Onsite Verification of the Comprehensive Nuclear Test Ban Treaty at Very Low Yields

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Abstract:
The United States has accused Russia and suspects China of violating the Comprehensive Nuclear Test Ban Treaty (CTBT) at very low yields - in the kilogram-range rather than kiloton range of chemical explosive equivalent energy yields. The accusation is that the tests involved supercritical chain reactions that are forbidden under the U.S. interpretation of the treaty. Offsite, there would be no detectable physical evidence to differentiate such tests from permitted subcritical tests except satellite images of suspiciously large containment vessels being emplaced in tunnels. However, if onsite inspections are allowed, it might be possible to measure gamma emissions from the fissions and neutron-activation product concentrations in a containment vessel to infer the energy released through fission during the test. Because subcritical tests have fission yields of less than a milligram of chemical explosive equivalent, the gamma activity beyond levels induced by natural background and diagnostic neutron and gamma-ray bombardment during the test might not be detectable. This could make the measurements more acceptable to the inspected party. Results, calculated with the open-access OpenMC transport code and the ONIX depletion code, are presented, identifying the most promising fission and/or activation products for onsite forensic inspections.

1) Introduction

The United States alleges that, "since declaring its testing moratorium [in 1992], Russia has conducted nuclear weapons experiments that have created nuclear yield and are not consistent with the U.S. 'zero-yield' standard." The U.S. standard is that the fissile material in any explosive experiment must remain subcritical. The United States has also expressed concern about the "lack of transparency" of China's activities at its nuclear test site leading to "concerns regarding China's adherence to the U.S. 'zero-yield' nuclear weapons testing moratorium adhered to by the United States, United Kingdom, and France."[2]

The United States conducts a vigorous program of experiments in which imploded plutonium shapes similar to the "pits" of its nuclear weapons are bombarded with neutrons to initiate a chain reaction but remain subcritical because of design modifications to the pits or the implosion system. For safety reasons, experiments that approach supercriticality are conducted underground at the Nevada National Security Site (formerly the Nevada Test Site). The limit of the current U.S. ambition is a peak average neutron multiplication factor of about 0.95 and a total number of about $2x10^{10}$ fissions during the implosion, i.e., a fission energy yield equivalent to about 0.6 joules or the equivalent of that from the detonation of 0.15 µg of chemical explosive.[3]

During its 1958-61 nuclear test moratorium, the United States conducted "hydro-nuclear experiments," very-low-yield supercritical experiments whose fission yields were limited to an energy release of less than that of the explosion of one pound (0.45 kg) of chemical explosive. The purpose was to deal with concerns that some U.S. weapon designs might not be "one-point safe," i.e., they might produce nuclear yield if the

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[2] U.S. State Department, *Adherence to and Compliance with Arms Control, Nonproliferation, and Disarmament Agreements and Commitments* (2021), https://www.state.gov/2021-adherence-to-and-compliance-with-arms-control-nonproliferation-and-disarmament-agreements-and-commitments/#_Toc69385136.

[3] D. J. Funk, "Enhanced Capabilities for Subcritical Experiments (ECSE): Portfolio Overview," rep. no. LA-UR-18-28253, Los Alamos National Laboratory, PowerPoint presentation (2019), https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-18-28253.

chemical explosive around the pit were detonated at a single point rather than simultaneously at multiple points.[4] The Soviet Union conducted 89 hydronuclear tests through 1989. A U.S.S.R. report on these experiments stated that "the yield did not exceed the yield typical for a chemical explosive," which could allow for nuclear yields up to the equivalent of tens of kilograms of chemical explosive.[5] Both hydronuclear and subcritical experiments have typically been conducted in underground tunnels in large containment vessels to prevent the dispersal of plutonium (Figure 1).

