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COG Validation for Foils and TLDs Irradiated by Lead and Polyethylene Reflected SILENE Reactor

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Abstract - *Multiple pulsed experiments performed at the CEA Valduc SILENE reactor in 2010 provided invaluable measurement data of activated foils and thermoluminescent dosimeters (TLDs) for validating COG, a Monte Carlo particle transport code, developed by Lawrence Livermore National Laboratory (LLNL). Various COG functionalities including neutron activation, volume detector, and the newly added delayed fission gamma ray options were tested. Using COG, the SILENE reactor, experimental configurations, and surroundings were explicitly modeled in three dimensions for two SILENE configurations, one reflected by lead and one reflected by cadmium-lined polyethylene. Unlike conventional two-step analysis in radiation shielding calculations, COG uses a direct one-step CRITICALITY/DETECTOR option for direct particle tracking from the reactor core to the detectors, eliminating biasing/approximations used in the two-step process. In general, calculated COG results agreed reasonably well with the measurement data except a few higher predictions in the concrete-shielded foils. The COG results indicated that the effect of the delayed fission gamma rays is insignificant because of the reflecting material around SILENE. For direct particle tracking, significantly large computing time is required for good statistics. A new feature, Criticality Detector Variance Reduction (CritDetVR) has been developed in a serial mode to apply variance reduction techniques in a hybrid criticality/shielding mode. This new feature saves significant computation time for the direct one-step process, and is being incorporated into the source code to improve COG performance on a multiprocessor machine.*

I. INTRODUCTION

Multiple pulsed experiments were performed [1] in October 2010 at the Commissariat á l'Énergie Atomique et aux Énergies Alternatives (CEA) Valduc SILENE reactor in France to simulate criticality accident excursions and provide experimental data to the criticality safety community for particle transport code validation. Three different single-pulse experiments were conducted including: (1) a pulse without any shielding materials around the SILENE reactor (Pulse 1), (2) a pulse with lead shielding (Pulse 2), and (3) a pulse with cadmium lined polyethylene shielding (Pulse 3).

Continuing efforts have been made to validate COG, a Monte Carlo code [2] developed by LLNL, using the measured SILENE data. Validation results for the bare SILENE reactor were previously published [3]. Unlike the conventional two-step analysis in radiation shielding calculations, a direct one-step criticality/detector calculation method was applied in COG to track neutron and gamma ray particles from the reactor to the detectors. This paper presents the COG modeling, simulation, and a complete set of COG results for the Pulse 2 and 3 experiments.

II. SILENE EXPERIMENTS

SILENE is an annularly-shaped tank reactor with internal and external diameters of 7.6 and 36 cm, respectively. The fuel in the core consists of a 93% enriched uranyl nitrate solution. Uranium concentrations in Pulses 2 and 3 are 70.66 and 71.24 grams per liter, respectively. The bottom of the fuel tank is one meter above the concrete floor. The fuel solution height varies depending on the types of experiments. For Pulse 2, the critical fuel height was 34.56 cm with the control rod fully in. A slightly higher fuel height of 38.54 cm was reported for the Pulse 3 experiment. A picture of the bare SILENE reactor [1] with collimators surrounding the reactor is shown in Figure 1.

Fig. 1. SILENE Reactor with Collimators.

1. Experiment Configurations

For Pulse 2, 20 cm-thick lead shielding material was used around the SILENE reactor. In Pulse 3, the lead shield was replaced with 26 cm-thick cadmium-lined polyethylene. The foil arrangement remained the same for these two experiments.

A cadmium control rod in the central annular region of the reactor controls the mode of operation by varying the speed with which the control rod is removed from the fuel region. A single pulse was produced by removing the control rod out of the core at a rate of 2 m/sec. Approximately seven seconds later, the reactor was shut down by fully inserting the control rod into the core, and opening the valve to drain the fuel solution from the core. It took approximately thirty seconds to completely drain the fuel out of the core. Figures 2 and 3 [4,5] show the fission rate versus time for Pulses 2 and 3, respectively.

