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Xenon and Particulates:
A *Qualitative* Discussion of Sensitivity to Nuclear Weapon Components and Design

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When North Korea conducted a fourth nuclear test two weeks ago, the Korean Central News Agency stated that "The first H-bomb test was successfully conducted in the DPRK at 10:00 on Wednesday, Juche 105 (2016)." Since the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is not in force, an on-site inspection is not possible. Although an "H-bomb" is unlikely, we are left speculating what to believe. This memo summarizes what evidence we can obtain from radionuclide measurements for different nuclear weapon types, and how we can detect the presence of specific nuclear weapon device components such as metals used. Most of what we learn requires quick extraction of aerosol samples containing gases and particulates. However, gases are unlikely to diffuse out from an underground nuclear test site soon after the test, and particulates would likely completely remain trapped underground.

Introduction

The International Monitoring System (IMS) operated by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) operates hundreds of sensors to monitor potential nuclear explosions. Through the IMS's vast network of seismic sensors, the CTBTO is able to distinguish human-caused explosions from earthquakes and, through time-distance correlation, pin-point where the event has taken place. When the event happened last week, the CTBTO quickly tweeted that "unusual seismic activity" had been detected in North Korea, or the DPRK, by twenty-seven different stations globally. The sheer size of the explosion leaves no doubt that the event was a nuclear explosion, since it would be highly impractical to assemble and detonate conventional explosives of that magnitude. [1] However, to have definite confirmation of the nuclear nature of the test, it is necessary to detect radioactive noble gases and particulates that are produced when a nuclear explosion occurs.

Therefore, in addition to the seismic sensors, the CTBTO operates eighty sensors that process air samples and trap particulates, and half of these detectors also extract radioactive noble gases such as xenon. If a nuclear test occurs, then the samples may contain radioactive isotopes that, when they decay, will emit characteristic gamma rays (symbol γ) allowing identification of the isotope in the sample. The samples are counted using high purity germanium detectors (HPGe) which can measure a gamma ray spectrum (a histogram of the intensity and energy of the gamma rays) of the sample. Each isotope has its own unique pattern and intensity of gamma rays, which act like a "fingerprint" of the isotope.

The CTBTO has selected over eighty-three different isotopes in order to cover a wide array of sources such as residue from components of the bomb, fission products produced, and activation products in the bomb itself or the surrounding air, land, and sea. Not all of these isotopes are relevant for underground tests, and in this memo, we will only discuss isotopes related to bomb components in order to determine what we can learn. In addition to the CTBTO, the United States, via the Air Force Technical Applications Center (AFTAC), operates the Constant Phoenix aircraft, an airborne lab trapping particles and analyzing them in "real-time". [2] So, while the CTBTO is limited to the isotopes it routinely analyzes, AFTAC does not have this restriction.

The purpose here is to evaluate *qualitatively* what we can learn about bomb types and components by assessing the gamma spectrum of particulates and gases released from the test site. We will focus on a subset of the materials in the Table 1 below.

Type of Bomb	**Function**	**Materials**
Primary (Fission Bomb)	Fission Fuel	Pu-239, Pu-241, Am-241, U-235, U-238
	Tamper	U-238, Lead, Tungsten, Beryllium
	Boosting Gas	Tritium, Deuterium
Secondary (Fusion Bomb)	Pusher	U-238
	Fission Fuel	As above
Radiation Case	Prevent escape of X-rays	U-238, Lead, Tungsten
Radiation Channel	Space between the primary, secondary and the radiation case	Empty or contain specialized aerogel. Composition classified
All	Flux monitors and tracers	Y, As, Rb, Zr, Rh, Ag, Tm, Ir, Au

Table 1: Primary components of a nuclear weapon and the materials of which they are composed. [3]

The general approach is to:

- Use ratios of specific fission products, which will be different depending on (1) which fissionable isotope fissioned, (2) the energy of the incident neutron and (3) time since nuclear test.

- Use the ratios of activation products to determine the energy spectrum of the neutrons produced. Activation products are produced when an isotope absorbs a neutron and subsequently emits one or more particles. Neutrons producing isotopes through (n,2n) have low energy production thresholds so high in energy that they tend to be in the high energy tail of the fission neutron spectrum. This implies that only high-energy neutrons can produce those activation products, while not many neutrons produced through fission would have a high enough energy to produce isotopes through (n,2n). So, if specific activation products are observed, it could indicate the presence of high-energy neutrons coming from fusion, not fission (see Figure 1 for further explanation). A note about notation: an (n,x) reaction implies *that* n *was absorbed by the target nucleus and produced a radioactive isotope that emitted* x. Thus an (n,2n) reaction implies that the produced nucleus did not change in element (because no proton was given up) but has one less neutron than the target nucleus. In the end, the number of nuclei have to be the same on both sides of the "comma" in (n,y). See Figures 2 for further explanation.

