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North Korean Plutonium Production

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In 1992, as part of its obligations under the Nuclear Non-Proliferation Treaty, North Korea declared that it had earlier separated abut 100 grams of plutonium from damaged fuel rods removed from a 25 megawatt-thermal (MW_t) gas-graphite reactor at Yongbyon. The plutonium was separated at the nearby "Radiochemical Laboratory." Separated plutonium is the raw ingredient for making nuclear weapons, but 100 grams is too little to make a crude bomb.

Following its inspections of North Korea's facilities, the International Atomic Energy Agency (IAEA) concluded that North Korea had separated more plutonium than it had declared to the Agency. However, the IAEA could not tell if the discrepancy was in grams or kilograms. Based on information gathered by intelligence agencies and IAEA inspections, North Korea may have already separated 6 to 13 kilograms of weapons-grade plutonium, enough for one or perhaps two nuclear weapons.

In spring 1994, North Korea unloaded the 25 MW_t reactor. Our best estimate of the amount of plutonium in this spent fuel is 25±8 kilograms, depending on how the reactor was run and how long the fuel was irradiated. If separated, this amount would be enough for four or five nuclear weapons. As of early October, however, North Korea has kept its June pledge to the U.S. not to separate this plutonium or refuel its reactor.

North Korea is building two more gas-graphite reactors. If completed, these reactors would increase North Korea's capability to make weapons-grade plutonium production by more than tenfold. Because of the danger posed by North Korea's plutonium program, the United States wants North Korea to close its plutonium separation plant and abandon its gas-graphite reactors in exchange for the supply of two light-water reactors. These reactors are more proliferation-resistant than gas-graphite reactors and their associated plutonium separation plant.

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INTRODUCTION

In the past several years, the global community has become concerned about North Korea's nuclear activities. In 1993, the U.S. CIA leaked its assessment that North Korea might have enough plutonium for one or two nuclear weapons. Shortly thereafter, many other analysts announced similar estimates.

However, these estimates may be high because no one would want to underestimate the amount of plutonium the North possesses, or wrongly ascribe the plutonium to a civilian application. Few doubt that the North intended to produce large quantities of plutonium for nuclear weapons, but it is unknown how much was made. Determining the true state of affairs will not be easy and will require a great deal more information from North Korea.

AN UNSAFEGUARDED REACTOR EMERGES

The plutonium at issue comes from a highly secretive nuclear program that started in the 1970s outside any international inspections. In the early or mid-1980s the U.S. intelligence discovered that the North was constructing a small reactor at Yongbyon, a nuclear complex about 100 kilometers north of Pyongyang. This reactor was reported to be between 20 and 30 megawatt-thermal (MW_t), and reliant on gas cooling and graphite for moderation. This type of reactor is ideal for producing weapons-grade plutonium, and it could produce enough weapons-grade plutonium for one nuclear weapon each year.

In response to Western concerns about this reactor, Russia successfully pressed North Korea to sign the Nuclear Non-Proliferation Treaty (NPT), which it did on 12 December 1985. International interest then faded, even after the reactor began operating in 1986. In 1989, however, the press reported the existence of a large, narrow structure at Yongbyon suspected of being a plutonium separation plant.[1] (Although plutonium is produced in nuclear reactors, it must be chemically separated from the irradiated fuel in special facilities before it can be used in nuclear weapons.) Thus, the CIA assumed that the North first produced plutonium in the small reactor, unloaded much of the irradiated fuel in the core, and subsequently separated the plutonium from the fuel in the separation plant.

Reports soon followed that the North was also building a much larger gas-graphite reactor for plutonium production at Yongbyon.[2] These reports mentioned a high-explosive testing site at Yongbyon suspected of being part of a rudimentary nuclear-weapon development program. (Extensive high-explosive testing would be necessary to build a nuclear weapon with plutonium.)

Aggravating the situation was the North's continuing refusal to allow International Atomic Energy Agency (IAEA) safeguards on all its nuclear activities, as required by the NPT. After a few more years of diplomatic wrangling, the IAEA and North Korea finally signed a safeguard agreement on 30 January 1992. It entered into force on 10 April 1992, and the political crisis finally appeared to be subsiding.