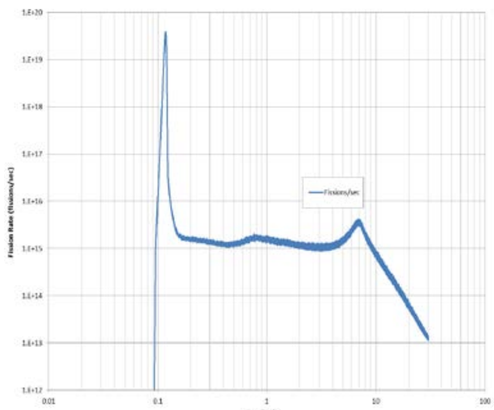

Fig. 2. Fission Rate as a Function of Time for Pulse 2.

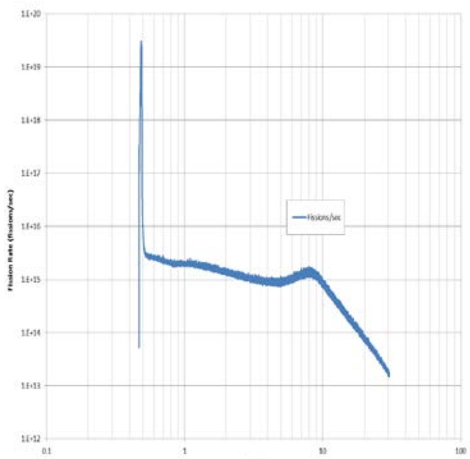

Fig. 3. Fission Rate as a Function of Time for Pulse 3.

During the Pulse 2 experiment, thirty-six neutron activation foils and ten TLDs were measured [6]. Thirty-one foil and ten TLD measurement data were provided from the Pulse 3 experiment [7]. The irradiated foils are small disks with a diameter of 2 cm and a thickness of less than 0.3 cm. Masses of the individual foils are less than 8 grams. The experimental configuration included seven measurement locations: Collimator A, Collimator B, Free-field, and Scattering Box 1, 2, 3, and 4. The distance from the center of the SILENE reactor to Collimators A, B, and Free-field is about 122 cm. The scattering box is positioned about 306 cm away from the core center. A set of Co, Au, In, Fe, Mg, and/or Ni foils and TLDs were positioned in these seven different locations. To study the effect of neutron scattering, a 20-cm thick standard concrete slab was placed between the reactor and the foils and TLDs in Collimator B for the Pulse 2 experiment. This slab was replaced with a Borobond slab in the Pulse 3 experiment. The foils and TLDs in the scattering box were placed on the 20-cm thick standard and magnetite concrete slabs, with some of them shielded by the concrete slab. Two 20-cm thick magnetite concrete slabs were placed at the front and the bottom of the scattering box. Exact chemical compositions of the standard and the magnetite concrete slabs are not known. Figure 4 [1] is a photograph showing a collimator foil holder with the neutron activation foils used in Collimator A, B, and Free-field. Measured activities (in Bq/g) are based on ^{59}Co(n,γ)^{60}Co, ^{197}Au(n,γ)^{198}Au, ^{115}In(n,γ)^{116}In, ^{115}In(n,n'γ)^{115m}In, ^{56}Fe(n,p)^{56}Mn, ^{24}Mg(n,p)^{24}Na, and ^{58}Ni(n,p)^{58}Co reactions. Note that ^{56}Fe(n,p) and ^{55}Mn(n,γ) produce the same activation product, ^{56}Mn. Therefore, the effect of Mn impurity in the iron foils needed to be evaluated. The trace Mn impurity in the iron foil is approximately 0.3 weight percent [1].

During Pulses 2 and 3, four criticality accident alarm system (CAAS) neutron detectors once used at the Rocky Flats Plant (Colorado, USA) were placed in four different positions to demonstrate the functionality and survivability of the neutron detectors to the effects of an actual criticality accident. As expected, criticality alarm indicator LEDs were illuminated by Pulses 2 and 3 and functioned as intended in actual criticality situations.

