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Sensitivity and Uncertainty Analysis of a Fixed Source Criticality Accident Alarm System Benchmark Experiment

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Outline

- The Experiment
- The Results
  - High Fidelity 3-D Model & Simplification
  - Sensitivity Analysis of Simplified Model
  - Benchmark Model Uncertainty
  - Computational Results compared with measurements
- Conclusions and Future Work

The Experiment

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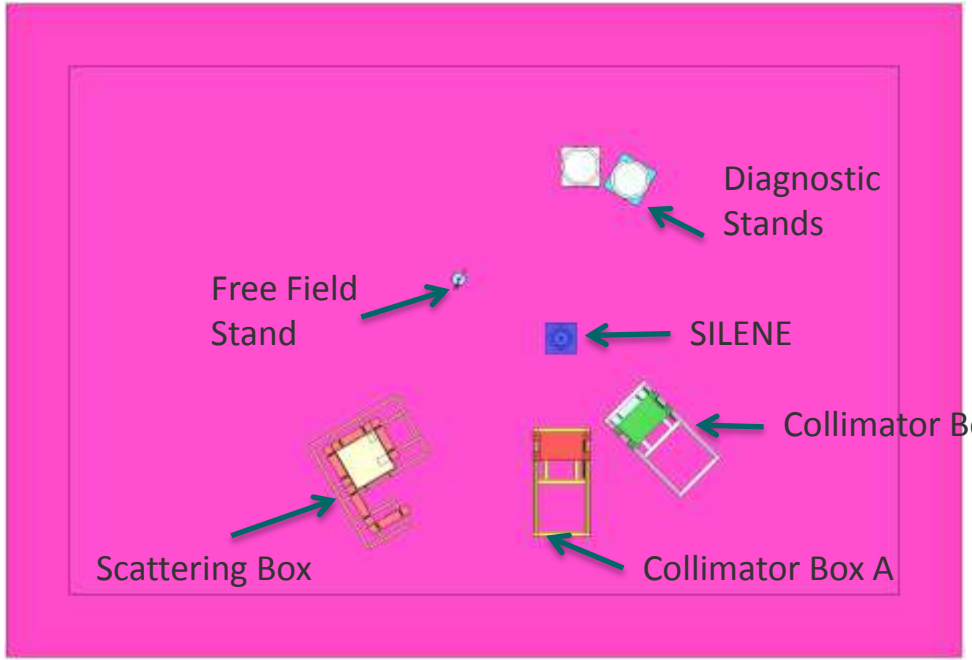
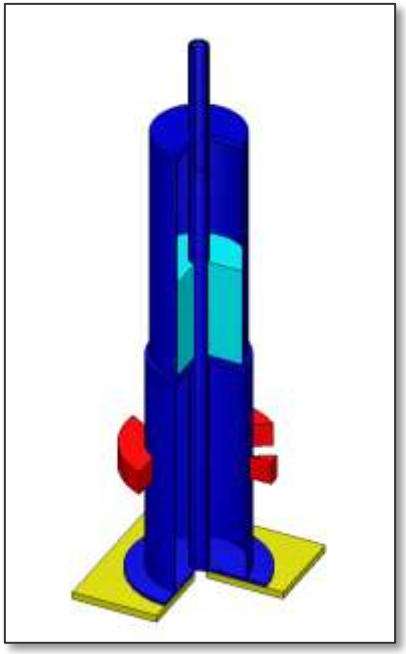
The Experiment

- The experiment was conducted at the CEA Valduc SILENE facility.
- SILENE uses 93.2% ^{235}U Uranyl Nitrate for fuel.
- The reactor can run shielded or unshielded with a lead or polyethylene shield.
- Four types of detectors were used:
  - Neutron Activation Foils for neutron activation
  - TLDs for Gamma Dose
  - CAAS detectors for “go or no go” (i.e. did they work?)
  - Liquid Scintillators for neutron and gamma spectra