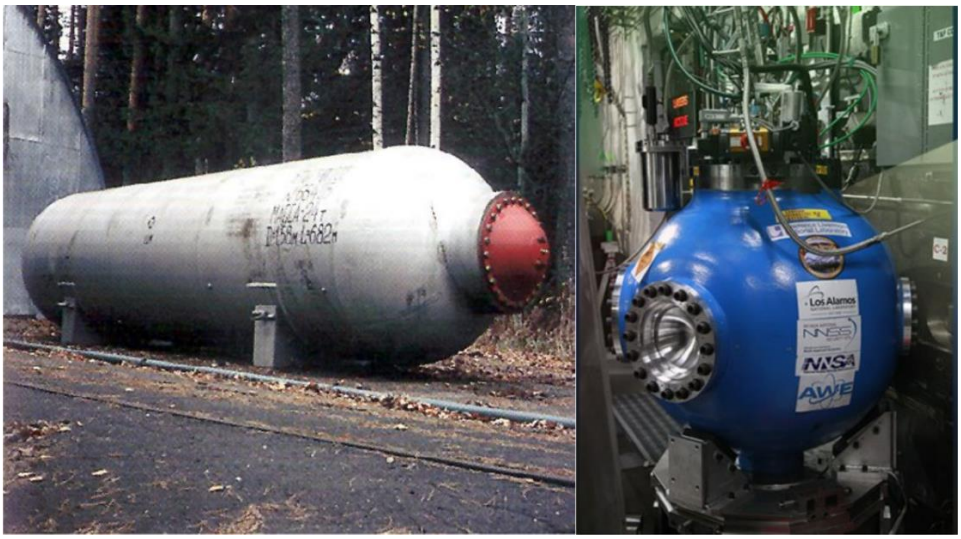

Figure 1. Left. Containment vessel "Kolba" used for Soviet hydronuclear experiments. According to the inscription in Cyrillic, the radius is 1.58 m and the length is 6.82 m.[6] *Right. A containment vessel for a U.S. subcritical experiment emplaced in its test chamber off a tunnel under the Nevada National Security Site. The diameter of the vessel is on the order of 1 m.*[7]

The fission yields of such small explosions could not be determined off-site. On-site inspections would be required. In this paper, we consider one possible on-site verification technique: measurement of the gamma rays from a containment vessel that has been used for an experiment.

These gamma rays would be from different sources:

1) The plutonium used in the experiment would be dispersed inside the containment vessel and would emit low-energy gamma rays.
2) The fission products produced by the experiment. These too would be dispersed inside the containment vessel.
3) Neutron-activation products in the containment vessel materials created by neutrons from the fission chain reaction.

[4] R. N. Thorn, D. R. Westervelt, *Hydronuclear Experiments* (Los Alamos National Laboratory, LA-10902-MS, 1987), https://www.osti.gov/servlets/purl/6646692.

[5] V. N. Mikhailov, N. P.Voloshin, A. M. Matushchenko, *Nuclear Tests of USSR, Hydronuclear Experiments. Plutonium Consumption Stock-Taking*, undated, https://inis.iaea.org/collection/NCLCollectionStore/_Public/29/067/29067933.pdf?r=1

[6] E. Harrell, D. E. Hoffman, *Plutonium Mountain: Inside the 17-year mission to secure a dangerous legacy of Soviet nuclear testing*, (Harvard Kennedy School, 2013) https://www.belfercenter.org/sites/default/files/files/publication/Plutonium%20Mountain-Web.pdf.

[7] N. O'Brien, "Subcritical experiment captures scientific measurements to advance stockpile safety" (Livermore National Laboratory, 2019) https://www.llnl.gov/news/subcritical-experiment-captures-scientific-measurements-advance-stockpile-safety.

2) Using gamma emissions to evaluate low-yield tests

2.1 Radioisotopes and gamma ray emissions

When a nuclear weapon experiment involves fission yield, both fission products and neutrons are created. The fission products are mostly radioactive and decay into stable isotopes. The produced neutrons travel through materials and can cause nuclei to transmute into radioactive isotopes, ("activation products"). After a low-yield test, the fission products will be scattered inside the containment vessel or plated on the inner side of the vessel wall. Activation products can be created within the vessel wall and even outside of it in, for example, the rock walls of a tunnel in which the experiment has been emplaced. A higher fission yield will lead to more fission and activation products.

When a radioisotope undergoes alpha or beta decay, the resulting nucleus is often in an excited state and de-excites by emitting one or more high-energy photons ("gamma rays"). The energies of these photons are characteristic of the emitting nucleus. Measuring gamma rays of particular energies, therefore, indicates the presence of the associated radioisotopes. Many of these gamma rays are energetic enough to be detected outside the containment vessel and could be used to verify the energy released through fission during an experiment. Gamma spectrum measurements have already been demonstrated as effective and non-intrusive techniques for the verification of nuclear warheads[8], special nuclear materials[9], or nuclear waste[10].

2.2 Gamma spectrum analysis

Before they can be measured outside of the containment vessel, gamma emissions from specific radioisotopes will travel through materials and undergo various interactions with atoms that will alter and shape the outcoming gamma spectrum. Through Compton scattering, for instance, photons interact with electrons and lose energy. This results in an attenuated emission line and a background signal made of lower energy photons. The gamma spectrum outside of the vessel will therefore be a set of discrete energy lines on top of a continuous background. The intensities of these lines are proportional to the fission yield of the nuclear weapon experiment.

Estimates of the approximate thickness and composition of the containment vessel are required, however, to correct for the attenuation of the gamma lines. This attenuation can be estimated by measuring ratios of two gamma peaks of different energies associated with the same fission or activation product. Since the ratio before attenuation is a known constant and the attenuation depends on the gamma ray's energy, comparing the measured ratio with the unattenuated ratio allows one to learn more about the thickness of the containment vessel or its composition. Since the containment vessel is expected to be more than 95% iron, the alloying metals will have a small impact on the estimate of the thickness. The concentrations of the alloying elements can also be estimated by looking at the relative strengths of the lines associated with their activation products.

