Revisiting North Korea's Nuclear Test

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On Oct. 9, 2006, the North Korean government officially declared the success of its first nuclear test.[1] A few days later, on Oct.16, 2006, the U.S. Director of National Intelligence stated that collected samples of radioactive debris confirmed the underground test of a nuclear device in the vicinity of P'unggye, with a yield of less than 1 kiloton (kt).[2]

Although there is little uncertainty over whether or not North Korea exploded a nuclear device, its low yield casts doubt not only over the degree of its success, but also over the nature of the test and its implications. An explosive yield of approximately 1 kt is much smaller than the initial tests of other nuclear states, which have ranged from about 10 to 20 kt. As a result, many scholars have interpreted the test as a failure or "fizzle," and argue that North Korea should not be recognized as a nuclear-weapon State. On the other hand, Chinese experts have stated that "if [North Korea] aimed for four kilotons and got one kiloton that is not bad for a first test …we call it successful, but not perfect."[3]

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A re-examination of the evidence of the North Korean nuclear explosion suggests that the test was likely not a failure if Pyongyang had planned for a yield of 4 kt, as it told Beijing prior to the event. If the design yield of the device was indeed 4 kt, then it is possible that North Korea was pursuing a more compact warhead, which may have profound implications for its ability to deliver a nuclear device with its missile capabilities.

Estimating Explosive Yield

In an effort to analyze the success of a nuclear test, it is critical to determine the actual yield of the nuclear explosion (nominal or explosive yield) as well as the yield that the device was designed to produce (design yield). A test with a 1 kt explosive yield from a nuclear device with a design yield of 1 kt would, of course, be a complete success. Conversely, the same 1 kt explosive yield from a device with a design yield of 50 kt would be a failure.

Without on-site measurements or North Korean cooperation, the best way to estimate the explosive yield of the Oct. 9 test is to analyze the seismic data of the explosion. Immediately following the test, reports from around the world noted a seismic wave magnitude (Mb) of between 3.5 and 4.9 on the Richter scale, equaling an estimated average seismic body wave magnitude of 4.2 ± 0.2.

Naturally, a degree of uncertainty exists in the conversion of seismic magnitude to explosive yield, which is affected by many different factors.[4] Similar seismic magnitude values can correspond to yields that differ by a factor of 10. For instance, variations in the geological structure of the test site can affect signal attenuation and will depend on the type of rock of the explosion cavity (hard, water-saturated rock versus dry, porous materials), or the way in which the explosion is emplaced (tamped versus detonated in a large cavity designed to muffle the signal). Also, for explosions below 10 kt it has been found that signals are not always transmitted to surrounding rock effectively,[5] thus increasing the uncertainty factor.

For known nuclear test sites, such as those in Russia, the seismic measurements would have an uncertainty factor of two.[6] Without better knowledge of the North Korean test site, it would be difficult to reduce uncertainty below a factor of two, especially when the test was of such a low yield. With an average magnitude value of 4.2 Mb, we can estimate the explosive yield (Y) of the North Korean test to be approximately 1 kt.[7] If we assume the more optimistic scenario of an uncertainty factor of two, then we can estimate with 95 percent confidence that the yield of North Korea's test was between 0.5 and 2 kt.[8]

Seismic Estimation of Explosion Yield by Country

Nation/Organization	Seismic Magnitude (Mb)	Reported Estimated yield (kt)
United States		
U.S. Geological Service	4.2	
Government		1.0
Los Alamos National Laboratory		0.5-2.0
Columbia University		0.2-0.7
South Korea	3.6-3.7	0.5
Government	later revised to 3.9	later revised to 0.8
Japan		
Japan Meterological Agency	4.9	
Kyushu University	4.4	0.3
Tokyo University		0.5-3.0
Russia		
Russian Academy of Science	4.0	
Defense Minister Sergey Ivanov		5.0-15.0
China		
Government	4.1-4.2	
Chinese experts		1.0
France		≤ 1.0
Atomic Energy Commission		
Norway		
Norwegian Institute of Seismology	4.2	
NORSAR*		1.0-10.0
CTBTO**	4.0	

*Norwegian National Data Center for verification with the Comprehensive Test Ban Treaty
**Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty

Fizzle, Failure or Success

Given that the yield of the North Korean test was indeed much smaller than the initial tests of other nuclear states, was the Oct. 9, 2006, test a success or failure?