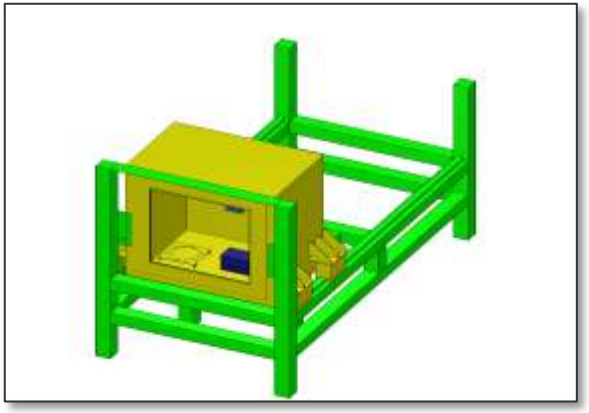
High Fidelity 3-D Model



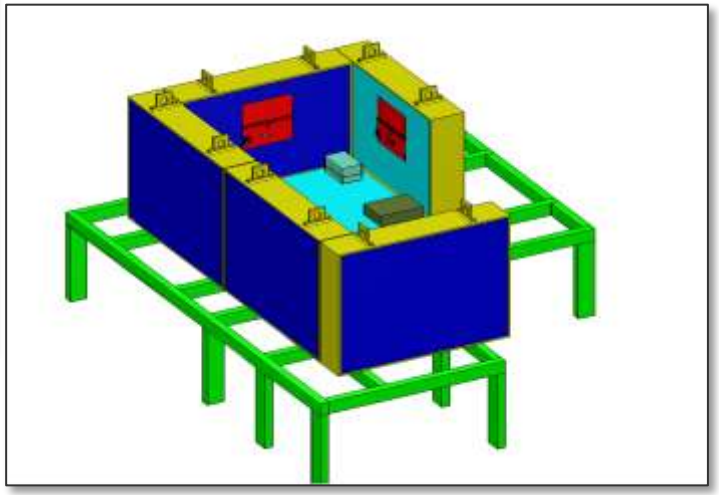
High Fidelity 3-D Model



High Fidelity 3-D Model



High Fidelity 3-D Model



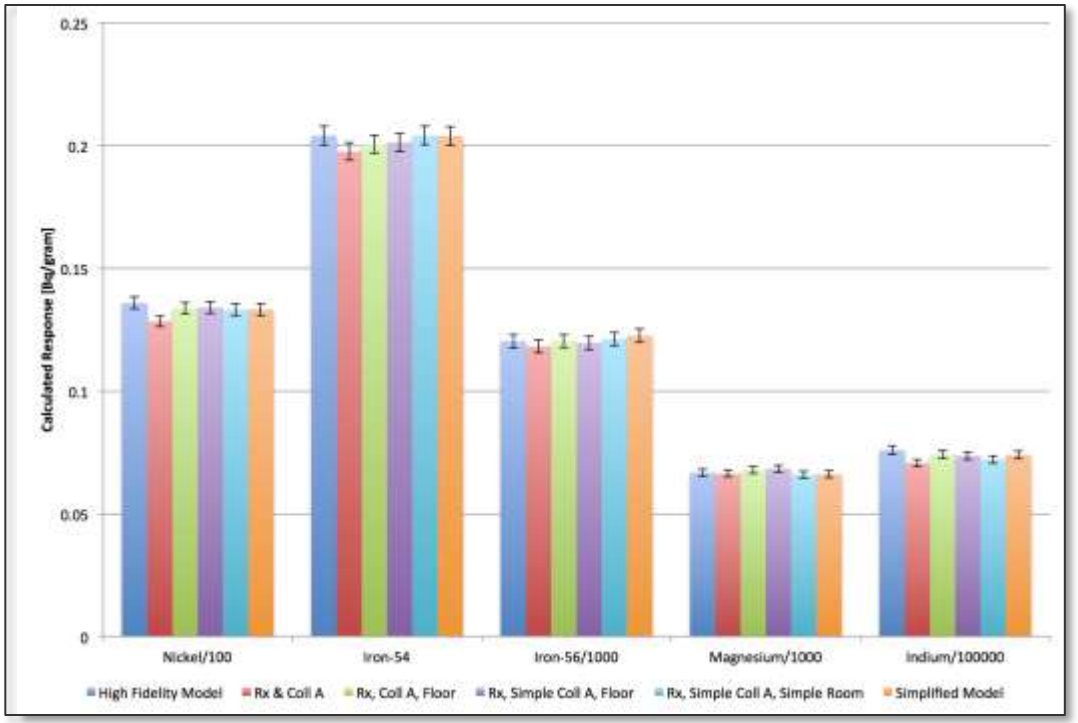
High Fidelity Model Results

Foil	Reaction	Computed Response [Bq/g]	Computed Uncertainty (± σ)	Computed Relative Uncertainty (± %σ)	Measured Response [Bq/g]	Measured Uncertainty (± σ)	Measured Relative Uncertainty (± %σ)	Ratio of Computed to Measured Response (C/E)
Threshold Reactions								
Ni	$^{58}Ni(n,p)^{58}Co$	13.592	0.121	0.8902	14.36	0.22	1.5320	0.9465
Fe	$^{54}Fe(n,p)^{54}Mn$	0.20415	0.002	0.9797	0.2062	0.0041	1.9884	0.9901
Fe[1]	$^{56}Fe(n,p)^{56}Mn$	120.30	1.395	1.1596	N/A	N/A	N/A	N/A
Mg	$^{24}Mg(n,p)^{24}Na$	66.780	0.7095	1.0624	61.1	1.15	1.8822	1.0930
In	$^{115}In(n,n',\gamma)^{115m}In$	7592.00	88.000	1.1591	8030	125.0	1.5567	0.9455
Thermal Reactions								
Au	$^{197}Au(n,\gamma)^{198}Au$	76491.0	804.50	1.0518	1.812×10^{5}	2850.0	1.5728	0.4221
Fe[2]	$^{55}Mn(n,\gamma)^{56}Mn$	2202.30	25.10	1.1397	N/A	N/A	N/A	N/A
Co	$^{59}Co(n,\gamma)^{60}Co$	71.0130	0.715	1.0069	66.1	0.85	1.2859	1.0743
In	$^{115}In(n,\gamma)^{116}In$	1.17200×10^{7}	1.19500×10^{5}	1.0196	9.11×10^{6}	1.75×10^{5}	1.9210	1.2865
Threshold + Thermal Reactions								
Fe	1 + 2	2322.6	25.1387	1.0824	2310	30.5	1.3203	1.0055