The change with time of the intensities of the gamma lines from different radioisotopes can be used to estimate the date of the test. By measuring ratios of gamma lines from two radioisotopes with different half-lives, one can estimate the time since the test without having to know the absolute densities of isotopes associated with these lines. This method is only valid for two isotopes of the same decay chain or produced by the same precursor. Since, in weapon-grade plutonium most of the fission products are created from

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[8] J. Yan, A. Glaser, "Nuclear Warhead Verification: A Review of Attribute and Template Systems," *Science & Global Security* 23, no. 3 (2015): 157–170, http://scienceandglobalsecurity.org/archive/sgs23jieyan.pdf

[9] P. U. Fehlau, G. Wiig, "Stabilized, hand-held, gamma-ray verification instrument for special nuclear materials," *IEEE Transactions on Nuclear Science*, vol. 36, no. 1, (1989): 1160-1165, https://www.osti.gov/biblio/6156564-stabilized-hand-held-gamma-ray-verification-instrument-special-nuclear-materials

[10] U.S. Department of Energy, *Nondestructive Waste Assay Using Gamma-Ray Active & Passive Computed Tomography. Mixed Waste Focus Area*. *OST Reference Number 2123* (DOE/EM-0470, 1999), https://www.osti.gov/servlets/purl/1246963

plutonium-239, it is possible, to a certain degree of approximation, to use the ratios of lines from any decaying fission products.[11] Equation 1 shows how the date can be calculated from the ratio of gamma lines emitted by two fission products.

$$t = (\lambda_B - \lambda_A)^{-1}\left[ln(\frac{FY_B}{FY_A}) + ln(\frac{\lambda_B}{\lambda_A}) + ln(\frac{C_B(T,\vec{N})}{C_A(T,\vec{N})}) + ln(R_{A,B})\right] \quad (1)$$

Where λ_i and FY_i are the decay constant and cumulative fission yields of fission product i from plutonium-239, respectively. $C_i(T,\vec{N})$ represents the attenuation factor of a gamma line emitted by fission product i in a containment vessel of thickness T and isotopic composition $\vec{N}$. Finally, $R_{A,B}$is the ratio of the counts for the gamma lines from the fission products A and B.

The time since the test can also be calculated by measuring ratios of gamma lines from activation products in the containment vessel. In this case, the two activation products need to belong to the same decay chain.

With knowledge of the properties of the containment vessel and the date of the test, it is possible to use the intensity of gamma lines to deduce the energy released by fission during the explosion. For instance, the total energy released by fission can be calculated via Equation 2 from the count detected for the gamma line of a fission product i.

$$E = E_{fission}\left[FY_i\ \lambda_i\ C_i(T,\vec{N})\ exp(-\lambda_i\ t)\right]^{-1} I_i \quad (2)$$

Where $E_{fission}$ is the energy release when plutonium-239 fissions and $I_i$is the intensity of the corresponding gamma line measured in counts/sec.

3) Hydronuclear test model and computer simulation

3.1 Physical model for an hydronuclear test

To assess the feasibility of the methods presented for onsite verification of very-low-yield tests, we have simulated the release of 7.9 Mj of fission energy during 1,600 shakes (1×10^{-8} seconds) in 3 kg of U.S. weapon-grade plutonium.[12] The 7.9 Mj is the amount of energy released by the fission of about 0.1 mg of plutonium ($2.5\text{x}10^{17}$ atoms), the equivalent of the detonation of about 2 kg of chemical explosive. The Nagasaki bomb, which released an energy of about $8.4\text{x}10^{13}$ joules, equivalent to the detonation of about 20,000 tons of chemical explosive, fissioned about 1 kg of plutonium. The 3 kg number is obtained by dividing the declassified amount of U.S. plutonium in the early Cold War period[13] by the declassified number of U.S. warheads.[14] We assume a plutonium isotopic makeup (weight percent) of Pu-238: 0.00012;

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[11] In reality, other plutonium isotopes contribute to the creation of the fission products. Since the yields of the same fission product differ from one plutonium isotope to another, knowledge of the isotopic makeup of the fissile material is required to use this method to date the event. For the application considered in this work (very-low-yield test with weapon-grade plutonium) plutonium-239 fission contributes to more than 96% of the production of fission products. The ratio of the fast fission averaged cross section of plutonium-240 to plutonium-239 is 0.75 (calculated with https://nucleonica.com/) and the ratio of their concentrations in the pit is 0.06. It is reasonable to neglect the contribution of other plutonium isotopes.

[12] The assumption on the energy release and the duration of the detonation are in close agreement with examples of hydronuclear tests described in: T. B. Cochran, *Hydronuclear Testing or a Comprehensive Test Ban?*, (Natural Resources Defense Council, Inc., April 10, 1984), https://fas.org/nuke/cochran/nuc_04109401a_122.pdf. The value of k_{eff} is set to a mid-range value between a maximum k_{eff} value of 1.02 at maximum compression, and a minimum value around 0.98 after 1600 shakes.

