Science Background of North Korea's Nuclear Bomb Program
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Historical Introduction

Since the 1960s North Korea has had nuclear fission reactors at its Yongyon facility. Its main reactor is a 5 MWe gas-graphite Magnox reactor, which fissions uranium to produce electricity for normal power consumption, and, as we will describe below, can create plutonium as a byproduct for nuclear weapons.

The existence of a nuclear reactor on North Korean soil might sound alarming on its own, but it was thought in the earlier days of nuclear power that the type of reactors that North Korea had would not be useful for bomb making. The uranium fuel needed for reactor operation has very little fissile U-235, certainly less than needed for a nuclear bomb. Reactor-grade uranium fuel is typically less than 5% U-235, whereas the nuclear bomb safe isotope U-238 accounts for over 95%. North Korea's gas-graphite reactor takes natural uranium as fuel with less than 1% U-235. To enrich the fuel further to the much higher concentrations of U-235 needed to make a bomb requires highly technical centrifuging techniques that separate the U-235 isotope from the U-238 isotope. This is technology and know-how that North Korea on its own did not possess.

An easier path to the bomb for North Korea is through plutonium. North Korea was suspected of working toward that aim in the late 1980s and early 1990s. Confrontation between North Korea and the United States over these suspicions led to the Agreed Framework in 1994, where North Korea agreed, among other things, to stop the reprocessing of nuclear fuel for the purposes of extracting plutonium for bombs, and to grant full inspection rights of the IAEA of North Korea nuclear sites. In exchange the U.S. agreed to provide oil and much needed humanitarian aid, to give North Korea security promises (i.e., the U.S. will not attack them), and to facilitate construction of a new light-water reactor that has much less proliferation concerns.

The 1994 Agreed Framework was voided when it was discovered in 2002 that North Korea had begun a uranium enrichment program [1]. Although uranium enrichment is not explicitly proscribed in the Agreed Framework [2], the U.S. interpreted this activity as a violation[1]. The uranium enrichment program was an attempt to implement the technology that the Pakistani

[1]North Korea says that enrichment was not in direct violation of the Agreed Framework, and that anyway the United States was not living up to its end (e.g., providing a light-water nuclear reactor in a timely fashion) so it is a moot point. Regarding whether enrichment was in direct violation, the Agreed Framework required that North Korea remain party to the Nuclear Non-Proliferation Treaty; however, that treaty does not forbid uranium enrichment. The closest direct statement in the Agreed Framework against uranium enrichment is the statement that "The DPRK will consistently take steps to implement the North-South Joint Declaration on the Denuclearization of the Korean Peninsula"[3]. This document clearly disallows uranium enrichment: "Under the Joint Declaration, the Democratic People's Republic of Korea (DPRK) and the Republic of Korea (ROK) agree not to test, manufacture, produce, receive, possess, store, deploy, or use nuclear weapons; to use nuclear energy solely for peaceful purposes; and not to possess facilities for nuclear reprocessing and uranium enrichment." However, technically speaking, the Agreed Framework does not say that North Korea must abide by all the terms of the Joint Declaration, but rather "take steps". One could interpret this as a failure of U.S.

scientist A.Q. Khan had provided to North Korea in the late 1990's. However, in recent years intelligence suggests that North Korea has not been able to, or has not desired to, put this technology to use [4].

North Korea quickly made their own counter-response by withdrawing from the Nuclear Non-Proliferation Treating, expelling IAEA inspectors and announcing the restart of their reactors and plutonium reprocessing. Several years later North Korea conducted two nuclear bomb tests in 2006 and 2009. These bombs were made of plutonium extracted from the spent nuclear refueling process.

Creating Plutonium in Nuclear Fission Reactors

Unlike uranium, plutonium cannot be mined. It must be created in a nuclear fission reactor. Let us first review the basics of how nuclear fission works.

The fuel of most nuclear reactors, and certainly the ones applicable to North Korea, is uranium. Naturally mined uranium is 99.3% uranium 238 (U-238) and 0.7% uranium 235 (U-235). U-235 is the fissile material that sustains a nuclear chain reaction that powers energy plants and bombs. For nuclear power plants the U-235 concentration often needs "enriching", but generally not above about 6%. On the other hand, uranium for a bomb needs to be enriched to at least 80%, although as low as 20% enrichment can lead to a destructive weapon [5].

