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Radionuclide Evidence for Low-Yield Nuclear Testing in North Korea in April/May 2010

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Between 13 and 23 May 2010, four atmospheric radionuclide surveillance stations, in South Korea, Japan, and the Russian Federation, detected xenon and xenon daughter radionuclides in concentrations up to 10 and 0.1 mBq/m^3 respectively. All these measurements were made in air masses that had passed over North Korea a few days earlier. This article shows that these radionuclide observations are consistent with a North Korean low-yield nuclear test on 11 May 2010, even though no seismic signals from such a test have been detected. Appendix 1 presents a detailed analysis of the radioxenon data and Appendix 2 describes a hypothetical nuclear test scenario consistent with this analysis, including the possibility that the test used uranium-235 rather than plutonium-239. The analysis suggests that the technical and analytical basis to detect small nuclear tests using radionuclide signatures may be more developed than is generally assumed.

INTRODUCTION

North Korea conducted its first nuclear test explosion on 9 October 2006. The test was carried out underground in a deep tunnel[1] and had an estimated yield of approximately 0.9 kt.[2] Due to the low yield its nuclear character was first questioned, but it was soon confirmed nuclear by regional and distant detections of mBq/m^3 range radioactive xenon isotopes.[3,4] Then, on 25 May 2009, a

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The views expressed in this publication are those of the author and do not necessarily reflect the views of the Swedish Defense Research Agency, the Comprehensive Nuclear-Test-Ban Treaty Organization, the South Korean Government, or any of the institutions involved in the routine reporting of data to the International Data Centre. Data made available from these sources is, however, greatly appreciated. The expert help in applying the WebGrape software to a non-CTBT station that was provided by Dr. Gerhard Wotawa at the Zentralanstalt für Meteorologie und Geodynamik in Vienna, Austria, is also greatly appreciated.

second nuclear test was carried out in the same tunnel system inside Mount Mantap some 40 km NW of the city of Kilchu in the northern part of the country. From careful seismic analyses the depths have been estimated as approximately 200 m for the 2006 test and 550 m for the 2009 test.[5] An alternative analysis is based on the orientation of a tunnel entrance that has been identified on satellite pictures (see, e.g., Google™ Earth 41.2808° N, 129.0856° E) and on a mining website message, written just before the first test, that cited a Chinese spokesman who, after talking to North Korean officials, referred to an upcoming test in a 2000 m long tunnel.[6] This gives a test-point just 1.5 km away from both seismic-based estimates, which, if a horizontal tunnel is assumed, is as much as 800 m below ground surface at the top of Mount Mantap.

The yield of the second test was estimated at about 4.6 kt,[7] a size that, together with the fact that the first test was nuclear, was enough for a general agreement that this was also a nuclear explosion—even though, this time no radioxenon was detected. The latter was a disappointment to many in the nuclear arms control verification community, but it should actually not have been such a surprise. With the 2006 experience in mind and the availability of a deep test point, it should have been possible for North Korea with some extra effort to stop in 2009 virtually all leaks that would be detectable off-site.[8] On-site radioxenon measurements would, however, have stood a good chance of confirming a test. Emissions driven by barometric lows through cracks and fissures in the bedrock could have produced local ground surface xenon-133 concentrations of several kBq/m^3 two weeks after the nuclear test and up to several mBq/m^3 as late as four months after the test.[9]

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) seeks to curb the nuclear arms race and proliferation by banning nuclear test explosions in all environments.[10] It has not yet entered into force as it awaits ratification by eight named nuclear capable States.[11] In the meantime, the Vienna-based Provisional Technical Secretariat (PTS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is building and operating a sensitive global verification system that aims to verify the treaty once it has entered into force. Out of 321 control posts, 80 will focus on the detection of particulate radionuclides,[12,13,14] and out of these 40 will also have noble gas analyzers that are able to monitor two isotopes (xenon-133 and xenon-135) and two meta-stable states of xenon (xenon-131m and xenon-133m), all of which are strong indicators of nuclear fission processes. Being constituents of a noble gas, these isotopes and states are generally quite difficult to fully contain, even when measures are taken to prevent their release, as they would be in the case of a clandestine test. It should be noted that during the time of frequent underground testing in the major nuclear weapons states it was quite common that radioactive noble gases leaked or seeped into the atmosphere, either due to containment failures or to drill-back operations to take samples for diagnostics.[15]

As of 1 September 2011, there were 64 radionuclide particulate and 27 xenon stations operating in the CTBT network.[16]

Numerous control posts that are similar or sometimes identical to stations deployed by the CTBTO also exist around the globe, where they are run for different national purposes, for early warning of, e.g., tsunamis and radiological accidents or for purely scientific reasons. In September 2007, South Korea inaugurated a national SAUNA[17] system at Geojin in the northeastern corner of the country.[18] SAUNA collects xenon for 12 hours from a stream of about 1 m^3/h of air through room-temperature columns filled with activated charcoal,[19] and then processes the sample during some 7 hours to produce a small volume (about 1.1 cubic centimeters) of xenon potentially containing one or more members of the above-mentioned radioxenon quartet.[20] With generally 11 hours and 10 minutes of counting on an electron and gamma ray sensitive coincidence detector system, minimum detectable concentrations (MDCs) of about 0.2 mBq/m^3 are reached for ^{131m}Xe, ^{133m}Xe and xenon-133. The MDC of xenon-135 is higher, about 0.9 mBq/m^3, due to the shorter half-life and significant decay during the analysis process.

OBSERVATIONS

In May 2010, radioxenon and radioxenon progeny radionuclides were detected at four sampling stations located 10 to 1260 km from the North Korean borders (Figure 1).[21] All these detections are listed in Table 1.[22]

Figure 1: The Korean peninsula seen from northwest and the stations where radioxenon and radioxenon daughters were detected in mid-May 2010 (color figure available online).

Table 1: Xenon and barium isotopes detected at Geojin, Takasaki, Okinawa and Ussuriysk in May 2010. The hours, upper levels and uncertainties at Geojin are given in italics to indicate that they are estimates based on good experience from similar SAUNA spectra. Uncertainties are given for k = 1 and upper levels are based on a risk level for first kind errors of 5 percent. All concentrations refer to an assumed constant value during the collection time, which is the standard way adopted by the CTBTO[23]

Station	Collection start UTC	Collection stop UTC	^{131m}Xe mBq/m^3	^{133m}Xe mBq/m^3	^{133}Xe mBq/m^3	^{135}Xe mBq/m^3	^{140}Ba μBq/m^3
Geojin	13 May *11:00*	13 May *23:00*	*<0.2*	*<0.2*	2.45 ± *0.2*	10.01 ± *0.6*	
Takasaki	15 May 06:46	15 May 18:46	<0.02	<0.06	<0.10	<0.61	
Takasaki	15 May 18:46	16 May 06:46	0.04 ± 0.03	<0.09	0.16 ± 0.07	<0.57	
Takasaki	16 May 06:46	16 May 18:46	0.05 ± 0.03	<0.08	0.23 ± 0.06	<0.47	
Takasaki	16 May 18:46	17 May 06:46	0.16 ± 0.07	<0.09	1.49 ± 0.11	<0.20	
Takasaki	17 May 06:46	17 May 18:46	<0.04	<0.05	0.52 ± 0.07	<0.06	
Takasaki	17 May 18:46	18 May 06:46	<0.11	0.10 ± 0.06	0.79 ± 0.09	<0.58	
Takasaki	18 May 06:46	18 May 18:46	0.06 ± 0.03	<0.02	<0.10	0.42 ± 0.23	
Takasaki	18 May 18:46	19 May 06:46	<0.07	<0.05	0.18 ± 0.06	<0.52	
Okinawa	15 May 00:23	16 May 00:23					81.9 ± 3.6
Okinawa	16 May 00:23	17 May 00:23					22.7 ± 2.2
Okinawa	17 May 00:23	18 May 00:23					27.5 ± 2.2
Okinawa	18 May 00:23	19 May 00:23					28.1 ± 2.3
Okinawa	19 May 00:23	20 May 00:23					50.8 ± 2.9
Okinawa	20 May 00:23	21 May 00:23					43.8 ± 2.8
Okinawa	21 May 00:23	22 May 00:23					5.2 ± 1.6
Okinawa	22 May 00:23	23 May 00:23					5.0 ± 1.5
Ussuriysk	15 May 01:44	16 May 01:44					4.1 ± 1.4
Ussuriysk	16 May 01:44	17 May 01:40					<15
Ussuriysk	17 May 01:40	18 May 01:40					12.2 ± 2.3
Ussuriysk	18 May 03:44	19 May 01:49					5.3 ± 1.6

Radioxenon isotopes were detected on 13 May 2010 at South Korea's national noble gas observatory near Geojin just south of the border with North Korea. These findings were first revealed by Representative Kim Seon-dong of South Korea's ruling Grand National Party.[24,25] Kim claimed that the Korea Institute of Nuclear Safety had detected a xenon-133 concentration of 2.45 mBq/m^3 and 10.01 mBq/m^3 of xenon-135 at Geojin, and that "The concentration ratio of the noble gas [xenon] . . . had remained below 0.55 since 2007, but suddenly jumped to 4.085 at 2:07 a.m. on May 15." The significant levels of fairly short-lived xenon-135 ($T_{1/2} = 9.14$ hours) indicated a quite recent event.[26] A similar xenon signal had not been previously detected at Geojin.[27]

On 15 May 2010, a 2.5-day episode of increased xenon-133 levels began at the CTBTO SAUNA xenon analyzer at Takasaki in Japan.[28] Also on 15 May 2010 and also in Japan, at the Okinawa CTBTO filter station, a weeklong sequence of barium- and lanthanum-140 observations started.[29] Finally, on 15, 16, and 18 May 2010, about ten times lower concentrations of lanthanum-140 were observed at the CTBTO filter station at Ussuriysk, in Russia.[30] Barium- and lanthanum-140 have never been seen by the stations at Okinawa and Ussuriysk before or after (except in the wake of the Fukushima accident on 11 March 2011). Also the xenon-133 episode in mid-May 2010 at Takasaki was unique; much for its size but perhaps more for its time profile that indicated that it was not due to a local emission. This is also supported by the meteorological analysis presented below, which points to a source in North Korea. The Takasaki observations corroborate the conclusions about low-yield nuclear testing but are not necessary for them.