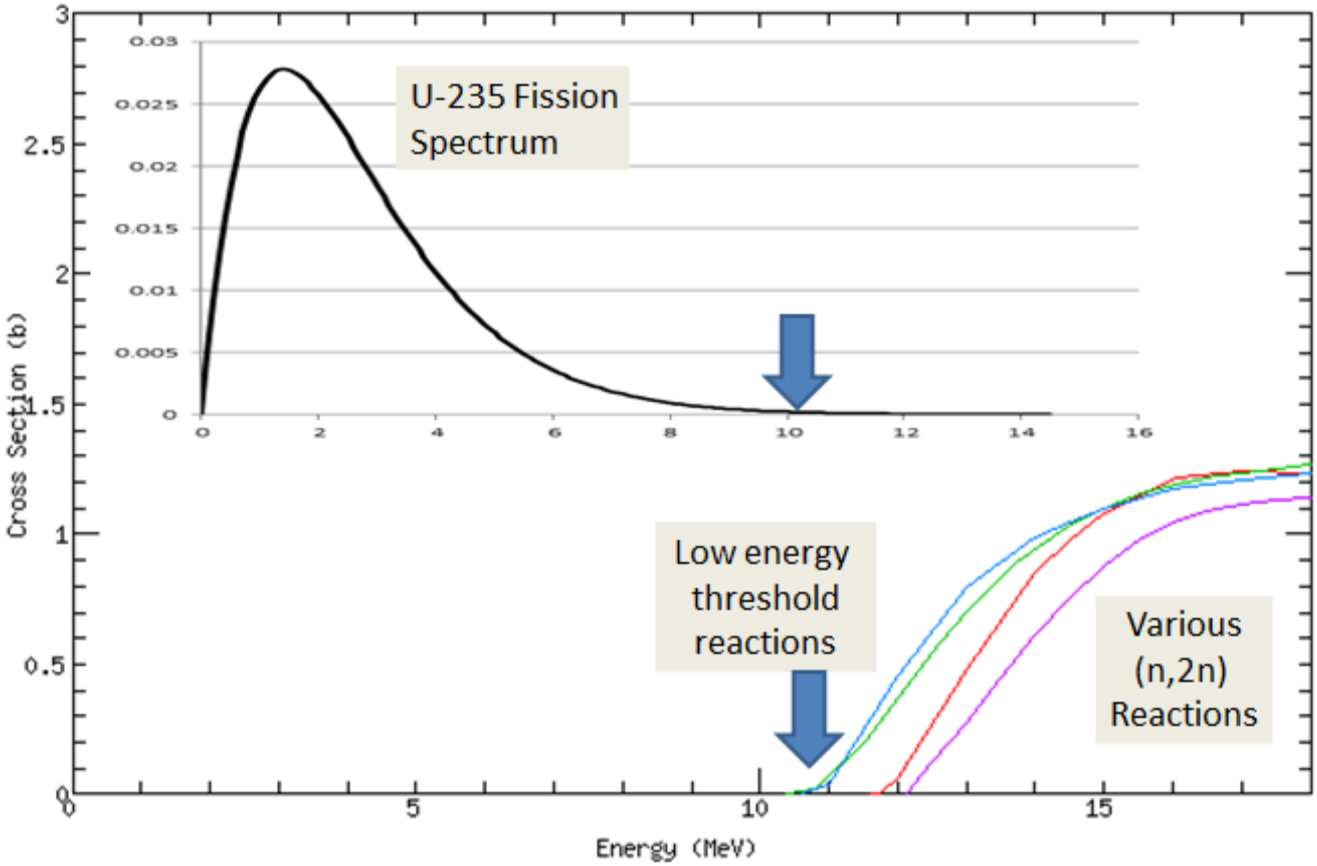

Figure 1: Figure shows essentially the likelihood (cross-section) for various (n,2n) activation reactions to occur as a function of neutron energy for different isotopes. Notice that generally (n,2n) reactions have high neutron threshold energies at which the reactions initiate. The figure shows that the (n,2n) reactions start to occur at around 10 MeV, which is in the high energy tail of the fission spectrum (see inset). So it is unlikely that fission neutrons can produce isotopes through (n,2n) reactions. The (n,2n) reactions are for Y-89 (red), As-75 (green), Rb-85 (blue) and Zr-90 (purple).