When U-235 is bombarded with thermal neutrons it spontaneously fissions into two elements and two or three neutrons. The first element has atomic mass number of around 95 ± 15 and the second element has atomic mass number of about 140 ± 15. The probability distribution for the two lighter elements in thermal fission of U-235 is plotted in fig. 1. The total integrated weight under the curve is normalized to 2, since two decay products must arise for each n+U-235 induced fission.

The binding energy liberated in the fision process generates heat in the reactor core which is then whisked away by cooling fluid to a steam turbine system that converts the energy into electricity. The extra neutrons that are released in the fission of a single U-235 go on to catalyze fusion among other U-235 atoms, thereby sustaining a chain reaction that produces steady energy until the fuel is "spent" or "burned up". Fig. 2 is a picture of this standard nuclear fission process.

Power plant operators are focussed on U-235 fission and will burn the fuel for as long as they efficiently get energy out. However, bomb makers have a different priority. Their priority is to make as much weapons-grade plutonium as they can. We shall comment later on how that changes the burn time of the uranium fuel, but let us first describe how plutonium is made.

Even after enriching natural uranium to contain more U-235, the fuel is still primarily U-238. U-238 is worthless, in a direct sense, for producing energy for the power plant. However, bombarding U-238 with neutrons ultimately produces Pu-239 which is a very coveted bomb

diplomats to cover the bases; nevertheless, few would disagree that it is in violation of the spirit of the Agreed Framework, and U.S. suspension of its obligations under it was not an unreasonable response.

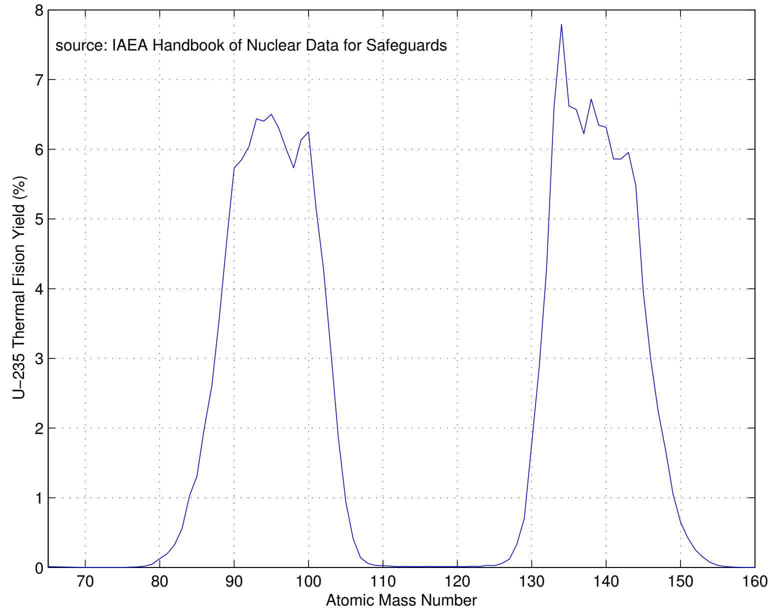

Figure 1: Distribution of atomic mass number of elements produced in thermal U-235 fusion. The plot is obtained from ref. [17]. The distribution is normalized to an integral of 2 since two elements are obtained from each fission.

material. Fig. 3 shows one process by which it is made. First, a neutron is absorbed by U-238 and is converted to U-239. However, U-239 decays within 30 minutes to Np-239 which then decays in about 57 hours to the dangerous Pu-239. These decays are so-called "beta decays", which only means that an electron is also released in the process, as indicated in the figure.

If the goal is to make a bomb, one does not want to fully burn the fuel in the reactor. Continual bombardment of the fuel rods converts Pu-239 to Pu-240 by absorption of an extra neutron. Pu-240 is detrimental to a bomb, because it spontaneously fissions too quickly to enable an explosion covering sufficient material. And since it is not technically possible, or at least technologically extremely problematic, to separate Pu-239 from Pu-240, it is most advantageous for a bomb maker to pull the fuel rods out of the reactor core when there is a lot of Pu-239 and when Pu-240 is not too copious. These are two conflicting requirements, as one needs to run some time for the first wish to come true (lots of Pu-239), but not too long for the second requirement (little Pu-240). Every reactor design has a different optimal fuel burn time for this purpose, but it is always a shorter time scale, even much shorter, than what is desired for pure power generation optimization.