THE ^{140}Ba DETECTIONS IMPLY A PROMPT EMISSION FROM AN EXPLOSIVE FISSION EVENT

No radionuclides other than ^{133m}Xe, ^{133}Xe, ^{135}Xe, ^{140}Ba, and ^{140}La were detected in this series of observations[31] and the signatures were unique for their stations. All four stations are in the vicinity of North Korea, and significant parts of the sampled air masses had passed North Korea before they reached the stations (see the meteorological analysis below). It is therefore plausible that these signals were due to a single fission source in North Korea with one or several related emissions of isotopes of xenon and possibly other noble gases.

Figure 2 shows the decay chains that include radioactive xenon isotopes and xenon meta-stable states with half-lives longer than 1 second that are created in fission and/or are daughter products of radionuclides directly created in fission. Figure 2 also gives the independent fission yields of all relevant isotopes for fission-neutron induced ^{235}U and ^{239}Pu fission.[32]

In mass-chain 140 the emission should have been by ^{140}Xe, which is a very short-lived nuclide (half-life 13.6 seconds) and this indicates a prompt and selective emission of noble gases, most probably driven by an explosive

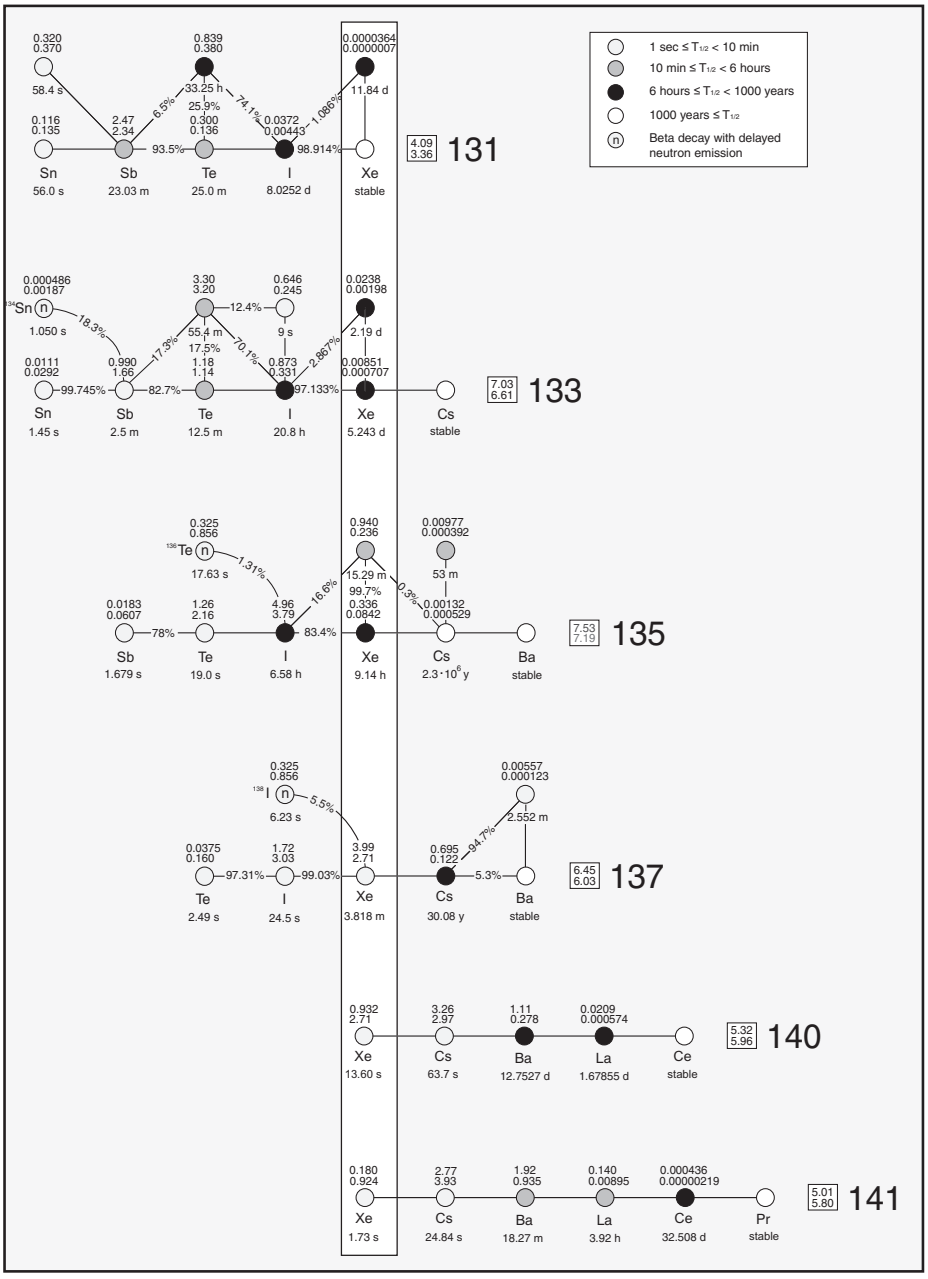

Figure 2: Fission product decay chains involving xenon isotopes with half-lives greater than 1 second. The decay proceeds from left to right via beta decay and sometimes from a meta-stable state to a ground state by gamma and/or electron conversion decay (internal transition, IT). The symbols are coded for half-life according to the legend in the upper corner, half-lives are given below the symbols, branching factors less than 100 percent are given on the decay lines, and independent yields (in percent) for fast neutrons incident on ^{239}Pu and ^{235}U are shown in dark gray and light gray respectively above the symbols. The corresponding chain yields are given in the box to the right (color figure available online).

fission process with vaporization of the remaining fissile material, to explain the needed rapid injection into the atmosphere through the unfissioned fuel and other barriers.

The measurement stations did not detect prominent volatile fission products like iodine-131, iodine-133, or tellurium-132. This implies that there must have been an effective filtering mechanism at work that contained non-noble gas debris. It is difficult to see how this could happen in non-explosive events that normally release xenon isotopes, such as nuclear power plants or research reactors during start-up, routine operation, shutdown, scram, or even an accident. Barium-140 has also never been detected in the atmosphere by sensitive radionuclide surveillance systems except after a nuclear explosion or a large reactor accident. In those cases, however, many other radionuclides that are neither noble gases nor decay products of such gases were simultaneously detected.

The Swedish surveillance network for radioactive aerosols has on two occasions picked up debris that was strongly enhanced in ^{140}Ba. In both cases, the sources were shallow underground nuclear tests, where particulate radionuclides in the cloud were scavenged within tens of seconds by fallback ejecta, leaving the short-lived noble gas ^{140}Xe-isotope free to escape, then decay to ^{140}Cs and ^{140}Ba that attach to microscopic particles, which after transport with the winds can be collected on a filter far away.[33,34,35]

The ^{135}Xe/^{133}Xe activity ratio of around 4 at Geojin on 13 May 2010 reported by Kim Seon-dong points at a ratio a few days earlier that is some hundred times higher (the half-life of this ratio is 9.86 hours). This far exceeds a ratio of 0.3–0.5 that calculations using the SCALE/ORIGEN nuclear systems modeling software (from Oak Ridge National Laboratory) suggest would be characteristic for a thermal nuclear power reactor at various degrees of fuel burnup. In a fast reactor the ^{135}Xe/^{133}Xe activity ratio is estimated from the chain-yields to be close to unity.[36] The emissions also could not have originated from a prompt-burst reactor used to study nuclear fission phenomena and radiation effects; these reactors go critical for just a fraction of a second, generating radiation and fission products. Assuming a uranium-fueled reactor, the ^{135}Xe/^{133}Xe activity ratio in this process is determined by the fast fission independent yields and would be as high as 1640.[37] The total number of fissions in a burst is, however, quite low (normally of the order of 10^{16} to 10^{17}) even in an accident.[38] This would give xenon concentrations of the order of nBq/m^3, or about 100,000 times below the detection limits at the sampling stations (see the discussion on atmospheric dilution below).

The remaining type of fission event that could potentially explain the detected radionuclide signals is an underground nuclear explosion. There was no seismic station in neighboring countries or elsewhere that detected anything suspicious enough at the time, however. The largest well-coupled explosion in North Korea that could go undetected by seismic sensors outside the country has been estimated at some 50 tons TNT-equivalent.[39] The next sections use

the measured radionuclide data to discuss the main characteristics of a possible nuclear explosion that could have provided the signals on 13 May and soon thereafter.

THE ^{140}La/^{140}Ba RATIO PUTS A POSSIBLE NUCLEAR EXPLOSION ON 10 OR 11 MAY 2010

The ^{140}Xe produced by fission and promptly injected into the atmosphere decays within minutes via ^{140}Cs to ^{140}Ba that together with *its* daughter nuclide ^{140}La can be used as a clock during the first week or so while the lanthanum/barium activity ratio increases from essentially zero towards an equilibrium value of 1.152.

The first Okinawa spectrum yielded a quite accurate ^{140}La/^{140}Ba ratio that gives a reasonably good estimate of the date and time when the fission/emission occurred. To get the most accurate determination, the 487.0 keV, 45.5 percent intensity, gamma in the ^{140}La-decay and the 537.3 keV, 24.39 percent intensity, gamma in the ^{140}Ba-decay were used. The fact that these energies are not very far away from each other minimizes the uncertainties introduced by the efficiency calibration. The classical Bateman equations for radioactive decay chains give, when integrated over the counting time, the following relation for the peak area ratio:[40]

$$\frac{N_{487}}{N_{537}} = \frac{\lambda_{La}}{(\lambda_{La}-\lambda_{Ba})} \cdot \frac{B_{487}}{B_{537}} \cdot \frac{\varepsilon_{487}}{\varepsilon_{537}} \cdot \frac{ccf_{537}}{ccf_{487}} \cdot \left[1 - \frac{\lambda_{Ba}}{\lambda_{La}} e^{-t\cdot(\lambda_{La}-\lambda_{Ba})} \frac{1-e^{-tc\cdot\lambda_{La}}}{1-e^{-tc\cdot\lambda_{Ba}}}\right]$$

Here λ_i is the decay constant of nuclide i, B_j is the γ to β branching ratio of photon j as given above, ε_j is the photo-peak efficiency of the detector for photon j, t is the time between the event and the start of counting on the detector and tc is the counting time on the detector.[41] The ccf_j is the true coincidence correction factor for photon j that, in close counting geometries, has to be applied for a gamma ray that is emitted in a cascade with other gamma rays or where there are several parallel decay routes between the initial and final states. The ccf_j is also a function of detector and sample geometry and thus has to be calculated (or measured) for each individual combination of radionuclide and detector.