INITIAL SAFEGUARDS DECLARATION

On 4 May 1992, North Korea provided the IAEA with its initial report of all nuclear material subject to safeguards. One of the IAEA's first inspection tasks was to verify the information in the North's initial declaration and assess its completeness.

From 11 to 16 May, IAEA Director General Hans Blix led a delegation to North Korea. Among the first sites this delegation visited was the unfinished plutonium separation facility at Yongbyon, which the North calls the "Radiochemical Laboratory." North Korean nuclear officials said that this facility had separated about 100 grams of plutonium in a single campaign in the spring of 1990. They also claimed that the plutonium came from a few damaged fuel rods taken out of the small reactor. The fuel's outer metal casing or "cladding" was damaged during the operation of the reactor, and therefore the fuel was removed from the core.

Following his visit, Blix reported that the Radiochemical Laboratory was about 80 percent complete, but only about 40 percent of the equipment was installed.[3] North Korean officials told the IAEA that the rest of the equipment had been ordered but not yet delivered. Blix said that if the plant were complete, "I have no doubt that it would have been considered a reprocessing plant in our terminology."[3]

During this initial visit, North Korean officials also told the IAEA that their scientists had first separated grams of plutonium in 1975 at the Isotope Production Laboratory. This plutonium was produced in a Russian-supplied "IRT" research reactor that began operation in 1975 and was placed under IAEA safeguards in 1977.

The IAEA delegation also toured three gas-graphite reactors, two of which were unfinished. At Yongbyon, the IAEA delegation visited the small 20–30 MW_t operating reactor and a 200 MW_t (estimated) gas-graphite reactor that was under construction. At Taechon in North Pyongan Province they visited the construction site of a 600–800 MW_t (estimated) gas-graphite reactor. North Korea told the IAEA all three reactors were part of an electricity production program and referred to these reactors by their electrical power, which are 5 megawatt-electric (MW_e), 50 MW_e, and 200 MW_e, respectively. After the IAEA's visit, North Korea extended a standing invitation to IAEA officials to visit any site in the North, even those not included in the initial report.

Inconsistencies Appear

Starting in the summer of 1992, the IAEA began to identify inconsistencies in the North's initial declaration. In particular, the IAEA became suspicious that the amount of plutonium declared was smaller than the actual amount separated in the Radiochemical Laboratory.

During its initial inspections of the Radiochemical Laboratory, the IAEA had collected "samples" of separated plutonium, of material caught up in separation processing steps, and of different types of nuclear waste generated during the various separation operations. According to an IAEA official, the facility operators were willing, but not prepared technically, to take samples from waste temporarily stored at the site. When inspectors asked for samples of the highly radioactive "fission product" waste, North Korean technicians had to improvise to access that waste. North Korean officials told the IAEA that this procedure caused some facility operators to receive excessive doses of radiation.

The samples were analyzed by the IAEA's laboratory at Seibersdorf, Austria, and by the IAEA's affiliated laboratories in Europe and the United States. These analyses uncovered discrepancies from the North's initial declaration and fueled suspicions that the North had separated more plutonium.

One set of analyses contradicted the North's declaration that it separated plutonium during only one campaign in 1990. The analysis was done by measuring the amount of americium-241 in "smear" or "swipe" samples from the "hot" insides of glove boxes at the end of the separation process, where freshly purified plutonium is handled. Since americium-241 is a decay product of plutonium-241, the amount of americium-241 in the samples can indicate the length of time that has passed since the plutonium was originally separated. The IAEA's analyses suggest that there were distinct separation efforts in 1989, 1990, and 1991.

A second inconsistency emerged when the IAEA tried to verify that the declared plutonium and the waste had originated from the same irradiated fuel rods. The IAEA compared the isotopic ratios of the plutonium remaining in several waste samples and glove boxes to the ratios in the separated plutonium. Both the separated plutonium and the trace quantities of plutonium in the waste samples and glove boxes should have had the same ratio of principal plutonium isotopes—239, 240, and 241. It was found that the fraction of plutonium-240 in the waste samples and the glove boxes differed from the fraction in the separated material. This inconsistency implies that additional fuel rods were processed.