A plutonium bomb can be made with approximately 10 kg of weapons-grade plutonium, and with special techniques only 1 kg is needed [6]. Weapons-grade plutonium is defined to be a plutonium sample with greater than 80% fissile plutonium. Fissile plutonium is Pu-239 and Pu-241. Non-fissile plutonium that exists in the fuel rods are the even number plutonium isotopes Pu-238,240,242. Although it is possible to build a plutonium bomb with a much lower fraction of fissile plutonium, the technological challenge increases dramatically as the fissile plutonium fraction decreases.

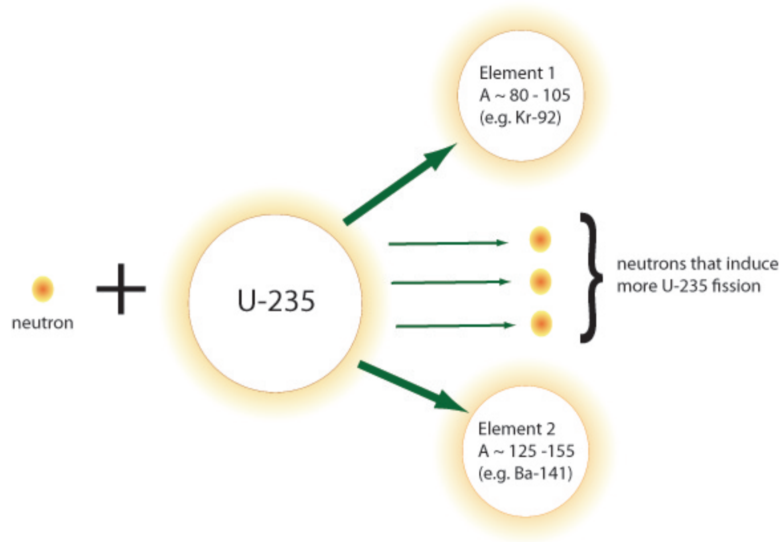

Figure 2: Nuclear fission accomplished by thermal neutron bombardment of U-235, which then spontaneously fissions to two lighter elements, neutrons plus heat that provides energy for power plant operation.

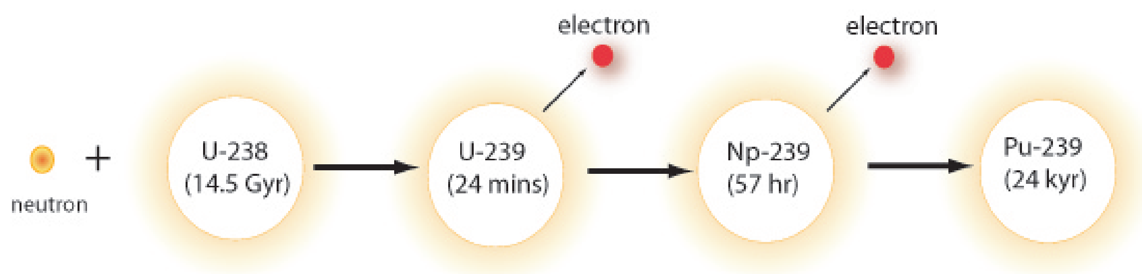

Figure 3: One pathway to create fissile Pu-239 through the irradiation of initial U-238 content in nuclear fuel.

Extracting Plutonium Through Fuel Reprocessing

In order to make a bomb with the plutonium created in the fuel rods of the reactor, the plutonium has to be extracted from the fuel rod. This presents a challenge because the spent fuel rods contain hundreds of other atoms and compounds, from uranium to tritium to barium to krypton to plutonium. Reprocessing the fuel rods according to the standard PUREX process involves several challenging steps [13, 14]: 1) Cut fuel rods open and cut the spent fuel into small pieces, 2) Dissolve the fuel elements in Nitric acid and drain off residues, 3) Put in tributyl phosphate (TBP) solution that binds effectively to uranium and plutonium but not to other fission products, 4) Mix and settle the solution to separate uranium and plutonium from the other fission products, 5) Add more nitric acid and a chemical reducing agent to separate plutonium from uranium.

Reprocessing of spent nuclear fuel can be very dangerous as there are many radioactive elements of differing properties that can be released when the cladding of the fuel rod is breached. Concerns over radioactivity and proliferation are reasons why reprocessing nuclear fuel is illegal for utilities in the United States. Despite the technological challenges involved in chemical reprocessing of spent nuclear fuel, it can be an easier path to a nuclear bomb than uranium. This assessment can only be correct if there is a nuclear reactor already in existence burning uranium fuel into plutonium within the fuel rods. In that case, as is applicable for North Korea, it is less challenging to extract plutonium for a bomb than it is to initiate sophisticated uranium enrichment centrifuging to make a uranium bomb.