To answer this question, one must first assume that North Korea tested a plutonium device (Pu-bomb) rather than a highly enriched uranium (HEU) device.[9] Little is known about North Korea's HEU activities. It is estimated that even if Pyongyang has a dedicated HEU program, it would be at a research and development stage or, at most, have the capacity of a pilot experimental facility. Yet, even if North Korea has the capability to produce enough fissile material and the necessary equipment, it would still be several years away from producing enough HEU for one or two bombs.[10] On the other hand, North Korea already has enough separated plutonium for several nuclear weapons.[11] Given this, the assumption that the device exploded on Oct. 9, 2006 was a Pu-bomb is reasonable and very likely the case.

A primary difficulty with plutonium devices is the phenomenon of "pre-detonation." This occurs as the plutonium-239 (Pu-239) used in nuclear devices inevitably contains some plutonium-240 (Pu-240), an undesirable isotope as it decays by spontaneous fission and emits background neutrons at a high rate. The high rate of neutron emission may cause the nuclear reaction not to be sustained for long enough, resulting in pre-detonation. This can happen, for example, if the detonators do not explode at the right time or if the neutron initiator misfires.[12] To reduce the probability of pre-detonation, a plutonium weapon would have to use an implosion device similar to the "Trinity" and "Fat Man" devices detonated over New Mexico and Nagasaki respectively, where conventional explosives surrounding the fissile material were used to rapidly compress the mass to a supercritical state.

The evidence suggests the test was not a failure.

The smallest possible yield resulting from pre-detonation is referred to as a "fizzle yield." Nuclear expert J. Carson Mark provided a criterion for identifying pre-detonation as the chain reaction of approximately e^{45} fissions initiated before maximum criticality is achieved.[13] He estimates that in assembly systems similar to Trinity's, the fizzle yield is approximately 2.7 percent of the design yield. Robert Oppenheimer gave a similar estimate for a fizzle: around 700 tons from a 20 kt nominal yield, or 3.5 percent of the design yield.[14]

Whether the North Korean test was a failure depends on the design yield of the device tested. If North Korea's design yield was 20 kt, as was the case for other states' first tests, then a yield of 0.5 kt could be a fizzle yield (because the ratio of the test yield to the design yield is 2.5 percent: 0.5 kt/20 kt), which is less than the defined threshold for a fizzle yield (approximately 3 percent). However, if North Korea planned a yield of 4 kt, even a test yield of 0.5 kt (12.5 percent of design yield) would not be a fizzle yield. Indeed, Chinese officials have told American nuclear experts and diplomatic officials that Pyongyang informed Beijing in advance that they had planned to conduct an explosive test of approximately 4 kt.[15]

The test may indicate that North Korea was pursuing a miniaturized warhead.

Based on Mark's simplified model of the behavior of an implosion design[16] and von Hippel and Lyman's calculations of the probabilities of different yields,[17] we can estimate the probability of a particular explosive yield based on a given design yield for the Oct. 9 North Korean nuclear test.[18] Assuming that the test used an implosion assembly system and weapons-grade plutonium (94 percent Pu-239), there was a 26 percent probability that the explosion yield would achieve the design yield of 4 kt; about 44 percent that the yield would be in excess of 2 kt (one half of the design yield); approximately 63 percent that the yield would be in excess of 1 kt; and approximately 78 percent that the yield would be in excess of 0.5 kt.

In summary, an actual explosive yield of between 0.5 and 2 kt would not be unusual for a design yield of 4 kt. Thus, if North Korea had indeed planned to test a low-yield device on Oct. 9, it would have been neither a failure nor a fizzle.

Probability of Explosive Yields based on Weapon Assembly (percent)[19]

Assembly System (Speed in relation to Trinity)	4kt	› 3kt	› 2kt	› 1kt	› 0.5kt
Assembly system ~ Trinity	26	33	44	63	79
Assembly system 2 x Trinity	54	62	71	85	95

Warhead Miniaturization

Why would North Korea wish to design and test a low-yield nuclear device? Historically, when other nations developed nuclear weapons, the yields of their first tests were generally in the range of 10-20 kt, a larger size that is more manageable for building weapons. Also, it generally takes more than one test to weaponize a nuclear device and mate it to a missile. If North Korea planned a low-yield test, it could indicate that it already had confidence in its ability to explode a larger nuclear device and is pursuing a more compact warhead.