This variation in isotopic ratios also revealed a third inconsistency. The IAEA calculated that the irradiation level of the fuel was higher than that claimed by the North. This inconsistency implies that the total amount of separated plutonium is higher than the North declared.

IAEA inspectors developed two possible scenarios to explain the inconsistencies. The first assumed that more fuel from the Russian-supplied research reactor was reprocessed than declared, resulting in, at most, a few tens of additional grams of separated plutonium. The other scenario assumed that additional fuel rods were taken out of the 5 MW_e reactor and reprocessed in the Radiochemical Laboratory, possibly resulting in several kilograms of separated plutonium.

North Korea insisted that virtually the entire first core remained in the reactor. For the North to have separated enough plutonium in the Radiochemical Laboratory to make a nuclear bomb, it would have had to remove much of the fuel in this first core. The North denied all IAEA accusations and accused the IAEA of misunderstanding the situation, but they provided few operating records to support their statements. For example, the North said that the differences in the plutonium isotopic ratios between the waste and product samples could be explained by the 1975 separation of plutonium from IRT reactor fuel. The North said that the waste from this separation had become mixed with the newer waste. With regard to the third inconsistency, it said that the IAEA did not properly account for variations in the irradiation of the spent fuel, leading to an inaccurate estimate of plutonium production.

Some U.S. and IAEA officials believe that a few of the inconsistencies could be explained, if the North's explanation of the reactor's operation is accepted. But others inconsistencies cannot be explained away, particularly those involving measurements in the glove boxes. In addition, intelligence agencies provided the IAEA with other information that further increased its suspicions that the North separated significantly more plutonium than it declared.

Suspect Waste Sites

In the fall of 1992, the IAEA began to receive information from member states on undeclared sites at Yongbyon, namely two camouflaged nuclear waste sites.

Moreover, according to a U.S. official, this information showed that these sites were camouflaged not long before the beginning of the IAEA's inspections.

The IAEA would like to inspect these two sites to determine if they contain radioactive waste generated during the process of separating plutonium. Inspections could prove that North Korea hid plutonium from the inspectors.

U.S. satellite photos taken over many years show what appear to be two camouflaged nuclear waste sites near the Radiochemical Laboratory which are big enough to handle large quantities of liquid and solid nuclear waste. One set of photos shows a suspected outdoor waste facility believed to be associated with the IRT research reactor. In early photos, the facility's layout resembles that of waste sites associated with Soviet-supplied research reactors. These sites have a distinctive pattern of round and square holes in an above-ground concrete structure for liquid and solid nuclear wastes. One Western official said it closely resembled a site in Iraq next to its Soviet-supplied research reactor. Later photos showed the same North Korean site covered by earth and landscaped, effectively hiding it from inspectors and satellite surveillance. The declared nuclear waste site located nearby is new and barely used.

The second suspected site is a building 50 meters long and about 150 meters east of the Radiochemical Laboratory (separated from it by a small ridge). Early photos show a two-story building, but in later photos the building has only one story because dirt has been pushed up around the lower story to turn it into a basement. The pictures also reveal two trenches which had connected the Radiochemical Laboratory with the building, suggesting the laying of pipes between the buildings. The IAEA would like to determine if the basement contains waste tanks holding reprocessing waste from the Radiochemical Laboratory.

In September 1992, before the IAEA received this intelligence information, inspectors visited the one-story building, taking advantage of the North's invitation to visit undeclared sites. During this visit, the inspectors saw what appeared to be a one-story building under military control, but they did not see any evidence of a basement. However, they did not have any inspection equipment that would have enabled them to find a hidden basement.

In late 1992 and early 1993, the IAEA asked the North several times for access to the two potential waste sites. In the case of the one-story building, the IAEA asked for access to the spaces under the floor of the building and permission to take samples from the building's below-ground level. Retracting its earlier offer, North Korea refused to allow inspectors to visit either site, claiming that they were nonnuclear military sites. The North said that the proposed inspections sought to confirm espionage information and would create a precedent for inspecting military sites.

