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Low-Yield Nuclear Testing by North Korea in May 2010: Assessing the Evidence with Atmospheric Transport Models and Xenon Activity Calculations

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This article investigates the possibility presented by De Geer (2012) that radionuclides detected at stations in South Korea, Japan, and Russia in May 2010 were evidence that North Korea conducted at least one unannounced low yield nuclear test on 11 May. It provides HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory Model) atmospheric transport modeling of the observed radionuclides assuming candidate origins in North Korea, ROK, Japan, Russia, mainland China, and Taiwan. Xenon activity calculations for reactor- and explosion-produced isotopes are used to ascertain possible release ratios and source terms. The HYSPLIT modeling finds that the most likely origin of the radionuclides is close to the site of North Korea's declared nuclear tests in 2006 and 2009. The activity calculations show that the source term is consistent with a nuclear test up to a few hundred tons yield. These results are discussed in the context of a decoupled but uncontained nuclear test by North Korea on 11 May 2010. If the scenario suggested by De Geer and supported here is correct, it seems that there is a significant possibility of detecting even a small, decoupled nuclear test in North East Asia using components of the International Monitoring System of the Comprehensive Test Ban Treaty.

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INTRODUCTION

In this journal, De Geer reported that in mid-May 2010 there were multiple detections of Ba-140, together with La-140, at Japan's Okinawa Comprehensive Test Ban Treaty (CTBT) International Monitoring System (IMS) particulate station, the first ever such detections of Ba-140 by the world-wide IMS; detections of Xe-135 and Xe-133 at the South Korean Geojin noble gas station near the North Korean border, at a ratio not observed over approximately 3 years of operation, and possibly at activity concentrations never before detected there; and, lower concentrations of La-140 and xenon detected respectively at the Russian Ussuriysk IMS and Japanese Takasaki IMS stations.[1] De Geer found from backward meteorological transport calculations, in combination with Web-Grape software, that the air masses carrying the particulates and noble gas to Okinawa, Geojin, Ussuriysk, and Takasaki had passed over North Korea a few to several days beforehand.[2] More recently Wotawa has broadly confirmed De Geer's atmospheric modeling.[3] De Geer postulates that North Korea conducted an unannounced, possibly decoupled, nuclear test.

The observed ratio of Ba-140 and La-140 at Okinawa was used as a clock by De Geer to time the event to 0600 UTC 11 May 2010, with an uncertainty range of +18 hours and −30 hours. A near prompt vent of noble gases occurred, including Xe-140 and Xe-137 which, due to their short half-lives of 13.6 seconds and 3.8 minutes respectively, quickly decayed into Ba-140, La-140, and Cs-137.[4] Ba-140, La-140, and Cs-137 were subsequently detected at Okinawa, whilst at Ussuriysk only the mass 140 species have been reported. In De Geer's model, approximately 36 hours after the explosion, another release of noble gases occurred, resulting in the Xe-133 and Xe-135 detections at Geojin. De Geer notes that a strong candidate for the release location could be the site of North Korea's nuclear tests in 2006 and 2009.

This article presents forward transport calculations in both simple trajectory and full plume concentration mode for candidate origins by location for the particulate and noble gas observations reported by De Geer. It considers as possible sources of the releases a nuclear explosion, a nuclear power reactor, and a medical isotope production facility. Atmospheric transport modeling, in both forward and backward trajectory mode, is detailed in the following section. Subsequently the potential source term for a nuclear explosion, with the aid of xenon activity calculations from both U-235 and Pu-239, is assessed to determine if such a source term is consistent with the observed concentrations. Results are interpreted in the context of a seismically decoupled but uncontained nuclear test.

ATMOSPHERIC TRANSPORT MODELING FOR THE GEOJIN AND OKINAWA DETECTIONS

Atmospheric transport modeling using single trajectories and turbulent plume dispersion was conducted using the July 2011 release of the Hybrid Single

Particle Lagrangian Integrated Trajectory (HYSPLIT4) code.[5] HYSPLIT has been successfully used for many different types of transport scenarios, including aerosols, chemical pollutants, and radionuclide species in CTBT-relevant scenarios.[6] This type of modeling can include significant uncertainties, both numerical and physical in nature; these are discussed in detail by Stohl and others.[7] From the ensemble of work reviewed in Stohl, which includes tracer experiments, a reasonable estimate for the deviation between a model and "true" trajectory appears to be about 20–30 percent of the total distance travelled. Cases have been reported where it is less, but cases have also been reported where the divergence is up to 180 degrees, i.e., the model and true trajectories are in opposite directions. An approximately linear deviation rate of $\leq$50–200 km/day—dependent on the spatial and temporal resolution of meteorological data—for travel time up to 4 days is probably appropriate.[8]

A full sensitivity study is beyond the scope of this article, though two meteorological data sets were trialed. As a "standard" the global re-analysis data archive—from the U.S. National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR)—was employed.[9] It is available 6-hourly on a 2.5 degree latitude-longitude grid. For certain calculations data from NCEP's Global Data Assimilation System (GDAS), 3-hourly on a 1 degree grid, was also utilized. Wotawa instead used data from the European Centre for Medium-Range Weather Forecasts with a spatial resolution of 0.5 degrees and a temporal resolution of 3 hours.[10]

Both re-analysis and GDAS data have been used extensively in the literature, though there has been little direct comparison between them. There is no consensus on which data set most faithfully reproduces actual observations. In some cases they are essentially equivalent, whilst in others GDAS was preferred.[11] The higher spatial resolution of GDAS over NCEP-NCAR re-analysis data suggests it would perform better overall, e.g., be less sensitive to interpolation errors. But this has been shown to not always be the case, suggesting the relative merits of the two data sets should be judged on a case-by-case basis, depending on parameters such as the local terrain and season.[12] Also, the resolution of the NCEP-NCAR re-analysis data is well suited to synoptic-scale phenomena, which is primarily the interest here. This thesis is to some extent supported by the work of Draxler, who used HYSPLIT and re-analysis data to quite successfully reproduce plumes of krypton-85 from the Savannah River reprocessing plant over distances up to 1000 km.[13]

North Korea's nuclear test site (NKTS) and its Yongbyon fissile material production complex are considered below as possible origins for the particulate and/or noble gas emissions. It seems logical that North Korea would conduct any additional nuclear tests at NKTS, given the existing infrastructure and experience at that location associated with its tests there in 2006 and 2009. The Yongbyon Nuclear Research Centre is where the fissile material was made for the 2006 and 2009 test devices. Several other known or suspected sites related to North Korea's nuclear program lie within about 50 km of Yongbyon.[14] Origin

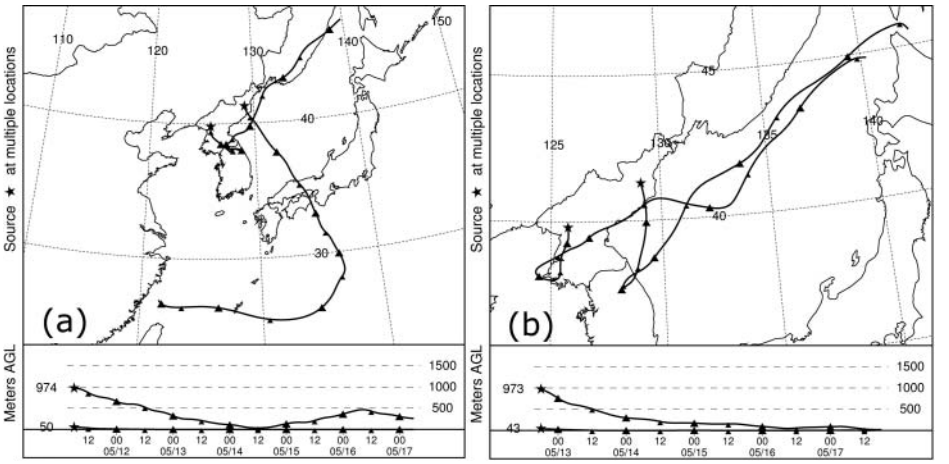

Figure 1: (a) Plume trajectories starting at 0600 UTC on 11 May 2010 from 1500 m Above Sea Level (ASL) from NKTS and 440 m ASL from Yongbyon (in the global re-analysis meteorological data used here the "mean" ground level at NKTS and Yonbyon is 526 m and 390 m ASL respectively). Representing a prompt vent, the trajectory from NKTS passes over Okinawa between 15 and 16 May 2010, in agreement with the first detection of barium-140 at Okinawa. **(b)** Plume trajectory starting 1800 UTC 12 May 2010. Representing a delayed release, and also using re-analysis meteorological data, the trajectory passes over Geojin around 13–14 May 2010, in agreement with the first detection of xenon-133 and xenon-135 at Geojin.

times are those calculated by De Geer for a prompt vent using the Ba-140/La-140 ratio, i.e., 0600 UTC on 11 May 2010, and a delayed release 36 hours later.

Figure 1a shows that a forward trajectory starting at the seismically determined co-ordinates of NKTS[15], and an elevation of 1500 m above sea level, passes almost directly over Okinawa at almost the precise time the respective detection was made. Origin times within the Ba-140/La-140-derived error bounds were also tried, but 0600 UTC on 11 May 2010 provided the most convincing trajectory for the Okinawa detection. The trajectory from Yongbyon does not pass close to Okinawa, first passing over ROK near Geojin before turning north and potentially passing over Ussuriysk. A detection at Geojin would have been made around the observed time, but its signature would have been of a prompt vent—the Xe-135/Xe-133 ratio would be higher and the Xe-133m activity would be higher than Xe-133—whereas no Xe-133m was detected at Geojin. Further, the Ussuriysk detections would have been significantly larger than observed.

For a delayed release, a forward trajectory starting at 1800 UTC on 12 May 2010 from NKTS passes very close to Geojin at the time of the respective detection. In this case, any origin time between about 6 hours earlier and 18 hours later could have produced a signal at Geojin at approximately the correct time. The trajectory from Yongbyon passes well north of Geojin a day or so later than the observed detection (Figure 1b). For an origin before 1800 UTC the

Yongbyon trajectory passes progressively closer to Geojin, whilst for an origin afterward it passes progressively further away. A significant observation supporting an NKTS-origin hypothesis is that the trajectories to both Okinawa and Geojin—and thus the air masses themselves—descend from the NKTS elevation to an altitude at which the plume could be detected by ground-based stations at approximately 100 m elevation above sea level.

Similarly, a backward trajectory from Okinawa passes over NKTS, in excellent agreement with prompt venting from a hypothesized explosion on 11 May 2010 at about 0600 UTC. Figure 2a shows the elevation behavior of the trajectory is also qualitatively correct. The trajectory also passes close to Yongbyon, but approximately 12 hours before the Ba-140/La-140-derived event time (though still within the error margin). For Geojin a satisfactory backward trajectory was also traced to NKTS for a 36 hour delayed release (Figure 2b). Once again the elevation behavior is qualitatively correct. In this case the trajectory does not pass near Yongbyon.

The analysis clearly suggests that North Korea provides a viable origin for the particulate and noble gas detections made at Okinawa and Geojin respectively, and that NKTS (or nearby) is the leading candidate within North Korea. The level of agreement between the atmospheric trajectory models and the radionuclide data—in both spatial and temporal co-ordinates—is quite remarkable, as is the fact that the only point at which the backward trajectories intersect is very near NKTS. That different meteorological data sets were used

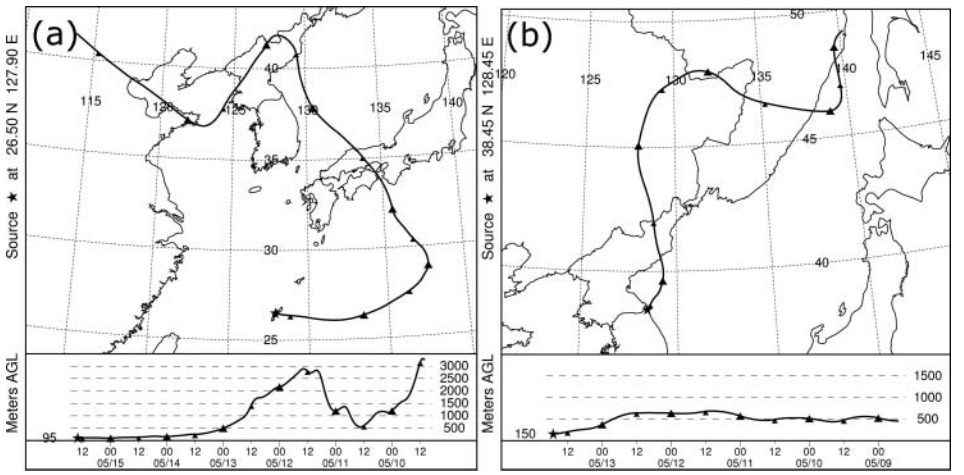

Figure 2: **(a)** Backward trajectory from Okinawa ending at 1400 UTC on 15 May 2010 (i.e., near the middle of the first collection period). The trajectory, using GDAS meteorological data, passes almost directly over NKTS at approximately the time of an explosion calculated by de Geer of 0600 UTC on 11 May 2010. **(b)** Backward trajectory from Geojin ending at 1700 UTC on 13 May 2010, the middle of the sampling period. The trajectory, using global re-analysis data, passes almost overhead of NKTS at a time close to the postulated 36 hour delayed release.

for forward and backward trajectories provides confidence in the robustness of the results, since in most cases ensembles of trajectories generated using global re-analysis and GDAS data were generally quite consistent.[16] Further, that different atmospheric transport codes—HYSPLIT in this work, Web-Grape in De Geer and FLEXPART in Wotawa—and three meteorological data sets provide consistent results gives even greater confidence.

The back trajectories from Okinawa and Geojin also serve to constrain other possible origins for the radionuclide emissions. For the Okinawa detections, small regions of eastern China, southern Russia, south-west Japan, and (less likely) South Korea present as possible origins. But in most cases the time at which trajectories pass over these regions is outside of De Geer's calculated fission event time, for example before in the case of China and later in the case of Japan. For the Geojin detections, Japan and South Korea appear to be ruled out, whilst the part of China that might be considered a possible source barely overlaps with that inferred from Okinawa back trajectories, and does not include any known nuclear facilities. From the ensemble of calculated back trajectories, the only location besides north-east North Korea that could be considered as a possible origin for both the Ba/La and Xe detections is the nearby Russian naval base at Bolshoi Kamen.

