gamma)^{60}Co$	< 1.0	5.27 yr
Gold	$^{197}Au(n,\gamma)^{198}Au$	< 0.01	2.70 days
Indium	$^{115}In(n,\gamma)^{116m}In$	< 0.01	54.3 min
Indium	$^{115}In(n,n'\gamma)^{115m}In$	320	4.49 hr
Iron	$^{54}Fe(n,p)^{54}Mn$	853	312 days
Iron	$^{56}Fe(n,p)^{56}Mn$	2913	2.58 hr
Magnesium	$^{24}Mg(n,p)^{24}Na$	4732	15.0 hr
Nickel	$^{58}Ni(n,p)^{58}Co$	402	70.9 days

The thickness of the foils varied depending on the material type. The thinnest foil, gold, was 0.25 mm thick, while the thickest, iron, was 3 mm thick. For the most part, the thickness of one type of foil was constant between all locations and experiments, e.g. all gold foils had the same thickness. There were four locations during the experiments where all the foils listed in Table I were present and three additional locations where only the gold, nickel, and cobalt foils were present. All seven locations with neutron activation foils were inside the SILENE reactor cell, and the placement of all foils was consistent between all three experiments.

2.2.2 Thermoluminescent dosimeters

Three different types of TLDs were used in these experiments to measure photon doses. One was provided by CEA Valduc and the other two were provided by Oak Ridge National Laboratory (ORNL). The TLD provided by Valduc consisted of an Al_2O_3 powder inside a capsule of aluminum. The TLDs from ORNL each used a ^{7}LiF sintered powder, but with different activators. The ORNL HBG TLD uses TLD-700 material (^{7}Li:Mg,Ti) while the ORNL DXT TLD uses TLD-707H material (^{7}LiF:Mg,Cu,P) [8]. Inside the SILENE reactor cell there was a set of all three types of TLDs next to five of the seven sets of neutron activation foils. Additionally, two sets of the ORNL TLDs were placed outside the reactor cell. These four TLDs outside the reactor cell were in a radiological controlled area that is inaccessible while SILENE is operating, but was outside the entire primary shielding surrounding SILENE.

2.2.3 Criticality accident alarm systems

Two different types of CAAS detectors were involved with these experiments. The Babcock International Group provided three of the first type of CAAS detectors, CIDAS [9], which measures photon dose and dose rate with a Geiger-Muller tube. The CIDAS will alarm if 280 nGy is detected in less than 1 second or if the dose rate exceeds 1 mGy/hr for more than 1 sec. CIDAS detectors are currently in use at the DOE Y-12 National Security Complex in the newly constructed Highly Enriched Uranium Materials Facility (HEUMF).

Lawrence Livermore National Laboratory provided four of the second type of CAAS detectors, which had formerly been used at the Rocky Flats facility in the United States [10]. The Rocky Flats CAAS will alarm when the detected neutron flux exceeds 500 n/cm^2. These detectors use a ^{6}LiF disc to absorb neutrons adjacent to a silicon detector to count the charged particles released by these absorption events.

None of these CAAS detector results will be included in the published benchmark evaluation, but were included to observe their behavior in general. Two of the CIDAS detectors and three of the Rocky Flats detectors were placed inside the reactor cell near the neutron activation foils and TLDs. The remaining third CIDAS detector and fourth Rocky Flats detector were placed outside the SILENE cell next to the ORNL TLDs that were placed outside the cell.

2.2.4 Liquid scintillators

The final detectors involved in the experiments were two BICRON BC-501A liquid scintillators. The scintillators are both right circular cylinders with dimensions 1 inch diameter × 1 inch height and 2 inches diameter × 2 inches height. These were included in the experiments to measure the neutron and photon spectra, which was accomplished by pulse shaped discrimination. The two BC-501A detectors were set up outside the SILENE reactor cell next to the ORNL TLDs and CAAS detectors. However, this location outside the reactor cell still required additional lead shielding around the scintillators to prevent the detectors from being saturated. This data will not be released as part of the initial benchmark evaluation. It is hoped that this data will be released in the future as a separate evaluated benchmark.