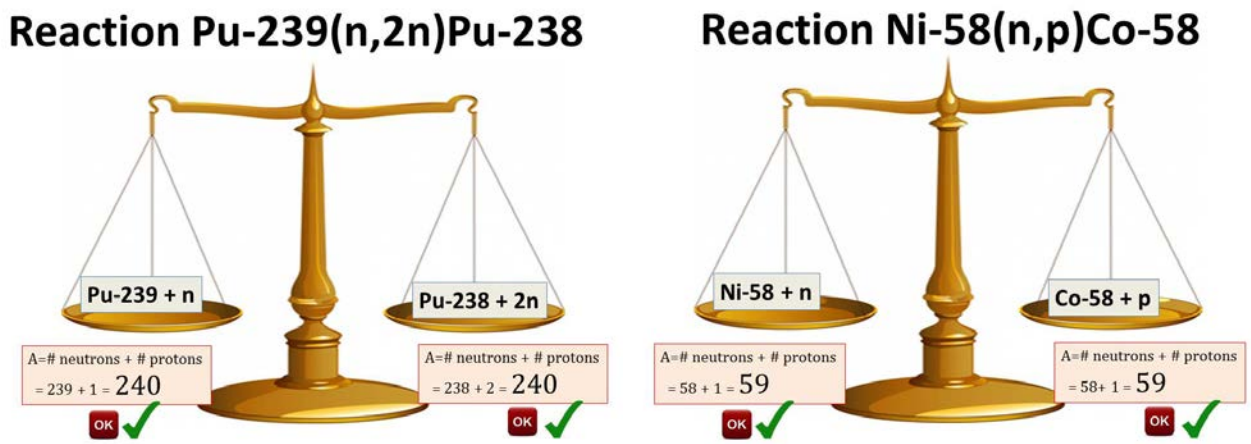

Figure 2: Figure showing the meaning of two reactions. The first reaction is a neutron being absorbed by Pu-239 and in the process emitting 2 neutrons to become Pu-238 (no element change). Notice that the sum of protons and neutrons is the same on both sides of the reaction (they have to balance). The other reaction is the isotope Ni-58 absorbing a neutron and subsequently emitting a proton to become Co-58. In the latter case, there is a change in element (from the metal nickel to cobalt) but the total number of protons and neutrons remains the same both sides of the reaction.

For gamma-counting, the isotopes must meet certain requirements such that the quantity of the isotope assessed should be high enough in the sample to be counted, must have an appropriate half-life so that the decay rate will be high enough, and must have characteristic gamma rays with strong enough intensity in the region of sensitivity of the gamma spectrometer. These quantities may change over time as (1) the concentration of isotopes change as they grow from fission products that decay into the same isotope and (2) as the isotope itself decays. For a *quantitative* assessment, all of these aspects of the isotopes, including relative abundances and chemical effects need to be taken into account, which is beyond the goals of this note. If the counting objectives are not met, then there may be other means for counting the ratio of isotopes. For example, by using Inductively Coupled Mass Spectrometry (ICP-MS) or other types of trace analysis which is also not discussed in this note. [4]

Radionuclide Signatures from Nuclear Tests

When a fission bomb detonates, the fissionable materials in the bomb fission rapidly, producing hundreds of distinct fission products while emitting a high local burst of neutrons in a distribution peaking at around 1 MeV and ranging from of 0.1 MeV to 10 MeV (see inset in Figure 1). The fission products are produced in an “M”-shaped distribution that cluster in two peaks around mass number 95 (number of protons plus neutrons for isotope) and 140. The depth of the valley of the “M” depends on the induced fission neutron energy, with low energy fission neutrons producing a deeper valley than high-energy 14 MeV fusion neutrons (See Figure 3). This difference in the isotope yield distribution can be exploited in order to determine the dominant neutron fission energy.[5] Neutrons produced can also bombard the bomb components and the surrounding environment and produce further isotopes through neutron activation reactions, where several neutrons or charged particles such

as protons or alphas are emitted (as mentioned before, this generally occurs primarily for high energy neutrons). Isotopes can also undergo neutron capture, where a neutron is absorbed and a gamma is emitted (this occurs primarily for low energy neutrons). Therefore, the ratio of isotopes produced by neutron capture and those produced through other activation reactions such as (n,2n) can give information about the neutron spectrum.

Some of the fission products escaping from the site of the blast are radioactive gasses like xenon isotopes, Argon-37 and Krypton-85. Krypton-85 is not useful because krypton gas is already present in the atmosphere, produced through spent fuel reprocessing and from past nuclear tests, and thus likely cannot be used as an indicator of a nuclear test (half-life=10.76 years). Argon-37 may be useful since its half-life is 35 days and has virtually no other anthropogenic sources. So, if unambiguously detected in levels above background, there is less need to depend on atmospheric modeling to attribute the detection to a specific source. On the other hand, there are many uncertainties associated with the use of Ar-37 for detection of nuclear explosions, which would need to be understood before detectors for Ar-37 can be put into practice. [6] The CTBTO has focused on detecting radioactive xenon isotopes evolved from the bomb since they have reasonable half-lives, low backgrounds, and are produced in large quantities from a nuclear explosion. [7] In particular, the CTBTO uses the ratios of four isotopes (Xe-131m (half-life=11.9 d), Xe-133m (2.19 d), Xe-133 (5.25 d), Xe-135 (0.38 d)) and atmospheric modeling to develop a sophisticated algorithm to correlate an observed detection above background to a specific nuclear test and to discriminate it from other sources. [8]

