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Scenarios and Spectra Set for CTBT OSI Information Barrier Testing

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Executive Summary

The Comprehensive Nuclear-Test-Ban Treaty limits radiation measurements during an on-site inspection to those isotopes the States Parties have agreed are appropriate for the purpose of determining if a nuclear explosion has occurred without revealing irrelevant confidential information. To accomplish this, the radiation detectors used will need to have information barriers that are proven to function reliably over the wide range of possible inspection uses and scenarios. In order to provide a basis set of spectra for testing proposed information barrier systems, PNNL and LLNL defined a set of treaty-compliant and non-compliant scenarios, and then independently developed a set of spectra relevant to those scenarios. Real spectra were utilized to the extent possible, such as to determine source intensity, but all scenario spectra were generated through radiation transport modeling.

Introduction

Under the Comprehensive Nuclear-Test-Ban Treaty (CTBT), on-site inspections (OSIs) may be called in order to obtain evidence concerning a possible nuclear test. Since the initial signing of the treaty, most of the technical effort by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has been focused on the development of the International Monitoring System (IMS), and the OSI capability is considerably less developed. Likewise, little of the United States' technical effort in support of the CTBT has been focused on OSI. Consequently, CTBTO's ability to conduct an OSI is at a much lower level of maturity than its ability to operate the IMS. Also, the U.S. understanding of the requirements for an effective OSI is comparatively immature from both technical and policy standpoints.

Paragraph 89(b) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) Protocol limits the radiation measurements to those isotopes and energies relevant to the determination that a nuclear explosion has occurred so as not to disclose irrelevant confidential information. A list of 17 particulate radionuclides has been developed. The NaI(Tl) and HPGe detectors used at an On-Site Inspection both in the field and at the base-of-operations analysis lab must contain information barriers so as to only detect these radioisotopes. In discussions at CTBTO meetings and workshops, these sorts of restrictions are sometimes referred to as "spectral blinding" or "information barriers".

The Provisional Technical Secretariat (PTS) of the CTBTO has acquired such detectors from commercial vendors but found their use to be quite problematic in terms of correctly identifying radioisotopes since even common benign background and calibration sources are not on the list of approved radionuclides. For the Integrated Field Exercise 2008 (IFE '08), CTBTO had handheld target radioisotope identification devices (RIIDs), which utilized NaI(Tl) scintillators (CTBTO 2008). The supplier provided a "limited nuclide identification" setting which could be turned on or off to provide the spectral blinding. This approach caused problems such as the faulty identification of ^{137}Cs as ^{132}I (the largest peaks are only 6 keV apart, though ^{132}I has many other strong peaks). Also for IFE '08, CTBTO had a "spectrally blind" 70% HPGe detector from Canberra using the Inspector 2000 MCA, and problems were noted for this detector as well. In both cases, the detectors were provided by the commercial vendors with rather incomplete attempts at implementing the information barriers. A more detailed study is needed before drawing conclusions.

These two examples show that technical guidance on information barriers is needed so that the appropriate detectors are ready prior to treaty Entry into Force (EIF). There are two basic options when implementing spectral blinding: 1) acquiring and analyzing the entire spectrum, but limiting the reporting to the selected isotopes; or 2) limiting the spectrum at acquisition, with analysis and reporting limited. The first approach is related to the "information barrier" authentication work performed with Russia several years ago and was advocated by a U.S. scientist at an early CTBT Workshop but not studied (Kreek et al. 1998). An alternative approach advocated by some countries but less likely to be feasible would be to use pulse height discrimination so that only energy "windows" are collected rather than entire spectra. This would be less intrusive as full spectra would never be acquired, but the approach has not been tested for effectiveness.

The OSI situation is much more complicated than the Authentication work studied by many of the DOE labs several years ago. That work (Kouzes et al. 2003; Luke et al. 2001; Seager et al. 2001; Whiteson and MacArthur 2000) was concerned with authenticating the presence of weapons-grade plutonium in bilateral monitoring situations without revealing classified information. Authentication progressed to the development of fairly sophisticated detector systems and demonstrations of them to the Russian Federation. Those efforts involved characterization of a single element in close proximity using high-resolution detectors with controlled and unchanging background, which is quite different than what is envisioned for OSI.

Prior to general acceptance, any OSI information barrier system must be assessed against a full range of scenarios. OSIs could involve both compliant and non-compliant scenarios. OSI measurements could involve strong or weak signals relative to varying amounts of background from natural and/or anthropogenic sources. In addition, detector calibration may not be ideal. In order to define the nature of the source of fission products, analysis behind an information barrier system must be able to perform not only qualitative radioisotopic identification, but also quantitative measurements, so that ratios of relevant radionuclides can be determined.