Calculations of the relevant ccfs were performed for the Okinawa detector with the Virtual Gamma Spectroscopy Laboratory (VGSL) code, which has been developed at the PTS in Vienna.[42] Monte Carlo simulations are used both to simulate the decay process with its gamma generation and the photon transport in the detector crystal and its surroundings. Due to the decay scheme of ^{140}Ba, the 537 keV gamma is virtually free from coincidence problems so $ccf_{537} = 1$, while ccf_{487} for the Okinawa detector according to the VGSL simulation is 1.2340 ± 0.0002. The US-built detector system RASA (Radionuclide Aerosol Sampler/Analyzer) installed at Okinawa is shown in Figure 3, where

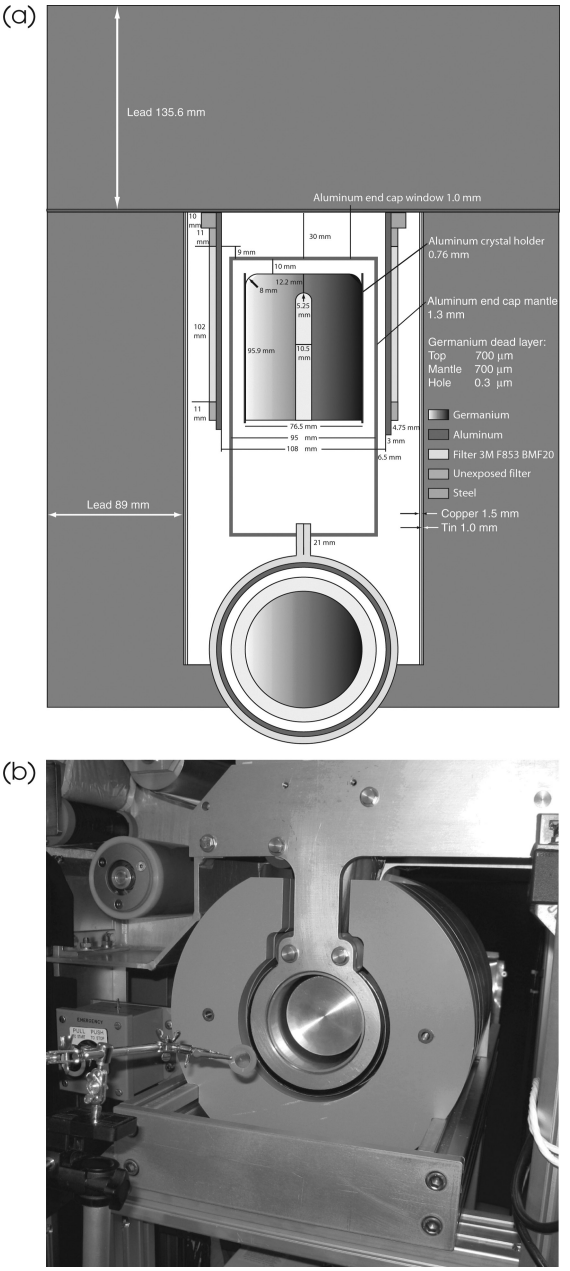

Figure 3: The Okinawa detector, opened in the front with the exposed filter wrapped around a cylindrical surface around the mantle of the detector (b). The close source-detector arrangement causes gamma photons that are emitted simultaneously, like all 487 keV ones in the decay of lanthanum-140 that are directly followed by a 1596 keV photon, to have a fair chance to hit the detector at the same time and thereby lift the pulse to a level corresponding to a higher energy while at the same time reducing the number of full 487 and 1596 keV pulses. Photo courtesy of CTBTO Preparatory Commission. The drawing in (a) shows views from above and from the front (color figure available online).

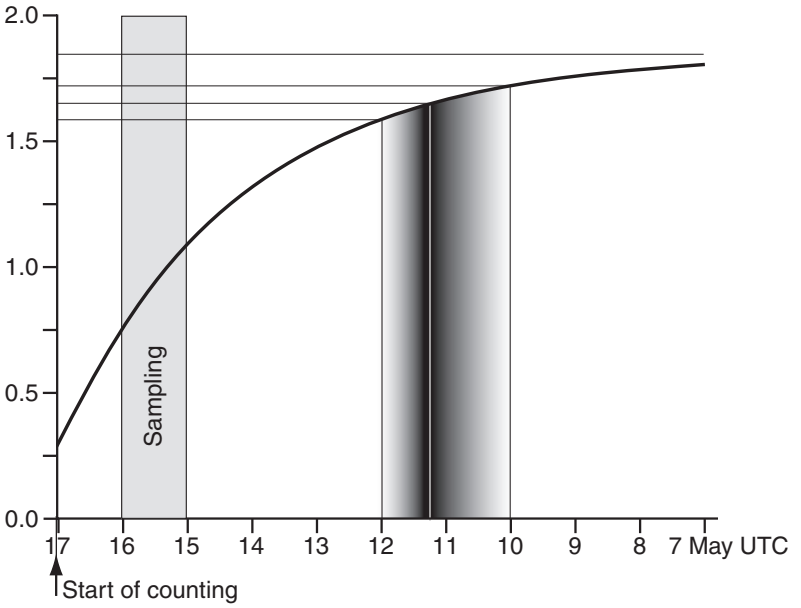

Figure 4: The ^{140}La 487 keV to ^{140}Ba 537 keV peak area ratio as a function of age assuming a prompt emission of ^{140}Xe. The measured ratio of 1.65 ± 0.07 (k = 1) in the 15 May Okinawa sample yields a production time and date of 06:00 11 May UTC +18 h/−30 h.

it can be seen how the filter is closely wrapped around a cylinder with the detector inside. A careful description of materials and geometry of the detector system is vital for the calculation of accurate correction factors. The $\varepsilon_{487}/\varepsilon_{537}$ efficiency ratio of the Okinawa detector set-up is 1.061. The area of the 487 keV gamma peak was slightly reduced by respectively 0.13 percent and 0.54 percent due to weak lines of nearly the same energies in the decays of the natural radon daughters thallium-208 and lead-214 that were present in the filter.

Figure 4 illustrates the dating process based on the sample collected on 15 May 2010 at Okinawa that provided both the earliest and the strongest signal and where the N_{487}/N_{537} ratio was found to be 1.65 ± 0.07 (k = 1).[43] The time of fission so determined was 06:00 11 May UTC 2010 +18h/−30h, which corresponds to the interval 00:00 10 May 2010 to 00:00 12 May 2010.[44] It is worth noting that if the true coincidence correction is neglected in the analysis the start of the time interval moves forward to 14:00 on 13 May 2010, i.e., as much as three days and 14 hours later. This shows that careful true coincidence corrections can be very crucial in gamma spectroscopy.

Another Indicator; Cesium-137 from Noble-gas Decay

The ^{140}Ba and ^{140}La radionuclides were believed to be detected at Okinawa as daughter activities of a promptly emitted noble gas isotope, ^{140}Xe. The

question then arises whether there should have been some other particulate noble gas daughter activities detected in the Okinawa filter(s).

The decay chains with fission xenon of half-lives above 1 second in Figure 2 show that besides ^{140}Ba/^{140}La, there are only 30.1 y half-life ^{137}Cs with its well-known 661.7 keV [85.1 percent] line and 32.1 d half-life ^{141}Ce with a line at 145.1 keV [48.3 percent] that are detectable non-gaseous daughters of a xenon isotope. In addition, many krypton isotopes are produced in fission that have half-lives greater than 1 second. Out of these, however, only 8.57 second half-life krypton-91 and 5.84 second half-life krypton-93 have daughters with any potential to be seen in the Okinawa spectra ($T_{1/2} \geq 6$ h and best gamma intensity $\geq$1 percent). These are strontium-91 (half-life 9.63 hours) with its most prominent gamma at 555.6 keV [62 percent] and ^{93}Y (half-life 10.18 hours) with a gamma at 947.1 keV [2.1 percent].

Based on cumulative noble gas fission yields and detector efficiencies, and by normalizing to the 537.3 keV ^{140}Ba peak area, the expected areas of these peaks in the Okinawa spectra can be estimated. Only ^{141}Ce then falls above its detection limit L_D.[45,46] In the first spectrum expected peak areas are 2.2 and 3.8 times the detection limit for fission of plutonium and uranium, respectively. The fact that ^{141}Ce was not detected can be explained by the 1.7-second half-life of its xenon precursor, which does not leave the gas enough time to escape from the test environment.

For ^{137}Cs, the expected peak areas fall at 0.6 (Pu) and 0.2 (U) times the L_D value. This long-lived nuclide has a xenon precursor with a half-life of 3.818 minutes and would benefit significantly from a later re-measurement at a laboratory. That indeed turned out to be the case for the samples obtained at Okinawa. Normally, samples where at least two so-called CTBT-relevant radionuclides[47] have been detected (with at least one being a fission product), are split and sent to two randomly selected CTBT certified laboratories.[48] With radon-daughter activities largely decayed away when the sample arrives at the laboratory and with longer counting times applied, the sensitivity increases at the laboratory for reasonably long-lived nuclides that survive the transport time to the laboratory. For the first Okinawa sample two laboratories reported 0.45 ± 0.03 μBq/m^3 and 0.44 ± 0.24 μBq/m^3 of ^{137}Cs; for the second sample one laboratory reported 0.24 ± 0.09 μBq/m^3. A 0.35 ± 0.07 μBq/m^3 detection was reported for the fifth sample (19–20 May 2010) and for the following sample one laboratory reported identification, but refrained from quantification. This pattern resembles the one for ^{140}Ba, which lends credibility to the conclusion that the detected cesium actually derived from the same noble gas emission.