ATMOSPHERIC TRANSPORT MODELING FOR THE USSURIYSK AND TAKASAKI DETECTIONS

Given their significantly lower signals less emphasis was placed on the May 2010 Ussuriysk (Russia) and Takasaki (Japan) detections when assessing their relation to a possible nuclear test in North Korea. Even so, HYSPLIT modeling does show that Ussiriysk can probably be connected back to NKTS, whilst the same cannot be easily done for Takasaki.

Given the rarity of Ba-140 or La-140 detections by the CTBT radionuclide network the detection of La-140 at Ussuriysk is strong circumstantial evidence for a nuclear test origin.[17] Whilst De Geer only reports detection of La-140—noting that the expected Ba-140 activities, extrapolated from observed La-140, are less than the minimum detectable concentration—Wotawa notes that Ba-140 was also present in the Ussuriysk filters.[18]

Yet there are several potential problems with the Ussuriysk detections. Firstly, as seen in Figure 1, it is difficult to see how a prompt vent makes its way north, despite the relative proximity of Ussuriysk to NKTS. However, given the order of magnitude lower activities inferred at Ussuriysk than detected at Okinawa, this problem may be alleviated by postulating that it arises from a "sub-plume" which broke off the main southward travelling plume. There is evidence in the HYSPLIT modeling that this may indeed have occurred (Figure 3). Also, assuming that the noble gas equipment of the IMS

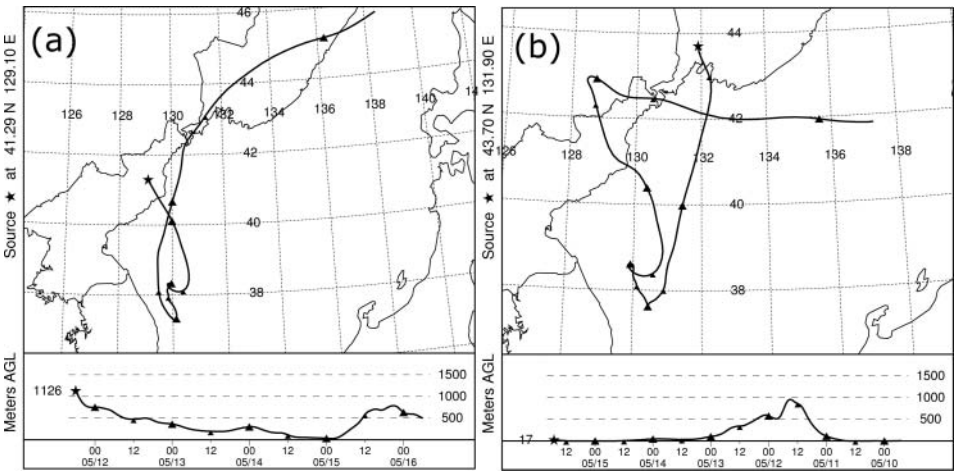

Figure 3: **(a)** Forward trajectory from NKTS beginning at 1800 UTC on 11 May 2010, within de Geer's fission event time window but 12 hours later than the best estimate. Note how the trajectory turns north on about 14 May 2010 and passes almost exactly over Ussuriysk at the time of the first detection of La-140 made there, i.e., between 0144 UTC on 15 May and 0144 UTC on 16 May 2010. If this is how the Ussuriysk detections occurred one would then have to postulate that some of the Ba/La, initially travelling south, got caught up for two days over the Sea of Japan off the east coast of the Korean Peninsula before being swept north again. There is evidence in Ussuriysk backward trajectories that this may be the case. **(b)** Backward trajectory from Ussuriysk ending at 1700 UTC on 15 May 2010, i.e., during the first sampling period. Note that between 11 and 12 May 2010—the approximate time of a prompt vent—the trajectory passes close to the suspected North Korean test site at approximately the correct elevation. It swirls around over the Sea of Japan between about 13 and 14 May before being swept north.

radionuclide station at Ussuriysk was operational at the time raises the question of why Xe was not detected. Perhaps part of the answer is that promptly vented Xe-135 would have gone through 10.5 half-lives, although this still leaves open the possibility of detecting Xe-133 and possibly also Xe-133m. More detailed calculations are needed to determine if the activities were above the minimum detectable concentration.

The 15–19 May Takasaki detections pose a different problem: the detection of Xe-135 on 18 May without a corresponding Xe-133 detection makes it hard to see how the signal could arise from a single source. The (uncorrected) Xe-135/Xe-133 ratio was $\geq 4 \pm 2$, about the same as the ratio at Geojin (possibly even larger) but detected 4–5 days later than Geojin. On the other hand the preceding three Takasaki samples had ratios of ≤ 0.13, ≤ 0.12, and ≤ 0.73. Assuming the same release source/origin, it is difficult to conceive of a scenario whereby an Xe-135/Xe-133 ratio could increase from one day to another, unless the later detection arose from an earlier release. But this would imply some complicated atmospheric transport.

Further, the Takasaki Xe-135/Xe-133 ratio on 18 May 2010 is inconsistent with a release from an explosion at any of the times nominated by De Geer.

For instance, at 48 hours—De Geer's postulated release time for the Takasaki detections—and assuming in-growth from iodine and other precursors, the initial Xe-135/Xe-133 ratio is about 1.4 for both HEU and plutonium (see Xenon activity and ratio calculations, below). For a regular plume it would be impossible for this ratio to increase between the source and receptor, and it would instead have had to arise from an earlier release when the initial ratio is much higher. But even the maximum possible explosive ratio—about 2500 from direct U-235 fission at ~1 hour after release—results in a ratio of about 0.01 a week later. It is therefore concluded that at least the 18 May 2010 detections at Takasaki did not originate from an explosion.

Also, several of the Takasaki Xe-133 detections, e.g., on 15–16 May and 18–19 May, were around 0.2 mBq/m^3, which several published reports suggest is about the "normal" background level at Takasaki and surrounding regions. For instance, Igarishi et al. suggest the Xe-133 background is $<$1 mBq/m^3 at Tsukuba, but with occasional excursions up to 10 mBq/m^3.[19] Takasaki is about 100 km north-west of Tsukuba and is expected to have a similar xenon background due to the prevailing winds on the Kanto Plain, on which they are both located.[20] More recently, Ringbom et al. give a mean Xe-133 activity of 0.22 mBq/m^3 from 1088 samples over a period of about 1.5 years during 2007 and 2008, with a 95th percentile of 0.58 mBq/m^3.[21] However, the maximum was 4.77 mBq/m^3 and detections $\geq$0.7 mBq/m^3 were relatively common, demonstrating that even the 16–18 May 2010 Xe-133 detections of 0.5–1.5 mBq/m^3 are not without precedent at Takasaki. The same data set demonstrates that the 18 May 2010 Xe-135 detection is also not statistically abnormal for Takasaki (Table 1).

Furthermore, Xe-131m was detected at Takasaki from 15–19 May 2010 in 4 of 8 samples, which is not commonly expected for nuclear explosions given its relatively low production. For instance, at any time up to at least 48 hours post-explosion, De Geer's favored release time for the Takasaki detections, the Xe-131m activity is a factor of at least 100, 1000 and 1000 less than that of Xe-133m, Xe-133 and Xe-135 for either U-235 or Pu-239. Yet one of these Xe-131m detections occurred in the same sample where Xe-135 was detected, but Xe-133 and Xe-133m were not. Also, the respective ratios are outside of the nuclear explosion regime.[22] Ringbom et al. also show that detection of Xe-131m at Takasaki is not uncommon, with mean, maximum, and 95th percentile of 0.02 mBq/m^3, 0.25 mBq/m^3 and 0.09 mBq/m^3 respectively, encompassing the values reported after the postulated nuclear test.[23]

Takasaki also was the only site where no backward trajectory was found that passed over North Korean territory. Much of the plume passed over Japan, including several days spent circulating over the Kanto Plain or its vicinity. A forward trajectory from NKTS starting at 0600 UTC 13 May 2010—48 hours after the postulated explosion, as inferred by De Geer—doesn't pass over Takasaki, unlike the forward trajectory calculations for Okinawa and Geojin.

Table 1: Xenon-133 and -135 background data for CTBT IMS stations in the vicinity of, or on, the Korean Peninsula. The mean Xe-133 activity at Geojin is taken from media reports describing the 14 May detection as "eight times higher than normal." Values of 0.00 indicate activities below the minimum detectable concentration, typically about 0.2 mBq/m^3 for Xe-133 and up to 3–4 times higher for Xe-135. For Kansong the data do not include the detections positively identified with the 9 October 2006 nuclear test, for which the Xe-133 activities were between 1.5 and 7.2 mBq/m^3.

Station, # samples	Xenon-133 Mean	Xenon-133 95th percentile	Xenon-133 Maximum	Xenon-135 Mean	Xenon-135 95th percentile	Xenon-135 Maximum	135/133 Mean
Geojin, ROK, 3 years	~0.3	—	2.45	—	—	10.01	≤0.55
Kansong, ROK, 82	0.24	—	0.90	0.00	—	—	—
Takasaki, JPX38, 1088	0.22	0.58	4.77	0.00	0.33	0.56	—
Beijing, CNX20, 144	0.15	0.51	1.08	0.00	0.00	0.46	—
Guangzhou, CNX22, 689	0.29	0.85	17.02	0.03	0.28	0.95	—
UlaanBaator, MNX45, 30	0.09	0.56	0.56	0.00	0.00	0.00	—

It is concluded from xenon activity and ratio considerations, as well as atmospheric transport modeling, that most or even all of the Takasaki detections are unlikely to have resulted from a nuclear explosion at NKTS.

Possible Origins for the Radionuclide Release Other than North Korea

Having demonstrated that NKTS provides a good option for the origin of the Okinawa, Geojin, and Ussuriysk detections, it remains to examine other possible options outside North Korea. This assessment includes possible non-explosive sources since most nearby countries are non-weapon states and North Korea is the only country in the region with a recently active nuclear testing program.

There have now been several studies comparing theoretical and observed xenon ratios for different applications of nuclear fission, such as power generation, medical isotope production, and explosions.[24] With only two detected isotopes and one well-established ratio it is impossible to unambiguously ascribe the Geojin xenon data to an explosion scenario. Such an explanation is however quite attractive given the detected activity levels are well above the normal background, not only for Geojin but also nearby IMS stations to the west and east.

Table 1 shows pertinent xenon background data for the CTBT IMS stations that effectively encircle the Korean Peninsula, as well as the two ROK national sites. The data are taken from various sources.[25] The sample numbers are non-ideal for Beijing and Ulaan Batoor, equating to only a few months or less of data, and equivalent numbers for the Ussuriysk RUX58 station would be highly desirable. But even despite these limitations the clear conclusion is that the May 2010 Geojin detections are unique from both local and regional perspectives. This suggests that whatever produced the detections reflects an exceptional event in that part of the world, despite the presence of so many nuclear fuel cycle facilities.

Further, the global set of xenon data from the International Noble Gas Experiment (INGE) reported in Kalinowski et al. suggests that the Geojin detections and upper limits are outliers.[26] For instance, the Xe-135/Xe-133 logarithmic mean is 0.05, compared to the observed Geojin ratio of around 4.1. Also, ratio upper limits with the two undetected isomers tend to enhance their outlier status, in the sense of taking them further away from the main group.

Emissions from Medical Isotope Production Facilities

The region around the Korean Peninsula does not host any large-scale—by world standards—medical isotope production facilities (MIPFs), where low-enriched uraium (LEU) or high-enriched uranium (HEU) targets are

irradiated for several days and subsequently dissolved in acid to extract Mo-99. Such facilities are instead located in Canada, South Africa, Belgium, and The Netherlands, which together account for about 96 percent of world Mo-99 production.[27] However, the HANARO 30 MWt reactor and an associated MIPF are located close to Geojin (i.e., Daejon in South Korea), and it may be presumed that other such facilities exist in China and Japan.

During the LEU or HEU target irradiation, the Xe-135/Xe-133 ratio decreases from 10–100 in the first few hours and falls to less than 2–3 shortly after the end of the irradiation. The ranges represent different irradiation conditions, such as neutron flux, target enrichment, and irradiation time. A day or two of cooling before dissolution further decreases the ratio.[28] Any release of sufficient activity to register at a remote noble gas detector will probably occur post-dissolution. The maximum expected Xe-135/Xe-133 ratio is therefore already below the as-observed ratio at Geojin.

Recent studies focused on detecting xenon emitted from the waste stacks of MIPFs, as well as at distances between a few kilometers and several hundred kilometers typically show very low Xe-135/Xe-133 ratios compared to the Geojin signal. For example, in three samples from November 2008 Tinker et al. observed Xe-135/Xe-133 ratios ranging from 0.004 to 0.072 at the stack of the ANSTO radiopharmaceutical facility in Sydney, and ten samples measured in Melbourne—approximately 500 km away—over the following months had a maximum Xe-135/Xe-133 ratio of 0.16 and a maximum Xe-135 activity of 0.33 ± 0.15 mBq/m^3.[29] Seven of the 10 measurements were upper limits. Similar findings are reported by Saey et al. for the Nuclear Technology Products Radioisotopes (Pty) MIPF in Pelindaba, South Africa and the Institut des Radioelements MIPF in Fleurus, Belgium.[30] This suggests it is highly unlikely that a single release from an MIPF could be responsible for the Geojin data.