It may have done this for several reasons. A smaller test could have been conducted for safety purposes, in an attempt to contain radioactive materials underground. However, it is well known that completely sealing an underground explosion cavity is actually easier with an explosion of 20 kt than for one of 1- 4 kt.[20] Thus, assuming North Korean scientists knew of this fact, the safety rationale for a miniaturized test (as some experts have emphasized) is negligible and may even be discounted entirely.

Rather, if the Oct. 9 test was indeed planned as a low-yield test, it may indicate that North Korea is pursuing a miniaturized warhead.[21] Based on nuclear design experience from other countries, it can be estimated that, even without nuclear tests, North Korea would still be able to make warheads weighing between approximately 500 kg and 1000 kg. For example, Sweden designed several implosion-type nuclear devices as light as 600 kg and with a yield of 20 kt in around 1960.[22] Israel's bomb is believed to be less than 500 kg (which was designed with only one "suspected" test). Such a low-yield nuclear test would build North Korea's confidence in its ability to make an even more compact warhead — using the results of a test with an already small design yield, it could possibly pursue the development of a warhead weighing approximately 500 kg or even less.

First Nuclear Tests

Nation	Year	Yield (kt)
United States	1945	21
Soviet Union	1949	20
United Kingdom	1952	25
France	1960	60
China	1964	20
India	1974	12
Pakistan	1998	9

In addition to the weight factor, the warhead must also be small enough to be mated to the appropriate missile. For that reason, weight-to-warhead size ratios should be considered. This is best estimated using an implosion Pu-bomb roughly based on the model set out by Fetter et al.[23] (As a comparison, modern U.S. warheads weigh 100-200 kg and have a warhead diameter of 0.28-0.48 m.)

Given these weight-to-size ratios, and the payload and body diameter of North Korea's existing missiles, the conclusion can be drawn that a warhead weighing around 500 kg could be feasibly mated to North Korea's current Scuds (with a range that covers South Korea), Nodong missiles (with a range covering Japan), or Taepodong 1 and 2 (both of which are two-stage rockets with an even longer range). A small warhead mated with a three-stage Taepodong 2 would also provide North Korea with the range to target the continental United States (although the July 4, 2006 long-range test was the latest in a series of failed tests for that missile system). Continued testing for a compact warhead as well as testing of its long-range missiles could allow North Korea's strategic nuclear-strike capability to expand from its current coverage of South Korea and Japan to U.S. territory.

This analysis is based on a number of estimates with considerable uncertainty, optimistic scenarios and relative unknowns. Yet, they all lie well within the realm of the possible and therefore lead to a number of alarming conclusions.

Warhead Weight versus Diameter (Implosive Device)[24]

Warhead Weight (kg)	130	200	400	500	600	800	1000
Diameter of Warhead (cm)	42	52	70	76	81	90	98

If North Korea had planned a design yield of 4 kt, the test was quite likely a success. If this indicates that Pyongyang already had confidence that it could explode a simple nuclear device and is pursuing a much more compact warhead that could be mated with its current and potential missile capability, then this would have profound implications for its neighbors and the international community. Since the current nuclear crisis began in October 2002, North Korea has continued unhindered in its efforts to increase its nuclear capabilities: it has produced and separated more plutonium, manufactured nuclear weapons (statements made Feb. 10, 2005), and most recently conducted a nuclear test. While the current turn of events are positive and North Korea appears more cooperative for the time being, time is not on the side of those who want to halt this threat. The longer the crisis lasts, the greater North Korea's nuclear capability will be, and the higher the stakes for all. Therefore, resolving this nuclear crisis is an urgent matter that must be addressed immediately.

A small warhead mated with a Taepodong 2 could reach the continental United States.

North Korean Ballistic Missiles and Potential Nuclear Strike Capability[25]

	Range (km)	Payload (km)	Body Diameter (m)	Inventory	Compatable?	Potential Target
Sud B	320	1000	0.89	~100	Possibly	partial South Korea
Scud C	500	770	0.89	~300	Possibly	South Korea
Nodong	1350-1500	770-1200	1.30	~100	Yes	Japan
Taepodong-1	1500-2500	1000-1500	1.3/0.88	~15	Yes	
Taepodong-2	3500-6000	700-1000	2.2/1.3	~5	Unknown	>6000km Hawaii, Alaska
Taepodong-2 (three-stage)	~15000	400-600	--	--	Unknown	North America

Notes

[1] The Korean Central News Agency, the official government news agency, issued the following statement: "The field of scientific research in the DPRK [North Korea] successfully conducted an underground nuclear test under secure conditions on Oct. 9, Juche 95 (2006), at a stirring time when all the people of the country are making a great leap forward in the building of a great, prosperous, powerful socialist nation. It has been confirmed that there was no such danger as radioactive emission in the course of the nuclear test as it was carried out under scientific consideration and careful calculation." For the full press release, see "DPRK Successfully Conducts Underground Nuclear Test," *Korean Central News Agency*, Oct. 9 2006, see http://www.kcna.co.jp.