The TLDs respond in a mixed field of neutrons and gamma rays. Three different types of TLDs were used [1] for the radiation dose measurements. These are 1) TLDs provided by CEA Valduc consisting of an Al_2O_3 powder inside an aluminum capsule, 2) HBG TLDs from Oak Ridge National Laboratory (ORNL, Tennessee, USA), and 3) DXT TLDs from ORNL. Measurement data of all of the three different types of TLDs are reported; however, only one type (the Valduc TLD) was modeled and simulated.

Fig. 4. Collimator Foil Holder with Neutron Activation Foils.

2. COG Modeling and Simulation

The SILENE reactor as well as the surrounding collimators, scattering box, foils, and TLDs were explicitly modeled in COG. COG [2] is a general purpose, multi-particle, high-fidelity Monte Carlo code developed by LLNL. It provides accurate simulation results for complex 3-D shielding, criticality safety, and activation problems. A newly developed feature in COG, Version 11.1 can generate, track, and score delayed fission gamma (DFG) rays born between two given times. Point-wise continuous cross-sections are used in COG and a full range of biasing options are available for speeding up solutions for deep penetration problems.

Building on the Pulse 1 COG model [3], SILENE models for Pulses 2 and 3 were developed with appropriate shielding materials. In Pulse 2, the lead reflector was added, and the Barite concrete slab in Collimator B was replaced with a standard concrete slab. A cadmium-lined polyethylene reflector replaced the lead as a reflector in Pulse 3. The standard concrete in Collimator B was replaced with Borobond. COG provides two and three dimensional pictures of the model. A perspective of the three dimensional picture can be produced by enabling the user to see the inner structure hidden inside the outer surfaces. Figures 5 and 6 show COG generated perspective views of the SILENE Pulse 2 and 3 experiments, respectively.

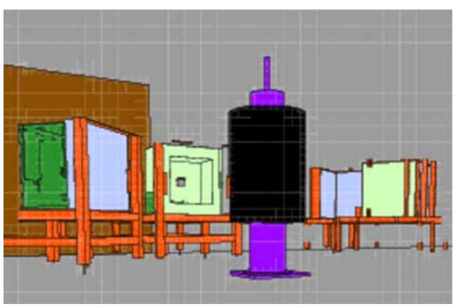

Fig.5. COG Perspective View of SILENE Pulses 2 Experiment.

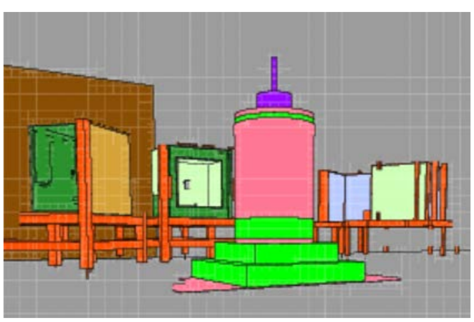

Fig.6. COG Perspective Views of SILENE Pulse 3 Experiment.

Each of the foils and TLDs were explicitly modeled in COG. Rotation and translation features were utilized to accurately position the Collimator B, Free-field foils, and Scattering Box 1, 2, 3, and 4. Note that the transient behavior of the neutron pulse was not analyzed in this study. Flux tallies in COG with the CRITICALITY option are based on a single fission. Calculated foil activities and the TLD doses are normalized to 2.14×10^{17} (Pulse 2) and 1.92×10^{17} (Pulse 3) fissions, respectively, to compare with the measurement data.

Radiation dose or neutron activation analysis is normally performed in a two-step process: First, the spatial and energy dependent source distribution for a reactor is calculated. Second, a fixed source problem is solved using the generated source distribution to calculate dose or activation rate at a detector. To speed up computation time, variance reduction techniques are often applied in the fixed source (second) part of the calculation. To eliminate this biasing and/or approximations in the two-step process, a direct one-step criticality/detector calculation method was applied to all of the SILENE foil and TLD activity and dose evaluations. The only downside is that without variance reduction techniques, each calculation requires significant number of computer nodes for good statistics. COG calculates reaction rates using the CRITICALITY source and DETECTOR option in a single computer run, tracking neutrons all the way from the reactor to the detector.