NUCLEAR REACTOR EMISSIONS

Whilst the Geojin Xe-135/Xe-133 ratio and individual activities are regionally unique and globally atypical, they are not necessarily globally unique. Nuclear reactors operating out of equilibrium, such as during start-up and shutdown, produce Xe-135/Xe-133 ratios larger than 1. Kalinowski and Pistner find a ratio of around 65 after the first hour of the first cycle for a light water reactor (LWR) with fuel enriched to 3.2–4.5 percent and that this ratio steadily decreases to an equilibrium value of about 0.25 after a month or two.[31] Calculations made for the present study are broadly consistent with this picture, although they indicate that it takes ~2.25 hours to reach a ratio of 65 (see section on Xenon activity and ratio calculations). Reported reactor releases show a maximum Xe-135/Xe-133 ratio of about 70, consistent with expectation.[32]

The variation of the isotope ratio with time after release can be used to place a reasonable constraint on the maximum distance between the release

and detection sites. With respective individual half-lives of 9.14 hours and 5.24 days for Xe-135 and Xe-133 the ratio half life is 9.855 hours. It would thus take approximately 40.5 hours for an initial ratio of 70 to decrease to about 4.1 (in-growth from Xe-133m into Xe-133 and Xe-135m into Xe-135 causes a small perturbation, increasing the time to ~41 hours). At an average wind velocity of 20 km/h the plume would travel ≥800 km. A conservative estimate would only consider nuclear reactors within a radius of about 1200 km of each of Geojin and Okinawa. Reactor sites in Japan, South Korea, mainland China, Taiwan, and Russia are considered below.

Japan can almost certainly be ruled out as the origin for the Geojin xenon detections given that the prevailing winds in that part of the world almost always run west-to-east. A powerful demonstration of this is that after the Fukushima accident the first detection in South Korea was made on 28 March 2011. So most of the radioactivity detected in ROK had travelled around the globe instead of being transported directly across the Sea of Japan.[33] Even so, given the potential significance of a covert North Korean nuclear test it is prudent to test for a Japan origin around the time of the detections.

One candidate source in Japan for the radionuclide release was the start up of Japan's Monju fast reactor on 6 May 2010, with criticality achieved on 8 May.[34] Although the reactor was only operating at zero power, several different types of alarms sounded over the following days, including from oxygen meters, sodium leak detectors, radiation detectors, and temperature sensors. According to the operators they were all false alarms due to problems with the respective measurement apparatus. It seems unlikely that the reactor suffered any problem that would have caused a significant (or even any) radioactive release.

However, the timing is "suspicious" and so Figure 4a shows forward trajectories from Monju, beginning at 0000 UTC on 7 May 2010 and repeating every 12 hours for several days afterward. One trajectory does pass over Okinawa, but it begins much earlier than the fission event time window—including error bounds—determined by De Geer from the Ba/La-140 Okinawa data. Since the Korean Peninsula is never reached, the Geojin detector could not have picked up any signal.

Figure 4b shows forward trajectories from six other sites in Japan with multiple nuclear reactors, beginning at 0600 UTC on 11 May 2010, the nominal fission event time calculated by De Geer. Trajectories originating at 0000 UTC on 10 May 2010 until 1200 UTC on 14 May 2010, encompassing the fission event time error bounds, show very similar behavior. Plumes do appear to pass over Okinawa at about the time of the first detections, but again the Korean Peninsula is not reached.

A second possible set of sources is in South Korea. Trajectories calculated for the time period from 0000 UTC on 10 May to 0000 UTC on 12 May 2010—encompassing the fission event time and its error bounds—from South

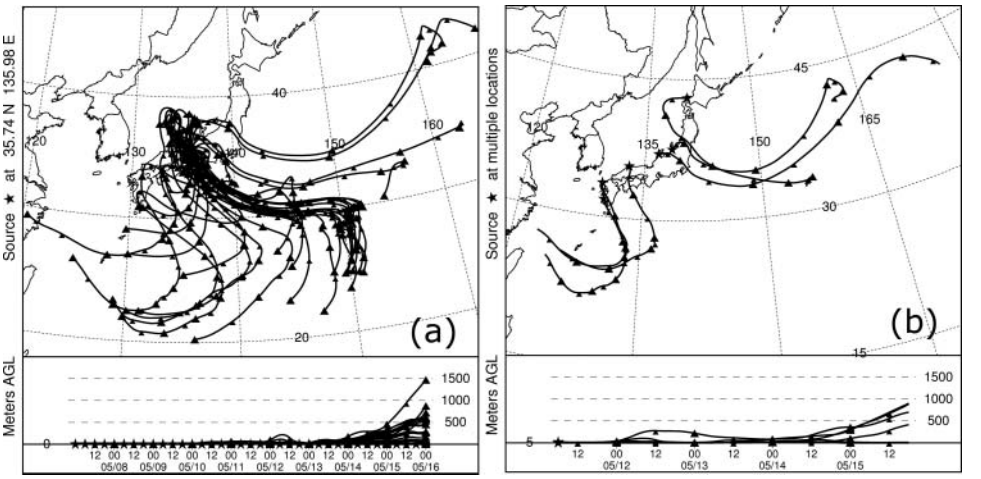

Figure 4: **(a)** Forward trajectories from the Monju fast reactor in Japan, beginning at 0000 UTC on 07 May 2010 and repeating every six hours from 100 m ASL. **(b)** Forward trajectories from six sites in Japan with multiple nuclear reactors—Tomari, Kashiwazaki, Shika, Shimane, Genkai, and Sendai—beginning at 0600 UTC on 11 May 2010 from 100 m ASL. These use global re-analysis data. That these reactor complexes essentially span the length and breadth of Japan suggests that trajectories from the several other power reactor complexes within Japan would show similar behavior.

Korea's Yeonggwang, Kori, Wolseong, or Uljin nuclear reactor complexes pass over Okinawa a few days later. But as shown in Figure 5a they are always approximately a day earlier than suggested by the Ba-140 and La-140 detections. Figure 5b shows that a trajectory from Uljin on 12–13 May passes near or over Geojin, but somewhat later than the xenon detections. Uljin is on the east coast of South Korea and is the closest power reactor complex to Geojin, with six 1000 MWe Pressurized Water Reactors (PWR). The 30 MWt research reactor HANARO, and associated radio-isotope production facility, do not present as a possible origin for the xenon detections.

The Chinese power reactor complexes at Tianwan and Qinshan are close enough to Geojin and Okinawa to be considered as possible origins.[35] Also, the 65 MWt China Advanced Research Reactor (CARR) in Beijing reportedly achieved criticality on 13 May 2010.[36] Whilst this post-dates De Geer's fission event time it is sufficiently close to consider it as a possibility, since the process to bring the reactor to criticality would likely have started several days beforehand. However, in all three cases the trajectories calculated for the fission event time window from De Geer either do not pass near Geojin or Okinawa, are several days removed from the observations, and/or at an elevation that would effectively render them undetectable. For instance, out of the hundreds of trajectories calculated only one (from Beijing) passes near both Geojin and Okinawa. But it begins at the earliest limit of De Geer's window and arrives at Geojin two days before the actual detection.

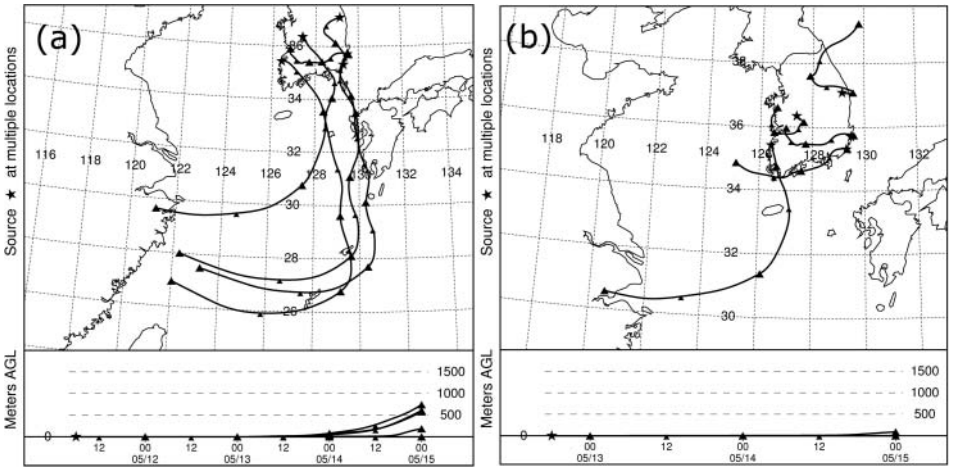

Figure 5: **(a)** Forward trajectory from all four ROK nuclear reactor complexes as well as the HANARO research reactor, beginning at 0600 UTC on 11 May 2010 at an elevation of 100 m ASL. No trajectory starting within De Geer's fission event time window passes near Geojin. From any of three reactor complexes the trajectory passes directly overhead of Okinawa, about a day earlier than observed. No trajectory passes near Geojin. **(b)** Forward trajectory from all four ROK nuclear reactor complexes as well as the HANARO research reactor, beginning at 1800 UTC on 12 May 2010 at an elevation of 100 m ASL. From the Uljin complex on the east coast the trajectory passes close to Geojin, though later than observed. The trajectory from HANARO and its medical isotope production facility does not pass over Geojin. These use global re-analysis data.

Another possible origin in China was the naval base near Dalian, where a nuclear-powered submarine was rumored to have experienced a radiation leak in late July 2011.[37] Starting between about 1200 UTC on 8 May to 1200 UTC on 9 May 2010 it is possible to generate a trajectory that passes near or directly over Geojin. However, for GDAS data the starting time is constrained to within a few hours of 1800 UTC on 8 May, and the arrival time is at least two days earlier than the actual xenon detection, with the trajectory at close to 1500 m elevation. For the global re-analysis data, there is more flexibility in when the trajectory begins, but it could be a day early or a day late depending on its precise starting time. For those trajectories where the signal could be detected on time, the plume is 4 days old and thus the Xe-135 would have passed through about 10 half-lives. It is also difficult to see how detections would occur at Okinawa, since trajectories beginning within the fission event time window approach no closer than about 500 km and arrive either early or late compared to the observations.

Power reactor complexes in Taiwan at Chinshan, Kuosheng, and Maanshan were tested as possible origins. In all cases trajectories calculated for the fission event time window and two days prior do not intersect with the Korean Peninsula, whilst the few trajectories that pass near Okinawa are typically several days removed from the observations and/or have ascended to an elevation well above the IMS station.

The final possibility considered was the Russian naval base at Bolshoi Kamen near Vladivostok, where nuclear-powered submarines are reportedly either based or being decommissioned. Given the relative proximity of Bolshoi Kamen to NKTS, and the success of the trajectory models for NKTS, it is probably the most suitable of all alternative locations based purely on meteorological considerations.

Trajectories from Bolshoi Kamen beginning early on 10 May initially travel west, before then turning south, but do not pass closer than about 200 km to Geojin, by which time the plume is at least 3 days old, or eight Xe-135 half-lives. Also, the few trajectories that initially travel inland would possibly have caused a larger signal at the nearby (about 100 km) Ussuriysk IMS station than was detected. From 11–14 May the trajectories head out over the Sea of Japan, and then over Japan itself, relatively close to Takasaki which should probably have picked up a stronger signal than it did. Some of these trajectories loop around and pass over or near Okinawa, but much later than the initial detection there. Thus, a submarine reactor release at Bolshoi Kamen remains possible, but unlikely.

The analysis presented in this section leads to a conclusion that a radioactive leak (or leaks) from a nuclear reactor or a medical isotope production facility is unlikely to be responsible for the Okinawa Ba/La and Geojin xenon detections. This follows not only from the model trajectory results, but also from the highly unusual nature of the detections compared to historical data. This conclusion is especially true if it is assumed that the Okinawa and Geojin detections ultimately originate from the same source location, even if separated in time. Potential non-NKTS solutions are somewhat contrived. Only one power reactor complex, Uljin in ROK, and one propulsion reactor complex, Bolshoi Kamen near Validivostok, could feasibly (though barely so) be the source of both sets of detections based on the meteorological trajectories. But this would necessitate multiple leaks (or a long-lasting leak) over a few days, perhaps suggestive of a problem with one of the reactors.

Further, as noted by De Geer, radioactive particulate species, such as iodines, would be expected to accompany the Okinawa (and Ussuriysk) Ba/La-140 detections if a reactor fuel leak was responsible. It is also unlikely that only noble gases like Xe-140 leaked, since this would presumably also occur at other reactors around the world and make Ba-140 and La-140 much more commonly detected species amongst IMS particulate stations. Also, as the few examples cited above testify, reactor leaks are difficult events to keep secret for long.

Xenon Activity and Ratio Calculations

To determine possible source release terms, xenon and daughter activities have been calculated both for Pu-239 and U-235 as candidate fissile materials,

and for both fast and thermal neutron induced fission. For fast fission the concentrations were calculated for a single, instantaneous event populating each species, i.e., an explosion, and then accounting for radioactive decay and ingrowth using the Bateman equations. A maximum explosive yield of 200 tons was assumed as it would probably be consistent with the "fusion" statement by North Korea.[38] All the isotope ratios are yield independent however, since the activities scale linearly at least approximately for the same neutron energy spectrum. For thermal neutrons the concentrations were calculated in the presence of a continuing neutron flux, i.e., representing a nuclear reactor, and then accounting for both radioactive decay/in-growth and thermal neutron capture populating and de-populating selected species. Standard equations for multi-member chains were used.[39]

Fission product chains and nuclear data (e.g., half-lives, fission product yields, branching ratios, neutron capture cross sections) were obtained from various sources.[40] Most fission product yield libraries are for mono-energetic neutrons, a simplification of the real situation. Also, some libraries quote fast fission yields at 400 keV, whilst others use 500 keV. So for consistency and unless otherwise noted, all the calculations presented here use the fission product yields from the Lawrence Berkeley National Laboratory (LBNL) Isotopes Project, whose heritage lies in England and Rider[41] and which are based on Evaluated Nuclear Data File (ENDF) B-VI yields.[42]

Radioactive decay chains were begun at Sn-131 for Xe-131m, Sb-133 for Xe-133m and Xe-133, and Te-135 for Xe-135m and Xe-135. In all cases the precursor half-life is less than 2 seconds, so that cumulative fission is assumed to occur into the first chain member and direct fission into the others. Since the Okinawa Cs-137 and Ba/La-140 detections are postulated to arise from a prompt, or at least very rapid, vent their chains are begun in the first possible fission product member for that mass number (Sb-137 and Te-140, with half-lives of 0.478 s and 0.894 s respectively). Direct or independent fission is thus considered for all chain members.