2.3 Shielding Materials

Since a variety of different shielding materials were used in these experiments, a brief description is warranted before the geometric configurations are described in the following sections. Nearly all the shielding materials were provided by the CEA, and a large majority of those were provided by CEA Saclay.

Two shields were provided by CEA Valduc. These shields were lead and polyethylene annuli that fit around the outside of the SILENE reactor core. The polyethylene shield is lined with a thin layer of cadmium on the inner and outer surfaces. These shields are used by CEA Valduc to modify the spectrum of neutrons and photons leaking from SILENE.

CEA Saclay provided several different types of concrete shields and two pieces of equipment referred to as collimators. The collimators are boxes that have five solid sides with a sixth side open facing the reactor. The walls of the collimator consist of layers of stainless steel, copper, lead, borated plaster with polyethylene, and an outer layer of stainless steel. The borated plaster with polyethylene is a unique material created by adding colemanite (an ore of boron and source of borax) and polyethylene beads to the plaster mixture, which is a gypsum plaster. The purpose of the collimators is to absorb particles that scatter in the reactor cell before they reach the detectors inside the collimators. The concrete shields are designed to be placed in front of the open side of the collimators shielding any detectors inside from SILENE. The concrete shields used during these experiments were made of standard concrete (density ~2.3 g/cm^3), barite concrete (density ~3.25 g/cm^3), and magnetite concrete (density ~3.9 g/cm^3), and all have dimensions of roughly 1 m × 1 m × 20 cm. Below in Figure 1 is a picture of the two collimators on their stands in the SILENE reactor cell (without any concrete shielding). These concrete shields and collimators were produced by CEA Saclay for a previous experiment conducted at the CEA Valduc SILENE facility.

Some of the concrete shields were used to form what is referred to as the scattering box. The scattering box created a location where several detectors could be placed, some with direct line of sight to SILENE and some shielded. Also, the walls of the scattering box would scatter particles from one detector location to another and increase the production of secondary photons in close

Figure 1. Collimators on their stands open and facing SILENE.

Figure 2. Scattering box on its stand facing SILENE.

proximity to the photon detectors inside the scattering box. CEA Valduc constructed the stand needed to support the scattering box. A picture of the scattering box can be seen in Figure 2.

The final shielding material, BoroBond™ [11], was provided by Y-12. BoroBond™ is a material produced by Ceradyne Boron Products in the US. A simplistic description of BoroBond™ is that it is a phosphate-based ceramic that is borated by adding B_4C and/or H_3BO_3. The BoroBond™ shields provided by Y-12 were roughly the same shape as the concrete shields provided by Cea Saclay, so that the BoroBond™ could shield the internal cavity of the collimators similar to the concrete shields. However, the BoroBond™ shields were not as thick as the concrete shields; they are either 2.54 cm or 5.08 cm thick.

2.4 Pulse 1 Configuration

During the first experiment, or pulse 1, SILENE was bare, i.e. unshielded. Surrounding SILENE, inside the reactor cell, were the two collimators, the scattering box, and a free field measurement location. The free-field location is a position in the reactor cell where detectors, supported by a small stand, are placed without any additional shielding or collimators. A photograph of this configuration can be seen in Figure 3. Below is a list detailing the configuration of the equipment and detectors inside the reactor cell.