The activity of the foil in Bq/g is converted using the following normalization factor, *A*,

$$\mathrm{A} = \frac{F\lambda N\sigma\Phi e^{-\lambda t}}{\rho}$$

where F is a total number of fissions, λ is the decay constant, N is atomic number density, σ is microscopic cross section, Φ is neutron flux, ρ is foil density, and t is the time between the start of the pulse and the time when the dosimetrist reported measurement activities. Note that $N\sigma\Phi$ is calculated by COG. Reaction rates (R-RATE option in COG) for (n,γ), (n,n'γ), and (n,p) were activated.

TLD doses were calculated using neutron/gamma ray fluence multiplied by a response function. The response function applied is the International Commission on Radiation Units and Measurements (ICRU) air kerma flux-to-dose conversion factors [8]. A newly developed feature in COG 11.1 can track and score delayed fission gamma (DFG) rays born between two given times. This DFG option was activated to estimate additional gamma ray contribution to TLDs for the 30 second solution drainage time.

III. RESULTS

COG results for Pulses 2 and 3 are summarized in Tables 1, 2, 3, and 4. Foil activities for Collimator A, Collimator B, Free-field, and Scattering Box 1, 2, 3, and 4 are presented in Tables 1 and 3. TLD doses are also compared in Tables 2 and 4. All of the results except for the indium foil cases are based on ENDF/B-VII.1 cross sections. The activities of indium foils were calculated using the 2002 Version of the International Reactor Dosimetry File (IRDF-2002) because of better agreement compared to ENDF/B-VII.1. Note that the calculated $^{56}Fe(n,p)^{56}Mn$ activities in Tables 1 and 3 include activities from $^{55}Mn(n,\gamma)^{56}Mn$ reaction due to the known impurity of 0.3 wt% ^{55}Mn in iron. The Mn impurity contributes more than 90% of the total activity in the iron foil.

In general, COG results for foil activities agree reasonably well with the measurement data except in a few higher predictions in the concrete-shielded foils. Chemical compositions of the magnetite and the standard concrete slabs were determined based on incomplete composition data [4,5]. Actual measurements of the hydrogen, boron, and chlorine contents in the concrete slabs will help for more accurate comparison with the measurement data.

Pulse 3 TLD dose results are in relatively good agreement with the measured data. However, Pulse 2 TLD doses from COG are about twice larger than the measurement values in Collimator A and Free Field areas. The reason for this over prediction is currently under investigation. The contribution of delayed gammas for Pulse 1 [3] was between 10 and 20 % of the total TLD dose, however, the effects of including delayed gammas in Pulses 2 and 3 are not significant due to the shielding materials of lead and polyethylene with cadmium.

IV. CONCLUSIONS

The direct one-step method applied in this validation work demonstrated that Monte Carlo codes can be used directly for radiation shielding calculations eliminating biasing and/or approximations used in the conventional two-step process. The effects of delayed fission gamma contributed were insignificant in Pulses 2 and 3 because of reflecting materials. To reduce calculation uncertainties for small foil tally volumes, additional large scale runs on massive parallel supercomputers are needed. To this end, a new one-step hybrid criticality/shielding-detector method was developed. This Criticality Detector Variance Reduction (CritDetVR) mode allows users to apply variance reduction methods in the one-step criticality/shielding calculation. COG interleaves criticality batches with shielding cycles in such a way that each shielding cycle transports the source neutrons generated by the preceding criticality batch. Each shielding cycle can employ any of the variance reduction methods to enhance scoring statistics at the detectors. This feature applied to a problem in a serial mode saved significant computer time. Currently, additional work is in progress to add a message passing interface (MPI) feature to run in parallel on a multiprocessing machine.