The total xenon concentration was obtained from the addition of all possible paths into the relevant isotope, being 11 for Xe-131m, 8 for Xe-133m, 16 for Xe-133, 3 for Xe-135m, 6 for Xe-135, 4 for Xe-137 and 3 for Xe-140. In the cases of Xe-137 and Xe-140 for nuclear reactor operation, β-delayed neutron emission from mass 138 and 141 chain members was also included, necessitating two and one additional paths respectively (although the total Xe-137 and Xe-140 concentrations changed very little with the inclusion of these additional paths).

Mass 137 and 140: The Okinawa Detections

From the detected concentrations in Table 1 of De Geer the Okinawa Ba-140/Cs-137 activity ratio is about 182 and 145 in the first and fifth samples,

which have the highest activities and best signal-to-noise ratio. The only other sample, on the second day, has a ratio of around 95±45, or alternatively maxima and minima of 166 and 62 using the error bounds on the individual activities. Backdated to the fission event time the initial ratio would be around 230. Assuming that all the Xe-140 and Xe-137 decayed into their Ba-140 and Cs-137 daughters, with no subsequent fractionation, then for direct fission into the two xenon isotopes the calculated Ba-140/Cs-137 ratios are 634 for U-235 and 383 for Pu-239. The "no fractionation" assumption should be fairly safe since the xenon half-lives are so short (as is the intermediate Cs-140 half-life) and so there is little time for fractionation to occur. For cumulative fission into Xe-140 and Xe-137 the corresponding ratios are 388 and 256 from U-235 and Pu-239 respectively.

The observed ratio of a few hundred is consistent with an explosive origin. Assuming that similar fractions of Xe-137 and Xe-140 escape the cavity and make it into the plume, then the fact that the observed ratio is closest to that of Pu-239 may suggest plutonium as the chain-reacting material. However this is not necessarily the case. The actual release may not have been prompt in the true sense of the word, but may instead have been delayed by anywhere between a few seconds to a few tens of seconds. Several events in the U.S. historical test program had such short delays before venting.[43] Given the short half-lives even a short delay will alter the xenon isotopic ratio, providing time for precursor in-growth. For instance, the I-137 precursor half-life is 24.5 seconds compared to 0.86 seconds for I-140.

Explosion calculations of Xe-137 and Xe-140 show that, for U-235 at ~17 seconds after the explosion, the daughter Ba-140/Cs-137 ratio reaches around 230. Figure 6 shows the evolution of the resultant Ba-140/Cs-137 ratio for a gas released after this time compared with the Okinawa ratios. Quite good agreement is obtained, reinforcing De Geer's observation that the Ba and Cs probably have the same origin. This assumes that the only physics affecting the Ba-140/Cs-137 ratio between the source and receptor is radioactive decay, i.e., there is no preferential enrichment/depletion of either isotope on their particle hosts during the days-long travel. For Pu-239 the corresponding release time is ~ 9 seconds. In both cases the total Ba-140 activity is only a factor ~2 less than for direct fission.

A delay in the release of 10–15 seconds after production in the fission explosion event is reasonable given the non-detection of Ce-141 noted by De Geer, for which the Xe-141 precursor half-life is only 1.7 seconds. Further, the delay cannot have been much more than a few tens of seconds as the 13.6 s half-life Xe-140 would then have almost completely decayed to its daughters which would then be trapped in the cavity. A similar methodology was used by Persson to infer a time lapse between explosion and debris release of less than 1 minute for an underground test at Semipalatinsk on 18 December 1966.[44] For

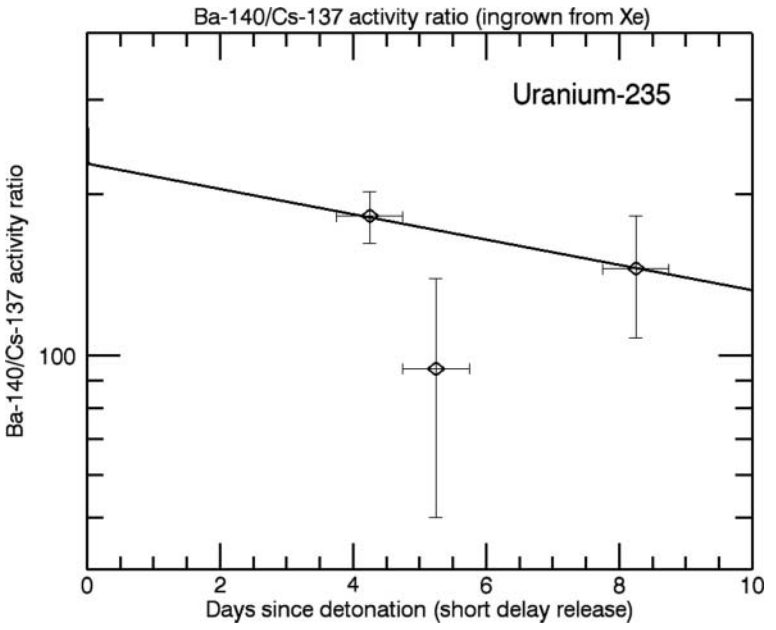

Figure 6: A plot of the barium-140/cesium-137 activity ratio for a vent occurring at 17.3 seconds after the explosion, using uranium-235 as the fissile material and the ENDF/B-VI fission product yield library. The released noble gas isotopes xenon-137 and xenon-140 rapidly decay into their daughters cesium-137 and barium-140 (via cesium-140) which then condense onto particulates and eventually fall out over Okinawa. A similar plot is obtained for Plutonium-239, but the release then occurs at 8.9 seconds to maintain consistency with the Okinawa ratios. The horizontal bars represent the 24 hour sampling period. The second sample ratio can be made consistent with the model by a slight delay of the vent by a further 3 or so seconds, and/or assuming the ratio uncertainty is better represented using the error bounds on the individual activities.

this event the debris was also enriched in Ba/La-140 and Cs-137, just like the present case, as well as Sr-89 and Sr-90.

An alternative scenario that might alter the direct fission isotopic ratios is fractionation during or shortly after the gas-to-particulate condensation process. For example, if the vent really was prompt then the factor of $\sim$17 difference in the Xe-137 and Xe-140 half-lives may result in a variable "conversion" from gas to particulate for the mass 137 and 140 chains. If for instance the relatively short half-lives in the mass 140 chain meant that this chain became depleted in the particulate matter then this could also account for a corresponding (and perhaps even larger) depletion in the mass 141 chain—with its even shorter half-lives—and explain the non-detection of Ce-141 in the Okinawa signal. Perhaps such depletion could result from a rapid wash-out of the particulates soon after the vent, which would have a proportionally larger effect on the mass 140 and 141 chains due to the Cs-140 and Cs-141 intermediaries between Xe and Ba-140 and Ce-141. However, these meteorological-induced

fractionation effects would need to act on very short time scales, i.e., minutes, which seems unlikely. There is insufficient data to discriminate between the ratio-changing scenarios of "rapid-but-delayed vent with precursor in-growth" versus "prompt vent with subsequent fractionation."

Reactor Release

Reactor calculations show that the xenon parents of Cs-137 and Ba-140 could not have been emitted by a reactor operating in equilibrium, for which the Xe-140/Xe-137 ratio is about 0.60, and the Ba-140/Cs-137 daughter ratio is ~30 (Figure 7). Light water reactor core-averaged parameters used were a macroscopic fission cross section of 0.25 cm^{-1}, neutron flux of 2.5×10^{13} cm^{-2} s^{-1} and fuel volume of 1.1×10^7 cm^3 (note, not the core volume). These are appropriate for either a pressurized or boiling water reactor (PWR and BWR respectively) of around 1000 MWe, the most common types in the region. Equivalent properties for a propulsion reactor were 10 cm^{-1}, 10^{13} $cm^{-2}s^{-1}$ and 3.4×10^4 cm^{-3}, appropriate for a 135 MWt Russian KLT-40 model.[45] The equilibrium ratio is achieved after only about 30 minutes of operation, due to the short half-lives of the xenon isotopes.

The reactor ratios very shortly after start-up are similar to the explosion ratios. However, plausibility arguments may exclude reactor start-up as a source of Xe-137 and Xe-140, and thus the Okinawa Cs-137 and Ba/La-140 detections. For instance, to obtain a similar quality fit to the Okinawa Ba-140/Cs-137 ratio data as in Figure 6 would require a reactor release to occur about one minute after start-up. At this point the total Xe activities from the LWR or propulsion reactor are one and two orders of magnitude respectively lower than for the 200 ton explosion case. So for a reactor situated relatively near NKTS, such as an LWR at Uljin in ROK or a propulsion reactor at Bolshoi Kamen in Russia, the xenon source term would have to be a significant fraction, of the order of a few to a few tens of percent, of the entire reactor inventory (see following section on plume concentrations). This is probably too high for a "non-accident" scenario, and at least for the propulsion reactor such a high release fraction for noble gases would probably mean that other species, such as iodines, would also have been emitted and subsequently detected. Admittedly the reactor start-up model considered is fairly simple, in the sense that reactors are not instantly brought up to full power but rather full neutron flux is achieved over a period of several days. Thus the time dependency of the Xe-140/Xe-137 ratio and absolute activities are more complicated than presented here. But it is not immediately clear that a more advanced model would help, since the initial xenon activities would be even lower.

Mass 133 and 135: The Geojin Detections

The Geojin Xe-133 and Xe-135 detections, and their ratio, are consistent with an explosive origin, as will be seen in following sections. Also, just like

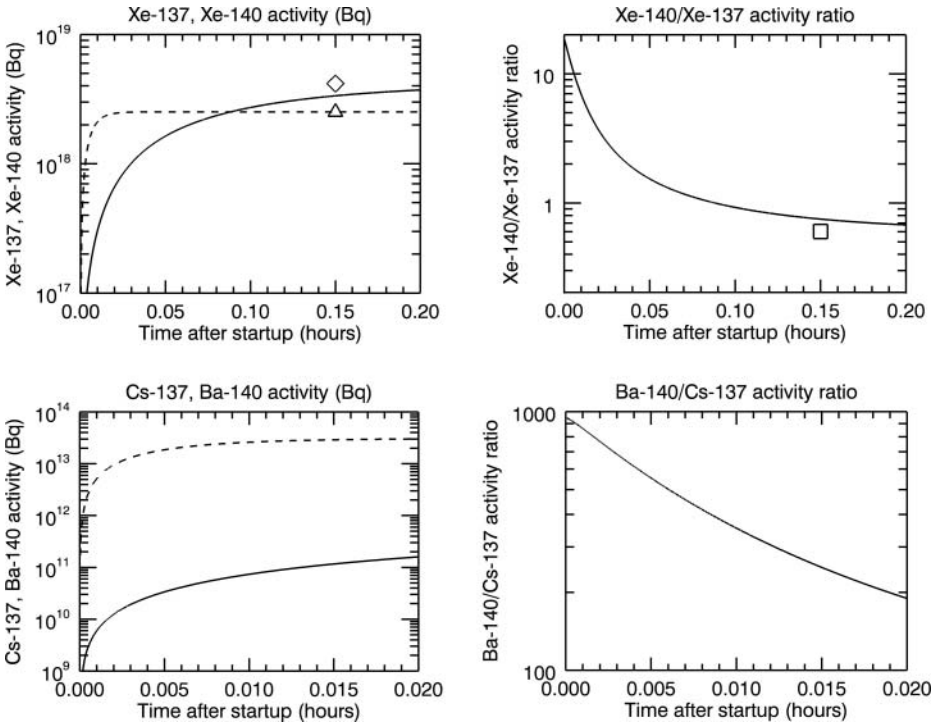

Figure 7: LWR calculations of xenon-137 (solid line) and xenon-140 (dashed line) total activities and their ratio, plus subsequent daughters cesium-137 and barium-140, for 72 seconds after reactor start-up. Open symbols represent equilibrium values. Importantly, the cesium-137 and barium-140 activities are only those resulting from decay of their xenon parents. Thus, whilst the xenon-140/xenon-137 ratio depicted here should be a good representation of that within the reactor fuel, the same is not true for the barium-140/cesium-137 ratio. The latter instead approximates the instantaneous ratio after the xenon noble gas isotopes have been released from the fuel matrix. The fission product yield library used was ENDF/B-VI.

the Okinawa Ba/La-140 and Cs-137 detections, the Geojin data cannot be attributed to a thermal reactor operating in equilibrium. The LWR Xe-135/Xe-133 equilibrium ratio is about 0.22, achieved after around 500 hours of operation, compared to the observed Geojin ratio of around 4.1 (Figure 8). This had already been noted by De Geer.