[13] U.S. Department of Energy, *Plutonium: The First 50 Years* (DOE/DP-0137, 1996) http://fissilematerials.org/library/1996/02/plutonium_the_first_50_years.html.

[14] U.S. Department of Energy, *Restricted Data Declassification Decisions 1946 to the Present,* Appendix D (RDD-8, 2002), https://fas.org/sgp/othergov/doe/rdd-8.pdf.

Pu-239: 0.9381; Pu-240: 0.0581; Pu-241: 0.00349; Pu-242: 0.00022[15] and that the plutonium is surrounded with a beryllium metal neutron reflector with an initial thickness of 2 cm. The radius of the pit under compression which would lead to a k_{eff} of 0.99 was computed with criticality searches using OpenMC and found to be 2.86 cm. The thickness of the compressed beryllium reflector is 1.72 cm.

It was assumed that the explosion takes place at the center of a spherical containment vessel with an outside diameter of 1 m and a thickness of 5.0 cm. The elemental makeup of the containment vessel metal is assumed to be (weight percent): Iron, 96.18; aluminum 0.01; titanium 0.02; vanadium 0.03; carbon 0.0645; manganese, 10.57; phosphorous, 0.0213, sulfur, 0.00413; silicon, 0.422; chromium, 0.675; nickel, 2.0; molybdenum, 0.42; copper, 1.15; niobium, 0.041.[16] Figure 2 shows a cross section of the geometry of the system modeled.

3.2 Neutronics and gamma transport computer simulations

Coupled simulations between OpenMC[17] and ONIX[18] were used to model the neutronics and isotopic depletion during the detonation of the pit as well as the decay of irradiated materials after the detonation. These programs are advanced open-source software for modeling nuclear systems. Neutron transport calculations with OpenMC used 100 batches with 10,000 neutron histories each and computed one-group parameters such as neutron flux and microscopic cross sections in the pit and the containment vessel. ONIX used these one-group parameters and a power density set to 1.64×10^8 kW/kg-Pu to deplete the system during the detonation (1,600 shakes) and, subsequently, modeled the decay of the irradiated materials for the following elapsed times after the experiment: one hour, one day, one month, six months, one year, two years, and five years. The nuclear data used for these simulations were taken from the ENDF/B-VII.0 library.[19] To model the production of fission products, ONIX used independent fission yields at fast-neutron energies when such data was available.[20]

For the transport of the gamma photons emitted by decaying radioisotopes after the test, it was assumed that fission products were uniformly plated on the interior surface of the containment vessel. A thin layer with a thickness of 8.65 μm was added to the geometry of the system, and was filled with the depleted material of the pit (thereafter referred to as the pit deposit).[21] Simulations of the transport of photons through the containment vessel wall and the resulting gamma spectrum were modeled with OpenMC. Since 2018, the code can model simplified gamma transport in addition to neutron interactions.[22] Four gamma reactions are modeled: coherent (Rayleigh) scattering, Compton Scattering, absorption through the photoelectric

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[15] N.J. Nicholas et al, *Capability and Limitation Study of the DDT Passive-Active Neutron Waste Assay Instrument* (Los Alamos National Laboratory, LA-12237, 1992), https://inis.iaea.org/collection/NCLCollectionStore/_Public/23/064/23064409.pdf.

[16] Values for the elemental composition of the containment vessel are the mid-ranges of values given in Table A.1 found in: *Base Materials for Critical Applications: Requirements for Low Alloy Steel Plate, Forgings, Castings, Shapes, Bars, and Heads of HY-80/100/130 and HSLA-80/100*, (NAVSEA Technical Publication, 2012). Dimensions were taken from: *Total Containment Vessels Market Survey Report*, (Space and Naval Warfare Systems Center Atlantic, 2014), https://www.dhs.gov/sites/default/files/publications/TVC-MSR_0714-508.pdf

[17] P. K. Romano et al, "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development," *Ann. Nucl. Energy*, 82, (2015): 90–97, https://www.sciencedirect.com/science/article/pii/S030645491400379.

[18] J. de Troullioud de Lanversin, M. Kütt, A. Glaser, "ONIX: An open-source depletion code," *Ann. Nucl. Energy*, 151, (2021), https://www.sciencedirect.com/science/article/pii/S0306454920306009.

[19] D.A. Brown et al, "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data," *Nuclear Data Sheets*, 148, (2018): 1-142, https://www.sciencedirect.com/science/article/pii/S0090375218300206.

[20] In total, this library includes fission yields from 22 actinides.

[21] It was assumed that the totality of the depleted pit material had been plated against the inner wall of the containment vessel. In reality, some of the pit material would have fallen at the bottom of the containment vessel.