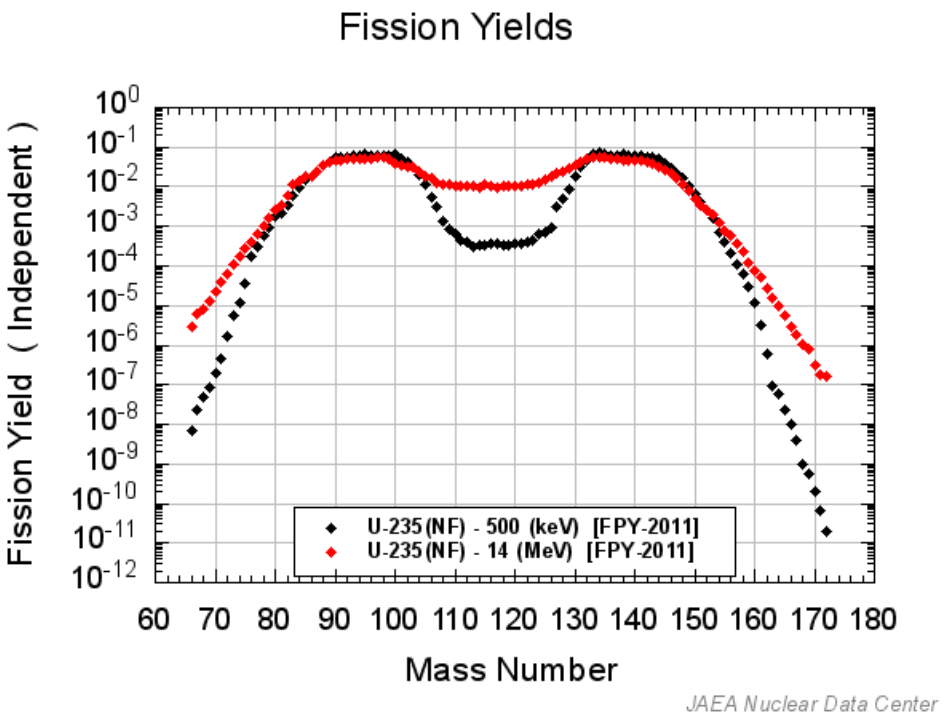

Figure 3: The U-235 fission product yield for two different neutron energies plotted as a function of mass number A. [9]

What Can We Learn About the Bomb if Both Particulates and Gases Were Observed?

Determining if Fission or Fusion Dominated Explosion

The fusion fuel in the secondary will consist of lithium deuteride (it appears in nature as two isotopes of lithium, Li-6 and Li-7. The D stands for the hydrogen isotope produced—in atomic form, it is called deuterium—when it has gained an extra neutron). Unfortunately, lithium deuteride does not have isotopes or reactions that would indicate a presence distinguishable from background levels. However, we can use the difference in flux and energy of fusion weapons compared to pure fission weapons to distinguish the dominant energy production mechanism in the bomb.

From previous bomb tests, we know that pure fission weapons generally capture neutrons (absorb a neutron and release a gamma ray) bomb components once rather than multiple capturing neutrons and producing high neutron number isotopes. However, thermonuclear bombs produce a high enough neutron flux and energy so that surrounding materials can multiple capture neutrons before they decay, and can also produce rare isotopes through (n,2n), (n,p), and (n,alpha) reactions. Therefore, observation of rare isotopes resulting from these reactions would indicate a thermonuclear bomb detonated even if the lithium deuteride or tritium can't be detected. This is often quantified in terms of the ratio of isotopes produced through the (n,gamma) neutron capture reaction to the isotopes produced through (n,2n) of the same element. If the the ratio is low, it would indicate that there is a strong fusion component in the weapon, and if the ratio is high it indicates a pure fission weapon. For example, if U-238 is the target, the ratio of U-239 (produced through (n,gamma)) and U-237 (produced by absorbing a neutron and then releasing two more) detection would allow the presence of a fusion component to be determined. In fact, if the ratio of (U-239/U-237) is approximately 1 it would indicate a strong fusion component; if the ratio was 10 or higher, it would imply a fission dominant weapon. [10]

Another method is to rely on the variation in the fission yield distribution in the first peak of the "M" distribution. The first peak is sensitive to the type of actinide that has undergone fission in the sense that the ratio of specific isotopes will be different for different fissile materials (see Figure 4). For example, the (Zr-97/Sr-91) ratio will be about 1 for U-235, 2 for Pu-239 and 1.4 for U-238 fission. Ratios such as these must be carefully interpreted for other means that these isotopes could be produced or chemical ways the ratios could be modified.

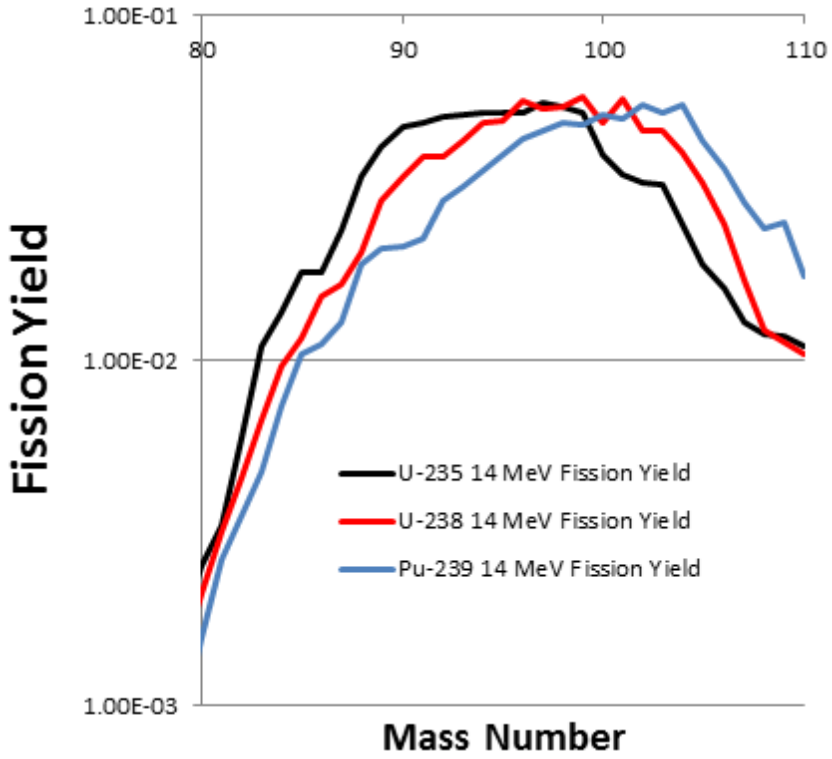

Figure 4: Similar to Figure 2 except zooming in on the first peak for 3 different fissionable nuclei. Notice the sensitivity of the neutron yield to the type of isotope producing the fission products. Data obtained from the JAEA Nuclear Data Center.