Again, however, the reactor ratio shortly after start-up is similar to that for an explosion. The release would probably have to occur within approximately the first 1–25 hours of operation, in order to be consistent with the ratios observed at Geojin. Figure 8 shows that after 25 hours the Xe-135/Xe-133 ratio drops below 5, whilst the Geojin observed ratio is around 4.1. Figure 8 also shows that before 1 hour the Xe-133m/Xe-133 ratio is $\geq$0.2. This would probably make Xe-133m detectable for the Geojin Xe-133 observed activity of 2.45 mBq/cm^3, given their relatively similar half-lives and assuming only a

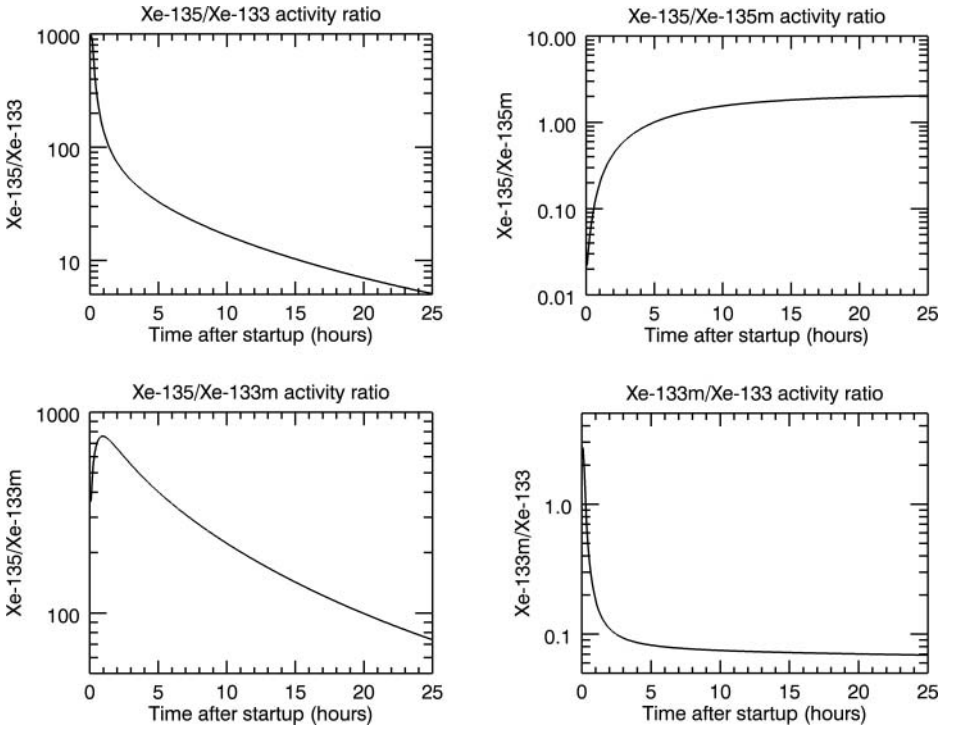

Figure 8: LWR calculations of various xenon ratios during the first 25 hours of operation. The fission product yield library used was ENDF/B-VI.

few days lapse between release and detection. These constraints are different from that of the Xe-140/Xe-137 case described above, which would thus make a single reactor release scenario inconsistent with the data (though as already noted the calculations are relatively simplistic compared to actual reactor start-up procedures).

PLUME CONCENTRATIONS

The preceding analysis of simple forward and backward trajectories—plus the difficulty in finding viable reactor release locations or scenarios—provides strong *prima facie* evidence for a nuclear test conducted at or near NKTS at about 0600 UTC on 11 May 2010. A nearly prompt vent of noble gases would have resulted in the daughter products Ba-140, La-140 and Cs-137 being detected at Okinawa, and probably also Ba-140 and La-140 signals at Ussuriysk. A second release of noble gases occurring some 36 hours later would lead to the Xe-135 and Xe-133 detections at Geojin. Whilst two separate reactor releases—either from the same reactor at two different times or two completely

different reactors—cannot yet be completely ruled out, such a scenario has several serious plausibility problems associated with it.

However, being merely an estimate of the centerline of an advected air mass undergoing both horizontal and vertical dispersion, the use of a single trajectory to infer a direct link between a source and receptor is problematic. Thus, whilst providing useful qualitative information on the path taken by an air mass, more complex atmospheric dispersion models are necessary to provide quantitative information. In the next section xenon activity calculations are combined with HYSPLIT plume concentration models to constrain the source term and consequent noble gas release fractions. These are used to assess consistency with the detected radionuclide activities.

Barium-140

Figure 9 shows a plume calculation for the Okinawa detection of Ba-140. The plume begins at NKTS at the nominal explosion time of 0600 UTC on 11 May 2010, with an activity release rate of 3.6×10^{13} Bq/hr of Ba-140 over an interval of 1 minute (to give a released activity of 6.0×10^{11} Bq).[46] Such a short release interval is dictated by the necessity to maintain consistency with the observed activity ratio (as well as the activities themselves), which rapidly decrease in the first minute after the explosion. At ~17 seconds post-explosion for U-235 and ~9 seconds for Pu-239—times which best match the observed Ba-140/Cs-137 activity ratio—the Ba-140 daughter product activity is around 2×10^{14} Bq. Therefore, the fractional release is only about 0.3 percent, consistent with what might be expected.[47] Averaged over a 24 hour interval from 0–300 m above sea level, this reproduces reasonably well the magnitude of the observed Ba-140 activity at the correct time.

The model plume remains detectable over Okinawa (above 5 μBq/m^3) for 4 days with dry deposition of the particulates, but only about 2 days with the inclusion of wet deposition. Turning deposition off completely, i.e., considering the plume as gaseous rather than particulate, maintains a concentration of $\geq$10 μBq/m^3 for a few days longer. A factor of 3 smaller release fraction is also appropriate in this case. The first few days of the model plume reasonably reflects the initial observations, namely the abruptness of the first detection going from 0 to around 100 μBq/m^3, and then dropping to a few tens of μBq/m^3 the next day. Thereafter the concentration steadily decreases to undetectable levels, at odds with the data which instead plateaus at 20–30 μBq/m^3 for 3 days, before rising again to 40–50 μBq/m^3 for 2 days and then rapidly decreasing to around 5 μBq/m^3 the following 2 days.

Thus, the 8 day longevity of the plume, and especially the second increase on the fifth day, cannot be reproduced with the fairly simple plume models attempted here. Backward trajectories from Okinawa may provide a clue to the solution of this dilemma. Such trajectories, calculated over the course of

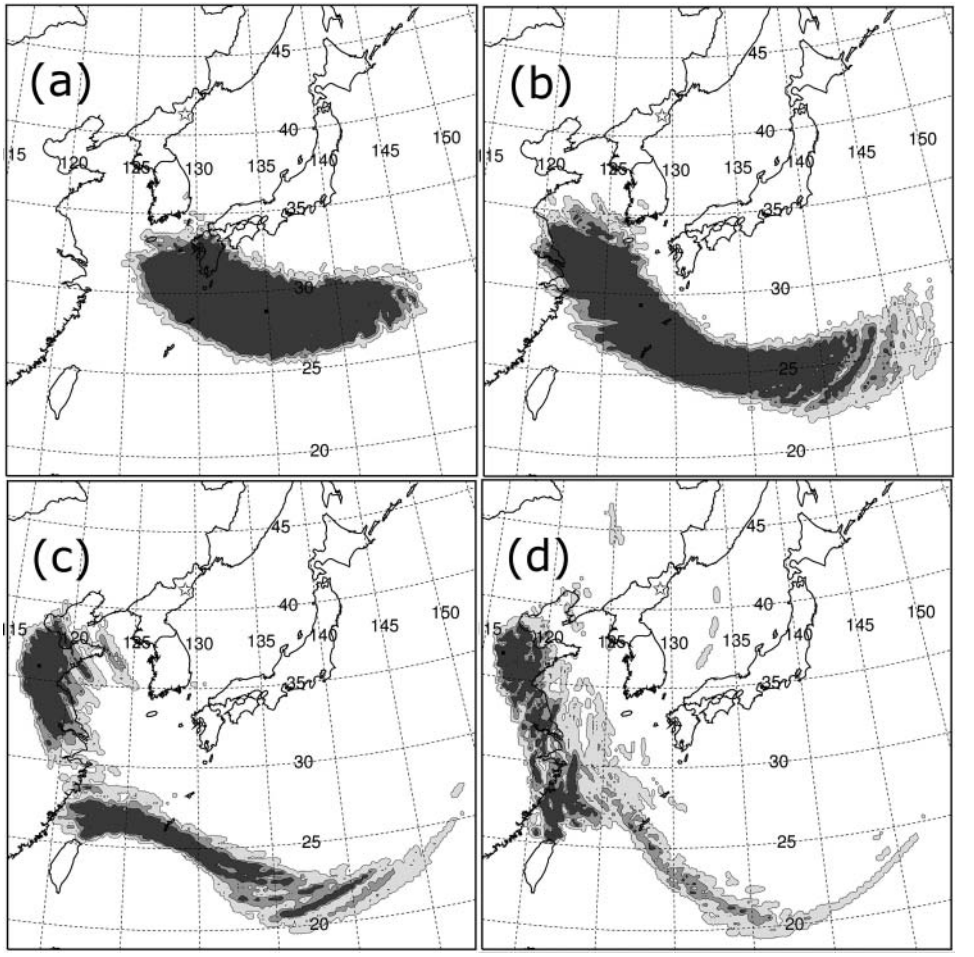

Figure 9: Plume calculation for barium-140 (daughter of promptly vented xenon-140) beginning at 0600 UTC 11 May 2010 at an elevation of 1500 m ASL, appropriate for the North Korean test site and global re-analysis meteorological data. Integration times are **(a)** 0000 UTC 14 May–0000 UTC 15 May, **(b)** 0000 UTC 15 May–0000 UTC 16 May, the first detection sample, **(c)** 0000 UTC 16 May–0000 UTC 17 May, **(d)** 0000 UTC 17 May–0000 UTC 18 May. The shaded contour levels represent concentrations >100 μBq/m^3, between 50 and 100 μBq/m^3 and between 5 and 50 μBq/m^3. This last contour remains over Okinawa for the next 24 hours as well. The predicted activity at Okinawa is around 100 μBq/m^3, consistent with the observed value of 81.9 μBq/m^3 in the relevant time frame. The model includes only dry deposition, using spherical particles with diameter $= 1.0$ μm and density $= 1.0$ g/cm^3.

the 8 days the plume was detected, show peaks and troughs in terms of their sensitivity to the region around NKTS. In other words, from 15–16 May the trajectory passes directly over or near NKTS at the nominal explosion time of De Geer, then moves away for the next 3 days, then returns to near NKTS between 19–20 May again at the explosion time, then back away again. This qualitatively reflects the observed plume behavior.

Plumes were also calculated for several reactor complexes in ROK and Japan. A release interval of 1 minute was again chosen, for the same reason as cited above for the explosion case. As expected from the trajectories seen in Figure 5, plumes from the four power reactor complexes in ROK, as well as Hanaro, arrive around 24 hours too early. This is regardless of whether the release starts at De Geer's best estimate within his fission event time window, or the error bounds of the window.

In the case of Japan, for start times of 0600 UTC on 11 May 2010, either no plume passes directly over Okinawa at the correct time, or only the edge of the plume skirts over or near Okinawa and then passes by without remaining overhead for the week or so evident in the actual data. Similar behavior is seen for other start times within the fission event time window, as well as instances where the model plume arrives a day or so later than observed and with a profile that would suggest a more gradual increase in the Ba-140 concentration (e.g., the Shimane complex). For the Ikata reactor complex a start time about 12 hours later—within De Geer's error bound for the fission event—does result in the plume arriving over Okinawa at the observed time. But its temporal profile does not match the observations, moving past Okinawa after 1 day. Significantly, the Monju fast reactor is almost certainly ruled out as a potential origin for the Okinawa detections.

For the Russian naval base at Bolshoi Kamen a plume using either global re-analysis or GDAS data—starting at or after 0000 UTC on 11 May and from 25–300 m above sea level—does not arrive above Okinawa before about 18 May, well after the first detections. However, a plume beginning at 1200 UTC on 10 May, within the event time error bounds, would arrive at Okinawa at the correct time.

Xe-135

Figure 10 shows a plume calculation for the Geojin detection of Xe-135, beginning at NKTS at the explosion time of T+36 hours, i.e., 1800 UTC on 12 May 2010 as inferred by De Geer. The activity release rate is 1.0×10^{13} Bq/hr of Xe-135 over an interval of 1 hour, to give a released activity of 1.0×10^{13} Bq. Assuming a precursor cut-off of 36 hours the total Xe-135 activity is about 6×10^{15} Bq for either U-235 or Pu-239, thus implying a fractional release of only about 0.2 percent, consistent with expectation.[48] Averaged over a 12 hour interval from 0–300 m above sea level this reproduces the magnitude of the observed Xe-135 activity at the correct time. Importantly, the model predicts that detectable concentrations of Xe-135 would probably not persist over Geojin during subsequent days, being close to or less than the minimum detectable concentration of 0.9 mBq/m^3.

Surprisingly, despite the forward trajectory model suggesting an emission from the Uljin nuclear reactor complex would pass over Geojin, a full plume

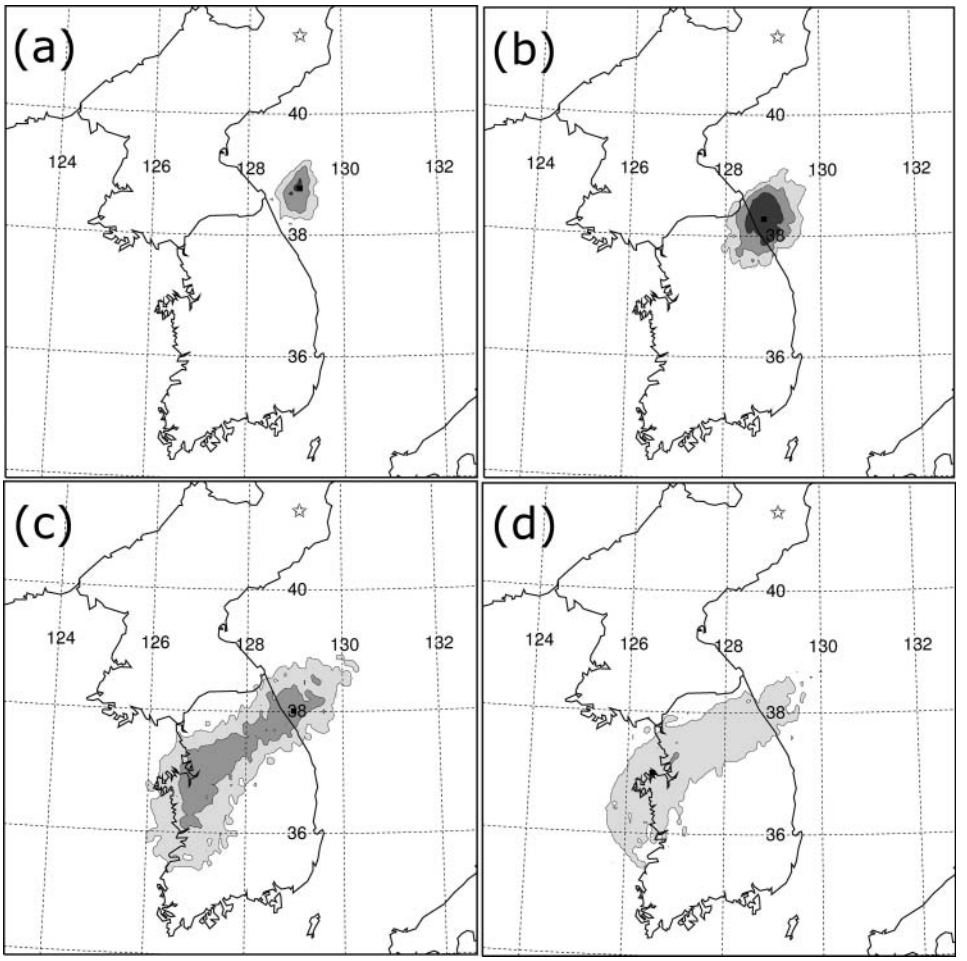

Figure 10: Plume calculation for xenon-135 beginning at 1800 UTC 12 May 2010 at an elevation of 1500 m ASL, appropriate for the North Korean test site and global re-analysis meteorological data. Integration times are **(a)** 2300 UTC 12 May–1100 UTC 13 May, **(b)** 1100 UTC–2300 UTC 13 May, i.e., the interval during which xenon was detected, **(c)** 2300 UTC 13 May–1100 UTC 14 May, **(d)** 1100 UTC–2300 UTC 14 May. The shaded contour levels represent concentrations >20 mBq/m^3, between 5 and 20 mBq/m^3 and between 0.6 and 5 mBq/m^3. The predicted activity at Geojin is nicely consistent with the observed value of 10 mBq/m^3 in the relevant time frame.

concentration calculation shows this not to be the case. This is consistent with original media reports at the time quoting officials that ROK could not be the source as the wind was blowing south.[49] Also, it is found that a plume from the Hanaro research reactor and its medical isotope production facility would not pass over Geojin. Unlike the case for Ba-140, no Xe-135 model plume from Bolshoi Kamen—beginning anywhere from 0000 UTC 10–13 May—passes over Geojin, and that which comes closest in time and space is already more than

3 days old. No candidates in Japan or China were modeled with a full plume concentration, as the trajectory models previously presented resulted in no plausible sites there.