[22] A. L. Lund, P. K. Romano, *Implementation and Validation of Photon Transport in OpenMC*, (ANL/MCS-TM-381, Argonne National Lab (ANL), 2018), https://publications.anl.gov/anlpubs/2018/12/149145.pdf.

effect, and pair production. When electrons are ejected from atomic shells, OpenMC also models the photon emissions from electrons refilling the shells. For the modeling of the electron transport, OpenMC uses the thick-target approximation.[23]

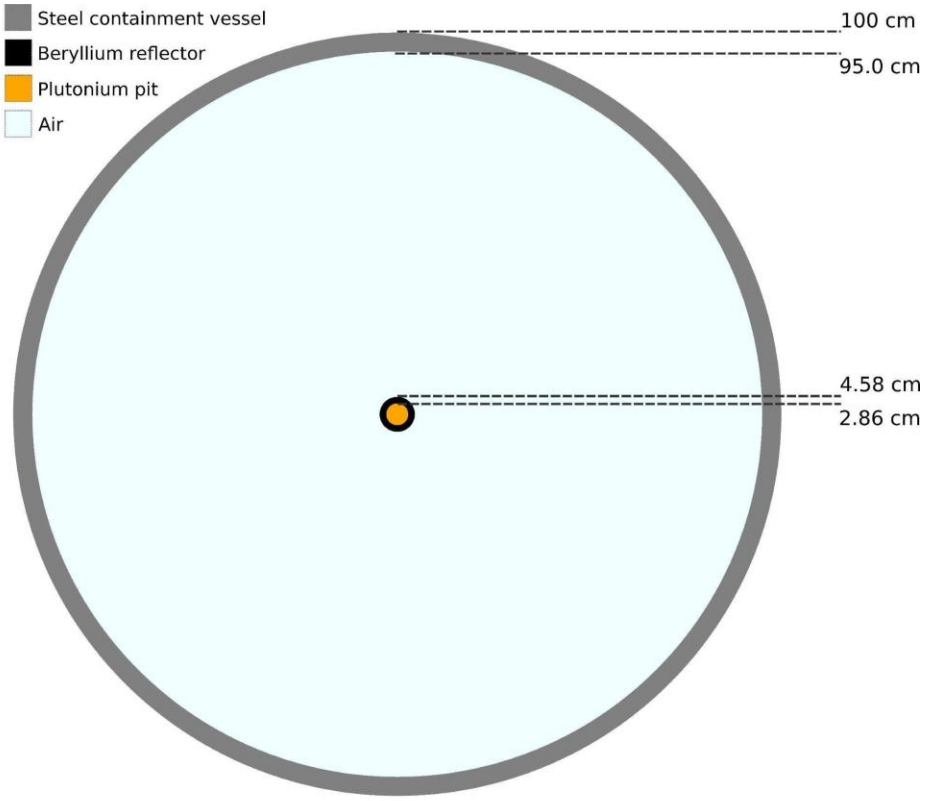

Figure 2. Cross sectional view of the geometry modeled for neutronics calculations. The plutonium pit and beryllium reflector at the center are compressed during the detonation.

The open-source PyNE 0.7.1 software was used to compile gamma lines and their probabilities for each radioisotope from the Evaluated Nuclear Structure Data File (ENSDF).[24] ENSDF is a database of decay information for over 3,000 nuclides provided by the IAEA. Data on gamma lines did not exist for some radioisotopes, but these isotopes were at densities low enough to be ignored. The intensity of each gamma line compiled by PyNE was then calculated from the densities of the corresponding radioisotope as computed by ONIX. OpenMC then used the resulting intensities and energies for each gamma line to start transport simulations of $1x10^9$ photons for each isotopic calculation produced by ONIX at different points in time after the test. Nuclear data on the photon cross sections were taken from the ENDF/B-VII.1 library.[25]

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[23] T. Kaltiaisenaho, "Implementing a photon physics model in Serpent 2," Master's thesis, Aalto University, May 2016, https://aaltodoc.aalto.fi/bitstream/handle/123456789/21004/master_Kaltiaisenaho_Toni_2016.pdf?sequence=1&isAllowed=y; F. Salvat, J. M. Fernández-Varea, J. Sempau, *PENELOPE-2011: A Code System for Monte Carlo Simulation of Electron and Photon Transport*, (NEA/NSC/DOC(2011)5, 2011), https://www.oecd-nea.org/upload/docs/application/pdf/2020-01/nsc-doc2011-5.pdf.

[24] A. Scopatz et al, "PyNE: Python for Nuclear Engineering," *SciPy 2012*, Austin, TX, USA, July 2012.

[25] M. B. Chadwick et al, "ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data," *Nuclear Data Sheets*, 112, Issue 12, (2011): 2887-2996, https://www.sciencedirect.com/science/article/pii/S0090375211001113.