Fig. 4 summarizes the steps needed to produce and extract plutonium for a bomb. The upper left panel begins with one metric ton of 3.75% U-235 enriched reactor fuel. Burning this amount of fuel will produce about 10 kg of plutonium, enough to make a nuclear bomb. If the fuel is fully burned for the purposes of optimal power generation for a nuclear power plant, the resulting isotopic and mass content is shown in the upper right box. The resulting Pu-239,241 fissile content is not very high, only 15%, and thus making a nuclear bomb of high yield is extremely challenging. If the fuel is burned for a shorter period of time, less of the non-fissile Pu-238, 240 and 242 is produced, and weapons-grade plutonium can result. This is then extracted from the fuel rods and an effective bomb can be made.

There is evidence that the yield from both of North Korea's nuclear tests was substandard. The yield was probably in the neighborhood of 1 kiloton of TNT equivalent for the 2006 test and perhaps a few kilotons for the 2009 test [11, 12], whereas a fully functional bomb would have yielded up to about 20 kilotons [12][2]. This indicates engineering problems in the construction of the bomb or problems in obtaining high content of fissile Pu-239 and 241 in the fuel. North Korea's problems were probably a combination of both of these. Nevertheless, a several kiloton "fizzle" bomb is very powerful and worthy of tremendous concern.

Detecting Illicit Fuel Reprocessing

The United States claimed that it was able to detect North Korea's illicit nuclear fuel reprocessing program without needing North Korean confessions. Graham Allison, former assitant secretary of defense for policy and plans, says that in the succeedings months after North Korea's pull-out in 2002 of the Nuclear Non-Proliferation treaty "U.S. air sensors along the North Korean border detected krypton-85, a telltale by-product of reprocessing" [10].

The detection of Kr-85 is challenging [7, 8]. A small reprocessing plant that makes 9 kg of plutonium per year releases only about 15 curies of radiation from airborne Kr-85 per day [7]. Two decades ago such a low radioactivity would require sophisticated equipment set up within kilometers of the reprocessing plant [7]. Newer techniques may be able to detect Kr-85 from reprocessing above the background radiation at distances of up to hundreds of kilometers away [8, 9], although best performance is in the southern hemisphere. The true capabilities are surely classified.

As for Allison's description of how U.S. intelligence detected North Korea's program, the

[2]As a comparison, the Nagasaki plutonium bomb dropped over Japan had a core of about 8 kg of plutonium ($>$ 90% Pu-239) and a yield of up to 25 kilotons [15].