ANALYSIS OF THE RADIOXENON SIGNATURES

When the Geojin radioxenon signature from 13 May 2010 is analyzed in detail it becomes clear that this xenon was not what one would expect from a

simple prompt and unmodified injection of radioxenon from a nuclear explosion. The $^{135}Xe/^{133}Xe$ activity ratio shows that the gas was basically virgin[49] and the non-detection of ^{133m}Xe poses a problem that can only be solved by assuming that the testing cavity was previously contaminated by xenon-133. Finally it is shown that the xenon-133 detected at Takasaki, if it was associated with the test as suggested by the quite unique signal and the meteorological analysis, must have escaped the test environment at a somewhat later stage, e.g., during an access to the cavity for diagnostic purposes. These three findings are explained in more detail and analyzed in Appendix 1.

Then in Appendix 2 a test scenario is described that can explain all the observations. It is admittedly a hypothetical scenario but it demonstrates that the complex signatures detected are not at all inconsistent with North Korean low yield testing in the spring of 2010. It allows narrowing down the explosion time to 11 May 2010 and it indicates that the fissile material used was uranium-235 rather than plutonium-239.

METEOROLOGICAL ANALYSES AND ESTIMATES OF THE SIZE OF EMISSIONS

To determine whether the radionuclide observations described above could be related to potential emissions in North Korea around 11 May 2010, the meteorological backtracking tool WebGrape was used. WebGrape is a code developed at the PTS to help member states look for source regions consistent with observations made by the CTBT radionuclide network.[50] The tool uses world weather observations that are regularly analyzed and assimilated by the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, England, to calculate potential source points on the globe that are connected to a given observation by non-vanishing so called source-receptor sensitivity numbers. By following a detection backwards in time, dilution factors are calculated and mapped that relate observed concentration averages during a given sampling time at a given station to possible prompt emissions across the globe.

With WebGrape so called quantitative Fields of Regard were calculated for the Okinawa, Ussuriysk, Geojin, and Takasaki detections. Some results are given in Figure 5 where the Okinawa and Ussuriysk ^{140}Ba detections are investigated for an emission time period of 09:00 to 12:00 on 11 May 2010 and the Geojin and Takasaki radioxenon detections are used to see whether delayed emissions would produce the radioxenon detections at Geojin and Takasaki. The delays were estimated to be about 35 and 48 hours respectively from a tool in WebGrape called Possible Source Region (PSR) that calculates a source map optimized to fit several detections as well as non-detections. In general, Figure 5 quite clearly shows that a common source of the measured nuclides should be possible to find in North Korea. These calculations are not accurate

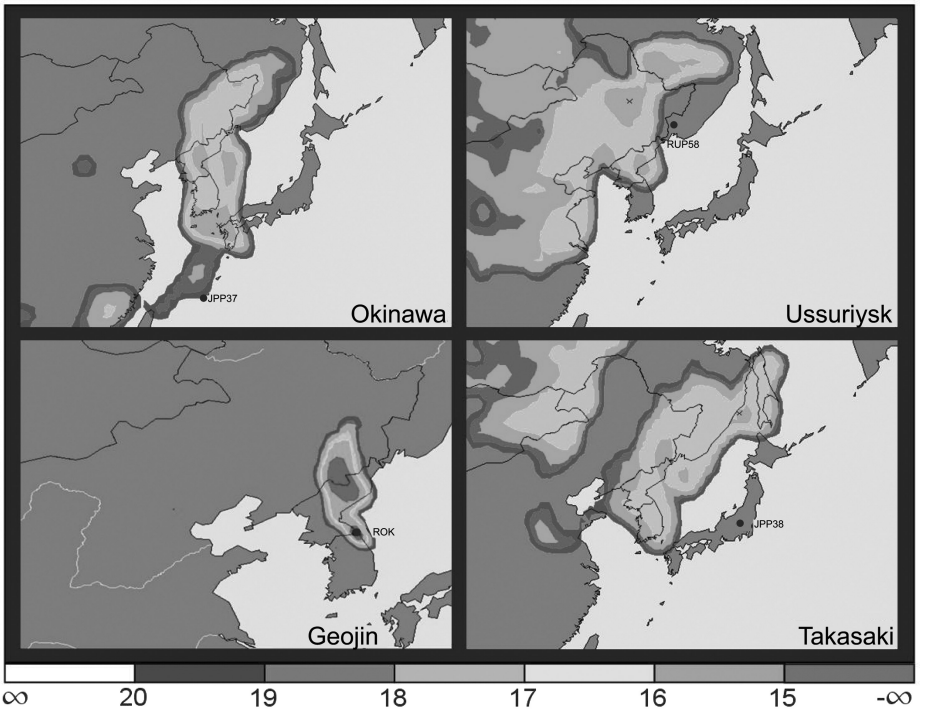

Figure 5: Differential Fields of Regard as calculated by WebGrape based on the first detections at the four stations indicated (for Takasaki the sample with the highest xenon-133 concentration was selected). The top plates refer to an emission between 09:00 and 12:00 on 11 May 2010 UTC (i.e., between 18:00 and 21:00 on 11 May 2010 KST), the Geojin plate refers to an emission 35 hours later and the Takasaki plate 13 hours later than that. The coding indicates *d* in the dilution factor 10^{-d} m^{-3} ($Bq{\cdot}m^{-3}/Bq$). Note that a lower *d* means a lower source term, and that the contour lines can only tell anything about the probability of the source location if there is a prior constraint on the source strength (color figure available online).

enough to exactly pinpoint the source even though suspected sites like Mount Mantap (41.30° N, 129.08° E) and Hagap[51] (40.08° N, 126.19° E) for the explosions and perhaps Yongbyon (39.80° N, 125.74° E) for an involved laboratory are well within the possible source areas on the maps. A more thorough study employing meteorological transport calculations forward in time from suspected sites would most probably do much better in localizing the emission point.

From the dilution factors in Figure 5 some broad conclusions can be drawn on the sizes of the emissions. For a measurement of A Bq/m^3 detected t days after the explosion of a fission product with a half-life of T days and a pertinent fission yield Y percent the corresponding emission measured in tons TNT-equivalent can be written as:

$$8.64 \times 10^6 \times A \times T \times e^{t \times \ln 2/T} / [\ln 2 \times Y \times N \times 10^{-d}]$$

Table 2: Leaks estimated from data at the four detection sites expressed in ton TNT equivalents. Cumulative fission yields are used except for Geojin where the independent yield is applied for the estimated fraction of virgin xenon. Values are given for plutonium and uranium fission and the three most central dilutions, 10^{-d}, in Figure 5.

	Okinawa	Ussuriysk	Geojin	Takasaki
A (Bq)	$8.19 \cdot 10^{-5}$	$1.22 \cdot 10^{-5}$	$2.45 \cdot 10^{-3}/46$	$1.49 \cdot 10^{-3}$
Nuclide	barium-140	barium-140	xenon-133	xenon-133
T (days)	12.7527	12.7527	5.243	5.243
t (days)	4.2	3.8	2.4	5.8
Y% (Pu; U)	0.932; 2.71	0.932; 2.71	0.00851; 0.000707	7.03; 6.61
d				
12			0.005; 0.059	
13			0.050; 0.59	
14			0.50; 5.9	
15	0.042; 0.12			
16	0.42; 1.2	0.059; 0.020		2.1; 2.2
17	4.2; 12	0.59; 0.20		21; 22
18		5.9; 2.0		210; 220

Here 10^{-d} is the dilution factor in m^{-3} and $N = 1.45{\cdot}10^{20}$ fissions per ton TNT-equivalent.

Table 2 shows the results for all four detection sites. As it is not known exactly where the testing took place (although Figure 5 shows that the mountainous areas in the north look quite plausible) the three most central dilution factors were selected for each station. For the prompt emission the Okinawa and Ussuriysk estimates are quite consistent at around one ton, give or take a factor of about 10. The Geojin estimate is similar while Takasaki indicates an emission one order of magnitude larger. It is also clear that the Takasaki pulse was not virgin, i.e., not directly produced in the fission event, as that would imply an unrealistically high emission between 10^3 and 10^6 tons. This means that there were at least three different emissions, a prompt one picked up by Okinawa and Ussuriysk, a virgin one picked up by Geojin, and a non-virgin one detected by Takasaki. The emissions are of the order of 1–10 percent of the possible yields discussed in Appendix 2.

CONCLUSIONS

Observations from the CTBT radionuclide network and from one national radionuclide control post in South Korea imply that an underground nuclear test may have been carried out in North Korea on 11 May 2010. To explain the radioxenon and radioxenon progeny radionuclide signals observed in neighboring countries it was necessary to consider three different emissions from such a

test, one prompt, one promptly cut off from its iodine precursors and later emitted into the atmosphere, and a third emission even later. The first emission was detected by significant barium-140 and/or lanthanum-140 levels at Okinawa in Japan and Ussuriysk in Russia, the second emission was detected by xenon-133 and xenon-135 at Geojin in South Korea, and the third emission by xenon-133 at Takasaki in Japan. The dating of the implied nuclear test was done by analyzing the $^{140}La/^{140}Ba$-ratio, where a correct treatment of true coincidence summing in the detector turned out to be instrumental. The low, or missing, ^{133m}Xe signal at Geojin could only be explained by a significant xenon-133 contamination of the test site beforehand, e.g., by a test previously carried out in the same chamber. That was corroborated by a North Korean official report on 12 May 2010 that referred to a successful nuclear experiment on 15 April 2010, but also by some radionuclide detections in Japan in mid- and late-April 2010. The radioxenon signal at Geojin indicated that the charge tested on 11 May 2010 used uranium-235 as the fissile fuel.