In order to provide a basis set of spectra for testing proposed OSI information barrier systems, PNNL and LLNL defined a set of scenarios and then independently developed a set of spectra relevant to those scenarios. Real spectra were utilized to the extent possible, but often computer simulations were necessary. In total, the spectra set is composed of 80 individual spectra. The spectra were limited to measurements with HPGe detectors. As the most sensitive (in terms of energy resolution) OSI spectroscopic detector, it is most prone to requiring an Information Barrier to prevent revealing the presence of non-relevant radionuclides, but also the most amenable to successful implementation of an Information Barrier.

OSI Scenarios

PNNL and LLNL defined eight OSI scenarios to define an assessment set for Information Barrier testing. They are as follows:

1) Nuclear explosion – strong underground release including particulates, assayed weeks after explosion

2) Nuclear explosion – weak activity with limited particulate release, assayed 1-2 weeks after explosion

3) Nuclear explosion – weak activity with limited particulate release assayed 1-2 years after explosion

4) Nuclear explosion – Gas-only release with subsequent decay-daughter particulate deposition, assayed weeks after explosion

5) Legacy testing debris assayed decades after explosion,
“Nevada Test Site” aboveground surface/shallowly buried or similar

6) Reactor accident – Predominantly volatile release, “Fukushima”

7) Reactor accident – Core release with refractories & volatiles, “Chernobyl”

8) Spent-fuel reprocessing waste site

Of these, the first four are treaty-noncompliant scenarios while the latter four are treaty-compliant.

Description of PNNL Spectra Set

PNNL simulated spectra for these scenarios using the GEANT4 framework (Agostinelli et al. 2003; Allison et al. 2006) for radiation transport modeling to generate high-statistics template histograms, which were then sampled to generate statistically independent spectra for a variety of signal/background strengths. The geometric model, shown in Figure 1, consisted of 300 g soil sample in front of an Ortec trans-SPEC-DX-100T detector. The sample and detector were inside a 101.6 mm (4”) thick lead shield. The detector is a coaxial high-purity germanium detector, with an outer diameter of 61.3 mm and length of 56.7 cm. The crystal was surrounded by a 1 mm thick can of aluminum, with 5.2 mm distance from the front of the can to the front of the active volume of the crystal. The sample was 65 mm in diameter and 60.3 mm thick, placed 2 mm from the front surface of the aluminum can of the detector. The dirt material was composed mostly of silicon and oxygen, with traces of other metals, with a density of 1.5 g/cm^3.

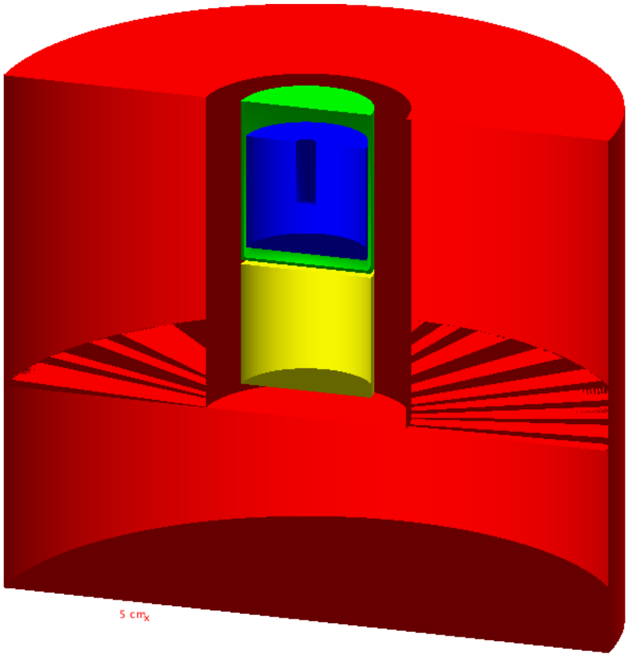

Figure 1. Cut away view of the modeled detector. The lead shield is red, the soil sample is yellow, the germanium crystal is blue and the aluminum can is green. The red fan pattern is an artifact of visualization in Geant4 where two surfaces meet flush.

Three different classes of template spectra were generated. There were two background template spectra, one coming from background terms within the soil sample and one coming from the room. The background template spectra were the same for all scenarios. The set of isotopic template spectra, containing the observed spectra from various fission products and actinides, varied for each scenario.

The soil background spectrum was generated assuming crustal abundance of ^{40}K, ^{232}Th and ^{238}U. The isotopes were allowed to grow in for 10^9 years to populate the decay chains appropriately. Finally, 200 pCi/kg of ^{137}Cs was added to the source term to account to account for fallout. The normalization for the soil background term was 218 photons/s/kg of soil. Photons of the appropriate energy were generated inside the soil, and then allowed to propagate through the soil and potentially into the detector.

The room background spectrum was generated using a surface source photon energy distribution derived from a high-purity germanium measurement of the soil at Hanford. The normalization for soil surface term was 2.37 photons/s/cm^2. The top of the shielding to the detector was left open. As a result, it was possible for photons from the room background term to scatter in the air and into the detector from the top. The room background contributions were more than an order of magnitude weaker than the soil-related background contributions.