Determining Which Fissile Material Used

The accurate composition of a nuclear weapon is classified but we know that the fission fuel will be predominantly U-235 or Pu-239, with a small fraction of Pu-240 to minimize neutrons from spontaneous fission. The mixture will also contain Pu-241 (half-life = 14.35 years) and daughter Am-241, depending on the age of the fuel. The bomb, depending on design, will also contain U-238, which acts as a tamper in a fission weapon to reflect escaping neutrons back into the weapon as well as a heavy "hammer" during the compression phase. In a thermonuclear weapon, the U-238 may act to absorb X-rays from the primary and compress the fusion fuel.

Fission products are produced with a different distribution for different fissionable materials. For example, in the case of xenon isotopes, the immediately produced fraction of isotopes from Pu-239 differs from that of U-235 by a factor of 10 for Xe-133 and 5 for Xe-135. [11] This sensitivity may allow us to distinguish the type of fissile material used in the bomb, but only if the xenon is collected within hours after the test. This is because these isotopes are also produced through the eventual decay of I-133 (I is the chemical symbol for the element iodine) (half-life= 0.87 days) and I-135 (half-life=0.27 days), which would quickly add to the immediately produced xenon and reduce differences due to explosion scenarios and fissile materials. Dr. Martin Kalinowski and his colleagues at the CTBTO have carefully studied these differences and compared them to Nevada Test

Site results. He found that Xe-135/Xe-133m and Xe-133m/Xe-133 were the most sensitive to fissile material differences (see Figure 5). However, xenon gas is often released at least a day after the explosion, making fissile material differences unobservable. [12] Note that even if airborne detectors were sent near the test site it is not likely that the xenon would have been released from the site. Therefore, even in this case, determining the type of fissile material would be challenging. [13]

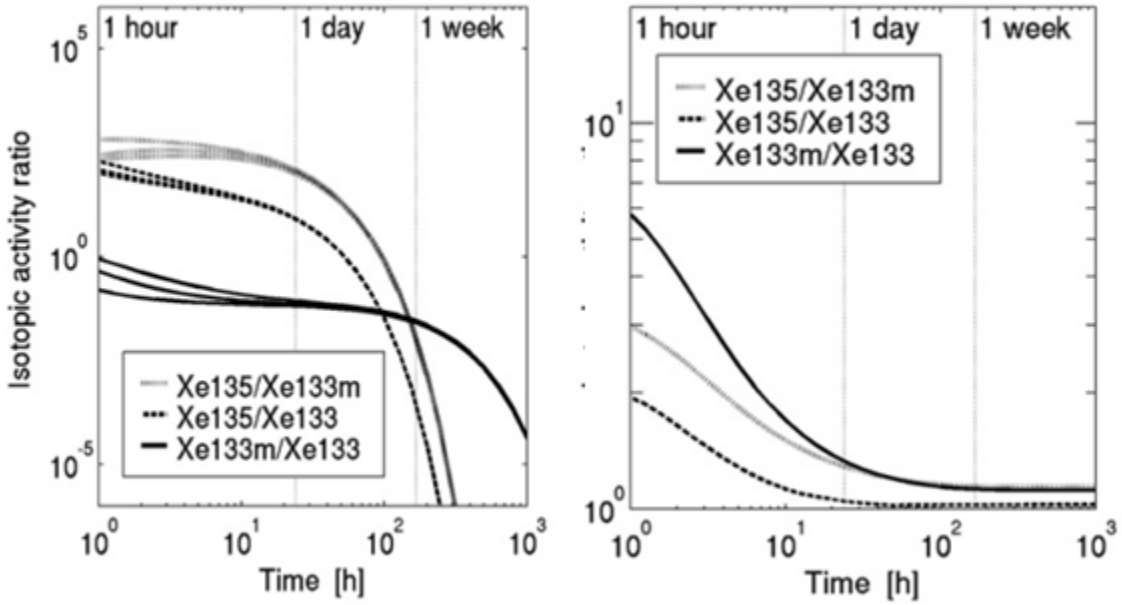

Figure 5: Figure extracted from [Kalinowski, Martin B. "Characterisation of prompt and delayed atmospheric radioactivity releases from underground nuclear tests at Nevada as a function of release time." Journal of environmental radioactivity 102, no. 9 (2011): 824-836.] showing the xenon isotope ratios for different explosion scenarios (Pu-239, U-235 fission and U-238 fission with fast neutrons). Right figure shows the ratio of the largest activity ratio divided by the smallest. The figures demonstrate that the fissile material sensitivities are greatly reduced hours after the test. [14]