[2] "Statement by the Office of the Director of National Intelligence on the North Korea Nuclear Test," *ODNI News* Release No. 19-06, Oct. 16, 2006. See http://www.odni.gov.

[3] Hecker, Siegfried, "Report on North Korean Nuclear Program," *Policy Forum Online* 06-97A, (San Francisco: Nautilus Institute, Nov. 15, 2006), http://www.nautilus.org/fora/security/0697Hecker.html.

[4] "Seismic Verification of Nuclear Testing Treaties," Office of Technology Assessment, OTA-ISC-361, (Washington, D.C.: Office of Technology Assessment, May 1988), http://www.wws.princeton.edu/ota/ns20/year_f.html.

[5] Ibid.

[6] The factor of uncertainty for a given measurement is defined as that number which, when multiplied by or divided into an observed yield, bounds the range which has a 95 percent chance of including the actual (but unknown) value of the yield (see ibid). A combined Mb (body wave) and Ms (surface wave) approach may reduce the uncertainty factor to 1.3.

[7] It should be noted that, for different design yields, the relationship between explosive yield Y (in kt) and magnitude (Mb) could be different. There is no formula for very low design yield (less than 5 kt). If we apply relation for 5.3kt $<Y<$120kt: Mb = 4.262+0.973 logY, then for an average value of Mb of 4.2, we can estimate an explosive yield Y of approximately 1 kt.

[8] It should also be noted that off-site air sampling could not have narrowed the explosive yield estimate. To further specify the yield estimate, on-site approaches would have been required, such as CORRTEX (Continuous Reflectometry for Radius versus Time Experiments) (see "Seismic Verification of Nuclear Testing Treaties", Office of Technology Assessment, OTA-ISC-361, (Washington, D.C.: Office of Technology Assessment, May 1988.) See http://www.wws.princeton.edu/ota/ns20/year_f.html) and radiochemical analysis. However, both would have required the host country's cooperation, which is currently not possible in the case of North Korea.

[9] It should be noted that some experts believe that measurements of radioactive noble gases alone can determine the fissile material used in the North Korean test. (see, e.g., Smith, Harold, "Nuclear Forensics and the North Korean Test," *Arms Control Today*, November 2006, http://www.armscontrol.org/act/2006_11/NKTestAnalysis.asp). However, we consider that it would be too difficult to distinguish between a Pu-bomb and HEU-bomb test using this method, particularly if detection occurs two or more days after a test (see, e.g., Kang, J., von Hippel, F. and H. Zhang, "Letter to Editor: The North Korean Test and the Limits of Nu-

clear Forensics," *Arms Control Today*, January/February 2007, http://www.armscontrol.org/act/2007_01-02/LettertoEditor.asp).

[10] Zhang, Hui, "Chinese Perspectives on the North Korean Nuclear Issue," Paper presented at the Institute of Nuclear Materials Management 46th Annual Meeting, (Phoenix, Arizona: July 10-14, 2005.) See http://bcsia.ksg.harvard.edu/BCSIA_content/documents/China_NK_paper_HuiZhang05.pdf.

[11] See, e.g., Albright, D. and P. Brennan, "The North Korean Plutonium Stock Mid-2006," *Institute for Science and International Security Report* (Washington, D.C.: Institute for Science and International Security, June 26, 2006) http://www.isis-online.org/publications/dprk/dprk-plutonium.pdf.

[12] Garwin, R. and F. von Hippel, "A Technical Analysis of North Korea's Oct. 9 Nuclear Test," *Arms Control Today*, November 2006. See http://www.armscontrol.org/act/2006_11/NKTest-Analysis.asp.

[13] J. Carson Mark was the director of the Theoretical Division at Los Alamos National Laboratory, 1947-1972. See, Mark, J. Carson, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, Vol. 4 No. 1, (1993), pp. 111-124.

[14] Robert Oppenheimer discussed a fizzle yield: "The possibility that the first combat plutonium Fat Man will give a less than optimal performance is about 12 percent...and about 2 percent chance that it will be under 1,000 tons. It should not be much less than 1,000 tons unless there is an actual malfunctioning of some of the components." See ibid.