By February 1993, the IAEA and the North had reached an impasse. The IAEA concluded that it could not fulfill its responsibilities under the safeguards agreement to confirm the correctness and completeness of the North's initial report on the inventory of plutonium.

Special Inspections

Faced with North Korea's refusal to resolve the inconsistencies, on 25 February 1993 the IAEA Board of Governors demanded "special inspections" of the two suspected nuclear waste sites at Yongbyon and set a 25 March deadline for the North to accede.

On 12 March 1993, North Korea announced that it was withdrawing from the Nuclear Non-Proliferation Treaty (NPT) under Article X of the treaty, which gives signatories the right to withdraw with three months notice if its supreme national interests are threatened. Then in a bizarre twist, the North suspended its withdrawal from the NPT in early June 1993, just days before its withdrawal would have gone into effect.

For the next year, the North engaged in a series of negotiations with the IAEA and the United States. These negotiations, however, were unsuccessful in ending the crisis, reestablishing safeguard inspections, or verifying the North's initial declaration.

Reactor Defueling

In April 1994, the North announced it had shut down its small reactor in order to refuel the core, which it said would begin as soon as 4 May. U.S. Secretary of Defense William Perry said publicly that this core contained enough plutonium for four or five nuclear bombs.

On 12 May, North Korea informed the IAEA that it had already started unloading the reactor without the safeguards measures the IAEA had requested, precipitating yet another crisis. The IAEA wanted to view the core unloading to ensure that the North did not divert fuel. It also wanted to obtain a few hundred irradiated fuel rods from specific locations in the core to determine whether the fuel had been in the core since the reactor started in 1986, as the North claims.

Although North Korea decided to allow the IAEA to observe the remainder of the fuel unloading, it refused to allow the IAEA to select fuel rods for later measurements. During consultations in Pyongyang from 25–27 May, the

North proposed to the IAEA that it could sample fuel rods after they were placed in the spent fuel pond. IAEA inspectors refused this offer as they would not know which section of the core the rods came from. The IAEA said, "without such identification, future measurements would be meaningless and the Agency's ability to verify non-diversion would be lost."

In a 27 May letter to the members of the United Nations Security Council, Blix reported that, "the fuel discharge operation at the reactor was proceeding at a very fast rate which was not in line with information previously conveyed to the Agency." Blix warned that if the fuel discharge continued at the same rate, within days the Agency would lose the ability to select fuel rods for later measurements in accordance with Agency standards.

Earlier, the North had told the IAEA that it planned to take two months to unload the reactor. Several U.S. and IAEA officials believed the North would take considerably longer to refuel the core. However, Blix said in his 27 May letter that the North had already unloaded almost half of the fuel in the core. The Washington Post reported on 1 June that U.S. officials said the North was using a new, faster unloading machine that was previously unknown to Western intelligence. An IAEA official said that the machine was delivered to the reactor a few weeks before unloading began. Another IAEA official said that the North had also accelerated its unloading rate to 24 hours a day.

On 2 June, the IAEA declared that the rapid unloading had made it impossible to select the desired fuel rods for later measurements. In a 2 June letter to the Security Council, Blix wrote that the IAEA's ability to determine past diversion of plutonium had been "seriously eroded." He added that because of the North's refusal to allow special inspections of the suspect waste sites and its unloading of the reactor core without the IAEA's required verification measures, the IAEA, "cannot achieve the overall objective of comprehensive safeguards in [North Korea], namely, to provide assurance about the non-diversion of nuclear material."

Because of the North's actions, the U.S. government announced on 3 June that it was breaking off bilateral negotiations with North Korea and moving to impose U.N. Security Council sanctions. One week later, however, the United States was struggling to develop a sanctions resolution that could overcome Chinese and Japanese opposition. As a result, the United States shifted to an alternate strategy that sought support for a gradual imposition of sanctions. A vote in the Security Council, however, was not expected for several weeks.