Evidence for a Boosted Weapon

A boosted weapon will contain deuterium (D) and tritium (T) gas (tritium is another isotope of hydrogen which has 2 extra neutrons and 1 proton), which are isotopes of hydrogen that fuse. The purpose of this fuel is not to add to the explosive yield but to improve the utilization of the fissile material of the bomb. Early boosting tests were performed at very low yields. For example, the Galileo and Fizeau nuclear tests (Operation Plumbob) both had a yield of only 11 kt and were single-stage boosted devices. [15] The TNT yield of the DPRK test was indeed low, which does not exclude boosting, but neither implies that boosting occurred. The bulk of the energy in a 'boosted' bomb is not from fusion neutrons, but is produced by the chain reaction neutrons that follow from the burst of fusion neutrons. In that sense, the neutron energy spectrum will not be significantly different from an 'unboosted' primary. The DT gas will be fused in a nuclear detonation and we cannot expect the D and T to be detected in quantities that can be discerned from background levels. However, a heavy U-238 tamper will not be

necessary for a 'boosted' fission primary and will be missing from the design—perhaps a way of distinguishing 'unboosted' from 'boosted' designs. There may be one "smoking gun" to determine whether the nuclear weapon used in a nuclear test was a 'boosted' weapon: namely, when the Pu-238/Pu-239 rate is high. Pu-238 is produced through (n,2n) reactions on Pu-239, which occurs primarily due to high energy neutrons from fusion and only marginally due to fission neutrons. So, if the Pu-238/Pu-239 is observed to be high, it may indicate that a boosted weapon has been used. Thermonuclear weapons, which use boosted primaries, reduce this ratio, not because of decreased Pu-238 production, but because of an increased Pu-239 production on the U-238 tamper. However, if the sample were collected early before the Np-239 (half-life=2.356 days) would have a chance to decay, the ratio would reflect more the Pu-238 production from Pu-239(n,2n)Pu-238 and would indicate a strong fusion component.

Evidence for Teller-Ulam Design

Swedish researcher Lars-Erik de Geer has used a method for determining if a Teller-Ulam [16]type design has been detonated, by using the fact that fissile materials close to the secondary (fusion energy source) would be exposed to a higher neutron flux than fissile materials separated from the secondary by some distance in the radiation channel. [17] This requires the evolution of particulates from the explosion, which is unlikely, unless the test was an above-ground test that would be immediately detected and would cause even greater consternation than an underground test. However, de Geer observed that if the plutonium/uranium trigger is close to the secondary, then the fusion neutron flux would fission the plutonium to the degree that little Pu-239 from the trigger would remain in the debris. If instead the primary were separated from the secondary at a certain distance, then some Pu-239 from the trigger would remain, since it would not have been exposed to a high neutron flux from the secondary. However, just measuring the concentration of Pu-239 is not enough to confirm the use of a Teller-Ulam mechanism in the bomb, because Pu-239 can also be formed through neutron interaction with the U-238 radiation case expected to surround the primary and secondary and form the Radiation Channel. The Pu-239 produced in this way results from the decay of U-239 to Np-239, which decays with a half-life of 2.355 days to Pu-239. De Geer used the 1976 November Chinese nuclear test as a way of testing the technique. He analyzed two samples, one sample only eight days after the explosion, so that the Pu-239 would not have grown from U-238 neutron capture, and another many months later when the bulk of the Pu-239 from U-238 neutron capture would have grown. He then subtracted the later measurement from the earlier measurement to extract the amount of trigger plutonium still left.

A simpler method also makes use of the fact that in a Teller-Ulam mechanism the primary and secondary would exposed to a different fusion neutron flux: compare the U-237/Pu-238 ratio that can only be produced through (n,2n) reactions on U-238 and the trigger Pu-239. Roughly speaking, if the same flux were applied to the metals, then the ratio would be about a factor 3.1 for 14 MeV neutrons. [18] However, if the fusion flux is less onto the Pu-239 trigger than the U-238, the ratio would be greater than 3 and may indicate of a plutonium trigger a distance away from the secondary.

Determining Presence of Device Materials

Presence of Steels

Stainless steels are composed of a wide variety of elements to enhance its physical and thermal properties such Cr, Ni, Co, Mo, Si etc., and are produced in many types. In nuclear weapons, however, it would be expected that low neutron absorbing steels would be desired, such as low cobalt steels. Detection of neutron interaction products would indicate the use of stainless steel in the bomb. See Table 2 below for possible isotopes that could be detected.

Target Isotope	**Isotope Produced**	**Reaction**
Fe-54 Fe-58	Mn-54 Fe-59	(n,p) (n,gamma)
Ni-58	Co-57 Co-57 Co-58	(n,pn) (n,d) (n,p)
Co-59	Co-60	(n,gamma)
Cr-50	Cr-51	(n,gamma)
Zn-64	Zn-65	(n,gamma)

Table 2: Measuring the presence of different elements in stainless steel by detecting the activation products produced by various high neutron energy reactions. Table shows the target isotope, the isotope produced and the reaction. [19] All of these isotopes produced may be detected in gamma detectors when they decay.

Furthermore, as de Geer demonstrated, if one hypothesizes low vs. high neutron energies, the ratios of certain isotopes that are produced will be different. Pinning down the general energy that produced the isotopes will allow other production modes to be rejected. For example, de Geer found that in Chinese nuclear tests the (Co-60/Co-57) ratio was high. Since Co-60 is likely produced through neutron capture on Co-59 and Co-57 is only produced using high-energy neutrons, the energies were likely not high. This in turn implies that Co-60, when produced through (n,p), must have occurred at a low rate as well, since it is also only produced by high-energy neutrons. This implies that Co-60 must have only been produced through neutron capture onto Co-59 requiring that Cobalt must have been present originally.

