SAND2010-3438C

Experimental validation of a coupled neutron-photon inverse radiation transport solver

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Abstract

Sandia National Laboratories has developed an inverse radiation transport solver that applies nonlinear regression to coupled neutron-photon deterministic transport models. The inverse solver uses nonlinear regression to fit a radiation transport model to gamma spectrometry and neutron multiplicity counting measurements. The subject of this paper is the experimental validation of that solver. This paper describes a series of experiments conducted with a 4.5-kg sphere of α-phase, weapons-grade plutonium. The source was measured bare and reflected by high-density polyethylene (HDPE) spherical shells with total thicknesses between 1.27 and 15.24 cm. Neutron and photon emissions from the source were measured using three instruments: a gross neutron counter, a portable neutron multiplicity counter, and a high-resolution gamma spectrometer. These measurements were used as input to the inverse radiation transport solver to evaluate the solver's ability to correctly infer the configuration of the source from its measured radiation signatures.

Keywords:
Gamma spectrometry
Neutron multiplicity counting
Radiation transport
Inverse problems

Introduction

Forward radiation transport is the problem of calculating the radiation field given a description of the radiation source and transport medium. In contrast, *inverse* transport is the problem of inferring the configuration of the radiation source and transport medium from measurements of the radiation field. As such, the identification and characterization of special nuclear materials (SNM) is a problem of inverse radiation transport, and numerous techniques to solve this problem have been previously developed.

This paper briefly describes an inverse radiation transport solver that applies nonlinear regression procedures to fit coupled neutron-photon deterministic transport models to gamma spectrometry and neutron multiplicity counting measurements [1, 2]. A series of benchmark experiments with polyethylene-reflected plutonium were conducted to evaluate the solver's accuracy by fitting transport models to data collected using a high-resolution gamma spectrometer, a gross neutron counter, and a neutron multiplicity counter.

Inverse radiation transport solver

The inverse radiation transport solver has three components:

- A deterministic radiation transport engine that calculates the neutron and photon radiation field from a model of the source. Discrete ordinates transport solvers solve for the neutron and photon flux given a model of the neutron and photon source terms and the transport medium. The transport medium is represented in one-dimensional spherical, cylindrical, or rectilinear geometry.
- Detector response models that calculate the response of radiation detectors to the computed field. Point models of detector response functions are used to transform the calculated radiation field into an estimated detector response. Detectors that can be modeled include gamma spectrometers, gross neutron counters, and neutron multiplicity counters.
- A nonlinear regression solver that minimizes the error between the observed detector response and the calculated response by varying parameters of the source model. A modification of the Levenberg-Marquardt nonlinear regression algorithm minimizes the error between the calculations and the measurements. The error metric is a chi-square metric, i.e., the sum of variance-weighted squared errors.

The inverse solver operates on an initial guess for a model of the source and one or more measured detector responses. At a minimum, a measured gamma spectrum is required by the solver. One or more source model parameters (e.g., the activity of a radionuclide or the dimensions of a region in the transport medium) are treated as variable. The inverse solver uses the Levenberg-Marquardt conjugate-gradient method to search for the variables that minimize the error between the calculated and measured detector responses.

Benchmark experiments

A series of benchmark experiments of polyethylene-reflected plutonium metal were conducted at the Nevada Test Site in January 2009. The plutonium source was measured using a high-resolution gamma spectrometer, a gross neutron counter, and a neutron multiplicity counter. Figure 1 shows the positions of the plutonium source and radiation instruments. The data collected during these experiments were used to evaluate the accuracy of the inverse transport solver.

Plutonium source

A photograph of the plutonium source is shown in Fig. 2. The source was a 4.5 kg sphere of 94%-^{239}Pu alpha-phase plutonium metal constructed in Los Alamos in the 1980s for criticality safety experiments [3]. The plutonium is clad in stainless steel 0.3 cm thick.

The source was measured bare and reflected by a series of nesting HDPE shells with total thicknesses of 1.27, 2.54, 3.81, 7.62, and 15.24 cm.

High-resolution gamma spectrometer

The gamma spectrometer was a portable 140%-efficient high-purity germanium (HPGe) detector cooled by a 3-liter capacity liquid nitrogen dewar. The HPGe crystal was shielded on its radial face by a 2.54-cm-thick bismuth annulus. The spectrometer was located 2 m from the plutonium source.

The gamma spectrum was measured to a maximum photon energy of about 11.7 MeV.

Gross neutron counter

The gross neutron counter was a SNAP (sealed neutron assay probe) designed and constructed by Los Alamos National Laboratory (LANL). The SNAP uses a single 4-inch-long, 1-inch-diameter, 10 atm

^{3}He proportional counter embedded in a layered moderator constructed from polyethylene and cadmium. The moderator is designed to give the SNAP a relatively constant sensitivity to neutrons with a wide range of energies. The SNAP was located 1 m from the plutonium source.

The SNAP also has a removable front cover constructed from HDPE that is 1 inch thick, which serves primarily to gauge the "hardness" of the neutron spectrum. The SNAP count rate was measured with this cover both on and off.