- SILENE unshielded/no reflector
- Collimator A unshielded
  - Full set of Table I neutron activation foils
  - One of each of the three types of TLDs
  - Rocky Flats CAAS
- Collimator B 20 cm barite concrete
  - Full set of Table I neutron activation foils
  - One of each of the three types of TLDs
  - Rocky Flats and CIDAS CAAS
- Free-field location
  - Full set of Table I neutron activation foils
  - One of each of the three types of TLDs
- Scattering Box (2 magnetite & 4 standard concrete shields)
  - Full set of Table I neutron activation foils
  - Three partial sets of neutron activation foils (gold, cobalt, nickel)
  - Two sets of ORNL TLDs
  - Four Valduc TLDs
  - Rocky Flats and CIDAS CAAS

Outside the reactor cell, near the heavy concrete doors that shield the entrance, is a table, and on or near this table is where the detectors outside the reactor cell are located. A picture of this table is shown in Figure 4. In Figure 3 the approximate location of this detector table is noted, but

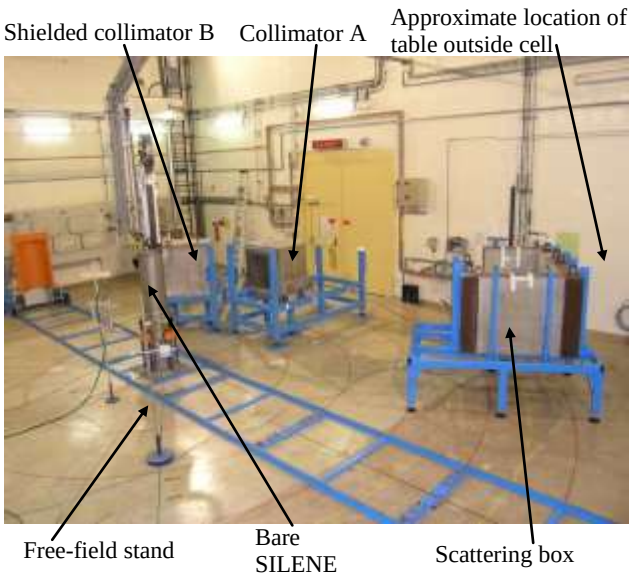

Figure 3. SILENE reactor cell pulse 1 configuration.

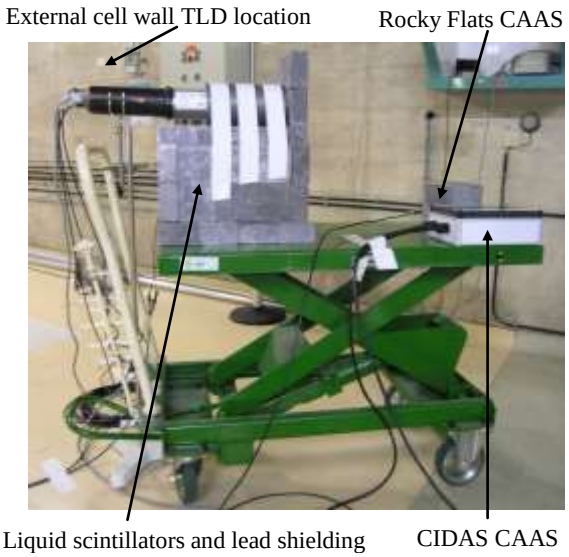

Figure 4. Table with detectors outside reactor cell.

the table is on the opposite side of the wall outside the reactor cell. Below is a list detailing the configuration of the equipment and detectors outside the reactor cell.

- External cell table
  - One set of ORNL TLDs
  - Rocky Flats and CIDAS CAAS
  - 1 in. & 2 in. BC-501A liquid scintillator
- External cell wall
  - One set of ORNL TLDs

2.5 Pulse 2 Configuration

The pulse 2 configuration is very similar to the first pulse with no changes to the detector arrangement. However, two changes were made to the shielding materials, the lead shield was installed around SILENE and the barite concrete in front of collimator B was replaced by 20 cm of standard concrete. Figure 5 shows SILENE and the lead shield.

2.6 Pulse 3 Configuration

Similarly, the only changes for pulse 3 involved the shielding materials. The polyethylene shield replaced the lead shield, while the standard concrete in front of collimator B was replaced by 7.62 cm of BoroBond™. Figure 6 shows SILENE with the polyethylene shield.