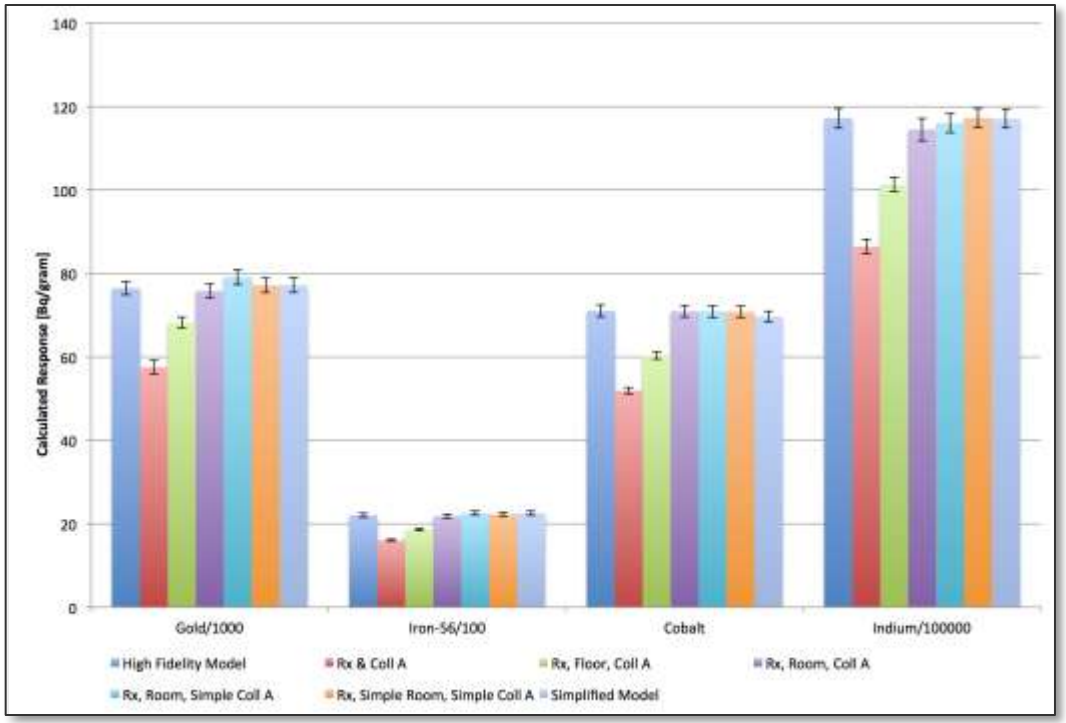
Model Simplification

- High Fidelity model too complex for benchmark Handbook.
- Simplifications to model evaluated by comparing computational results of altered model to the original high fidelity results.
- Initial simplification was made by removing all model components EXCEPT the reactor, the collimator box, and the activation foils inside their aluminum frame inside the collimator box.
- Computed results from initial simplification were not statistically equivalent. Therefore, various aspects of model were systematically added in and the results compared.
- Simplified model was finalized as SILENE, the box portion of collimator box A and a simplified representation of the entire reactor cell (ceiling, walls, and floor all present with no doors or rail system in model).

Model Simplification: Threshold Responses



Model Simplification: Thermal Responses



Simplified Model Sensitivity

- Benchmark experiment had many known uncertainties to which the computational model could be sensitive.
- Selected those known uncertainties that directly impacted the Pulse 1 model associated with collimator box A.
  - Thickness of the activation foil
  - ^{235}U enrichment of uranyl nitrate fuel
  - Density of the PPB9 (polyethylene) in collimator box
  - Presence of impurities in the foils and aluminum frame
- Threshold foil reactions turned out to be essentially insensitive to any changes associated with the above parameters and so no sensitivity coefficients were computed for the threshold reactions.

Thermal Foil Sensitivity Coefficients

Parameter	S	σ_s
Gold Foil		
Foil Thickness	0.6816	0.0099
^{235}U Number Density	-0.2099	0.0290
PPB9 Density	-0.2152	0.0319
Cobalt Foil		
Foil Thickness	0.7497	0.0112
^{235}U Number Density	-0.3282	0.0295
PPB9 Density	-0.2664	0.0280
Indium Foil		
Foil Thickness	0.4290	0.0064
^{235}U Number Density	-0.2207	0.0272
PPB9 Density	-0.0948	0.0280
Iron Foil (Iron-56)		
Foil Thickness	Not Sensitive	
^{235}U Number Density	-0.3598	0.0351
PPB9 Density	-0.1307	0.0474

Benchmark Uncertainty

- Each of the sensitivity coefficients computed for the thermal foils was converted to a benchmark uncertainty associated with that parameter by multiplying the known experimental uncertainty with the computed sensitivity coefficient.
- The total benchmark uncertainty for each foil was computed by combining the individual parameter uncertainties (square root of the sum of the squares).
- The reported total number of fissions was reported as having an uncertainty of 4%. Every thermal and threshold foil response was required to include this as part of the benchmark uncertainty since the total number of fissions was used to convert the computed responses from a per fission basis to a total value by multiplying by the total number of fissions.