XE-135 RELEASE MECHANISM AND ISOTOPIC RATIOS

De Geer's model considers the second release to have been of so-called virgin xenon, i.e., xenon which was promptly vented out of the explosion cavity but then trapped in the sealed tunnel or a side-drift before being released at T + 36 hours, perhaps during tunnel ventilation so that experimental equipment could be recovered. There are certainly examples of this type of release during other nuclear test programs.[50] In this case no in-growth from iodine and other precursors could occur and probably no fractionation expected. Only radioactive decay could alter the initial isotopic ratios.

Alternatively the xenon may have been non-virgin vented directly from the cavity 36 hours after the explosion, as gas found its way to the surface via a collapse chimney and subsequently through cracks and fissures—either pre-existing or opened up by the explosion—in the surrounding rock mass. Such delayed releases also have precedent in historic test programs, and may be "assisted" by the passage overhead of atmospheric low pressure systems.[51] In this case significant in-growth of precursors would occur, as well as probably fractionation, so that along with radioactive decay there are at least three processes altering the initial isotopic ratios.

A third possibility combines aspects of the previous two, namely that noble gas vented into the "holding shaft" a few hours after the explosion, but was only released into the atmosphere during the tunnel purging some 32–34 hours later. In this model there would be some in-growth of precursors, but probably little or no fractionation given the limited time available. The xenon activity calculations presented here allow a consistency check on these models.

The Xe-135 activity from direct fission (i.e., virgin xenon, with no in-growth from precursors) is 7.3×10^{14} Bq for U-235 and 3.8×10^{15} Bq for Pu-239 for a 200 ton explosion. There is very little change for a precursor cut-off at 10–20 seconds, the release time found to best coincide with the Ba-140/Cs-137 ratio observed at Okinawa. Assuming that up to 1 percent of the noble gases are vented to the "holding shaft"—a reasonable figure given the fraction of ~0.3 percent inferred from the Okinawa detections and associated plume calculations—then the respective activities are 7.3×10^{12} Bq for U-235 and 3.8×10^{13} Bq for Pu-239. Subsequently there will be an initial spike in the Xe-135 activity from in-growth from Xe-135m, so that approximate activities after 36 hours are 1.2×10^{12} Bq (U-235) and 5.9×10^{12} Bq (Pu-239). These are less than the activity of 10^{13} Bq actually required in the plume concentration model to account for the Geojin detection, and are therefore probably unrealistic.

A virgin release into the "holding shaft" larger by factors of at least ten and two for U-235 and Pu-239 respectively would be required for the activity to be sufficient to account for the Geojin detections.[52] Perhaps this could occur in the manner proposed by De Geer, namely that the larger release was of gas vented from the shot cavity but mostly held up by a tunnel closure, whilst the smaller release was of gas that also escaped through this closure. Otherwise it would require that two separate initial releases occurred with different release fractions, namely ~0.3 percent for the immediate-escape Okinawa detections and ≥2–10 percent for the delayed-escape Geojin detections. In either case, close to 100 percent of the held-up xenon would need to be released during the tunnel ventilation.

Both the work of De Geer and that presented here have trouble accounting for the Xe activity ratios detected at Geojin using either purely virgin or purely aged (i.e., with precursor in-growth) xenon. De Geer's problem is that for his virgin, but delayed, release model Xe-133m should have been detected along with Xe-133. Indeed, the initial Xe-133m activity is higher than of Xe-133 itself. But only an upper limit of Xe-133m was measured at Geojin, with the corresponding Xe-133m/Xe-133 upper limit ratio being 0.077 from De Geer. At Geojin 59 hours after the explosion—the interval between UTC 0600 11 May and 1700 13 May, the latter being the middle of the sampling period—predicted Xe-135/Xe-133 and Xe-133m/Xe-133 ratios from virgin Xe (or even with a 10–15 second delay) would be 16.5 and 1.6 respectively with U-235 (or 7.2 and 1.6 with Pu-239). The xenon ratio disagreements between the data and his model prompted De Geer to postulate a first test conducted around 15 April—after a second consideration of the data and analysis this has been withdrawn.[53]

As already noted, an alternative model is that the precursor cut-off time was around 36 hours after the explosion, at which point the xenon was released directly from the shot cavity (or chimney). Figure 11 shows the resultant ratios compared to the Geojin data, in this case assuming Pu-239 fission (though the situation is almost identical for U-235 fission by this relatively late time). In this and subsequent plots the originally reported Xe-135/Xe-133m ratio has been corrected in the same manner as done by De Geer to allow faithful comparison to the Bateman equations. Clearly the predicted Xe-135/Xe-133 ratio is too low, being around 0.66 in the middle of the 12 hour Geojin sampling interval, compared to the observed (though corrected) figure of 1.18 ± 0.12. On the other hand the two other ratios are consistent with the observed upper limits.

It is not necessarily the case that the non-ideal match to the Xe-135/Xe-133 ratio makes this model untenable. There is enough leeway in the detonation and release times, given their respective uncertainties and that of the atmospheric modeling itself, to bring the calculated ratio into reasonable agreement with that observed. For instance, even a 3 hour delay in the detonation to 0900 UTC on 11 May, and a corresponding 3 hour delay in release to 2100 UTC on

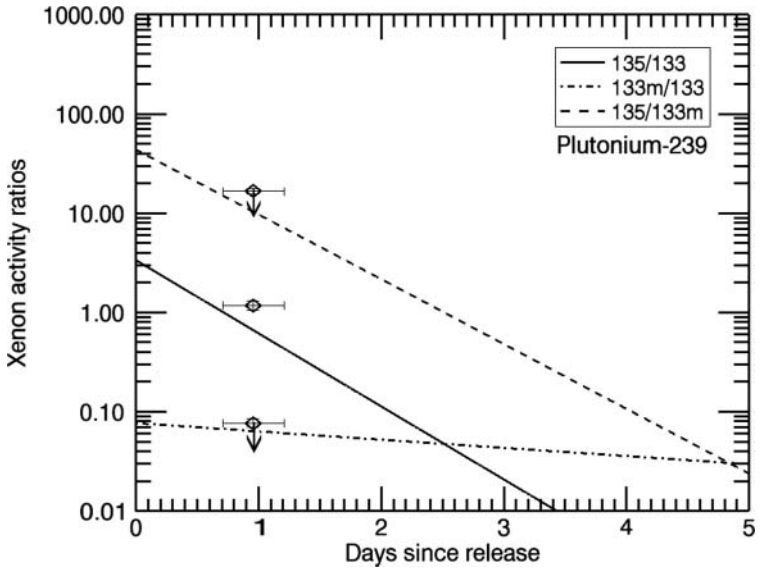

Figure 11: A plot of the xenon activity ratios at Geojin 23 hours after release from the explosion cavity, which in turn occurred 36 hours after the explosion, with consequent precursor in-growth during that time. The horizontal bars through the data points reflect the 12 hour Geojin sampling period. Fissile material is Plutonium-239 with the ENDF/B-VI fission product yield library.

12 May, brings all ratios into agreement within their error bounds. Also, uncertainties on any particular fission product yield can be relatively large. As an example, for the ENDF/B-VII.1 library and U-235 fast fission the Xe-135, Xe-135m, I-135, Te-135 and Sb-135 independent yields and uncertainties are $(1.20 \pm 0.28)\times10^{-3}$, $(1.86 \pm 1.19)\times10^{-3}$, $(3.60 \pm 0.29)\times10^{-2}$, $(2.47 \pm 0.57)\times10^{-2}$ and $(2.46 \pm 1.57)\times10^{-3}$ respectively. Similar levels of uncertainty are seen for the mass 133 chain. It thus seems clear that all the uncertainties together could easily conspire to produce a factor of $\leq$2 difference between predicted and observed Xe-135/Xe-133 ratios.

Also, fractionation amongst fission product elements within the shot cavity and chimney is a well known phenomenon, related to the volatility and/or refractory nature of the particular fission product, its precursors, their half-lives, and the overall explosion phenomenology.[54] For example, despite their relatively low volatility, Cs-137 and Sr-90 are found to be enriched above nuclear explosion cavities, and within the so-called collapse chimneys (or alternatively depleted in the debris melt puddle at the bottom of the cavity). This is because their precursors include the short-lived noble gas isotopes Xe-137 and Kr-90, which, due to their high volatility, are able to travel large distances through fractures and fissures during the cavity cooling phase.

It may seem unlikely that there could be fractionation between xenon isotopes. However, their three immediate precursors, namely iodine, tellurium, and antimony, have very different half-lives. For instance, the Sb-133, Te-133, Te-133m, and I-133 half-lives are 2.5 m, 12.5 m, 55.4 m, and 20.8 h respectively, all longer by large factors than their mass 135 counterparts Sb-135, Te-135, and I-135 of 1.68 s, 19.0 s, and 6.57 h. The decay chain from antimony to xenon goes in order of increasing volatility, with iodine in particular being quite volatile and hence probably mobile. Depending on the temporal and/or spatial cooling profiles of the cavity and chimney, the relatively rapid conversion of the mass 135 chain into highly volatile species suggests a scenario where I-135 and Xe-135 could migrate further than I-133 and Xe-133, and so become enriched in the chimney. Such a scenario could be consistent with the statement in Lay et al. that "tellurium and antimony precursors . . . do not readily release their xenon decay products."[55] Alternatively, or in addition, chemical reactions between iodine and other elements have more time to occur with I-133, the resulting compounds of which would probably also be less mobile and so trap the Xe-133 daughter further underground. These processes could then result in a relatively high Xe-135/Xe-133 ratio when a passing low pressure system draws gas out of sub-surface rock fractures and fissures. As support for the contention that fractionation can perturb isotopic ratios, a description of the use of xenon as a device performance diagnostic states that early time sampling (e.g., before cavity collapse) is much preferred, as the xenon is mostly attributable to their independent yield.[56] On the other hand interpretation of intermediate-time samples is "complicated" and diagnostic application of xenon "questionable."

One advantage of this model is that it naturally explains the low Xe-133m/Xe-133 ratio. Whilst fractionation can affect their activities it obviously cannot change their ratio, as the two isomers arise from the same fission product decay chain. Another advantage is that a relatively low release fraction, a few tenths of a percent, of the total xenon content is required to account for the detected concentration. Thus, there is no reason to invoke a previous test, for which there are both plausibility and atmospheric modeling issues to be addressed.

The third release model for the Geojin detections combines aspects of the previous two, but still without the necessity of invoking a previous test. Using U-235 as the fissile material, if venting into a "holding shaft" occurred around 1.7 hours after the explosion, with consequent in-growth from precursors, then all predicted ratios at Geojin 57.3 hours later agree with the data. See Figure 12. The respective venting time for Pu-239 is 3.65 hours, but in this case the Xe-133m/Xe-133 ratio is a factor of about 1.9 higher than the upper limit detection of 0.077. This probably doesn't rule out Pu-239, since the use of different fast fission yield libraries can cause large variations in xenon isotope

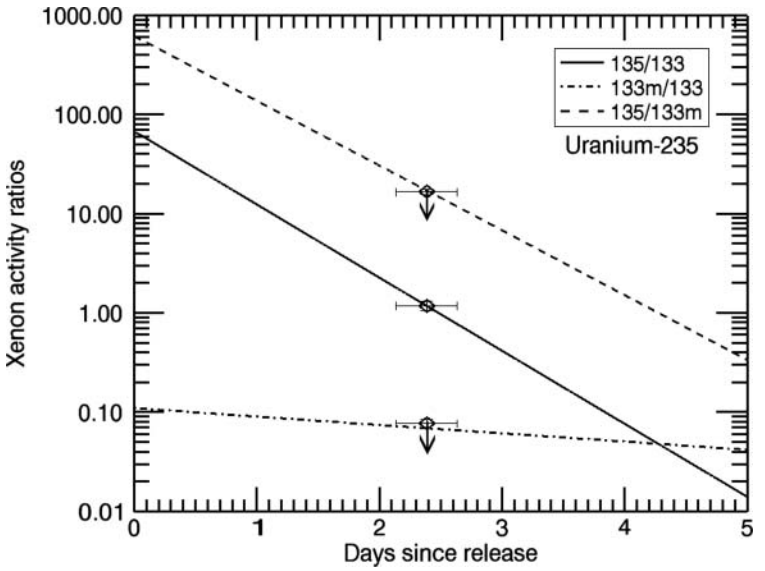

Figure 12: A plot of the xenon activity ratios at Geojin, assuming that noble gases were vented from the cavity into a "holding shaft" 1.7 hours after the explosion, but only released into the atmosphere 34.3 hours later. Precursor cut-off is also 1.7 hours. Fissile material is uranium-235 with the ENDF/B-VI fission product yield library.

populations, and as seen above there can be large uncertainties in individual isotopic yields within any one particular library.