3 PRELIMINARY EXPERIMENTAL RESULTS

In the following sections all the available preliminary measurement data will be presented. All the neutron foil activations and CEA Valduc TLD doses for pulse 1 are ready for preliminary release. The ORNL TLD doses for all three pulses are also available on a preliminary basis. All the final experimental data will be published as part of the ICSBEP benchmark. No data for the photon and neutron spectra measured by the liquid scintillators is available. Finally, a few comments will be made about the performance of the CAAS detectors. Below in Table II are some characteristics of the three critical pulses.

3.1 Neutron Activation Foils

At this time only the neutron foil activations for pulse 1 are ready for preliminary release. One full set of Table I activation foils were present in collimator A, collimator B, the scattering box, and at the free-field location. However, three additional reduced sets of foils were also present in the scattering box. These measured activities, per unit mass, following the end of the critical pulse are

Figure 5. SILENE surrounded by the lead shield.

Figure 6. SILENE with half the polyethylene shield.

Table II. Critical pulse characteristics

Pulse	Core Shield	Number of Fissions*	Solution Critical Height (cm)	Solution Final Height (cm)	Duration of Pulse (sec)
1	None	1.88×10^{17}	37.333	41.871	7
2	Lead	2.14×10^{17}	31.322	34.560	6
3	Polyethylene	1.92×10^{17}	34.641	38.541	6

* The relative uncertainty on the number of fissions is 5% (2 sigma).

presented in Table III. Note that the ^{24}Na activity of the Mg foil in the scattering box is not reported because there was not enough activity available to produce a quality measurement and the derived activity immediately following the critical pulse.

3.2 Thermoluminescent Dosimeters

Preliminary doses for all the ORNL TLDs are available at this time, but doses for the CEA Valduc TLDs are only available for pulse 1. A full set of TLDs (2 from ORNL and 1 from Valduc) were placed next to each of the full set of Table I activation foils. A second full set of TLDs were placed inside the scattering box along with two more CEA Valduc TLDs. Finally, two sets of the ORNL TLDs were placed outside the reactor cell. The total dose for each TLD is presented in Table IV. The measurement results for the Valduc TLDs are air kerma for a ^{60}Co equivalent source while the results for the ORNL TLDs are air kerma for a ^{137}Cs equivalent source. The large uncertainties for the ORNL TLDs outside the reactor cell are due to the measured doses being low; some are very near the control TLD (background) dose. The results for the DXT dosimeters outside the reactor cell for pulse 3 were indistinguishable from the control TLD dose.

3.3 Criticality Accident Alarm Systems

The Rocky Flats CAAS (3 in the cell and 1 outside) were all powered by multiple batteries for these experiments. The Rocky Flats CAAS alarmed as expected in nearly all cases. The exception was the Rocky Flats CAAS in the scattering box. The alarm LED for this detector did not turn on for pulses 2 and 3. It was determined that the battery powering this LED was dead. These CAAS also have a display on them that show the integrated number of counts, and the counts recorded for pulses 2 and 3 indicate that the alarm LED would have turned on if power had been available.