ACKNOWLEDGMENTS

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Table 1. Comparison between Measured Foil Activities and COG Results for Pulse 2.

Position	Foil ID	Reaction	Measurement Data		COG		Total C/E[(a)]	Total $1\sigma^{(b)}$(%)
			Activity (Bq/g)	$1\sigma_e$ (%)	Activity (Bq/g)	$1\sigma_c$ (%)		
Collimator A	Co021	$^{59}Co(n,\gamma)^{60}Co$	60.9	2.15%	72.9	1.13%	1.1974	2.43%
	Au06-A10	$^{197}Au(n,\gamma)^{198}Au$	6.88E+04	1.55%	8.53E+04	1.56%	1.2402	2.20%
	In10-A10	$^{115}In(n,\gamma)^{116m}In$	7.95E+06	2.10%	8.80E+06	1.18%	1.1069	2.41%
		$^{115}In(n,n'\gamma)^{115m}In$	6100	1.70%	5547	1.26%	0.9094	2.12%
	Fe025	$^{56}Fe(n,p)^{56}Mn$	2020	2.50%	2229	1.46%	1.1035	2.90%
	Mg002	$^{24}Mg(n,p)^{24}Na$	24.8	2.00%	30.7	8.58%	1.2375	8.81%
	Ni014	$^{58}Ni(n,p)^{58}Co$	6.86	1.60%	7.24	1.89%	1.0559	2.48%
Collimator B	Co012	$^{59}Co(n,\gamma)^{60}Co$	32.3	2.15%	27.3	1.92%	0.8452	2.88%
	Au04-A10	$^{197}Au(n,\gamma)^{198}Au$	3.101E+04	1.55%	3.016E+04	2.60%	0.9725	3.03%
	In11-A10	$^{115}In(n,\gamma)^{116m}In$	3.84E+06	1.95%	3.61E+06	1.86%	0.9407	2.69%
		$^{115}In(n,n'\gamma)^{115m}In$	940	1.95%	1247	2.70%	1.3265	3.33%
	Fe033	$^{56}Fe(n,p)^{56}Mn$	1040	1.45%	902	2.87%	0.8673	3.22%
	Mg002	$^{24}Mg(n,p)^{24}Na$	5.52	5.60%	9.23	17.10%	1.6720	17.99%
	Ni02	$^{58}Ni(n,p)^{58}Co$	1.271	1.60%	1.800	3.81%	1.4163	4.13%
Free Field	Co015	$^{59}Co(n,\gamma)^{60}Co$	62.7	2.25%	75.7	1.21%	1.2069	2.55%
	Au02-A10	$^{197}Au(n,\gamma)^{198}Au$	6.43E+04	1.55%	7.63E+04	1.59%	1.1867	2.22%
	In004	$^{115}In(n,\gamma)^{116m}In$	7.85E+06	1.90%	9.18E+06	1.19%	1.1694	2.24%
		$^{115}In(n,n'\gamma)^{115m}In$	5210	1.75%	4526	1.26%	0.8688	2.16%
	Fe019	$^{56}Fe(n,p)^{56}Mn$	2084	1.25%	2555	2.10%	1.2260	2.44%
	Mg026	$^{24}Mg(n,p)^{24}Na$	26.4	3.60%	30.3	8.91%	1.1463	9.61%
	Ni012	$^{58}Ni(n,p)^{58}Co$	6.34	1.60%	6.82	1.94%	1.0756	2.51%
Scattering Box 1	Co027	$^{59}Co(n,\gamma)^{60}Co$	24.4	2.25%	30.3	2.03%	1.2425	3.03%
	Au009	$^{197}Au(n,\gamma)^{198}Au$	2.412E+04	1.55%	2.995E+04	2.57%	1.2418	2.52%
	In003	$^{115}In(n,\gamma)^{116m}In$	2.91E+06	2.25%	3.55E+06	1.98%	1.2208	3.00%
		$^{115}In(n,n'\gamma)^{115m}In$	323	1.70%	306	5.97%	0.9463	6.21%
	Fe035	$^{56}Fe(n,p)^{56}Mn$	881	1.25%	1036	2.67%	1.1759	2.95%
	MgSNAC	$^{24}Mg(n,p)^{24}Na$	1.206	3.15%	1.058	31.70%	0.8771	31.86%
	Ni027	$^{58}Ni(n,p)^{58}Co$	0.323	2.00%	0.376	11.20%	1.1630	11.38%