To compute the resulting gamma spectrum that comes out of the containment vessel, a current tally with 3,000 1-keV energy bins (i.e. from 0 to 3,000 keV) was set all around the containment vessel, 1 cm from the surface. To obtain gamma spectra of the emissions from the pit deposit and activation products in the containment vessel separately, each simulation was divided into two photon transport calculations: one where only photons from the pit deposit were modeled, and one where only photons from the activation products were modeled.

4) Gamma spectrum analysis of the numerical model and suggested implementation

4.1 Identifying gamma lines with the numerical model

Figure 3 shows the energy spectrum of the gammas coming out of the containment vessel for the hydronuclear test model described above. Spectra of emissions coming from the pit deposit and the activation products in the containment vessel are plotted separately. Gamma spectrometers would measure the sum of these two spectra, but the current display is preferred as it facilitates identification of the origin of each line. The first plot shows the spectra after one month of decay, the second after six months of decay, and the third after one year of decay. Several lines that could potentially be used to deduce the properties of the containment vessel, the time since the test, and its fission yield are labeled with their energies and the names of their associated isotopes. Some lines were not labeled to make the plot easier to read, but could also be used to gain information on the test. At one month, emissions from the pit deposit dominate the spectrum and only gamma lines from fission products can be measured.

Gamma peaks associated with the alpha decay of plutonium-239 are indicated with black arrows. While few of these peaks are visible one month after the test, due to the long half-life of plutonium-239, with time, they become more predominant, with new lines appearing at higher energy levels. The intensities of these peaks, in combination with the attenuation factor in the containment vessel, would allow an estimate of the amount of plutonium used in the experiment and, perhaps, of its isotopic composition. If this information is considered sensitive, the presence of these peaks will make the methods presented in this work more challenging to implement. One way to circumvent this issue would be to limit the energy range of gammas measured to regions with no measurable plutonium lines. Hardware or software for data processing that would hide or delete information on these peaks similar to information barriers for warhead authentication could also be used.[26]

Figure 3 shows that many pairs of gamma lines from the same radioisotopes can be used to verify the thickness and composition of the containment vessel with the method described in Subsection 2.2. One month after the test, lines from barium-140, ruthenium-103, zirconium-95, lanthanum-140, cesium-136, europium-156, and iodine-132 can be used. After six months, lines from fission and activation products can both be used. These are lines from the fission products ruthenium-103, zirconium-95, and lanthanum-140 and cobalt-58 (three lines), iron-59, and cobalt-60 from the activation products. Almost the same set of lines can be used one year after the test except for lanthanum-140, which concentration in the pit deposit has become too small. Figure 4 shows how some of these ratios change with the thickness of the containment vessel. The curves were obtained by modeling the transport of photons through a vessel of pure iron with an outside radius of 1 m and where the thickness of the vessel was varied from 1 to 15 cm. It can be seen how different ratios change when the thickness increases. Gamma peak ratios of cobalt-58 (0.864 MeV / 1.674 MeV) and ruthenium-103 change the most and could be effectively used to deduce the thickness. Due to its lower sensitivity to the vessel thickness, the ratio from zirconium-95 might lead to less accurate estimates of the thickness.

[26] M. Kütt, A. Glaser, "Vintage electronics for trusted radiation measurements and verified dismantlement of nuclear weapons," *Plos one* 14.10 (2019): e0224149, https://doi.org/10.1371/journal.pone.0224149.
K. Seager et al, "Trusted radiation identification system," *Proceedings of the 42nd Annual INMM Meeting*, (2001), https://media.nti.org/pdfs/SNL-12_SAND2001-1866C.pdf

Additional information on the composition of the containment vessel can be gained by looking at the intensity of activation products lines. Lines associated with cobalt-58 and cobalt-60 can indicate the presence and concentration of nickel and copper, and lines associated with radioisotopes of iron and manganese can inform on the concentration of these elements.

Various lines from fission products can be used to date the event. Since the production of fission products by isotopes other than plutonium-239 can be neglected, ratios from any combination of lines can be taken. The more the ratio changes with time, the more accurate the dating will be. It is, therefore, preferable to choose fission products that result in peak ratios that are more sensitive to time. Such is the case for the ratios of the shorter-lived fission products to the cesium-137 (30 years half-life) line at 0.662 MeV.

The cumulative yield of cesiums-137 from plutonium-239 fast fission is 6.3%. On that basis, 1.6×10^{16} atoms of cesium-137 would have been produced. The initial decay rate would be about 1.2×10^{7} s^{-1}, of which 85% would be associated with the 0.662 MeV gamma-ray. The cumulative fission yield of zirconium-95 (64 days half-life) is about 4.7%. Its initial decay rate will be 1.5×10^{9} s^{-1}, but after a year (5.7 half-lives), it would be down to 2.8×10^{7} s^{-1} with about half the decays associated with the 0.757-MeV gamma rays. The ratio of the counts in the zirconium-95 0.757 MeV peak over the number in the cesium-137 0.662 MeV peak would go from 65 down to 1 within one year. None of the activation products lines generated by the simulation can be used for dating the test, since none of them are produced by the same precursors or belong to the same decay chain.