Table III. Preliminary pulse 1 measured neutron foil activities

Position	Reaction	Activity (Bq/g)	Relative Uncertainty (2 sigma)
Collimator A	$^{59}Co(n,\gamma)^{60}Co$	6.610×10^{1}	2.6%
	$^{197}Au(n,\gamma)^{198}Au$	1.812×10^{5}	3.1%
	$^{115}In(n,\gamma)^{116m}In$	9.110×10^{6}	3.8%
	$^{115}In(n,n'\gamma)^{115m}In$	8.030×10^{3}	3.1%
	$^{54}Fe(n,p)^{54}Mn$	2.062×10^{-1}	4.0%
	$^{56}Fe(n,p)^{56}Mn$	2.310×10^{3}	2.6%
	$^{24}Mg(n,p)^{24}Na$	6.110×10^{1}	3.8%
	$^{58}Ni(n,p)^{58}Co$	1.436×10^{1}	3.1%
Collimator B	$^{59}Co(n,\gamma)^{60}Co$	2.242×10^{1}	2.6%
	$^{197}Au(n,\gamma)^{198}Au$	2.426×10^{4}	3.1%
	$^{115}In(n,\gamma)^{116m}In$	3.000×10^{6}	3.7%
	$^{115}In(n,n'\gamma)^{115m}In$	1.196×10^{3}	3.3%
	$^{54}Fe(n,p)^{54}Mn$	3.110×10^{-2}	3.9%
	$^{56}Fe(n,p)^{56}Mn$	7.790×10^{2}	2.8%
	$^{24}Mg(n,p)^{24}Na$	1.000×10^{1}	7.4%
	$^{58}Ni(n,p)^{58}Co$	2.120×10^{0}	3.3%
Free Field Location	$^{59}Co(n,\gamma)^{60}Co$	6.620×10^{1}	2.4%
	$^{197}Au(n,\gamma)^{198}Au$	6.950×10^{4}	3.0%
	$^{115}In(n,\gamma)^{116m}In$	8.780×10^{6}	4.9%
	$^{115}In(n,n'\gamma)^{115m}In$	6.860×10^{3}	3.2%
	$^{54}Fe(n,p)^{54}Mn$	1.961×10^{-1}	4.1%
	$^{56}Fe(n,p)^{56}Mn$	2.403×10^{3}	2.8%
	$^{24}Mg(n,p)^{24}Na$	5.910×10^{1}	4.1%
	$^{58}Ni(n,p)^{58}Co$	1.299×10^{1}	3.2%
Scattering Box 1	$^{59}Co(n,\gamma)^{60}Co$	2.227×10^{1}	2.4%
	$^{197}Au(n,\gamma)^{198}Au$	2.414×10^{4}	3.0%
	$^{115}In(n,\gamma)^{116m}In$	2.710×10^{6}	3.7%
	$^{115}In(n,n'\gamma)^{115m}In$	5.250×10^{2}	3.2%
	$^{54}Fe(n,p)^{54}Mn$	1.058×10^{-2}	7.4%
	$^{56}Fe(n,p)^{56}Mn$	8.480×10^{2}	2.6%
	$^{24}Mg(n,p)^{24}Na$	---	---
	$^{58}Ni(n,p)^{58}Co$	7.060×10^{-1}	3.5%
Scattering Box 2	$^{59}Co(n,\gamma)^{60}Co$	2.559×10^{1}	2.2%
	$^{197}Au(n,\gamma)^{198}Au$	2.539×10^{4}	3.3%
	$^{58}Ni(n,p)^{58}Co$	2.900×10^{-1}	4.1%
Scattering Box 3	$^{59}Co(n,\gamma)^{60}Co$	4.404×10^{1}	2.2%
	$^{197}Au(n,\gamma)^{198}Au$	4.460×10^{4}	3.1%
	$^{58}Ni(n,p)^{58}Co$	3.240×10^{0}	3.4%
Scattering Box 4	$^{59}Co(n,\gamma)^{60}Co$	3.993×10^{1}	2.2%
	$^{197}Au(n,\gamma)^{198}Au$	3.870×10^{4}	3.1%
	$^{58}Ni(n,p)^{58}Co$	3.330×10^{0}	3.3%

Table IV. Preliminary pulse 1 measured TLD doses (Gy) and relative uncertainties (coverage factor k=2)