[(a)] Ratio of calculated to measurement results

[(b)] $\sqrt{\sigma_e^2 + \sigma_c^2}$

Table 1. Comparison between Measured Foil Activities and COG Results for Pulse 2 (Continued).

Position	Foil ID	Reaction	Measurement Data		COG		Total C/E[(a)]	Total $1\sigma^{(b)}$(%)
			Activity (Bq/g)	$1\sigma_e$ (%)	Activity (Bq/g)	$1\sigma_c$ (%)		
Scattering Box 2	Co024	$^{59}Co(n,\gamma)^{60}Co$	28.1	2.15%	34.4	1.88%	1.2227	2.86%
	Au006	$^{197}Au(n,\gamma)^{198}Au$	25830	1.50%	33331	2.34%	1.2904	2.78%
	Ni028	$^{58}Ni(n,p)^{58}Co$	0.1898	1.65%	0.2160	15.50%	1.1382	15.59%
Scattering Box 3	Co031	$^{59}Co(n,\gamma)^{60}Co$	45.7	2.10%	56.1	1.52%	1.2284	2.59%
	Au011	$^{197}Au(n,\gamma)^{198}Au$	4.37E+04	1.60%	5.38E+04	1.83%	1.2316	2.43%
	Ni022	$^{58}Ni(n,p)^{58}Co$	1.75	3.15%	1.79	4.13%	1.0250	5.19%
Scattering Box 4	Co036	$^{59}Co(n,\gamma)^{60}Co$	41.2	2.20%	48.6	1.60%	1.1797	2.72%
	Ni025	$^{197}Au(n,\gamma)^{198}Au$	3.90E+04	1.65%	4.90E+04	1.99%	1.2575	2.59%
	Au010	$^{58}Ni(n,p)^{58}Co$	1.83	3.30%	2.08	6.22%	1.1378	7.04%

[(a)] Ratio of calculated to measurement results

[(b)] $\sqrt{\sigma_e^2 + \sigma_c^2}$

Table 2. COG Calculated TLD Doses Compared with Measurement Data for Pulse 2.

Position	Measured Data (Gy)	$1\sigma_e$ (%)	Delayed Fission Gamma	COG						Total C/E[(a)]	Total $1\sigma^{(b)}$ (%)
				Neutron Dose (Gy)	$1\sigma_n$ (%)	Gamma Dose (Gy)	$1\sigma_g$ (%)	Total (Gy)	$1\sigma_s$ (%)		
Collimator A	0.82	2.38	w/o DFG	1.06	1.44	0.60	4.90	1.66	5.11	2.02	5.63
			w/ DFG	1.07	1.44	0.65	4.55	1.72	4.77	2.10	5.33
Collimator B	0.55	10.00	w/o DFG	0.27	2.95	0.30	7.24	0.57	7.82	1.04	12.69
			w/ DFG	0.28	2.95	0.31	6.76	0.59	7.38	1.07	12.43
Free Field	0.56	2.58	w/o DFG	0.94	1.59	0.29	6.06	1.23	6.27	2.19	6.78
			w/ DFG	0.92	1.61	0.33	6.44	1.25	6.64	2.22	7.12
Scattering Box 1	0.40	-	w/o DFG	0.25	3.22	0.34	6.06	0.59	6.86	1.48	-
		-	w/ DFG	0.23	3.31	0.33	6.77	0.56	7.54	1.40	-
Scattering Box 2	0.30	-	w/o DFG	0.26	3.30	0.22	7.59	0.48	8.28	1.60	-
		-	w/ DFG	0.22	3.44	0.23	6.98	0.45	7.78	1.50	-
Scattering Box 3	0.42	3.57	w/o DFG	0.51	2.29	0.28	7.34	0.79	7.69	1.88	8.48
			w/ DFG	0.49	2.21	0.30	6.24	0.79	6.62	1.88	7.52
Scattering Box 4	0.78	22.44	w/o DFG	0.46	2.32	0.27	7.18	0.73	7.55	0.94	23.67
			w/ DFG	0.49	2.25	0.21	6.77	0.70	7.13	0.90	23.54