The May 2010 test was not detected by any seismic station or network and must therefore have been quite low-yield (less than 50 ton TNT equivalent or possibly up to some 200 ton if some decoupling is assumed). The fact that such experiments were still detected by another technology in the currently evolving CTBT verification system as well as by a national control post suggests that there are fewer and fewer grounds for countries to refuse ratifying the CTBT by questioning the effectiveness of its verification regime. It also shows that the CTBT verification system sometimes is capable of detecting underground nuclear tests of significantly lower yields than what was anticipated when the treaty was opened for signature 15 years ago.

APPENDIX 1: ANALYSIS OF THE RADIOXENON SIGNATURES

The radionuclide observations in May 2010 in South Korea, Japan, and Russia indicate an explosive fission event; but they are not consistent with detections of a simple, prompt, and unmodified release of radioxenon from such an explosion. A more complex explanation is required. The xenon-133 and xenon-135 detected at Geojin on 13 May 2010 are analyzed below and it is concluded that this xenon was produced directly in the fission process (i.e., it was virgin xenon). The non-detection of ^{133m}Xe at Geojin poses a problem that can only be solved by assuming that the testing cavity was previously contaminated by xenon-133. Finally it is shown that the xenon-133 detected at Takasaki, if it was associated with the test as suggested by the pulse shape and by the meteorological analysis, must have escaped the test environment at a somewhat later stage, e.g., during an opening of the testing cavity for post-test diagnostic purposes.

The High $^{135}Xe/^{133}Xe$ Activity Ratio at Geojin Implies Emission of Virgin Xenon

A $^{135}Xe/^{133}Xe$ ratio of 4.1 ± 0.4 was reported for Geojin. To analyze this observation, one has to re-correct the reported concentrations back, or rather forward, to the counting time. In the CTBT and SAUNA radionuclide systems, spectrum raw data is always corrected to an assumed constant air concentration during the sampling time. For an accurate comparison between measured radioxenon data and theoretical calculations there is a need to undo this correction by multiplying the reported concentrations by the factor

$$\frac{1}{\lambda^2 \cdot ts \cdot tc} \cdot \left[1 - e^{-\lambda \cdot ts}\right] \cdot e^{-\lambda \cdot tp} \cdot \left[1 - e^{-\lambda \cdot tc}\right]$$

where ts, tp, and tc are the sampling, processing and counting times and λ is the decay constant.

Xenon-133 is theoretically somewhat more complicated to correct, and thus also re-correct, as there is in-growth from ^{133m}Xe, but in a standard SAUNA measurement the effect is well below 1 percent and thus clearly insignificant here. For the SAUNA ts, tp, and tc are generally 12 hours, 7 hours, and 11 hours 10 minutes, respectively. With this schedule, the correction factor for the $^{135}Xe/^{133}Xe$ activity ratio can be calculated to be 0.2884. That gives what can be called the spectrum-average activity concentration ratio of $(4.1 \pm 0.4) \times 0.2884 = 1.18 \pm 0.12$ for $^{135}Xe/^{133}Xe$ in the Geojin sample.[52] This number can conveniently be compared to full Bateman treatments based on given source scenarios. To do such calculations a program was written in Mathematica® that in full detail treats all branches in the decay chains of interest[53] based on input data from ENSDF[54] and JEFF 3.1.1[55] as given in Figure 2.

The $^{135}Xe/^{133}Xe$ spectrum-average ratio of 1.18 ± 0.12 turns out to be quite high when it is compared to the corresponding theoretical value in debris with full in-growth from the precursors. For both plutonium and uranium fission it varies between 0.021 and 0.64 when the fission event is moved forward in time through the interval determined by the $^{140}La/^{140}Ba$ dating. A not very plausible reason would be that the explosion time actually was 9 hours later than the upper limit of that interval, or at around 9:00 on 12 May 2010; such a scenario is also contradicted by other information discussed in Appendix 2.

Virgin xenon exhibits a $^{135}Xe/^{133}Xe$ spectrum-average ratio between 0.30 and 11.9 for plutonium and between 0.92 and 35.8 for uranium fission through the explosion interval. It would obviously be possible to reproduce the observed ratio by assuming a suitable precursor cut-off time,[56] as that would yield a mix of virgin and non-virgin xenon. A precursor cut-off at 15 minutes after plutonium or uranium fission at 06:00 on 11 May 2010 would, e.g., well fit the observations. As such, an early emission might lead to detections at Geojin

earlier than 13 May 2010. One can also consider some delay before the early separated gases are emitted to the atmosphere. This is discussed in more detail in Appendix 2.

In next section it is shown that a significant part of the xenon-133 detected at Geojin must have come from an extraneous source. That would give an even higher $^{135}Xe/^{133}Xe$ spectrum-average ratio, which in turn would imply an even shorter cut-off time and an even more virgin emission from an explosion around 11 May 2010.

The Low $^{133m}Xe/^{133}Xe$ Activity Ratio at Geojin Implies Extraneous ^{133}Xe

No ^{133m}Xe was reported from Geojin, which means that its concentration was below 0.2 mBq/m^3 (Table 1). That gives a $^{133m}Xe/^{133}Xe$ activity ratio of less than $0.2/(2.45–0.2) = 0.089$. After multiplication with a correction factor of 0.8684, determined in the same way as the factor for the $^{135}Xe/^{133}Xe$ ratio above, this value yields a $^{133m}Xe/^{133}Xe$ spectrum-average activity ratio of less than 0.077. For this ratio an explosion at 06:00 on 11 May 2010 and a precursor cut-off at 15 minutes that fitted the $^{135}Xe/^{133}Xe$ ratio, the Bateman calculations give a ratio of 0.65 ± 0.20 for plutonium and 0.20 ± 0.03 for uranium, numbers that are respectively 8.4 and 2.6 times higher than the upper bound on the observation. Matching the two ratios thus seems to be impossible.

But it is possible, if it is assumed that a significant part of the longer-lived xenon-133 that was emitted had another source than the explosion around 11 May 2010. With that the 11 May explosion-related $^{133m}Xe/^{133}Xe$ ratio could be increased to fit the calculations. And as pointed out above for the $^{135}Xe/^{133}Xe$ ratio, it would just "make the 11 May explosion-related Geojin sample" more virgin.

The Takasaki Xenon Must Have Come From a Delayed Emission

Radioxenon and radioxenon-daughter species were thus detected in mid-May at four different sites some 300 km to 1500 km away from central North Korea in southern to northeastern directions (Figure 1). Three of the stations have either particulate or noble gas instruments. The station at Takasaki is equipped with both a RASA particulate and a SAUNA xenon system and both were operational at the relevant time. A prominent 1.5 mBq/m^3 xenon-133 pulse was seen in the latter while there were no signs at all of ^{140}Ba in the former. In the noble gas emission hypothesis, ^{140}Ba must result from a prompt emission and the $^{140}Ba/^{133}Xe$ activity ratio, based on the independent yields without any ingrowth from precursors, at an age of about six days would stay at around 100 assuming plutonium fission and around 1300 if uranium is assumed. That gives expected ^{140}Ba concentrations of 0.15 and 2.0 Bq/m^3

respectively, which is 10,000 to 100,000 times the detection limit. This means that the xenon observed at Takasaki could not have originated in a prompt emission from a nuclear explosion around 11 May 2010. A delayed emission, e.g., in connection with some access to the test cavity, is, however, fully consistent with the data.

APPENDIX 2: A HYPOTHETICAL TEST SCENARIO

The complex interpretation of the May 2010 radionuclide observations presented here raises questions about whether these findings can be explained by a realistic nuclear testing scenario. It is of course not possible to state that a hypothesized scenario is in all details the correct one, but finding one that explains all the observations lends credibility to the basic interpretation.

In addition there is corroborative information that can be taken into account like an official North Korean news report issued on 12 May 2010 about success with "fusion reactions." This report also suggested an explanation of the extraneous xenon-133 implied by the Geojin sample as it reports that those "reactions" occurred on 15 April 2010. That inspired a careful look for corroborating evidence of a low-yield nuclear test around that day and two such instances were actually found.

The *Rodong Sinmun* Report on 12 May 2010

On 12 May 2010 the North Korean official daily morning newspaper *Rodong Sinmun* reported that "scientists of the DPRK succeeded in *nuclear fusion* reaction on the significant occasion of the Day of the Sun" (emphasis added).[57] This report was published just one to three days before the xenon and xenon progeny nuclides started to be detected at stations, south, west, and northeast of North Korea. This would seem consistent with the inference that a nuclear explosion took place in North Korea in that period.

One problem with identifying the May 10 or 11 explosion with the event reported by the North Korean government is that the newspaper refers to an event on "the Day of the Sun," which is a public holiday in North Korea on April 15, one month earlier.[58] Taking this information at face value, one could, however, explore the possibility that a nuclear test actually *was* carried out on the Day of the Sun. Such a test would leave non-gaseous fission products locked in the test cavity, and xenon-133 precursors would have ample time during a month to fully decay to xenon-133. The xenon-133 would of course also decay during that month but with a significant amount still left to "join" the virgin xenon fraction in May. A subsequent test on 10 or 11 May 2010, perhaps in some respects more successful, could then with just a slight twist of the truth on 12 May be referred to as a success on the very special Day of the Sun, as

probably planned initially. Other Day-of-the-Sun xenon isotopes would not be detectable in mid-May either due to comparably short half-lives (^{133m}Xe and ^{135}Xe) or very low production (^{131m}Xe).

A second test carried out in a cavity from a previous test would not be without precedent;[59] at a minimum, the Soviet Union has pursued this technique in the past.[60] The cavity can also have been extended to a size that would provide some decoupling capabilities. Partial decoupling factors of up to 1.4 have been predicted for spherical cavities in various media with a radius of 3.42 m/kt$^{1/3}$.[61] This translates to 2.0 m for a 0.2 kt explosion. As the aspect ratio of the volume is not critical[62] the cavity could well be a cylindrical gallery with a diameter of 2 m and a length of 10 m, something that could be easily prepared in a mining tunnel or possibly in an old cavity after one of the first two tests in North Korea. With somewhat larger but still reasonable dimensions a decoupling factor of 4 could be achieved, which means that a test explosion in North Korea of up to some $4 \times 50 = 200$ tons could be carried out without being detected by foreign seismic stations and networks. Doing several low-yield tests in the same cavern would also have an economical value as after several tests where more than 99 percent of the fissile material[63] remains, the cave is a virtual mine of expensive nuclear fuel.