		Pulse 1		Pulse 2		Pulse 3	
Position	**TLD**	**Dose**	**Rel Err**	**Dose**	**Rel Err**	**Dose**	**Rel Err**
Collimator A	Al_2O_3	6.61	4.4%				
	HBG	6.03	6.0%	1.06	6.0%	5.38	6.0%
	DXT	7.07	6.0%	1.02	6.0%	7.13	6.0%
Collimator B	Al_2O_3	0.820	3.4%				
	HBG	0.874	6.0%	0.620	6.0%	3.17	6.0%
	DXT	0.773	6.0%	0.573	6.0%	3.53	6.0%
Free Field Location	Al_2O_3	3.72	5.0%				
	HBG	5.02	6.0%	0.760	6.0%	4.83	6.0%
	DXT	5.86	6.0%	0.589	6.0%	5.60	6.0%
Scattering Box 1	Al_2O_3	0.580	4.0%				
	HBG	0.576	6.0%	0.402	6.0%	0.202	6.0%
	DXT	0.488	6.0%	0.371	6.0%	0.184	6.0%
Scattering Box 2	Al_2O_3	0.440	3.1%				
	HBG	0.398	6.0%	0.350	6.0%	0.115	6.0%
	DXT	0.398	6.0%	0.294	6.0%	0.149	6.0%
Scattering Box 3	Al_2O_3	1.76	2.4%				
Scattering Box 4	Al_2O_3	1.87	5.9%				
External cell table	HBG	1.3×10^{-4}	35%	1.1×10^{-4}	40%	1×10^{-5}	150%
	DXT	5×10^{-5}	60%	5×10^{-5}	60%	---	---
External cell wall	HBG	1.7×10^{-4}	30%	5×10^{-5}	60%	2×10^{-5}	100%
	DXT	2×10^{-5}	100%	2×10^{-5}	100%	---	---

Another issue with the Rocky Flats CAAS that was noticed during the experiments was that counts were being recorded before any pulses had been performed and several hours after each pulse had been performed. It was determined that the pulse shape discrimination algorithm used by these CAAS did not adequately distinguish counts due to photons and ^{4}He and ^{3}He counts produced by neutron absorption in ^{6}Li. In short, these CAAS are sensitive to photons as well as neutrons.

The CIDAS CAAS detectors (2 in the cell and 1 outside) were powered by a power supply provided by Babcock. During pulse 1 all three of the CIDAS CAAS were arranged on a single circuit, i.e. only one power supply was used. The power supply indicates the alarm condition if any one of the detectors on its circuit alarms due to detecting a criticality. After pulse 1 the power supply successfully alarmed. On closer inspection, the CIDAS detector in collimator B, the one closest to SILENE, indicated an alarm but the other two did not. This is due to all three detectors being on the same circuit and detecting the pulse at the same time. During pulses 2 and 3 the two CIDAS detectors inside the cell used a single power supply and the third CIDAS detector outside the cell used a second power supply. During pulses 2 and 3 both power supplies alarmed successfully. The CIDAS detector in collimator B indicated an alarm again, and the other one on the same ring did not. However, the CIDAS detector outside the reactor cell, with the independent power supply, also alarmed during pulses 2 and 3.

In a standard CIDAS system there are three power supplies with three detectors per location (one on each power supply circuit). These will all alarm because they are on separate circuits. The power supply arrangement used during these experiments is not typical.

4 BENCHMARK EVALUATION

The evaluation of these experiments is also a joint effort between the US DOE and the French CEA. At this time some preliminary computational results are available to compare to the preliminary pulse 1 measured data. In the following sections a brief description about the codes and methodologies used during the evaluation are presented, which is followed by the comparisons between measured data and computational results.

4.1 Scale Evaluation

These experiments are being modeled with Scale 6.1 using the CAAS modeling capability [4] of the MAVRIC [3] sequence. This requires that the experiments be modeled in two steps. The first step is to calculate the spatial and energy-dependent source distribution for each critical configuration of SILENE, which is done using the KENO-VI [12] eigenvalue code with multigroup cross sections. These source distributions are then used in by the Scale MAVRIC sequence to calculate the response of the detectors in the experiments. The MAVRIC sequence uses a fixed source multigroup S_N code, Denovo [13], to calculate neutron and photon importances (adjoint fluxes), which are used to automatically create weight windows and biasing parameters for the source distributions calculated by KENO-VI for use in the fixed source multigroup Monte Carlo code Monaco [3].