Benchmark Uncertainty

Parameter	S	R	x	σ_x	$\sigma_{R,x}$	% $\sigma_{R,x}$
Gold Foil						
Foil Thickness	0.6816	7.7183E04	0.025 cm	2.5E-03	5.2608E03	6.816
^{235}U Number Density	-0.2099	7.7183E04	1.669503E-04 at/b-cm	3.3390E-08	-3.2401	4.1979E-03
PPB9 Density	-0.2152	7.7183E04	1.02 g/cm^3	0.102	-1.6610E03	2.152
Total Fissions					7.520E15	4.0
				Total		**8.1908**
Cobalt Foil						
Foil Thickness	0.7497	6.9614E01	0.2 cm	2.0E-02	5.2190	7.4971
^{235}U Number Density	-0.3282	6.9614E01	1.669503E-04 at/b-cm	3.3390E-08	-4.5694E-03	6.5639E-03
PPB9 Density	-0.2664	6.9614E01	1.02 g/cm^3	0.102	-1.8546	2.6641
Total Fissions					7.520E15	4.0
				Total		**8.9053**

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Benchmark Uncertainty

Parameter	S	R	x	σ_x	$\sigma_{R,x}$	% $\sigma_{R,x}$
Indium Foil						
Foil Thickness	0.4290	1.1708E07	0.1 cm	1E-02	5.0227E05	4.2900
^{235}U Number Density	-0.2207	1.1708E07	1.669503E-04 at/b-cm	3.3390E-08	-5.1678E02	4.4139E-03
PPB9 Density	-0.0948	1.1708E07	1.02 g/cm^3	0.102	-1.1091E05	0.9473
Total Fissions					7.520E15	4.0
				Total		**5.9415**
Iron Foil (Iron-56)						
Foil Thickness	Not Sensitive					
^{235}U Number Density	-0.3598	2.2501E03	1.669503E-04 at/b-cm	3.3390E-08	-1.6192E-01	7.1961E-03
PPB9 Density	-0.1307	2.2501E03	1.02 g/cm^3	0.102	-2.9409E01	1.3070
Total Fissions					7.520E15	4.0
				Total		**4.2081**

Final Results Summary

- The benchmark uncertainty for each foil reaction was combined with the computational uncertainty (Monte Carlo) to determine the final amount of total uncertainty associated with each computed estimate of response.
- The simplified model computational results were used to compute final estimates of the C/E for each foil reaction and the total uncertainty associated with the estimates were propagated through the final C/E estimate using propagation of error.
- The gold foil was not reported as part of the final results due to the discovered error in the pulse 1 measurement.

Final Results Summary

Foil	Simplified Calculated Response [Bq/g]	Calculated Uncertainty (± %σ)	Benchmark Uncertainty (± %σ)	Total Uncertainty (± %σ)	Measured Response [Bq/g]	Measured Uncertainty (± %σ)	C/E	C/E Uncertainty (± %σ)
Threshold Foils								
Ni	13.325	0.9094	4.0	4.1021	14.360	1.5320	0.9279	4.3788
Fe-54	0.2039	0.9294	4.0	4.1066	0.2062	1.9884	0.9888	4.5627
Fe-56[1]	122.57	1.1259	4.0	4.1554	N/A	N/A	N/A	N/A
Mg	66.134	1.0343	4.0	4.1316	61.100	1.8822	1.0824	4.5401
In	7402.1	1.1193	4.0	4.1537	8030	1.5567	0.9218	4.4357
Thermal Foils								
Au	7.7183×10^4	1.0518	8.1908	8.2581	1.812×10^5	1.5728	N/A	N/A
Co	69.614	1.0069	8.9053	8.9620	66.1	1.2859	1.0532	9.0538
In	1.1708×10^7	1.0196	5.9415	6.0284	9.11×10^6	1.9210	1.2852	6.3271
Fe-56[2]	2.2501×10^3	1.1397	4.2081	4.3597	N/A	N/A	N/A	N/A
Thermal + Threshold								
Fe-56 (1 + 2)	2372.67	1.0153	5.8059	5.8940	2310.00	1.3203	1.0271	6.0401