On 10 June, the IAEA Board of Governors moved to impose its own sanctions by voting to suspend about $250,000 per year in technical aid to North Korea. In response, the North formally withdrew from the IAEA. Its withdrawal from the IAEA, however, did not nullify its commitment to allow IAEA inspections required under the NPT. Despite the escalation in tensions, North Korea permitted IAEA inspectors to maintain their watch of the spent fuel. By this time, almost all the fuel had been discharged from the reactor and stored in a nearby spent fuel storage pond.

Fearing that economic sanctions would only increase the likelihood of war on the Korean Peninsula, former President Jimmy Carter went to North Korea to mediate an end to the crisis with its leader Kim Il Sung. An immediate result of Carter's personal diplomacy with Kim Il Sung was that the negotiations were resumed.

Following Carter's visit, President Clinton announced on 22 June that North Korea had agreed to "freeze" its nuclear program, effectively ending the latest standoff over the North's nuclear program. In return, Clinton said that the United States would suspend its drive to impose sanctions on North Korea and would resume its bilateral negotiations with the North to resolve the nuclear issues.

The freeze announced by the North included a commitment not to reload the small reactor with fresh fuel or to reprocess the discharged fuel while bilateral negotiations were proceeding. The North also agreed that IAEA inspectors could remain at Yongbyon to verify that reloading or reprocessing did not occur. The North also agreed to maintain the "continuity of safeguards," a commitment it had made many times in the past but it did not agree to allow the IAEA to determine if it diverted any plutonium in the past.

The sudden death of Kim Il Sung on 8 July has complicated the situation. Nevertheless, the United States and North Korea reached an agreement on 12 August that: (1) reaffirmed the North's commitment to maintain the freeze on its nuclear program while bilateral negotiations proceed; and (2) established a list of elements that should be included in any final resolution of the nuclear issue. These elements include replacing its two larger gas-graphite reactors with modern, more proliferation-resistant light-water reactors financed with Western assistance, foregoing reprocessing, verifiably sealing the Radiochemical Laboratory, and remaining a member of the NPT.[4]

Although tensions have been reduced, as of the end of September a final settlement is far from realization. North Korea continues to mistrust both the United States and South Korea. Following Kim Il Sung's death, the Carter-brokered meeting between the heads of North Korea and South Korea was indefinitely postponed, eliminating hopes for a quick reduction in tensions on the peninsula. The question of the North's past plutonium diversion is no closer to resolution, despite North Korea's stated intention to remain in the NPT. Because the recently discharged fuel is difficult to store safely, technical reasons may make it more difficult for North Korea to maintain its no-reprocessing pledge for long. Likewise, the desire for electricity may lead North Korea to refuel the small reactor.

PLUTONIUM-PRODUCTION REACTORS

The small operating reactor and the two under construction use a design that depends on carbon-dioxide gas cooling and graphite moderation. In the West, this type of reactor is called a "magnox" reactor or a gas-graphite reactor.

Britain and France developed this type of reactor in the 1950s to make plutonium for nuclear weapons and to produce electricity. Designs of this type of reactor are largely unclassified, and the reactors are fairly easy to build. The North appears capable of building this type of reactor without significant foreign assistance.

The disadvantage of this type of reactor is that it discharges irradiated spent fuel that typically requires plutonium separation. The spent fuel is difficult to store safely for an extended period or to dispose of in a geological repository. The outer casing of the North's fuel uses a magnesium alloy. This type of cladding breaks down when exposed to moisture and the radioactive material escapes. Under certain conditions, the uranium metal spontaneously burns when exposed to air. If the fuel burns, a significant fraction of the radioactive materials can be released into the environment (see "North Korea's Corroding Fuel" in this issue).

20–30 Megawatt-Thermal Reactor

Construction of the reactor at Yongbyon started in 1980, and the reactor began operation in 1986.[5] Although estimates of its total power vary between 20 and 30 MW_t, a midpoint of 25 MW_t is used in subsequent discussions. According to U.S. officials, the reactor had start-up problems during its first few years of operation, although by 1990 or 1991 they say it was operating at 20–30 MW_t. One official added that U.S. intelligence agencies do not know precisely the power output of this reactor during its first several years of operation.