The multigroup cross sections used in the Monaco calculations have 200 neutron groups and 47 photon groups and are based on ENDF/B-VII.0. This cross-section library is a standard transport library available with distributions of Scale 6.1. These transport cross sections also provide the detector response functions to calculate the neutron foil activation. One exception to this is for the ^{115}In(n,n'γ)^{115m}In reaction. The response function for the elastic scattering reaction in indium is taken from the 2002 version of the International Reactor Dosimetry File.

4.2 TRIPOLI-4 Evaluation

The continuous energy TRIPOLI-4 [5] Monte Carlo transport code has been extensively applied on criticality safety, radiation shielding, and reactor physics calculations [14-16]. In this benchmark, different calculation modes of the code are being performed to analyze the pulse 1 experiment.

The combinatorial geometry option [15] and T4G display tool [17] were first applied to model the SILENE reactor, multi-layer collimators, concrete shields, scattering box, and fission neutron source measurement facilities. The experimental concrete room was also modeled so as to consider the room scattering effect in these calculations. Both the CEA-V5 nuclear data library based on JEFF-3.1.1 [18] evaluation and the 2002 version of the International Reactor Dosimetry File were used in this study for neutron transport and detector response calculations.

Under the criticality mode of TRIPOLI-4 a fission neutron source distribution was initially calculated for pulse 1 with the standard flux tally. Using the calculated neutron source distribution and the measured fission neutron intensity (Table II), a parallel shielding mode TRIPOLI-4 calculation was applied to calculate the detector responses of the fast neutron activation foils, ^{58}Ni(n,p), ^{54}Fe(n,p), ^{115}In(n,n'γ), ^{24}Mg(n,p) and ^{56}Fe(n,p).

A separate shielding mode model is being developed to calculate the slow neutron detector responses, ^{115}In(n,γ), ^{59}Co(n,γ), and ^{197}Au(n,γ). Different types of detectors are being added into this slow neutron calculation model to properly consider the self-shielding effect of the detectors in the TRIPOLI-4 run. A coupled neutron-photon model is also in preparation to calculate the TLD dosimetry experiments with variance reduction options. These options are helpful to improve the secondary photon production in calculations.

4.3 Computational Results: Fast Neutron Activation Foils

Some preliminary Scale 6.1 and TRIPOLI-4 results for the pulse 1 neutron foil activities are presented in Table V. In Table V are comparisons between the measured foil activities and the calculated foil activities. These comparisons are presented as ratios of the calculated results to the experimental results (C/E), so perfect agreement is represented by a ratio of 1.0 with a relative uncertainty of 0%. The computational uncertainty of the Scale calculations are all less then 5.0% and are less than 1.5% for the TRIPOLI calculations. These computational uncertainties along with the measurement uncertainties have been used to calculate the uncertainties of the C/E ratio.