When exploring a hypothesis of an earlier test it is of great interest to carefully look for detections in the region in the weeks following 15 April 2010. Two interesting instances are found. Starting on 20 April 2010, a 36-hour pulse of xenon-133 was observed at Takasaki (Figure 6) and between 27 April 2010 and 2 May 2010 there was an unusually long sequence of cesium-137 detections at Okinawa. All values were close to the detection limits but as they appeared in consecutive samples they represented clear signatures. The xenon-133 pulse at Takasaki was measured in three consecutive samples. The WebGrape analysis in Figure 6 shows that a xenon-133 emission around 15 April 2010 somewhere in North Korea could well have been the source of these Takasaki xenon-133 observations a few days later. Similarly, the ^{137}Cs pulse at Okinawa could also

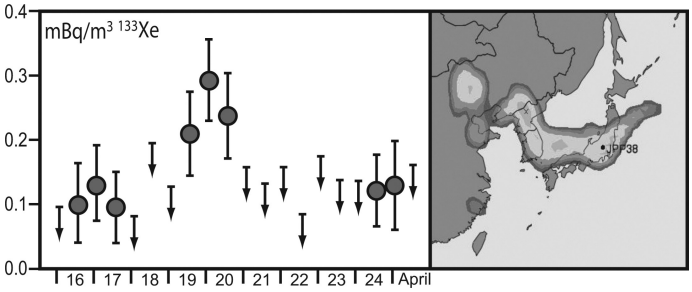

Figure 6: The xenon-133 signal at Takasaki in late April 2010. The arrows mark upper levels. The map is a four day Field of Regard referring to 20 April that shows that the source could well have been an emission in DPRK around 15 April 2010. For a legend see Figure 5 (color figure available online).

be due to an emission (in this case of ^{137}Xe) in North Korea at the relevant time, but since ^{137}Cs is occasionally observed in the region and the distance to Okinawa is about 1600 km it is not used here as a strong support for the hypothesis of a mid-April 2010 test. If the cesium sequence *was* due to such a test in North Korea, it would be the result of a not fully prompt emission (because ^{140}Ba was not detected) of ^{137}Xe, which has a half-life of 3.818 minutes.

Constructing a Scenario that Fits all Observations

It is of course not possible to describe with full confidence all the circumstances that would produce the radionuclide signatures that were observed. The probability, however, that a low-yield underground nuclear explosion was carried out on 11 May 2010, or possibly, the day before, is significant. Based on the assumption that all xenon and xenon progeny signals detected in mid-May 2010 were the results of emissions due to that explosion, the analysis above suggests that there could have been three separate emissions from the test site. First, the ^{140}Ba detections required a prompt emission; second, there is evidence that the xenon-135 detected at Geojin came from an emission of virgin radioxenon delayed by one or two days; and third, there is evidence that the signal at Takasaki was due to non-virgin radioxenon emitted from the site another day or so later. Most of this fits observed nuclide ratios at different times and weather patterns that would have transported the radionuclides to the respective detection points with correct timing.

There is one exception, however: the Geojin data requires that there was an extraneous source of xenon-133 in the corresponding emission. It was not possible to find a reasonable process where gas emitted during the first hour, which would increase the xenon-133 levels in the atmosphere, would produce the observed full signature. Only by assuming that there was xenon-133 present in the cave before the 10 or 11 May 2010 explosion, a fitting signature could be reproduced. The best correspondence was reached when the initial underground gas contained 45 times more old than fresh xenon-133. Moreover, this fit also requires that the fissile material was ^{235}U. It was not possible to find a solution for plutonium. Figure 7 shows the calculated and observed ^{135}Xe/^{133}Xe and ^{133m}Xe/^{133}Xe spectrum-average activity ratios, both including the relevant uncertainties. Such a dominance of old xenon-133 might appear surprising, but the reason is the very high ratio of nearly 10,000 between cumulative (aged or non-virgin) and independent (virgin) yields for ^{235}U. For the same reason this dominant contribution (by activity) of aged ^{133}Xe corresponds, for uranium fission, to no more than 0.5 percent if it is measured in ton TNT, like in Table 2. For plutonium fission the number is 6 percent due to the ten times higher independent to cumulative yield ratio. Such a small share (especially for uranium) of aged xenon could well have been fixed in pores on the

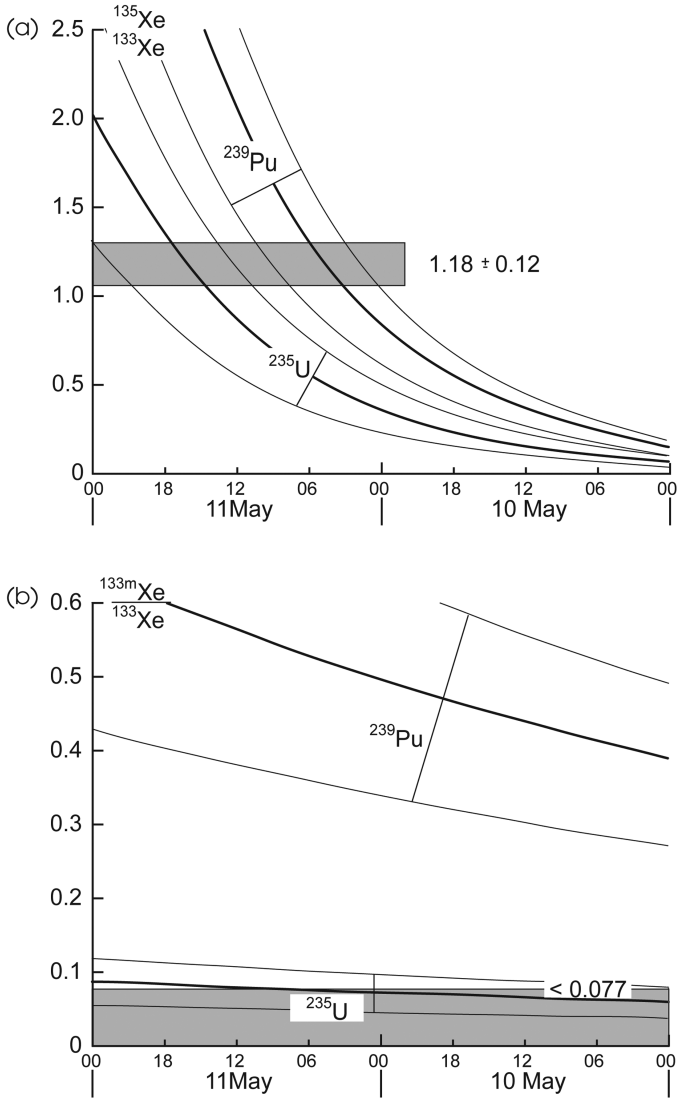

Figure 7: Spectrum average activity ratios calculated for the Geojin sample as a function of fission time within the range deduced from the Okinawa barium/lanthanum-140 data. Virgin xenon with xenon-133 "amplified" by a factor 45 from a previous explosion in the same cavern is assumed. The gray boxes represent the measurement. The thinner lines indicate the uncertainty limits given by the JEFF 3.1.1 database.

rock surfaces and in cracks and fissures of the cave and then been set free by the second explosion. Another possibility is that the two tests were carried out in two adjacent cavities where the wall between them was broken by the second explosion. As shown in Figure 7, this analysis indicates that the

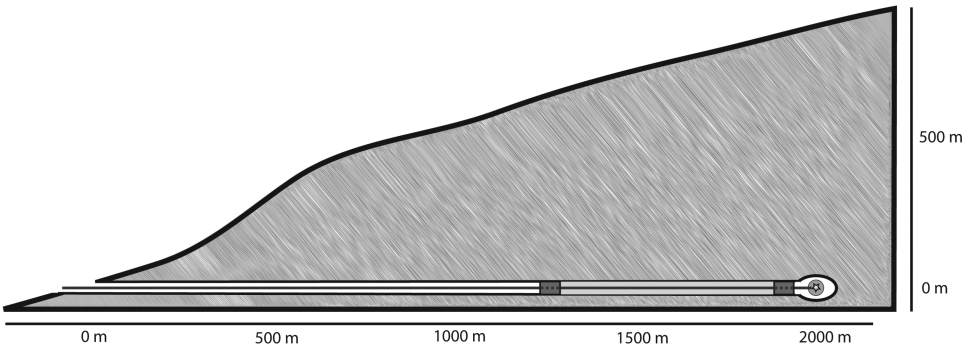

Figure 8: A possible testing scenario that could satisfy all radionuclide observations in a long tunnel with a modestly excavated cavity (or possibly two adjacent ones) at the end where repeated low-yield tests are done. The black boxes are sealing devices with the penetrating line symbolizing control and diagnostics cables from the test point to the outside. Promptly after detonation the very high-pressure forces some virgin noble gases through the seals, most probably along the cable penetrations. The gases that pass both seals constitute the first emission that soon gives rise to barium-140, and the virgin noble gases plus aged xenon-133 that only pass the first seal is accumulated in the darker space between the seals. This gas will later be, at least partly, released, when the space is accessed for diagnostic reasons. Then when the inner seal is opened for the same reason there is a possibility for a third emission, this time of non-virgin noble gases (color figure available online).

second explosion was more likely to have occurred on 11 May 2010 than on 10 May 2010.