[15] The author had confirmed this with Christopher Hill, chief U.S. negotiator for the Six Party Talks, when he spoke at Harvard's Kennedy School of Government; see also Hecker, Siegfried, "Report on North Korean Nuclear Program", *Policy Forum Online* 06-97A, (San Francisco: Nautilus Institute, Nov. 15, 2006.) See http://www.nautilus.org/fora/security/0697Hecker.html. In addition, some scholars may argue that Pyongyang may have been lying about its design yield to Beijing for various reasons. For example, if lacking confidence in a higher test yield from a larger design yield, Pyongyang may have understated the design yield so that a lower explosive yield would still show the test a success. However, this is unlikely as the lie would have been revealed under several scenarios including an explosive yield near or greater than 4 kt. The balance of the evidence suggests it would have been unlikely for Pyongyang to run such a risk.

[16] Mark, J. Carson, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, Vol. 4 No. 1, (1993), pp. 111-124.

[17] Von Hippel, F. and E. Lyman, "Appendix: Probabilities of Different Yields," *Science and Global Security*, Vol. 4 No. 1 (1993) pp. 125-128.

[18] My estimations are based on the following assumptions: the device contained about 6 kg Weapons-grade Plutonium (WGPu: 6 percent Pu-240); spontaneous fission (SF) neutrons produced at rate of $3*10^5$ /sec; $t_0=10^{-5}$ s (t_0: the time interval through which the system is supercritical prior to completion of the assembly as the shock wave from the high explosive reaches the center); $t=10^{-8}$s (t: the lifetime of a fission neutron); and that the designed yield was 4 kt, as Beijing had been told.

[19] Assuming North Korea used 6 kg of WGPu, with a design yield 4 kt.

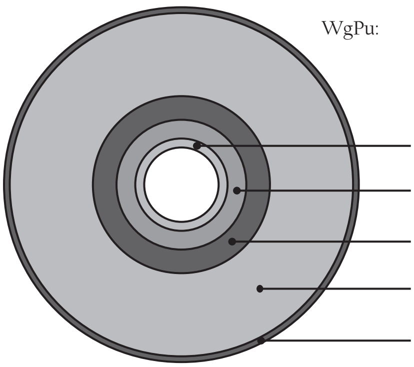
[20] Hecker, Siegfried, "Report on North Korean Nuclear Program," *Policy Forum Online* 06-97A, (San Francisco: Nautilus Institute, Nov. 15 2006.) See http://www.nautilus.org/fora/security/

0697Hecker.html.

[21] It should be noted that there is not an explicit relationship between either warhead weight or size and the warhead yield. However, past nuclear tests by other nuclear states show a rough trend that lower-yield tests could be aimed at pursuing lighter warheads. Here, I assume the possibility that this trend could fit the North Korean test situation. See "Complete List of All U.S. Nuclear Weapons" *The Nuclear Weapons Archive*, Oct. 16, 2006. See http://nuclearweaponarchive.org/Usa/Weapons/Allbombs.html.

[22] Sweden had terminated the program by 1965.

[23] It should be noted that this article assumes that the first North Korean test device was designed with the Nagasaki-type solid core as discussed by Mark (Mark, J. Carson, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, Vol. 4 No. 1, (1993), pp. 111-124), which has no behavioral relationship to the design of the Fetter et al hollow-core design as discussed here: Fetter, S., Frolov, V., Miller, M., Mozley, R., Prilutsky, O., Rodionov, S. and R. Sagdeev, "Detecting Nuclear Warheads," *Science and Global Security*, Vol. 1 No. 3-4, (1990) pp. 225-302. A more consistent approach may be needed to start with the Nagasaki design and try to estimate how much the yield would have been reduced if one reduced the tamper and high-explosive mass. However, we can assume that if North Korea continued to pursue warhead miniaturization, it could develop the Fetter et al hollow-core design in the future.



[24] See, e.g., Li, Bin "Nuclear Missile Delivery Capabilities in Emerging Nuclear States," *Science and Global Security*, Vol. 6 No. 3,(1997) pp. 311-331; Fetter, S., Frolov, V., Miller, M., Mozley, R., Prilutsky, O., Rodionov, S. and R. Sagdeev, "Detecting Nuclear Warheads," *Science and Global Security*, Vol. 1 No. 3-4, (1990) pp. 225-302.

[25] "North Korea Missiles" See http://www.globalsecurity.org/wmd/world/dprk/missile.htm.