This reactor produces weapons-grade plutonium. Although the fuel remains in this reactor for several years, the total irradiation of the discharged fuel is small. However, the fuel is irradiated long enough to ensure that sufficient weapons-grade plutonium is produced to warrant recovery. The level of irradiation is measured in terms of "fuel burn-up," or the total amount of energy extracted per tonne of fuel. The units of burn-up are megawatt-thermal-days per tonne of fuel (MW_t-d t^{-1}).

The North's reactor must first be shut down before the fuel can be unloaded. Prior to being unloaded, the reactor core contained about 48 metric tons of natural uranium fuel. The fuel is in the form of short fuel rods; each is roughly 50 centimeters long and 3 centimeters in diameter, and has a mass of about 6.2 kilograms. The core contained a total of about 7,700 fuel rods, located in 812 fuel channels in the core. Each channel can hold up to 10 fuel rods stacked one on top of the other. According to a U.S. official, the reactor is designed to hold a total of about 8,000 fuel rods, but the reactor contained fewer than the maximum because damaged rods had been removed earlier. The fuel unloading machine refuels the reactor through the top of the core.

Maximum Possible Plutonium Production Estimate

The annual weapons-grade plutonium production of this type of reactor can be represented by the following equation:

$$\text{plutonium} = P \cdot C \cdot 365 \text{ days} \cdot 0.9 \times 10^{-3}$$

P is the reactor's thermal power in MW_t; C is the capacity factor, which represents the ratio of the total annual heat output to the annual heat output based on continual full-power operation. This ratio is often stated to be the fraction of the year that the reactor operates at full power. The last factor in the equation is a standard plutonium conversion factor for a gas-graphite reactor when the plutonium is weapons-grade (less than six to seven percent plutonium-240 + plutonium-242). This conversion factor can vary by up to 10 percent, depending on the specific isotopic composition of the weapons-grade plutonium.[6] Weapons-grade plutonium would correspond to burn-ups less than about 800 to 1,000 MW_t-d t^{-1}.

Using this formula, a maximal estimate can be derived by assuming that the reactor operated at full power an average of 80 percent of the time. Such consistent operation is probably at the limit of this reactor's capability. Actual reactor operating time might be significantly less, especially during startup.

When operating at a thermal power of 25 MW_t an average of 80 percent of the time, this equation shows that the reactor can produce about 6.6 kilograms of weapons-grade plutonium per year. If the small reactor operated consistently at this capacity factor for eight years (from 1986 until the spring of 1994), it could have produced 53 kilograms of weapons-grade plutonium. (To achieve this, the reactor must have been unloaded at least once before the May/June 1994 refueling.) Few, however, believe that this reactor has operated consistently at such a high capacity factor.

Maximum Possible Spent Fuel Discharge: 1989 Refueling

Another type of worst-case estimate assumes that the North unloaded the first core several years ago, but that the reactor did not operate as well as assumed in the previous scenario.

In December 1993, the public learned about a long shutdown of this reactor that could have enabled the North to unload some or all of the fuel in the reactor core. Secretary of Defense Les Aspin said 7 December on the MacNeil/ Lehrer News Hour that,

> in 1989 the North Koreans shut down their reactor for 100 days, and that would have given them enough time [to extract some fuel] . . . Depending upon how much plutonium they processed and their capabilities of putting that together into a bomb, they might have gathered enough plutonium for a bomb, maybe a bomb and a half at the outside, perhaps.

A U.S. official said in June 1994 that Aspin's 100-day statement was an order of magnitude estimate of the length of the reactor shutdown. He said that the actual length of the shutdown was significantly less, closer to 70 days.

Estimating the amount of fuel (and the contained plutonium) that the North could have unloaded from the core during the 1989 shutdown requires several pieces of information. Since much of this information is unknown, any estimate is highly uncertain. The most important information is whether North Korea had one or two refuelling machines in 1989.