[(a)]Ratio of calculated to measurement results

[(b)] $\sqrt{\sigma_e^2 + \sigma_n^2 + \sigma_g^2}$

Table 3. Comparison between Measured Foil Activities and COG Results for Pulse 3.

Position	Foil ID	Reaction	Measurement Data		COG		Total C/E[(a)]	Total $1\sigma^{(b)}$(%)
			Activity (Bq/g)	$1\sigma_e$ (%)	Activity (Bq/g)	$1\sigma_c$ (%)		
Collimator A	Co029	$^{59}Co(n,\gamma)^{60}Co$	4.55	2.20%	4.58	4.25%	1.0066	4.79%
	Au007	$^{197}Au(n,\gamma)^{198}Au$	6.51E+03	3.00%	6.18E+03	5.85%	0.9493	6.57%
	In13-A10	$^{115}In(n,\gamma)^{116m}In$	6.68E+05	1.70%	7.05E+05	4.01%	1.0556	4.36%
		$^{115}In(n,n'\gamma)^{115m}In$	993	1.55%	853	3.31%	0.8586	3.65%
	Fe026	$^{56}Fe(n,p)^{56}Mn$	187.9	1.55%	198.0	10.80%	1.0538	10.91%
	Mg09-A10	$^{24}Mg(n,p)^{24}Na$	16.2	4.30%	14.0	13.39%	0.8652	14.06%
	Ni019	$^{58}Ni(n,p)^{58}Co$	2.153	1.60%	2.101	4.20%	0.9759	4.49%
Collimator B	Co014	$^{59}Co(n,\gamma)^{60}Co$	0.66	1.15%	0.72	11.00%	1.0909	11.06%
	Au003	$^{197}Au(n,\gamma)^{198}Au$	1.17E+03	1.55%	1.24E+03	11.33%	1.0569	11.44%
	In14-A10	$^{115}In(n,\gamma)^{116m}In$	1.098E+05	2.30%	9.584E+04	9.67%	0.8728	9.94%
		$^{115}In(n,n'\gamma)^{115m}In$	411	1.60%	376	4.12%	0.9145	4.42%
	Fe017	$^{56}Fe(n,p)^{56}Mn$	41.6	1.80%	37.1	17.32%	0.8918	17.41%
	Mg08-A10	$^{24}Mg(n,p)^{24}Na$	7.69	3.10%	6.38	15.96%	0.8301	16.26%
Free Field	Co030	$^{59}Co(n,\gamma)^{60}Co$	5.00	2.20%	5.35	4.30%	1.0709	4.83%
	Au002	$^{197}Au(n,\gamma)^{198}Au$	5.55E+03	1.60%	5.46E+03	5.44%	0.9829	5.67%
	In12-A10	$^{115}In(n,\gamma)^{116m}In$	5.87E+05	2.20%	6.39E+05	4.29%	1.0894	4.82%
		$^{115}In(n,n'\gamma)^{115m}In$	841	3.10%	715	3.25%	0.8505	4.49%
	Fe023	$^{56}Fe(n,p)^{56}Mn$	214	2.80%	219	5.80%	1.0234	6.44%
	Mg10-A10	$^{24}Mg(n,p)^{24}Na$	14.7	4.10%	12.7	12.18%	0.8641	12.85%
	Ni008	$^{58}Ni(n,p)^{58}Co$	1.794	1.60%	2.041	5.11%	1.1379	5.35%
Scattering Box 1	Co035	$^{59}Co(n,\gamma)^{60}Co$	2.167	2.20%	2.264	6.78%	1.0448	7.13%
	Au005	$^{197}Au(n,\gamma)^{198}Au$	2.36E+03	3.20%	2.68E+03	7.79%	1.1335	8.42%
	In001	$^{115}In(n,\gamma)^{116m}In$	2.65E+05	1.90%	2.81E+05	6.65%	1.0595	6.92%
		$^{115}In(n,n'\gamma)^{115m}In$	58.8	1.85%	61.2	15.02%	1.0412	15.13%
	Fe022	$^{56}Fe(n,p)^{56}Mn$	78.3	1.65%	83.3	8.21%	1.0639	8.37%
Scattering Box 2	Co025	$^{59}Co(n,\gamma)^{60}Co$	2.517	1.20%	2.761	6.37%	1.0971	6.48%
	Au10-B10	$^{197}Au(n,\gamma)^{198}Au$	2509	1.50%	2500	7.51%	0.9966	7.66%
Scattering Box 3	Co032	$^{59}Co(n,\gamma)^{60}Co$	3.91	2.15%	4.11	5.71%	1.0523	6.10%
	Au012	$^{197}Au(n,\gamma)^{198}Au$	3910	1.55%	4200	6.60%	1.0741	6.78%
Scattering Box 4	Co018	$^{59}Co(n,\gamma)^{60}Co$	3.471	1.15%	3.810	5.42%	1.0976	5.54%
	Au004	$^{197}Au(n,\gamma)^{198}Au$	3670	3.00%	3617	6.10%	0.9856	6.80%