For this model with U-235 at least 2 percent of the noble gases must be vented into the "holding shaft" at 1.7 hours post explosion. At that time the Xe-135 activity is 1.5×10^{14} Bq. With in-growth from Xe-135m plus decay the activity after 34.3 hours, when the gas is released to the atmosphere, is 1.1×10^{13} Bq. This is then sufficient to account for the detected concentration at Geojin, assuming all of it is released.

DISCUSSION

The possibility of an unannounced North Korean nuclear test in May 2010 has proven controversial, principally due to the lack so far of a seismic detection of such an event. However, that the actual radionuclide data and modeling evidence is bookended by suggestive statements from within North Korea seems like a remarkable coincidence.[57] Further, the possibility of a faked test by North Korea, or even a reactor accident within North Korea, can be almost totally excluded. The short half-life of especially Xe-135 dictates that it had to be created in a fission reaction only days before its detection. But as far as is known North Korea did not have an operating nuclear reactor in May 2010. Also, a faked test would presumably have required spent reactor fuel rods to

have been exploded with conventional high explosive. But in that case if the rods were sensibly given time, say weeks, to cool down before being transported then there would have been very little Xe-135 and Xe-133 contained therein, and similarly for Ba-140 and La-140. And even if not, reactor calculations show that it is highly unlikely that the activity ratio between Xe-135 and Xe-133 in discharged fuel would be larger than 1, let alone as high as the ratio of ~4 detected at Geojin.

De Geer proposed a scenario of a decoupled test in which the explosion occurs within a large cavity, which acts to decrease the amplitude of seismic waves such that the test goes undetected or, if detected and discriminated from a chemical explosion (e.g., from mining), leads to a lower seismic-based yield being inferred. The possibility of decoupling has long figured in discussions of the verifiability of a CTBT.[58]

Nuclear explosion decoupling was demonstrated by the US in 1966 when the 0.38 kt Sterling device was detonated inside a ~17 m radius cavity at a depth of 828 m, which had been excavated by the 5.3 kt Salmon explosion in 1964.[59] Other less well known decoupled U.S. shots were Mini Jade of 26 May 1983, Mill Yard of 9 October 1985, and Diamond Fortune of 30 April 1992. Details are scarce on these events, but all were low-yield detonations in ~11 m radius hemispherical cavities.[60] The USSR conducted a nuclear decoupling experiment in 1976; the A-III-2 device with a yield of 8–11.5 kt was fired inside a 33–38 m radius spheroidal cavity at a depth of 987 m, which had been excavated by the 64 kt A-III event in 1971.[61] The yield-to-cavity volume ratios of Sterling and A-III-2 were around 20 and 50 kg/m^3 respectively. Respective decoupling factors of the US and USSR experiments were approximately 70 for both Sterling and Mill Yard and 15–30 for A-III-2, where the decoupling factor (DF) is defined as the degree by which the amplitude of long period (i.e., low frequency) seismic waves is reduced.[62] The body wave magnitude is then reduced by $\log_{10}$(DF).[63]

Stevens et al. analyzed decoupling in non-spherical cavities in granite with chemical explosions, and found both partial and full (chemical) DFs ranging from ~35 to ~130 for yield-to-cavity volume ratios $\leq$10 kg/m^3.[64] Above about 15 kg/m^3 the DF drops precipitously to just over 10, whilst the modeling suggested this drop occurs at around 25–50 kg/m^3. Assuming that chemical explosions couple a factor of two better than nuclear ones, as found in many studies, then these experiments would imply similar nuclear DFs for yield-to-cavity ratios a factor of two higher, in good agreement with the nuclear data cited above (even though in salt).[65] Similar results were found by Murphy et al. for high explosive (HE) experiments in limestone cavities, who also found that decoupling was relatively insensitive to the shape of the cavity, such that cylindrical cavities with length-to-width ratios of 6–12 gave similar DFs as equivalent volume spherical cavities.[66]

Based on the 2006 and 2009 test yields a rough estimate can be made of the decoupled magnitude of a 200 ton test at the North Korean test site.[67] Recent

analysis using independent methodologies and both short and long period data suggest that the yields of the 2006 and 2009 tests were at least about 1 and 5 kt respectively, especially for a depth-of-burial around 200 m in 2006 and 550 m in 2009.[68] These yield estimates use a chemical calibration explosion of known yield in NE China between NKTS and station Mudanjiang (MDJ) in China,[69] or use both the 2006 and 2009 test data and an extensively tested seismic source model to simultaneously solve for the yield and burial depth, and thus cancel out ill-constrained propagation variables, or use a full moment tensor inversion and seismic source model appropriate for North Korea.[70] For the purposes of this work 1 kt and 5 kt are taken as representative yields of the 2006 and 2009 North Korean nuclear tests.[71] Scaled-depth-of-burial (SDOB) are assumed to be ~200 and 320 m/kt$^{1/3}$ respectively.[72] With these yields, and a maximum likelihood estimate of the body wave magnitude difference of 4.62–3.94 = 0.68, an approximate m_b-Y relation for the North Korean test site can be constructed.[73] With no account for depth-of-burial or upper mantle attenuation the relation is $m_b = 0.973 \times \log_{10} Y + 3.94$. Thus, the "expected" magnitude of a 0.2 kt event would be around $m_b = 3.26$.[74]

According to Kvaerna et al. even an m_b of 3.26—for a fully coupled 200 ton event, would not necessarily mean automatic detection with the IMS plus station MDJ in China, for which the detection threshold is around 3.5.[75] This is defined as an estimate at the 90 percent probability level of the smallest seismic event that could be detected by three or more stations in the network at a signal-to-noise of $\geq$4. Lower magnitude events could be detected, but specific data processing would be required, or, in other words, an analyst would have to know where to look.[76] Further, discrimination between a nuclear or chemical (e.g., mining) event becomes increasingly more difficult at lower magnitudes.

Several different methods could be used by North Korea to decouple the test. For instance, assuming they had not collapsed, in May 2010 North Korea may have had two pre-existing cavities excavated by their two previous tests. Again using 1 and 5 kt at depths of 200 and 550 m, their radii would have been about 13.5 m and 16.7 m respectively (using a standard formula for cavity radius, R_c, as a function of depth-of-burial, h, and yield W in granite, namely $R_c = 75.1 \times W^{1/3}/h^{0.323}$).[77] Leith suggests the full decoupling radius for a 1 kt explosion at a depth of 828 m is 20 m in granite.[78] At the same depth the radius for 0.2 kt is 11.5 m, using cube-root scaling. At depths of 200 m and 550 m the radii are 18.5 m and 13.2 m, again using cube-root scaling. So if the 2010 postulated explosion took place in the 2006 cavity then partial decoupling could have been achieved, whilst if it took place in the 2009 cavity then it could have been fully decoupled.

Precedents of nuclear explosions in granite, e.g., 13 by France in Algeria and 3 by the US, suggest, however, that cavities collapse soon after the explosion, probably within about an hour.[79] However, this may not be the problem it appears to be, as the result is a so-called rubble chimney, a roughly cylindrical

region comprising fallen boulders and which extends upwards by several cavity radii. At the top is an apical void—seen for all three U.S. shots in granite, namely Hardhat, Shoal, and Piledriver—which, together with the void spaces between the boulders, presumably equates to the original cavity volume. Chimneys are thus highly porous media, and a subsequent explosion would probably couple much less efficiently, for much the same reason known for alluvium at NTS.[80]

Small-scale HE experiments suggest that explosions within a rubble chimney can achieve high decoupling factors.[81] Sykes cites several (unidentified) instances where a nuclear test was conducted in the rubble chimney of a previous test, noting that they did generate smaller than normal seismic waves, reducing m_b by a similar amount as for a "poor coupling" medium.[82] This presumably refers to dry, porous tuff or alluvium, which, for porosity around 20 percent, may result in m_b up to 0.75–1 unit lower than for "good coupling" material.[83] Such a scenario could serve to decrease the magnitude of a 200 ton explosion in North Korea from 3.26 to about 2.26–2.51, or an apparent yield of 19–34 tons, using the approximate m_b-Y relation.

North Korea could have used a naturally occurring cavern in the vicinity of NKTS to conduct a decoupled test, or it could have purposefully excavated a cavity, which needn't have been spherical. Leith notes that the engineering stability of most underground openings relies on the relative strength of the smallest dimension of the opening, and that excavation of such structures—with a largest unsupported span of around 20 m—is a technology widely available and commonly practiced.[84] This is likely to be the case in North Korea, and probably has signatures little different from normal mining and tunnel excavation operations. At a "standard" depth of 400 m the full decoupling radius for a spherical cavity in granite is about 15 m. This then is the shortest dimension of a non-spherical cavity for full decoupling. Since aspect ratios of 4:1:1 have been demonstrated to provide equivalent decoupling then dimensions of 60:15:15 m would be sufficient, as this provides an equivalent volume to the spherical case.

Even if only partial decoupling was achieved then the DF could be 30 and the expected magnitude about $3.26 - \log_{10}(30) = 1.78$. The implied yield would then be ~6.0 tons using the approximate m_b-Y relation. If fully decoupled, with a DF of 70, the expected magnitude would only be about $3.26 - \log_{10}(70) = 1.41$, implying a yield of ~2.5 tons. This possible magnitude and inferred yield is consistent with the measured magnitudes and known yields of several chemical explosions conducted in NE China, near the North Korea-China border and less than 200 km from the North Korean test site.[85] One had a yield of 1.45 tons, buried at a depth of 28.8 m, and registered an m_b of 1.66 (measured using Lg waves). Using the established factor of two conversion between chemical and nuclear coupling the yield and SDOB are 2.90 tons and 202 m/kt$^{1/3}$, similar to the inferred SDOB of the 2006 nuclear test.[86] The approximate m_b-Y

relation for the North Korean test site would suggest a yield of 4.5 tons, less than a factor of two different than the actual yield (albeit corrected).

As shown by the Chinese chemical explosions, magnitudes as low as about 1.7 can be detected in this part of the world, although presumably one would need to know where and what time to look.[87] However, at NKTS itself or its near vicinity the minimum detectable m_b may be somewhat higher as the additional ~200 km path to the northern seismic station MDJ would suffer further signal loss. Chun et al. found the region to be highly attenuating of Lg waves, probably due to relatively high crustal temperatures, and note its similarity to that of several tectonically active regions, including the Basin and Range Province in which the Nevada Test Site is located.[88] They suggested that previously measured m_b(Lg) of the 2006 test needed to be corrected upwards by around 0.35 magnitude units. Also, most paths to South Korean stations cross the continental margin of the Sea of Japan, where the thinner crust also highly attenuates Lg waves. This can result in a difference of up to 1 magnitude unit between purely continental paths and those that cross the margin.[89]

Many recent independent studies have found that North Korea and the surrounding region have geophysical properties that suggest it to be highly attenuating not just of Lg waves, but of several other seismic wave types as well. Such properties include a mantle lid velocity[90] of $\leq$8 km.s^{-1}, low velocities of S- and P-waves[91] down to depths of several hundred kilometers, heat flow[92] of $\geq$60 mW/m^2 and inefficient transmission of Sn waves.[93] The generally accepted view on upper mantle attenuation, represented by the parameter Q, is that it results from higher mantle temperatures (T) at depths of about 200–400 km, which in turn result in slower seismic velocities (V).[94] Whilst the relationship between T, V, and Q is not always perfect, Artemieva et al. find that they do correlate in the Sino-Korean craton, terming it an unexpectedly "hot region."[95]

Perhaps in some support of this line of reasoning, Kvaerna et al. find the site-specific threshold monitoring capability for the IMS to be between 2.3 and 2.5, improved to 2.1–2.3 and perhaps down to 2.0 with the addition of station MDJ.[96] This is defined as an estimate, at the 90 percent probability level, of the largest hypothetical seismic event at a given site or in a given region that could possibly have occurred. In other words it is the upper limit magnitude of non-detected events, and higher than the chemical explosion magnitudes in NE China. Schaff et al. find a somewhat lower threshold at NKTS itself of around 1.4–1.7 during 10–11 May 2010 using the 2006 and 2009 seismic signals at MDJ as a template.[97] As indicated above, this would correspond to a fully coupled yield of ~2.5–5.0 tons (although Schaff et al. use a different m_b-Y equation that suggests a yield of 0.16–0.40 tons, i.e., 160–400 kg, which seems unrealistically low based on the work here).[98] For the north-east area of North Korea Schaff et al. instead suggest a lower limit local magnitude M_L of $\leq$2.0. With an M_L of the 2006 test of 3.6 this would suggest a lower limit fully

coupled yield of ≤6.5–13 tons, assuming a 2006 yield of 0.5–1.0 kt and a slope of the magnitude-yield relation of 0.85.[99]

Therefore, the absence of a seismic detection does not necessarily preclude the possibility of a 200 ton nuclear test conducted by North Korea on 11 May 2010. It is entirely consistent with what is known about the physics and past practice of decoupling, the geophysics of NKTS, and its detection and monitoring thresholds. If the postulated test yield was less than 200 tons, say 100 tons or even 50 tons, then the situation is made even harder for seismic detection, whilst it would still be consistent with the radionuclide data, merely requiring the release fraction to increase by a factor of 2–4 and so still be less than about a percent.[100]

A DECOUPLED BUT UNCONTAINED NORTH KOREAN TEST?