The signal spectra consisted of contributions from the various fission products and actinides. The signal spectra varied with each scenario, as described below. The isotopes were distributed randomly throughout the soil sample, and then allowed to decay using the GEANT4 Radioactive Decay Module. The energy deposited from all particles that interacted with the active volume of the germanium was scored for each decay. Charge collection, electronics and signal processing was not modeled. With this approach, possible pileup in the detector from different photons from the same decay was automatically accounted.

The energy deposited in the detector by the simulation was smeared by the energy resolution of the detector. The radiation transport modeling records the energy deposited, but does not account for various energy broadening mechanisms. As a result, it was necessary to broaden the simulated spectra to replicate observed measurements. The simulated energy deposited spectra were broadened with a Gaussian distribution with a standard deviation of

$$\sigma(E) = \left(0.335 + 2.51 \cdot 10^{-4} E + 6.53 \cdot 10^{-3} \sqrt{E}\ \right) keV,$$

where *E* is in keV. This curve was determined from fits to a spectrum measured using an Ortec trans-SPEC-DX-100T detector.

Several spectra were generated from each scenario for the equivalent of a one-hour live time measurement. The mean contributions from the sample and room background were constant for each spectrum, while the isotopic contributions were varied so that the ratio of the sum of the isotopic contributions relative to the sample background varied from 10^{-3} to 10^3 for ten spectra. For each component of a scenario spectrum with a specific signal/background ratio, the spectrum was built by randomly sampling the various template histograms for a specific number of events. The number of events sampled was calculated by first determining the mean number of events expected for that component for a one hour measurement, and then randomizing the mean number following Poisson statistics. In this manner, the spectra are statistically independent.

The isotopic contributions for each scenario varied, as described below:

Scenario 1 (Nuclear Explosion – Strong release weeks after): The radionuclides chosen corresponded to 99.99999% of the total activity from a Pu nuclear explosion (table 4) at one month decay as listed in (Perkins and Jenquin 1997).

Scenario 2 (Nuclear Explosion – Limited particulate release weeks after): The radionuclides chosen corresponded to 99.99999% of the total activity from a Pu nuclear explosion (table 4) at one-month decay as listed in (Perkins and Jenquin 1997). To differ this "limited particulate" release from the "strong" release in Scenario 1, ^{137}Cs and iodines were reduced by a factor of ten, ^{140}Ba, ^{140}La, Te, Sb, Sn, Ru, and Rb were reduced by a factor of 10^4, and all other radioisotopes were eliminated. Three short-lived daughters of the allowed isotopes were also included, ^{137m}Ba from ^{137}Cs, ^{106}Rh from ^{106}Ru and ^{103m}Rh from ^{103}Ru.

Scenario 3 (Nuclear Explosion – Limited particulate release one year after): This scenario is similar to Scenario 2, except that the particles are allowed to decay for one year instead of one month.

Scenario 4 (Nuclear Explosion – Gas-only release weeks after): To simulate a gas-only release, only the ^{137}Cs (and ^{137m}Ba) and ^{131}I from a ^{239}Pu nuclear explosion (table 4) at one month as listed in (Perkins and Jenquin 1997). The ^{131}I contribution was reduced by a factor of 10^4.

Scenario 5 (Old Test Site Debris): The radionuclides chosen were from the earth activation products from a Pu nuclear explosion (table 6) as listed in (Perkins and Jenquin 1997). An initial list was generated of radionuclides corresponding to 99.99999% of the total activity at 600 days. Those radionuclides were then allowed to grow-in over 58 years, so that the activity of the radionuclides represents site debris 60 years post-detonation.

Scenario 6 (Reactor Accident – Volatile Release): The radionuclides chosen were selected from the "US DOE/NNSA and DoD Response to 2011 Fukushima Incident: Radiological Soil Samples" data set at data.gov (*Data Catalog*). Each record in the dataset contains information about where and when the sample was collected, how the measurement was performed, and a single result. Only samples collected two to four weeks after the earthquake were included. In addition, datasets that reported non-positive activities or did not report on a specific isotope were eliminated, leaving a total of 687 records for individual isotopes. The activity of each record was corrected to the time of the earthquake, and then the average activity of all records for an individual isotope was determined. Finally, the averaged activity was aged for 3 weeks after the earthquake.

Scenario 7 (Reactor Accident – Core Release): The radionuclides chosen were selected from an analysis of a HPGe measurement of an air filter sample collected at the time of the Chernobyl accident. Simulations of the air filter samples were performed to adjust the relative intensity of the various radionuclide signatures to match well the observed intensities in the filter sample

Scenario 8 (Spent fuel processing site): The radionuclides chosen were from the fission products of a pressurized water reactor (table 1) with a three year cool-down time as listed in (Perkins and Jenquin 1997).

Summary

This report describes a series of spectra generated through radiation transport modeling to enable the testing of information barrier systems for OSI in support of the CTBT. Eight different scenarios were defined, four compliant and four non-compliant, with 10 different levels of signal intensity compared to the background.

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