The fact that the analysis suggests that that the fissile material was uranium is a plausible finding as uranium is the preferred fissile material in low-yield nuclear experiments to avoid the effects of the high stray neutron background associated with plutonium. To keep the explosive yield of a critical assembly low, the initial compression must be comparably slow and that implies extra sensitivity to stray neutrons and a risk that the fission reactions are initiated too early for a successful and well-controlled experiment.[64]

So *one* possible scenario could be the following (see Figure 8 for a graphical representation):

- In a deep tunnel in North Korea, like the one in Mount Mantap, a gallery was excavated that was capable of decoupling the seismic signal from a nuclear explosion by a factor of 4 or more. The tunnel was closed by at least two sealing complexes,[65] one closer to the cave and one closer to the tunnel entrance.
- There was one nuclear test explosion below some 200 ton TNT equivalent on or near 15 April 2010. The test might have failed in some respects, and there was therefore no announcement of success around the Day-of-the-Sun. Residual radionuclides deposited in pores on cave surfaces as well as in cracks and fissures.

- On 11 May 2010, there was a second nuclear test in the same or in an adjacent cave. Due to the initially very high pressure, virgin and aged (residues from an experiment in mid-April 2010) noble gases were promptly pushed out of the test cave through the two barriers built in the entrance tunnel. This leakage could reasonably have happened along control and signal cables from the test point to the tunnel entrance, which is a classical problem in underground testing. Condensation should have been quite a quick process and the filtering must have been very effective as there were no traces of even volatile iodine or tellurium radionuclides in the samples where ^{140}Ba/^{140}La was detected.
- The gas that made it through both barriers gave rise to the ^{140}Ba/^{140}La detections at Okinawa and the ^{140}La detections at Ussuriysk but some gas was also caught in the volume between the two barriers when the initial high pressure decreased.
- In the morning of 12 May 2010 (KST), nuclear fusion success was officially announced.
- On 11 or 12 May 2010, testing staff opened a door in the outer barrier and the mix of virgin and aged gases in the volume between the two barriers escaped to the atmosphere. Perhaps the gas mixture was compressed into a test tube to be taken to a laboratory like Yongbyon for analysis and diagnostics. That opens up the possibility that the virgin plus aged gas might have escaped from the laboratory rather than from the test tunnel entrance. These gases were blowing towards Geojin, from the test site, from the laboratory or from both. It is still possible, however, that the virgin gases detected at Geojin were part of the prompt emission, something that would simplify the scenerio. For a better understanding of this, careful forward meteorological analyses from suspected sites have to be done.
- On 13 or 14 May 2010, a door was opened in the inner barrier and non-virgin xenon-133 was emitted to the atmosphere. That cloud was detected at Takasaki.

It is impossible to determine the credibility of the report in *Rodong Sinmun* that suggested thermonuclear reactions had successfully been achieved. The report continued to say that the experiments dealt with "development of new energy desired by mankind," which was further specified as "...safe environment-friendly new energy the source of which is abundant." But as military fusion is a simpler problem than civilian fusion one could suspect that the report was actually about some military fusion success.

And if the North Korean announcement is taken seriously as a military success there are low-yield nuclear test scenarios in the range of 10 to 200 ton TNT equivalent that could replicate all radionuclide findings and that would produce significant amounts of thermonuclear reactions in a volume

of deuterium-tritium gas or even lithium deuteride that would prove success.[66] This would probably be done by on-line time-of-flight measurements that demonstrate the presence of 14.1 MeV neutrons. There is no way, however, that small scale fusion in a nuclear test can be determined from distant detections of leaking noble gases.

It is also significant that the analyses indicate that the May 2010 nuclear test most probably used a device based on highly enriched uranium, something that sheds new light on North Korea's enrichment capabilities and/or possible disguised co-operation agreements with other states with nuclear ambitions.[67] Covering up any such connections could perhaps have been the reason why in November 2010 the former Director of Los Alamos National Laboratory, Siegfried Hecker, was somewhat mysteriously invited to inspect a newly built centrifuge installation at Yongbyon.[68]

On 19 October 2011, Representative Park Sun-young of the minor Liberty Forward Party in South Korea, citing a North Korean military official, claimed that North Korea has operated a uranium enrichment facility on the west coast since 2006 and that the country has already been developing nuclear weapons using enriched uranium since 2007, switching from its plutonium production program.[69] If true, that puts the Hecker visit in new light, and it is obviously in line with the present findings.

The test scenario considered in this Appendix is speculative but could explain all features of the xenon and xenon progeny nuclides detected in South Korea, Japan, and Russian Federation in mid-May 2010 and in late April 2010. This scenario involved two nuclear tests carried out in the same cavity (or two adjacent ones), one in mid-April 2010 and one in the first half of May 2010. The idea of a mid-April explosion was supported by a plume of xenon-133 detected at Takasaki around 20 April and also by an official announcement by the North Korean government. This analysis allows improving the accuracy of the estimate of the date of the second explosion, placing it on 11 May 2010, and it also suggests that the fissile material in the 11 May 2010 explosion was highly enriched uranium. As there were no seismic detections of the tests, well-coupled explosions should have been below 50 tons. It was judged, however, that a reasonable decoupling could extend the upper limit up to 200 tons.

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1. In strict vocabulary a tunnel has one opening in each end. If there is just one opening, which is normal in horizontal underground nuclear testing, it is correctly called an adit. As the discrepancy is here not very important the term "tunnel" is used for both.

2. J. R. Murphy, B. C. Kohl, J. L. Stevens, T. J. Bennett, and H. G. Israelsson, "Exploitation of the IMS and Other Data for a Comprehensive, Advanced Analysis of the North Korean Nuclear Tests," (paper presented at the 2010 Monitoring Research Review Orlando, Florida, 21–23 September 2010), <https://na22.nnsa.doe.gov/mrr/2010/PAPERS/04-11.PDF>.

3. A. Ringbom, K. Elmgren, K. Lindh, J. Peterson, T. W. Bowyer, J. C. Hayes, J. I. McIntyre, M. Paninsko, and R. Williams, "Measurements of Radioxenon in Ground Level Air in South Korea Following the Claimed Nuclear Test in North Korea on October 9, 2006," *Journal of Radioanalytical and Nuclear Chemistry*, 282(2009): 773–779.

4. P. R. J. Saey, M. Bean, A. Becker, J. Coyne, R. d'Amours, L.-E. De Geer, R. Houge, T. J. Stocki, R. K. Ungar, and G. Wotawa, "A Long Distance Measurement of Radioxenon in Yellowknife, Canada, in Late October 2006," *Geophysical Research Letters* 34, L20802 (2007).

5. J. R. Murphy et al. , *op. cit*.

6. North Korea Plans "Nuclear Test in Coal Mine," *Mining Top News*, <http://www.miningtopnews.com/ north-korea-plans-nuclear-test-in-coal-mine.html>.

7. J. R. Murphy et al. , *op. cit*.

8. Such efforts could include investing in more sealing devices in the tunnel or actually drilling a vertical hole at the end of the tunnel, a hole that is carefully stemmed after the test device has been installed at the bottom.

9. L.-E. De Geer, "Sniffing out Clandestine Tests," *Nature*, 382(1996): 491–492 and C. R. Carrigan, R. A. Heinle, G. B. Hudson, J. J. Nitao, and J. J. Zucca, "Trace Gas Emissions on Geological Faults as Indicators of Underground Nuclear Testing," *Nature*, 382(1996): 528–531.

10. O. Dahlman, J. Mackby, S. Mykkeltveit, and H. Haak, *Detect and Deter: Can Countries Verify the Nuclear Test Ban* (Heidelberg: Springer, 2011).

11. The nuclear capable states are defined as those that possessed power or research reactors at the time of the negotiation of the CTBT. As of January 2012, there remain eight identified nuclear capable states to ratify the CTBT; these are China, Egypt, India, Iran, Israel, North Korea, Pakistan, and the United States.

12. The word *particulate* means that the radionuclides are attached to or distributed within microscopic particles. Suspended in the atmosphere they are also referred to as an aerosol. Most radionuclides created in atmospheric nuclear explosions are of this type. They are easily collected by blowing air through a filter and by analyzing the gamma radiation from such samples with a germanium detector one reaches extremely high sensitivities.

13. M. Matthews, J. Schulze, "The Radionuclide Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty Organization: From Sample to Product," *KERNTECHNIK*, 66(2001): 102–120.

14. K. M. Matthews, and L.-E. De Geer, "Processing of Data From a Global Atmospheric Monitoring Network for CTBT Verification Purposes," *Journal of Radioanalytical and Nuclear Chemistry*, 263(2005): 235–240.

15. Dahlman et al. , *op. cit*., 63–64.

16. Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), <http://www.ctbto.org/>.

17. SAUNA is an acronym for "Swedish Automatic Unit for Noble gas Acquisition."

18. A. Ringbom, T. Larsson, A. Axelsson, K. Elmgren, and C. Johansson, "SAUNA—A System for Automatic Sampling, Processing and Analysis of Radioactive Xenon," *Nuclear Instruments and Methods in Physics Research A*, 508(2003): 542–553.

19. The fact that the sampling is here referred to as being done at room temperature is because at the time of design this was a very unorthodox approach that is greatly simplifying the process.

20. Air contains 87 ppb of stable xenon isotopes.

21. The distances to the Mount Mantap test site varied broadly within the same bearings between 330 and 1660 km.

22. The sampling period at Geojin is inferred from the time given by Kim Seon-dong and the SAUNA analysis schedule.

23. When needed, this can be recalculated to any other standard, and that is actually done in the text with the Geojin data to provide values that can more directly be compared with mass chain dynamics (Bateman) calculations. At Ussuriysk it was actually lanthanum-140 that was detected but based on the near equilibrium observed at Okinawa and assuming a common source for the Ussuriysk and Okinawa detections, these lanthanum values were recalculated to barium-140 values for ease of comparison. All these derived barium-140 values were below the detection criterion for barium-140, which shows that lanthanum-140 normally provides the most sensitive means to detect mass chain 140.

24. "Radioactivity Detected after N. Korea Nuclear Fusion Claim," in *Chosun Ilbo*, a major daily newspaper in South Korea, 21 June 2010, <http://english.chosun.com/site/data/html_dir/2010/06/21/2010062101166.html>.

25. "Did NK Conduct a 3rd Nuclear Test in May?," in *The Korea Times*, an English language daily newspaper in South Korea, <http://www.koreatimes.co.kr/www/news/nation/2010/10/116_74808.html>.