Seismic decoupling of a nuclear test does not imply that the test will be contained with regard to radionuclide release. North Korea's 2006 test did vent and was detected in South Korea, Canada, and over the Sea of Japan.[101] More generally, as noted by Leith, there are qualitative reasons to believe that a cavity decoupled test is more likely than a fully coupled test to vent noble gases.[102] Containment would depend to a large extent on the state of pre-existing stress in the rock and associated cracks, fractures, fissures, and geologic faults. These provide a natural pathway for gas to migrate to the surface. Such faults in the rock may be created and/or widened when the cavity is explosively excavated, such as by a single nuclear explosion or blasting with conventional high explosive. Leith notes that an evader may conduct preliminary chemical explosive tests within the newly created cavity to study the migration of hot gases, although extrapolating to a nuclear explosion of higher yield would still be fraught with uncertainty.

There is evidence of such behavior from HE experiments and the U.S. nuclear test program, presented by Smith.[103] He notes that partially decoupled nuclear events have a mixed containment record, citing the 5 March 1966 Red Hot explosion, a tunnel event in tuff at Rainier Mesa which vented the noble gases krypton and xenon as well as several iodine isotopes.[104] On the other hand, according to Smith, fully coupled and fully decoupled events are somewhat better contained. Though data on partially and fully decoupled tests are presumably statistically limited, the historical nuclear data is suggestive and seemingly supported by the HE experimental results in Smith's paper. In the Junior Jade program a set of five HE experiments with progressively higher decoupling show increasingly higher loss of cavity pressure immediately after the explosion. This in turn suggested a progressively greater loss of containment, consistent with the observed number and extent of post-shot fractures through which gas could escape.

As already noted the historical U.S. nuclear test program provides several close analogues to the postulated North Korean test, namely low yield explosions conducted in an underground cavity sufficient to result in at least partial decoupling. These include shots Red Hot of 5 March 1966, Mini Jade of 26 May 1983, Mill Yard of 9 October 1985, and Diamond Fortune of 30 April 1992. An even closer analogue is the Tiny Tot test, which was a low yield (less than 500 tons) tunnel shot conducted on 17 June 1965 in a 10 m radius hemispherical cavity in granite at a depth of about 110 m.[105] According to Merritt, Tiny Tot was placed in the center of a flat granite face, and was intended to provide direct information on the ground shock and cratering of a surface burst on hard rock.[106] The size of the Tiny Tot cavity was chosen to reduce forces on the wall to within the elastic range of the rock, which is effectively the definition of full decoupling. Merritt also notes that the stemming of shots fired in cavities is more difficult than for closely tamped shots. For Tiny Tot the stemming was a system of plugs within the entry tunnel designed to resist the forces inside the cavity and thus retain radioactivity within the cavity. In the test, radioactivity appeared almost immediately between first and second plugs, with high radiation levels reached in 10 minutes. Over a few hours activity penetrated past the second plug, as well as through a sand plug. An uncontrolled release of predominantly noble gases, particularly xenon, occurred from the mouth of the Tiny Tot shaft at about 15 minutes post explosion and lasted for almost 15 hours.

Definite decoupling was achieved, despite the fact that the device was not in the center of the cavity but rather contacting the flat granite face. But the actual decoupling factor has not been published. Merritt does however note that two seismic stations within 150 and 170 km did not register a signal above the noise level, even though they had detected the nearly co-located 5.7 kt Hard Hat event of 15 February 1962.

CONCLUSION

Forensic analysis has been conducted of the radionuclide detections in and near the Korean Peninsula in May 2010 reported by De Geer.[107] This has included both forward and backward atmospheric transport modeling to produce possible trajectories and plume concentrations, as well as activity calculations of both reactor and explosion-produced xenon. The results of this study are as follows:

1. Despite the presence of around 100 civil nuclear fuel cycle facilities in and around the Korean Peninsula, the mid-May detections of xenon daughter particulates at Okinawa and of xenon itself at Geojin are locally and regionally unique amongst relevant historical data. The Okinawa detections are also globally unique since the voluntary moratorium on nuclear testing

in the last 15–20 years. The relatively high Xe-135/Xe-133 ratio at Geojin also suggests a globally very unusual event.

2. In agreement with De Geer and Wotawa[108] it is found that North Korea provides the best candidate origin for the Okinawa and Geojin detections. That different atmospheric transport codes and meteorological data sets give consistent results provides confidence in their robustness. Within North Korea the models favor the region around the known nuclear test site over that around the fissile material production complex at Yongbyon, also in agreement with Wotawa. No other nuclear power, research or propulsion reactor candidate origins within ROK, Japan, mainland China, Russia, or Taiwan provide as good a match to the timing of the detections. Only NKTS presents itself as a viable origin for *both* the Okinawa and Geojin detections, even though two separate xenon releases approximately 36 hours apart are required.

3. Neither the Ba-140/Cs-137 nor Xe-135/Xe-133 ratios are consistent with a nuclear reactor operating in equilibrium. The Xe-135/Xe-133 ratio is also higher than what has been published for samples measured at the waste gas stack of medical isotope production facilities. Both ratios could be consistent with a nuclear reactor at start-up but require a complex release sequence. Also, if Xe-137 and Xe-140 were routinely released from reactors during their start-up process then their daughter products, especially Ba-140 and La-140, would be detected much more frequently throughout the world, at odds with actual experience. Further, a reactor accident seems unlikely since other particulates would almost certainly have been detected, and such occurrences are almost invariably eventually reported by the media.

4. The detected radionuclide concentrations are consistent with possible source terms from a low yield, i.e., up to a few hundred tons, nuclear explosion conducted at 0600 UTC on 11 May 2010, the time found by De Geer. Depending on the precise release mechanism the noble gas release fraction need only be a few tenths of a percent for both releases. The detected activity ratios are also consistent with a nuclear explosion. The analysis cannot clearly discriminate between U-235 and Pu-239 as the fissile material in the test.

5. The lack of a seismic detection is not necessarily surprising given the location of NKTS, with paths both to the north and south suffering relatively high attenuation of regional waves, though for different reasons. A 200 ton test decoupled by a factor of $\geq$30 would produce a body-wave magnitude of $\leq$1.8, less than the published monitoring threshold of NKTS using the most sensitive stations. Such decoupling has been amply demonstrated for many nuclear and chemical explosions in a variety of media and in a

variety of cavity configurations. That the test vented noble gases is also not surprising in the context of the historical nuclear test data base.

The data, modeling, and analysis point to an unannounced nuclear test by North Korea on 11 May 2010. A seismically decoupled but radiologically uncontained nuclear explosion provides the simplest explanation. Nothing yet has been found to rule out or make unlikely such a scenario, and no other viable location or physical process has been identified that could explain the data in their entirety. That the radionuclide detections were bracketed before and after by intriguing statements from North Korea itself is suggestive of something significant, and of a nuclear nature, occurring in the relevant timeframe.

If the scenario suggested here and by De Geer bears some relation to what actually occurred then it is an unequivocal demonstration of the efficacy of the CTBT International Monitoring System, and that the probability of detection is high even for the case of a decoupled test. It will provide pause for thought for any future evader considering a covert nuclear test. On the other hand, if a nuclear explosion is not responsible then there is a need to improve the current understanding of noble gas and particulate emission mechanisms from non-explosive nuclear sources, and thus avoid any future "false alarms."

POSSIBLE FUTURE WORK

Suggestions are summarized here for future work which could shed further light on this issue.

1. The modeled particulate plume passes over a large swathe of southern Japan for 3 days before it arrives over Okinawa, at predicted Ba-140 concentrations of at least a few hundred micro-Becquerel per cubic metre and possibly even over 1000 μBq/m^3. A search should be made for any such detections, or of longer-lived Cs-137, in SW Japan, perhaps at reactor complexes or other nuclear-related facilities.
2. So far only gamma emitting isotopes have been detected on the May 2010 Okinawa particulate filters. If feasible, beta emitters such as Sr-90, with a half-life of $\sim$29 years, also should be looked for. The Kr-90 parent has a half-life of $\sim$32 seconds and a direct fission yield similar to that of Xe-140. Its activity ratio with Cs-137 could provide another constraint on the origin.
3. As suggested in Persson, it is possible that autoradiographs of the Okinawa filters could distinguish between particles with radioactivity that originated from gaseous precursors—giving a uniform blackening—versus those where the Ba/La-140, Cs-137 and Sr-90 were directly released. The latter may occur in a reactor accident, leading to discrete, so-called "hot

particles," possibly resembling fallout particles from atmospheric nuclear tests.

4. Since the HYSPLIT dispersion models do not reproduce all features of the observed Okinawa plume, especially the two concentration peaks separated by a few days and the overall plume duration, more sophisticated modeling to explore a wider parameter space is required. Finer resolution, using detailed local weather conditions around Okinawa, and/or optimized particulate properties with deposition inclusive of re-suspension, may be required.

5. Statistics are required for the temporal behavior of xenon detection, and thus the xenon background, at the Ussuriysk RUX58 CTBT IMS station, and specifically if any elevated levels were detected around the time of the postulated nuclear test. Also, more complete statistics for the Beijing CNX20 and Ulaan Baator MNX45 stations would be useful to better constrain the typical xenon background of the region.

6. Assuming a reactor emission, the detectability in the Okinawa spectra of other isotopes with noble gas precursors, including those with krypton parents, should be determined. Noble gas isotopes with half-lives shorter than about 10 seconds could be especially diagnostic, since they would not escape an explosion cavity before they decayed, a constraint not relevant for the reactor release scenario. Possible isotopes might be Ce-141, Sr-89, Sr-91, Y-91, and Y-93. Related to this, more realistic modeling of noble gas inventories during the days-long start-up process of a nuclear reactor should be conducted to determine whether the predicted isotopic ratios are consistent with those inferred from the data.

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16. Most notably, forward trajectories—from starting heights spanning 2500 m and horizontal offsets of ±0.1 degrees in latitude and longitude—always started out in the same directions. For instance, those from NKTS to Okinawa, beginning at De Geer's fission event time, always initially head south-east toward and then cross the Sea of Japan. But approaching Japan, or during or after crossing it, GDAS trajectories become

more susceptible to different starting positions, whether horizontal or vertical. They diverge more, including travelling in opposite directions as trajectories which reach higher altitudes get "caught" in the west-to-east North Pacific jet stream. Also, forward trajectories from NKTS to Geojin always begin by travelling almost due south for both data sets. For all re-analysis trajectories the path continues south, taking it close to Geojin before turning around and heading north. For GDAS trajectories the northward turn occurs shortly after crossing over the coast of North Korea, except for starting heights above about 1400 m. For the latter the behavior is similar to re-analysis trajectories. Backward trajectories from Okinawa are very similar for re-analysis and GDAS data. The GDAS trajectories, calculated at and within ±0.25 degrees of the Okinawa IMS station latitude and longitude, approach closest to NKTS. Those of re-analysis data, with positional offsets of ±0.5 degrees, skirt the very northernmost part of North Korea, near the border with Russia and China. This is well within the expected accuracy of single trajectories, especially for such a temporally long and spatially extended path. Backward trajectories from Geojin show more variation between the two data sets, and for GDAS data between positional offsets of ±0.25 degrees. Re-analysis data produces trajectories which approach closest to NKTS, and little variation is seen for ±0.5 degree offsets. For GDAS data most trajectories still do pass over North Korea, but are over the sea about 100 km east-south-east of Geojin at the postulated delayed release time.

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32. Kalinowski and Pistner (2006), *op. cit*. The INGE data presented in Kalinowski et al. (2010, *op. cit.*) do include Xe-135/Xe-133 ratios up to almost 100 (see their Figures 6 and 12). Since these are presumably from monitoring stations remote from a nuclear facility, they imply that the intrinsic (i.e., emitted) ratios would be even higher. They may represent reactor releases in the first couple of hours after start-up, for which ratios of several hundred could be expected (see Xenon activity and ratio calculations). Unfortunately no context is provided for these detections, so their absolute activity levels or specific origin are unknown. However, Kalinowski et al. do note that they were measured somewhere in North America or Europe, and thus could not be from any Asian INGE station close to the Korean Peninsula. Also, their corresponding Xe-133m/Xe-133 ratios are always greater than about 2, unlike the Geojin detections. It seems unlikely then that these abnormally high Xe-135/Xe-133 ratios would be relevant to this study.

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in mono-energetic neutron energies between 0.5 and 2.0 MeV have been pooled with fission neutron spectrum yields.

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use of the term "thermonuclear" in the statement is suggestive and probably argues against accelerator-based D-T or D-D fusion. It could refer to fusion in a plasma focus device, but equally it could refer to fusion achieved by the high temperature and pressure of a low yield fission explosion. It is also notable that on 9 April 2010 a North Korean Foreign Ministry spokesman was quoted by KCNA, in response to the recently published U.S. Nuclear Posture Review, as saying "As long as the U.S. nuclear threat persists, the DPRK will increase and *update various type nuclear weapons* as its deterrent in such a manner as it deems necessary *in the days ahead*." Then on 20 April 2010 the international media carried reports that North Korea had been preparing for a nuclear test since February and would conduct it in May or June. The reports quoted an anonymous diplomat as saying that the test would involve a *level of technical proficiency significantly enhanced* from the 2006 and 2009 tests. Similarly, in response to disclosures about U.S. Cold War-era tactical use of nuclear weapons on the Korean Peninsula the KCNA quoted the Foreign Ministry on 28 June 2010 saying that it underscored "the need for the DPRK to bolster its nuclear deterrent in a *newly developed way*."

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71. In particular, these bring into better agreement - than simplistic magnitude-yield formulae - the explosive yields inferred from body (short period) and surface (long period) seismic wave data.

72. The scaled-depth-of-burial is defined as the depth-of-burial D (in meters) divided by the cube root of the explosive yield Y (in $kt^{1/3}$). The SDOB used by the USA for full containment was $\sim$ 122 $m/kt^{1/3}$, so that the actual burial depth became $D=122 \cdot Y^{1/3}$. Russia and the former Soviet Union used slightly different formulae, which included a dependence on the moisture content of the medium [OTA 1989, U.S. Congress, Office of Technology Assessment, The Containment of Underground Nuclear Explosions, OTA-ISC-414 (Washington, DC: U.S. Government Printing Office, October 1989); Vitaly V. Adushkin and William Leith, 2001, "The Containment of Soviet Underground Nuclear Explosions," U.S. Geological Survey Open File Report 01-312].

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