Presence of Titanium

Titanium is found in the following isotopic abundance: Ti-46 (8.25%), Ti-47 (7.44%), Ti-48 (73.72%), Ti-49 (5.41%), and Ti-50 (5.18%). Unfortunately, most of the neutron interactions that occur with reasonable probability result in stable nuclides or have long half-lives and thus cannot be detected with reasonable sample counting times in gamma detectors. The only reaction that would indicate the presence of titanium in the device would be (n,p) reactions onto Ti-46 and Ti-47 which would produce Sc-46 (84 d, 0.89 MeV gamma) and Sc-47 (3.35 d, 0.159 MeV gamma) isotopes.

Presence of Gallium

Plutonium metal occurs in many different crystal forms (known as allotropes) with varying levels of malleability, brittleness, density, etc. The most desired form is the δ-phase, where the metal is the easiest to machine and remains stable at high temperatures. [20] Alloying plutonium with gallium helps keep the metal in the δ-phase and thus gallium is expected to also be present in the bomb. Measuring the presence of gallium will be difficult because the isotopes produced are all stable. Gallium occurs in nature as Ga-69 (60%) and Ga-71 (40%). Ga-71 can radiatively absorb a neutron producing Ga-72, which can be detected (0.839 MeV gamma), but it will decay with a 14-hour half-life to Ge-72, which is stable. Ga-69 can produce Ga-68 through (n,2n) but this will decay in 68 minutes to a stable isotope.

Presence of Silver and Gold

Electronic components of the bomb will contain gold, silver, and perhaps copper. However, these will be low in quantity compared to the other bomb components. Gold can be determined through the production of Au-198 by radiative capture which will beta decay with a half-life of 2.7 days and be detected (0.411 MeV gamma). The presence of gold can also be determined through the (n,2n) reaction which produce a 9-hour metastable state and a longer 6-day state which would decay primarily through electron capture and be detected (0.148 MeV) as it decays to Pt-198. Silver is found in nature as Ag-107 (51.839%), and Ag-109 (48.161%). Radiative capture on both isotopes results in two metastable isotopes, Ag-108m (152,000 d, 0.723 MeV gamma) and Ag-110m (250 d, 0.657 MeV gamma), which have long half-lives that make it difficult to detect. Silver can also be detected through the (n,2n) reaction onto Pb-107 which results in a metastable Ag-106m state, which has an 8-day half-life considerably less than the neutron capture metastable states.

Presence of Lead and Tungsten

Lead (Pb) and tungsten (W) may be present in the bomb, including antimony (Sb), which is used to increase the strength of the lead. Lead is found in nature as: Pb-204 (1.4%), Pb-206 (24.1%), Pb-207 (22.1%), and Pb-208 (52.4%) and over thirty other isotopes are known. Unfortunately, most of these isotopes will not result in detectable isotopes through neutron activation. However, Pb-204 can be detected (0.279 MeV gamma) through

the production of Pb-203 through the (n,2n) reaction which subsequently decays to stable Tl-203. Tungsten is present in the form of W-180 (0.120%), W-182 (26.498%), W-183(14.314%), W-184(30.642%), and W-186 (28.426%) and is known to have almost thirty other isotopes. Radiative capture onto W-186 results in a 1 day W-187 state which beta decays to Re-187 and allows the presence of tungsten to be confirmed (0.785 MeV gamma detected).

Presence of Added Tracers and Flux Monitors

In addition to the bomb components, during nuclear tests isotopic targets are added in order to determine the neutron flux and yield through (n,2n) production of radioactive isotopes that could be detected after the test. There is evidence that Chinese nuclear tests used yttrium and gold for this purpose while French and US tests used iridium as activation targets. [21] Other possible targets for this purpose are As-75, Rb-83, Zr-90, Rh-103, Ag-107, Tm-169, Ir-192, and Au-197. The activation products of all of these isotopes have high probabilities of production and produce gammas that can be detected.

Other isotopes are added as tracers for determining isotope production rates of the same element and neutron fluxes in different locations in the weapon. The isotopes are chosen so that they are not themselves produced as fission products during the explosion but will produce other isotopes that can be detected after the explosion. Discussions of tracers used in this way are rarely mentioned in the literature, but known examples are: U-233, Np-237, Pu-238, Pu-242, Am-241, Am-243, and Cm-244. Other isotopes used as tracers in nuclear weapons are Co-57 and Ba-133; these have been detected in radioactive fallout from Chinese nuclear tests.

Presence of Beryllium

Beryllium is found in the form of Be-9 and is used as a neutron reflector in nuclear weapons to prevent neutrons from escaping. It also enhances the neutron flux through (n,2n) reaction from high energy neutrons. [22] In fusion, neutron energies Be-8 can be produced through the (n,2n) reaction. However, Be-8 has a very long half-life and will not be detected using gamma ray detectors, but may be detected using other trace methods.

Conclusion

In this memo, we described some of the techniques that may be used to determine aspects about the bomb type and materials used in the components. The goal of this note was not to describe the sensitivity of the technique but rather to describe some of the methods qualitatively. For a full quantitative treatment, including the probability of detecting specific radionuclides under various scenarios, see K. M. Matthews, “The CTBT verification significance of particulate radionuclides detected by the International Monitoring System,” which summarizes several reports on the issue. [23]

End Notes

[1] To put it in perspective, assuming 10 kilotons of TNT were detonated, the radius of a spherical cavity would have to be 11.3 meters: a tunnel of 670 meters long with 3m x 3m tunnel cross-sections.