Neutron multiplicity counter

The neutron multiplicity counter was an nPod designed and constructed by LANL. The nPod uses fifteen 15-inch-long, 1-inch-diameter, 10 atm ^{3}He proportional counters embedded in a polyethylene moderator block. The moderator is wrapped in cadmium to minimize the nPod's sensitivity to neutrons reflected by the floor and walls.

The nPod records detection events in list mode with 1-µs time resolution, and this event log was used to accumulate the Feynman-Y metric of variance to mean, $Y = \sigma^2 / \mu - 1$, where μ and σ^2 are the mean of and variance in the number of counts observed for a given counting time.

Validation results

For each configuration of the plutonium source, the inverse solver attempted to fit a one-dimensional transport model to:

- The gamma spectrum
- The SNAP count rate with the front cover both on and off
- The nPod count rate
- The Feynman-Y versus counting time measured by the nPod

The initial model for each case was a 1-kg solid sphere of weapons-grade α-phase plutonium metal, surrounded by a 1-cm-thick layer of iron, with an outer layer of 1-cm-thick HDPE. The Levenberg-Marquardt regression solver was permitted to adjust the dimensions of each layer in the model until it minimized the error in the calculated gamma spectrum, neutron count rates, and Feynman-Y relative to the measurements of the same quantities. Table 1 summarizes the fits obtained by the inverse solver. In the table, the estimated plutonium mass, neutron multiplication, and reflector thickness are compared to the actual values for each configuration of the plutonium source.

Table 1. Source configuration parameters estimated by the inverse solver compared to the actual parameters

Reflector	**Plutonium Mass (kg)**		**Neutron Multiplication**		**Reflector Thickness (cm)**	
	Estimated	Actual	Estimated	Actual [a]	Estimated	Actual
None	4.3	4.5	4.4	4.4	N/A [b]	0.0
0.5 inch	4.6		5.4	5.5	0.6	1.3
1.0 inch	4.3		7.0	7.8	2.5	2.5
1.5 inch	4.3		9.6	10.4	4.0	3.8
3.0 inch	4.4		14.6	16.3	7.5	7.6
6.0 inch	4.2		15.6	17.1	15.0	15.2

[a] The "actual" neutron multiplication was estimated using MCNP5.

[b] For the bare case, no reflector was included in the initial model.

Conclusion

Benchmark experiments with polyethylene-reflected plutonium were conducted to validate the inverse radiation transport solver developed by Sandia National Laboratories. The experiments collected gamma spectrometry, gross neutron counting, and neutron multiplicity measurements of a 4.5-kg plutonium metal sphere reflected by polyethylene up to 15.24-cm thick. In each case, the solver estimated the correct plutonium mass and neutron multiplication within 10% of their actual values. The solver did exhibit a tendency to underestimate mass and multiplication; the possible reasons for this trend are currently under investigation.

Acknowledgments

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of the Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

[1] J. Mattingly and D. J. Mitchell, IEEE Nuclear Science Symposium Conference Record (2008), 1265.

[2] J. Mattingly, IEEE Nuclear Science Symposium Conference Record (2009), 1350.

[3] J. Mattingly, Sandia National Laboratories Technical Report SAND2009-5408/R3 (2009).

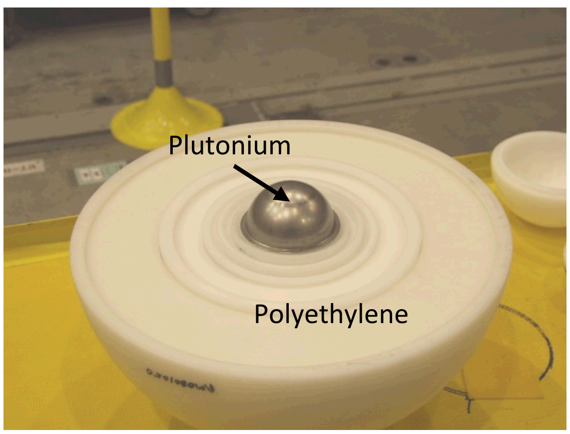

Figure 1. Plutonium metal sphere and polyethylene reflectors

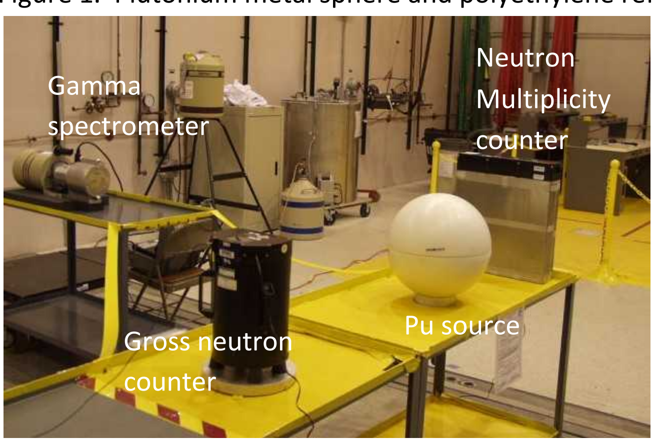

Figure 2. Photograph showing the relative position of the plutonium source and instruments