To estimate the energy released during the test, lines from radioisotopes with long half-lives should be used to reduce errors stemming from uncertainties on the estimated time of the event. Gamma lines from cesium-137, cobalt-60 (5.2 years half-life), and manganese-54 (312 days half-life) are good candidates for estimating the energy released during the test.

4.2 Implementing methods to verify fission yield with gamma spectra measurements

In the context of the inspection of a containment vessel used for a very-low-yield test, inspectors should use neutronics and isotopic depletion modeling of the system in a predictor-corrector process. Closed-formed formulas that relate the measured ratios or intensities of gamma lines to the test's parameters could be used to improve first-order guesses. By integrating any new pieces of information deduced with previous calculations or given by the host, successive simulations should converge toward a more accurate model of the test and allow narrowing down the range of possible values for the energy released by fission.

In the first phase of the inspection, the host should be first required to provide all relevant information on the properties of the containment vessel and the settings of the experiment. Properties of the vessel include the thickness and composition of the material. Specific experiment settings such as external neutron sources used for diagnosis should also be indicated. These neutron sources, sometimes collimated into beams, can irradiate regions of the vessel through which they pass with resulting higher concentrations of activation products. Knowledge of such aspects of the experiment would allow the inspectors to factor out additional radioactivity induced by external neutrons or avoid measuring gamma spectra near regions exposed to neutron beams. The mass and isotopic composition of the pit would likely remain secret, and inspectors should factor uncertainties around these two parameters into their simulations.

Inspectors should start by verifying the information given on the thickness and the composition of the containment vessel. Measuring multiple ratios of pairs of gamma lines associated with the same radioisotopes would allow the inspectors to incrementally narrow down the possible combinations of thickness and composition consistent with these ratios. In the second phase, inspectors should use the parameters on the containment vessel previously computed to carry out new simulations and combine numerical results with gamma peak ratios measurements to deduce the date of the test. Finally, with knowledge of the time since the test and by comparing the intensities of selected gamma lines with numerical results, inspectors could produce a range of estimates for the energy released by fission. For each of the parameters that inspectors seek to estimate, using multiple measurements would help narrow down the range of possible values.