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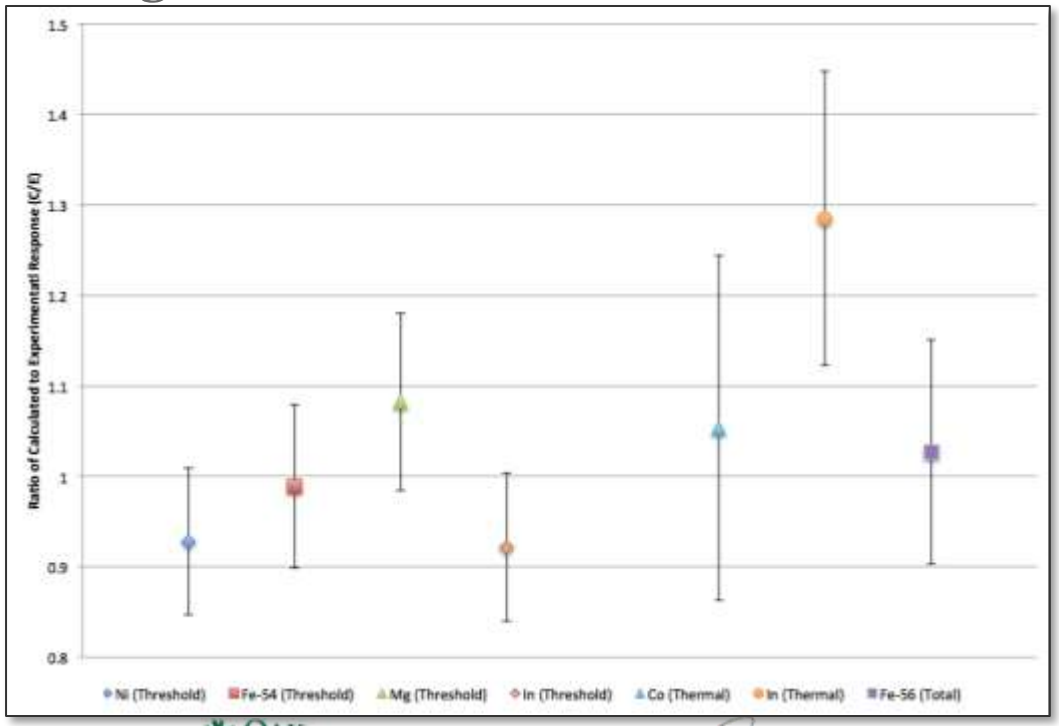
Final Results Summary

(error bars 2 sigma)



Conclusions

- Both the High Fidelity and Simplified computational models generate acceptable estimates of neutron activation when compared to the measured dosimetry.
- Previous shielding benchmarks were considered to be in good agreement with as much as 30 percent relative error. The estimates of response in this benchmark all have relative errors of less than 10 percent (with one exception) – a factor of 3 increase in accuracy from previous efforts.
- The thermal indium foil estimate error of 28% allows this reaction to be used as benchmark quality data (given that previous benchmarks included data with such high relative errors) but given the accuracy of the other foil estimates seems to indicate the need for further study.
- The measured dosimetry data from pulse 1 and collimator box A is acceptable to be used as a CAAS benchmark.

Future Work

- There were no “known” uncertainties associated with the the composition and density of the reactor cell concrete. Because of this variations associated with these parameters was left to be done as part of future work.
- Similarly, other materials in the collimator box (lead, copper, steel) could also contribute benchmark uncertainty and should be studied further.
- The systematic methodology used to derive the simplified computational model for collimator box A needs to be used to derive acceptable simplified models for the remaining pulse 1 components (collimator box B, scattering box, and the free field stand).
- Once the appropriate simplified models for the remainder of pulse 1 have been determined – all of the simplified models need to be used to estimate the gamma responses and compare them to the measured TLD data.
- Pulse 2 and pulse 3 need to be studied in a similar fashion so as to publish the final two benchmarks associated with this experimental effort.