26. Evaluated Nuclear Structure Data File, ENSDF file, maintained by the National Nuclear Data Center (NNDC) at Brookhaven, USA, <http://www.nndc.bnl.gov/ensdf/>. Apart from fission yields all nuclear data in this report is taken from ENSDF.

27. Not to be confused with the Swedish SAUNA flown to South Korea in October 2006 that did detect xenon isotopes from the first North Korean nuclear test in the vicinity of Geojin.

28. International Data Centre Website, <http://www.ctbto.org/expert-area>. Users must be nominated by the Permanent Mission of a State Signatory with an accredited Permanent Representative (or Permanent Observer) to the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization.

29. International Data Centre Website, *op. cit*.

30. *Ibid*.

31. The small concentrations of ^{131m}Xe that were detected are disregarded as they were typical background values for this somewhat longer-lived isotope.

32. JEFF 3.1.1, Joint Evaluated Fission and Fusion File, Nuclear Energy Agency, reached via JANIS 3.2 at <http://www.oecd-nea.org/janis/>. All fission yield data in this report is taken from JEFF 3.1.1.

33. These tests were carried out on 18 December 1966 at the Soviet Semipalatinsk test site and on 23 March 1971 north of Perm in the Soviet Union. The latter test was done to study whether nuclear explosions could be used to turn the Pechora river flow south for irrigation purposes.

34. G. Persson, "Fractionation Phenomena in Activity from an Underground Nuclear Explosion," *Health Physics*, 16(1968): 515–523.

35. B. Eriksen, "Undersökningar av luftburet radioaktivt material härrörande från en underjordisk kärnladdningsexplosion i USSR den 23 mars 1971," (in Swedish). "A study of airborne radionuclides from an underground nuclear explosion in the USSR on 23 March 1971." FOA 4 report C 4502-A1.

36. At fission neutron energies there are no significant side reactions in the two xenon isotopes, in contrast with the situation at thermal energies, where xenon capture cross sections are very large, especially in xenon-135.

37. Using data from Figure 2, the $^{135}Xe/^{133}Xe$ activity ratio can be estimated to [0.0842/0.000707] * [5.243 * 24 / 9.14] = 1640.

38. T. P. McLaughlin, S. P. Monahan, N. L Pruvost, V. V. Frolov, B. G. Ryazanov, and V. I. A. Sviridov, "A Review of Criticality Accidents, 2000 Revision," *Los Alamos Report*, LA-13638, May 2000.

39. T. Kværna, F. Ringdal, and U. Baadshaug, "North Korea's Nuclear Test: The Capability for Seismic Monitoring of the North Korean Test Site," *Seismological Research Letters*, 78(2007): 487–497 and T. Kværna, personal communication, 18 Feb. 2011.

40. H. Bateman, "The Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations," *Proceedings of the Cambridge Philosophical Society* 15(1910): 423–427.

41. A CTBT particulate filter is nominally collecting aerosols during 24 hours, waits for 24 hours and is measured during 24 hours. The formal requirements, however, allow 10% deviations from these numbers as long as the sum is kept below 72 hours. This is to give time for authentication procedures, check source measurements, and other local needs. For the 15 May 2010 Okinawa filter the counting time happened to be 22 minutes short of 24 hours.

42. R. Plenteda, "A Monte Carlo Based Virtual Gamma Spectroscopy Laboratory," Ph.D. Thesis, Institute of Atomic and Subatomic Physics, Vienna, Austria (2004) and L.-E. De Geer and R. Plenteda, "VGSL, The Virtual Gamma Spectroscopy Laboratory," Presentation at the International Committee for Radionuclide Metrology (ICRM) gamma spectroscopy working group meeting at Laboratoire National d'Essais (LNE), Paris, France, April 2009.

43. k is the coverage factor used in modern uncertainty estimates. k = 1 corresponds to the older notion of ± one sigma (σ).

44. UTC is the Coordinated Universal Time and is used throughout this article except when otherwise noted. At a few instances the local time, KST or Korean Standard Time, is used where KST = UTC + 9 hours. Neither UTC nor KST apply daylight saving time.

45. L. A. Currie, "Limits for Qualitative Detection and Quantitative Determination—Application to Radiochemistry," *Analytical Chemistry*, 40(1968): 586–593.

46. L.-E. De Geer, "Currie Detection Limits in Gamma-ray Spectroscopy," *Applied Radiation and Isotopes*, 61(2004): 151–160.

47. L.-E. De Geer, "Comprehensive Nuclear-Test-Ban Treaty: Relevant Radionuclides," *KERNTECHNIK*, 66(2001): 113–120.

48. Ten out of the sixteen prescribed CTBT laboratories are currently certified and in operation.

49. The word "virgin" is here used to refer to the part of a fission product that is produced directly in the fission process. It corresponds to the concept of independent fission yield in Figure 2. The term "non-virgin" is correspondingly used to refer to the part that results from precursor decay.

50. A. Becker, G. Wotawa, and L.-E. De Geer, "Review of New PTS Modelling Capabilities Supporting the Emerging CTBTO-WMO Response System Including a Proposal for Standardized Model Intercomparison," World Meteorological Organization (WMO), WWW, CBS(ERA-CG(INF.1(Doc.8.3 (8.III.2004).

51. More information on the Hagap unidentified underground facility in the Myoyang Mountains can be found at <http://www.globalsecurity.org/wmd/world/dprk/myohyang-imagery.htm>.

52. The spectrum-average activity is based on the peak area in the spectrum divided by branching, efficiency and live counting time.

53. L.-E. De Geer, "The Xenon NCC Method Revisited," FOI, Swedish Defence Research Agency report, FOI-R-2350–SE (2007).

54. Evaluated Nuclear Structure Data File, *op. cit*.

55. JEFF 3.1.1. Joint Evaluated Fission and Fusion File, *op. cit*.

56. *Precursor cut-off time* is the time when the radioxenons are separated from all its precursors such that no further radioxenon will be formed by iodine decay in the separated volume.

57. Korean News Service, News from the Korean Central News Agency of DPRK, Pyongyang, **"**DPRK Succeeds in Nuclear Fusion," 12 May 2010, <http://www.kcna.co.jp/index-e.htm>.

58. A public holiday celebrating the birthday of North Korea's late founder Kim Il Sung, who was born on 15 April 1912. It is interesting to note that 15 April 2012 is his 100th birthday.

59. A. A. Spivak, "Methods of Evading Detection by a Nuclear Explosion Monitoring Network under Special Conditions," In *Monitoring a Comprehensive Test Ban Treaty*, E. S. Husebye, and A. M. Dainty, Eds. (Dordrecht: Kluwer Academic Publishers, 1996).

60. W. Leith, "Geologic and Engineering Constraints on the Feasibility of Clandestine Nuclear Testing by Decoupling in Large Underground Cavities," U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia, Open File Report 01-28, 2001.

61. D. King, B. Freeman, D. Eilers, and J. Johnson, "The Effective Yield of a Nuclear Explosion in a Small Cavity in Geologic Material: Enhanced Coupling Revisited," *Journal of Geophysical Research*, 94(1989): 12375–12385.

62. W. Leith., *op. cit*.

63. T.B. Cochran and C.E. Paine, "The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," in *Nuclear Weapons Databook* (New York: Natural Resources Defense Council, 1995). According to Cochran and Paine, a country with medium technical capability can make a 1 kt fission bomb with about 1.5 kg plutonium or 4 kg highly enriched uranium (HEU), containing 30 and 80 kt respectively of potential fission energy. A 200-ton plutonium or uranium bomb thus consumes less than one percent of the fuel.

64. This is a parallel to why plutonium is not suitable in a gun-type nuclear warhead and why the implosion scheme with a more rapid criticality acceleration sequence had to be invented to use plutonium, which is otherwise a much more weapons prone fissile material due to its significantly lower critical mass.

65. V. N. Mikhailov, Y. V. Dubasov, and A. M. Matushenko, "Nuclear Explosions in the USSR: The North Test Site," Interagency Expert Commission on assessment of radiation and seismic safety of underground nuclear tests, Scientific-Industrial Association, V. G. Khlopin Radiation Institute Report, St Petersburg, 1999.

66. If the *Rodong Sinmun* report is taken at face value, the test might have been designed to involve thermonuclear processes. There are some low-yield nuclear test scenarios in the range of 10 to 200 ton TNT equivalent that could replicate all radionuclide findings and that would produce significant amounts of thermonuclear reactions in a volume of deuterium-tritium gas. The lower limit is taken from an authoritative U.S. National Academy of Science report, which indicates that "partial developments of primaries for thermonuclear weapons" can be done in the range of 0.01 to 2 kt (*Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty* [Washington, DC:

National Academy Press, 2002]). The upper limit is set by the detection capabilities of the CTBT and other seismic networks in the region for a modestly decoupled explosion and the fact that nothing suspicious was detected. Tests at the lower end of this range can presumably improve understanding of the radiation implosion mechanism in modern thermonuclear charges by employing miniature secondaries, and "partial yield verification of . . . boosted-fission weapons" can reportedly be done at the higher end of the range (T. B. Cochran and C. E. Paine, *The Role of Hydronuclear Tests and Other Low-Yield Nuclear Explosions and Their Status Under A Comprehensive Test Ban* [Washington, DC: National Resources Defense Council, 1995]).

67. S. Tisdall, "China Pressed over Iran and North Korea's Nuclear Trade," *The Guardian*, <http://www.guardian.co.uk/world/2010/nov/28/china-iran-north-korea-nuclear>, 28 Nov. 2010.

68. S. S. Hecker, "A Return Trip to North Korea's Yongbyon Nuclear Complex," CISC Stanford University Report, 20 Nov. 2010 and S. S. Hecker, "What I Found in North Korea—Pyongyang's Plutonium Is No Longer the Only Problem," *Foreign Affairs*, 9 Dec. 2010.

69. Kim Eun-jung, "N. Korea Operating Second Uranium Enrichment Facility: Lawmaker," Yonhap News Agency, 19 October 2011, <http://english.yonhapnews.co.kr/national/2011/10/19/18/0301000000AEN20111019008600315F.HTML>.