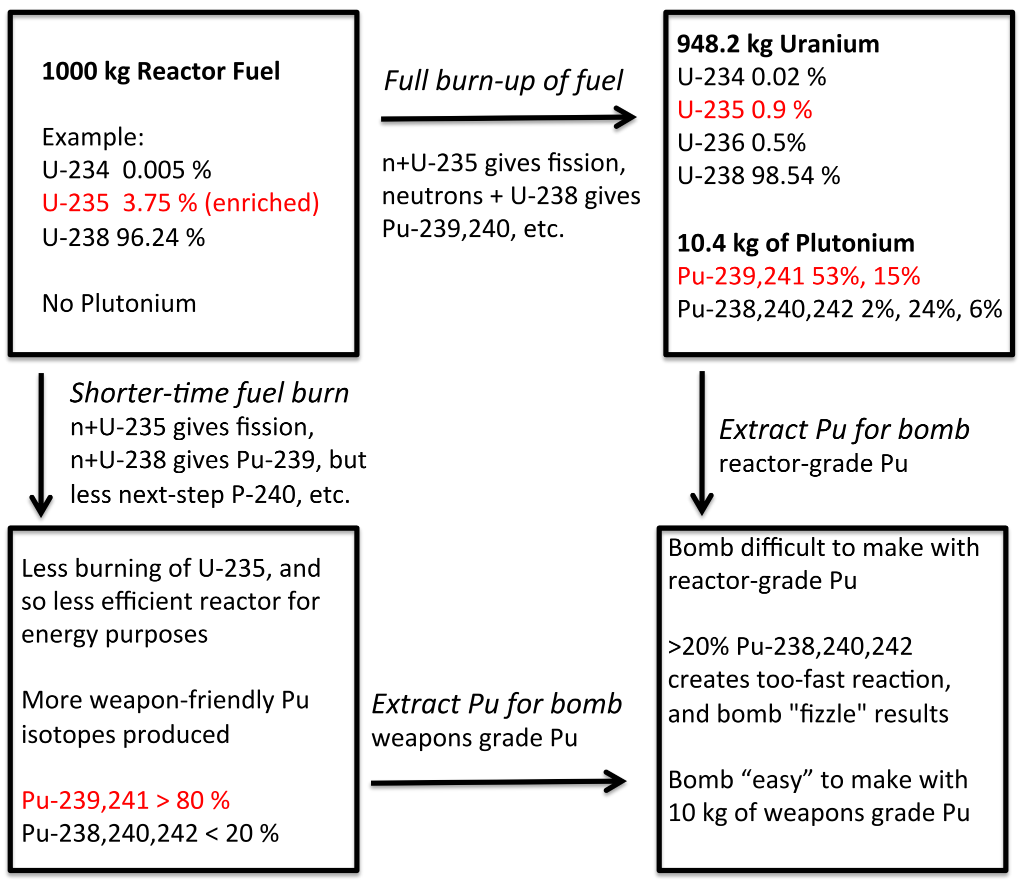

Figure 4: Summary of the steps needed to make a plutonium nuclear bomb. Isotopic and mass contents obtained from ref. [16]. This plot should be viewed as schematic with many details suppressed. For example, the top two boxes are typical numbers for Light Water Reactor (LWR) fuel burning. However, the LWR does not easily allow rapid fuel rod changes, which is why it is less worrisome for proliferation and why the United States proposed to build one for North Korea under the Agreed Framework. On the other hand, rapid, "online refueling" needed to produce significant amounts of Pu-239 is much easier to accomplish through gas-graphite Magnox reactors, for example, which do not require enriched uranium for its initial fuel. This is the type of reactor North Korea has, which the U.S. wanted shuttered. Reprocessing the fuel from that reactor is what enabled them to obtain high-grade plutonium for their nuclear weapons.

border between North and South Korea is 200 km away from the Yongbyon site, which is stretching the capabilities of reliable Kr-85 detection from modest reprocessing activities. Given publicly available information, it is hard to know how U.S. intelligence community could have concluded that a definitive signal of reprocessing for plutonium was achieved from that intelligence alone. Other intelligence indicators, or more reliable (due to proximity) Kr-85 detectors set up nearby, from either clandestine land operations at the facility, or sea-based operations only 50 km away, may have contributed to the evaluation. Nevertheless, given the existence of North Korea's bombs, we have in hindsight high confidence that they did reprocess spent nuclear fuel. Furthermore, North Korea said they were restarting their fuel reprocessing, although statements from North Korea are often not reliable. There are understandable reasons for them to "pretend" to be very advanced in their nuclear bomb making capabilities. How we came to a firm conclusion that they were reprocessing is an interesting separate question.

Current Challenges: New Reactor and Uranium Enrichment

North Korea likely has an arsenal of between 4 to 12 plutonium nuclear weapons [18, 19] achieved through years of reprocessing described above. Developments within the last year indicate that North Korea is well advanced in making its own Light Water Reactor (LWR) nuclear power plant and its own uranium enrichment facilities.

North Korea wants the world to know of their advanced progress, and invited three American scientists to show their work. A report from Siegfried Hecker on this visit [19] to North Korea's nuclear facilities on November 12, 2010 brings up two main concerns. One is the shoddy workmanship and materials for the LWR, which could lead to a reactor accident imperiling the health of its citizens, and the citizens of nearby countries. A second concern is the apparent advanced state of its centrifuge enrichment technology. There is evidence that the plant is less than two years old, but also evidence of long-term activities in uranium enrichment. North Korea surely achieved aid from the outside to get to this level, according to Hecker.

There are multiple risks of allowing North Korea to achieve a high functioning uranium enrichment facility. First, they would be able to dramatically increase their nuclear stockpiles over time. Equally important, they could initiate international trade of highly enriched uranium (HEU). There is concern that they may be willing to sell HEU on the black market to help bolster their dire economic situation – a concern partly born from accusations that they had state-sponsored the production and distribution of heroin [20], at times to find enough cash to support their embassies abroad [10][3]. Selling HEU would be especially concerning since it has a low radiation profile, making it relatively safe to transport and hard to detect, an ideal material to handle for unsophisticated organizations with destructive intentions.

[3]State-sponsored drug peddling appears to be on the wane [21], although it is speculated by some that it is due mostly to increased pressure from China [22], a benefactor that North Korea cannot ignore.

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