Table V. Fast neutron activation foil computational results

		Scale 6.1		TRIPOLI-4	
Position	**Reaction**	**Ratio: C/E**	**Relative Uncertainty (2 sigma)**	**Ratio: C/E**	**Relative Uncertainty (2 sigma)**
Collimator A	$^{115}In(n,n'\gamma)^{115m}In$	0.94	4.4%	0.94	4.0%
	$^{54}Fe(n,p)^{54}Mn$	1.00	5.1%	1.02	4.1%
	$^{56}Fe(n,p)^{56}Mn$	0.05	3.8%	<< 1.0	3.0%
	$^{24}Mg(n,p)^{24}Na$	1.12	4.9%	1.03	4.0%
	$^{58}Ni(n,p)^{58}Co$	0.97	4.3%	0.96	3.2%
Collimator B	$^{115}In(n,n'\gamma)^{115m}In$	0.70	3.7%	*	
	$^{54}Fe(n,p)^{54}Mn$	0.66	4.1%	*	
	$^{56}Fe(n,p)^{56}Mn$	0.01	3.5%	<< 1.0	3.0%
	$^{24}Mg(n,p)^{24}Na$	0.59	7.8%	*	
	$^{58}Ni(n,p)^{58}Co$	0.65	3.6%	*	
Free Field Location	$^{115}In(n,n'\gamma)^{115m}In$	1.04	7.7%	0.94	5.0%
	$^{54}Fe(n,p)^{54}Mn$	0.97	5.7%	0.99	3.0%
	$^{56}Fe(n,p)^{56}Mn$	0.05	4.2%	<< 1.0	3.0%
	$^{24}Mg(n,p)^{24}Na$	1.13	5.3%	1.05	4.1%
	$^{58}Ni(n,p)^{58}Co$	0.98	5.0%	0.95	3.3%
Scattering Box 1	$^{115}In(n,n'\gamma)^{115m}In$	1.00	8.5%	*	
	$^{54}Fe(n,p)^{54}Mn$	1.09	8.4%	*	
	$^{56}Fe(n,p)^{56}Mn$	0.01	4.1%	<< 1.0	3.0%
	$^{24}Mg(n,p)^{24}Na$	---	---	---	---
	$^{58}Ni(n,p)^{58}Co$	1.13	5.8%	*	
Scattering Box 2	$^{58}Ni(n,p)^{58}Co$	1.35	10.8%	*	
Scattering Box 3	$^{58}Ni(n,p)^{58}Co$	0.87	5.6%	1.02	4.2%
Scattering Box 4	$^{58}Ni(n,p)^{58}Co$	0.91	7.9%	1.06	3.9%

* The C/E ratios of these measurement positions depend significantly on the density and the hydrogen content of the concrete shield blocks.

5 CONCLUSIONS

Three benchmark shielding experiments using the SILENE pulse reactor, at CEA Valduc in France, have been successfully conducted as a joint effort between the US DOE and French CEA. The documentation of the experimental configurations and materials has been completed. Now the analysis of the measurement data is underway, as well as the computational evaluation of these

experiments. It is planned to publish the computational evaluation of these experiments in the ICSBEP Handbook. Presented in this paper are preliminary measurement results for the neutron foil activations and CEA Valduc TLD doses for pulse 1 of these experiments. Preliminary ORNL TLD doses have been presented for all three experiments.

Comparisons between Scale 6.1 and TRIPOLI-4 simulations and the experimental measurements of the fast neutron activities have also been presented. In general all of these computational results compare well with the measured data, with two exceptions. The first exception is the comparison between simulations and the measurements inside collimator B, which was shielded by barite concrete. The lack of agreement between the simulations of collimator B and the measurements have called into question the density and/or composition of the barite concrete shield. Particularly since the simulations of collimator A agree with the measurements. Similar questions have also been raised about the concrete of the scattering box, but the comparisons for the activities inside the scattering box are much better than for collimator B. As a result, CEA Saclay and Valduc are verifying the data provided for the density and composition of all the concrete shield blocks. In particular the data concerning the hydrogen content of the concrete shield blocks is being reviewed, which is data that is very important to the simulation of neutrons activation foils primarily sensitive to low energy neutrons. The second exception is the comparison between simulations and the measurements of the ^{56}Fe(n,p)^{56}Mn reaction. In all cases the C/E ratio for this reaction is much less than 1.0. The TRIPOLI results for these simulations are not shown explicitly in Table V, but the TRIPOLI and Scale simulations result in similar C/E ratios. Therefore, CEA Valduc is revaluating the analysis of the measurement data from pulse 1 that derived the activity due to ^{56}Fe(n,p)^{56}Mn reactions.

Once these questions about the concrete shields and ^{56}Fe(n,p)^{56}Mn reactions are resolved the evaluation of pulse 1 will be finalized. The evaluation of pulses 2 and 3 will begin in 2012, and the final benchmark evaluations will be presented to the ICSBEP in 2014.

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