[(a)] Ratio of calculated to measurement results,

[(b)] $\sqrt{\sigma_e^2 + \sigma_c^2}$

Table 4. COG Calculated TLD Doses Compared with Measurement Data for Pulse 3.

Position	Measured Data (Gy)	$1\sigma_e$ (%)	Delayed Fission Gamma	COG						Total C/E[(a)]	Total $1\sigma^{(b)}$ (%)
				Neutron Dose (Gy)	$1\sigma_n$ (%)	Gamma Dose (Gy)	$1\sigma_g$ (%)	Total (Gy)	$1\sigma_s$ (%)		
Collimator A	5.29	2.27	w/o DFG	0.11	0.52	4.40	1.65	4.51	1.73	0.85	2.85
			w/ DFG	0.10	0.55	4.59	1.59	4.69	1.68	0.89	2.82
Collimator B	3.15	5.08	w/o DFG	0.04	0.88	2.53	2.21	2.57	2.38	0.82	5.61
			w/ DFG	0.04	0.86	2.78	2.78	2.82	2.91	0.90	5.85
Free Field	4.79	6.89	w/o DFG	0.10	0.54	4.20	1.74	4.30	1.82	0.90	7.13
			w/ DFG	0.11	0.53	4.29	1.67	4.40	1.75	0.92	7.11
Scattering Box 1	0.20	-	w/o DFG	0.02	10.71	0.10	11.10	0.12	15.42	0.60	-
			w/ DFG	0.02	11.32	0.10	11.43	0.12	16.09	0.60	-
Scattering Box 3	1.01	5.94	w/o DFG	0.05	0.71	0.89	3.65	0.94	3.72	0.93	7.01
			w/ DFG	0.05	0.74	0.90	3.51	0.95	3.59	0.94	6.94
Scattering Box 4	1.14	3.38	w/o DFG	0.04	0.83	1.04	3.49	1.08	3.59	0.95	4.93
			w/ DFG	0.04	0.82	1.03	3.4	1.07	3.50	0.94	4.86

[(a)] Ratio of calculated to measurement results

[(b)] $\sqrt{\sigma_e^2 + \sigma_n^2 + \sigma_g^2}$

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