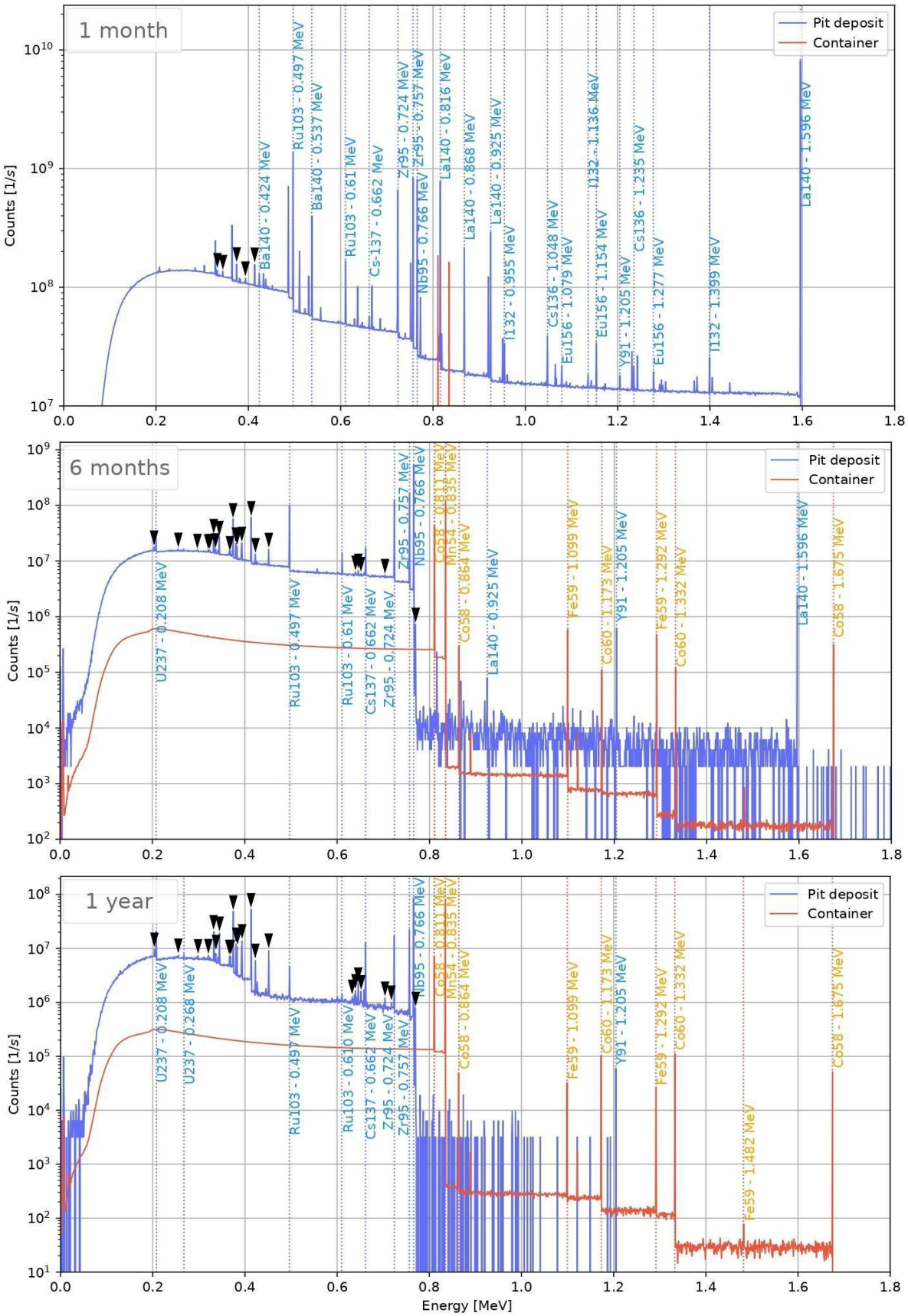

Figure 3. Gamma spectra from the pit deposit (red) and containment vessel (blue) at one month (top), six months (middle), and one year (bottom) after a hydronuclear test in which 3 kg of plutonium released a fission yield of 7.9 MJ . Black arrows indicate plutonium-239 gamma lines.

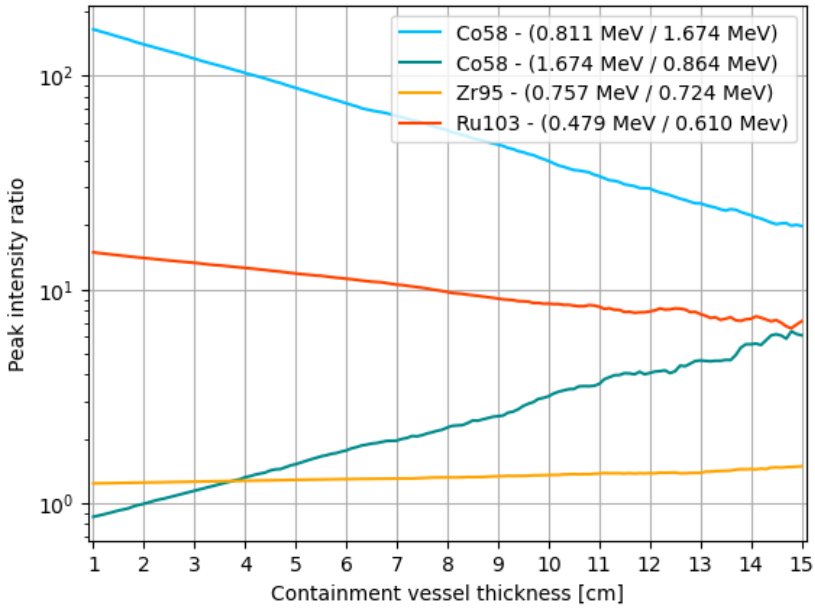

Figure 4. Gamma peak ratios against thickness of the containment vessel for gamma lines emitted by various radioisotopes. The data plotted was produced by simulating the transport of photons in a pure iron vessel with an outer radius of 1 m. The thickness of the vessel wall was varied from 1 to 15 cm.

Conclusion

This work presents a technical approach for verifying the fission energy released by very-low-yield tests carried out in containment vessels. This approach relies on onsite inspections where gamma emissions from the containment vessels are measured and compared with modeled results. Techniques are described for estimating the thickness of the containment vessel, its composition, the date of the test, and, finally, the fission energy released.

Numerical models of a plutonium fission event inside a containment vessel have been used to conduct neutronics and isotopic depletion simulations with open-source software. These simulations produced isotopic concentrations for various gamma-emitting radioisotopes. Transport of the resulting gamma photons was simulated and produced gamma spectra for multiple times after the test. Using these spectra, gamma lines associated with specific radioisotopes that could be used for the measurements were identified. Finally, a step-by-step implementation of these methods in the context of an inspection was proposed.

In essence, this paper shows that it might be possible to use gamma emissions to estimate the yields of past nuclear weapon experiments. Additional work is planned to further assess the practicability and accuracy of the methods discussed in this paper. First, a simulation of a gamma detector will be added to the numerical model, and the methods will be tested on the gamma spectra measured by this detector. Various limitations need to be better defined and analyzed, such as whether plutonium-239 decay lines would have to be blocked from being counted and the possible interference created by background radiation. We plan to focus on providing qualitative and, if possible, quantitative analyses of the uncertainties that affect the methods presented here. A better understanding of these uncertainties and how they propagate could be used to design practical methods that maximize their accuracy.