[2] http://theaviationist.com/2016/01/07/wc-135-in-action-near-nk-after-nuke-test/

[3] Note that we denote isotopes of an element as: X-A where X is the chemical element of the isotope and A is the sum of the number of protons and neutrons. For example, Pu-239 is an isotope plutonium where the sum of the number of protons and neutrons is 239.

[4] For elemental sensitivity see: http://www.elementalanalysis.com/services/inductively-coupled-plasma-icp/

[5] De Geer, Lars-Erik, Rune Arntsing, Ingemar Vintersved, Jan Sisefsky, Siv Jakobsson, and Jan-Åke Engström. "PARTICULATE RADIOACTIVITY, MAINLY FROM NUCLEAR EXPLOSIONS, IN AIR Aim PRECIPITATION IN SWEDEN MID-YEAR 1975 TO MID-YEAR 1977." (1978). See pg 54. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/11/543/11543720.pdf

[6] Medalia, Jonathan. North Korea's 2009 Nuclear Test: Containment, Monitoring, Implication. DIANE Publishing, 2010. https://www.fas.org/sgp/crs/nuke/R41160.pdf

[7] How large? An example from Ted Bowyer's presentation: "if a; the activity vented from a 1 kiloton nuclear detonation was diluted by the entire earth's atmosphere (10^{18} m^3) it would yield a concentration in the atmosphere of 0.5 Bq/m^3". The detection limit of radionuclide sampling is 1e-5 Bq/m^3. See: http://elliott.gwu.edu/sites/elliott.gwu.edu/files/downloads/events/2.2%20Bowyer.pdf

[8] The CTBTO has found that different anthropogenic sources of radioactive xenon such as from civilian nuclear nuclear reactors can be discriminated by using the isotopic xenon ratios. See:[Kalinowski, Martin B., Anders Axelsson, Marc Bean, Xavier Blanchard, Theodore W. Bowyer, Guy Brachet, Simon Hebel et al. "Discrimination of nuclear explosions against civilian sources based on atmospheric xenon isotopic activity ratios." Pure and applied geophysics 167, no. 4-5 (2010): 517-539.]

[9] http://wwwndc.jaea.go.jp/index.html

[10] De Geer, Lars-Erik, Rune Arntsing, Ingemar Vintersved, Jan Sisefsky, Siv Jakobsson, and Jan-Åke Engström. "PARTICULATE RADIOACTIVITY, MAINLY FROM NUCLEAR EXPLOSIONS, IN AIR Aim PRECIPITATION IN SWEDEN MID-YEAR 1975 TO MID-YEAR 1977." (1978). See pg 38..

[11] This is known as the independent fission yield. See: http://wwwndc.jaea.go.jp/cgi-bin/FPYfig

[12] Kalinowski, Martin B. "Characterisation of prompt and delayed atmospheric radioactivity releases from underground nuclear tests at Nevada as a function of release time." Journal of environmental radioactivity 102, no. 9 (2011): 824-836. See Figure 13.

[13] Note that a similar effect has been observed by Dr. Hui Zhang (Belfer Center, Harvard) and me by assuming the production fast neutron independent yield and calculating the decay of the isotopes assuming different separation times between the xenon precursors and the xenon isotopes. See: http://belfercenter.ksg.harvard.edu/files/NKSampling_INMM07_Hui.pdf

[14] Kalinowski, Martin B. "Characterisation of prompt and delayed atmospheric radioactivity releases from underground nuclear tests at Nevada as a function of release time." Journal of environmental radioactivity 102, no. 9 (2011): 824-836.

[15] Norris, Robert Stan, and Thomas B. Cochran. United States Nuclear Tests: July 1945 to 31 December 1992. Natural Resources Defense Council, 1994.

[16] Teller-Ulam design is a type of nuclear weapon which has a separate fission (primary) and fusion (secondary) stage, and compression of the fusion stage is occurs due to radiation coming from the fission stage. Idea can be extended to include multiple stages in a chain of stages compressing fusion fuel. The Teller-Ulam advance made the largest yield nuclear bombs possible.

[17] De Geer, Lars-Erik. "The radioactive signature of the hydrogen bomb." Science & Global Security 2, no. 4 (1991): 351-363.

[18] This assumes U-238(n,2n)U-237 and Pu-239(n,2n)Pu-238 cross sections of 0.91 b and 0.291 respectively.

[19] Matthews, K. M. The CTBT verification significance of particulate radionuclides detected by the International Monitoring System. Ministry of Health, National Radiation Laboratory, 2005. See Table 5, pg 29.

[20] https://www.fas.org/sgp/othergov/doe/lanl/pubs/00818035.pdf

[21] De Geer, L-E. "Comprehensive nuclear-test-ban treaty: relevant radionuclides." Kerntechnik 66, no. 3 (2001): 113-120.

[22] International Advisory Committee. (1998). The radiological situation at the atolls of Mururoa and Fangataufa. Main report. See discussion pg. 12.

[23] Matthews, K. M. The CTBT verification significance of particulate radionuclides detected by the International Monitoring System. Ministry of Health, National Radiation Laboratory, 2005.