Based on a comparison with British Calder Hall reactors, a 70-day shutdown might have provided only enough time to unload about half the core.[7] Before this recent reloading, the North told the IAEA that it would take about two months to change the core. However, with two machines unloading the fuel, the North took less than one month to unload almost all the fuel in spring 1994.[8] In summary, these estimates imply that at least one-half of the core could have been unloaded in 1989, or roughly 25 to 50 tonnes of spent uranium fuel.

The plutonium concentration in the irradiated fuel is derived from information about average fuel burn-up. The average irradiation level of fuel discharged in 1989 can be estimated from information gathered by the IAEA during its initial inspections at the Radiochemical Laboratory. The plutonium in the samples taken by the IAEA had isotopic compositions of slightly more than 97.5 percent plutonium-239, equivalent to about 2.25 to 2.5 percent plutonium-240. Based on unclassified U.S. government studies of gas-graphite reactors, irradiated fuel that contains such a fraction of plutonium isotopes has an average burn-up of roughly 300 to 330 MW_t-d t^{-1}. Fuel with this burn-up contains about 0.27 to 0.30 kilograms of weapons-grade plutonium per tonne of uranium fuel.[6] In subsequent calculations, the midpoint of this range is used.

If the values calculated above represented the average burn-up of all the fuel in the core in 1989, the 50-tonne core would contain about 14 kilograms of weapons-grade plutonium. To produce 14 kilograms of plutonium in the core, the reactor would have had to operate at the equivalent of 25 MW_t about 55 percent of the time from 1986 through 1989. According to a U.S. official, the reactor operated poorly during its first year and a half of operation. Afterward, it gradually approached its nominal power.

If only 25 tonnes of fuel were discharged in 1989, then this fuel contained an estimated seven kilograms of plutonium, assuming the same average burn-up as above for the discharged fuel. In this case, the burn-up of the fuel remaining in the core is likely to be significantly less than the average burn-up of the discharged fuel. Reactor operators typically remove the higher burn-up fuel first if they are unloading only a portion of the core, because this fuel contains a higher concentration of plutonium.

According to a U.S. official, the average burn-up of all the fuel in the core in this case would have been only 200 MW_t-d t^{-1}. At this average burn-up, the core would have contained in total about 10 kilograms of plutonium. This amount in the core corresponds to the reactor operating at 25 MW_t about 35 to 40 percent of the time since it started.

An average burn-up of only 200 MW_t-d t^{-1} is consistent with the available information about the reactor's operation in its early years. Under normal conditions, burn-ups vary greatly depending on the location of the fuel in the core. The burn-up of fuel in the center of the core is several times greater than near the periphery. In addition, according to an IAEA official, the North said that the fuel irradiation had not been symmetrical in the core during the first years of the reactor's operation. This official said that the control rod pattern, which determines the irradiation level or "neutron flux" in different regions of the core, was asymmetrical, depressing the neutron flux on one side of the reactor. In addition, chemical impurities in the fuel might have also caused significant asymmetries in the neutron flux in the core. Although North Korea has given the IAEA this information, it has not provided operating records to substantiate these claims.

In any case, based on information collected by the IAEA, the 25 to 50 tonnes of fuel possibly discharged in 1989 contained between 7 and 14 kilograms of weapons-grade plutonium.

Minimum Spent Fuel Discharge

A lower bound on the amount of plutonium is that which could be extracted from those fuel rods which North Korea declared damaged, removed, and reprocessed. The North has declared that it processed some fuel rods in the Radiochemical Laboratory. These rods reportedly contained a total of about 0.13 kilograms of plutonium, of which about 0.09 kilograms were recovered. The rest went into the waste or processing equipment. Using the above assumptions, this amount of plutonium would correspond to a total of about 450 kilograms of uranium fuel, or about 70 damaged fuel rods.

Spring 1994 Refueling of the Core

In April 1994, the North shut down the small reactor for refueling. U.S. and IAEA estimates of the amount of plutonium in the core vary between about 20 and 30 kilograms of weapons-grade plutonium. Under the previous assumptions about the fuel irradiation levels, this core would contain about 10 to 14 kilograms of weapons-grade plutonium. However, the irradiation levels of the current fuel rods are believed to be significantly higher than they were for fuel in 1989. If this core is the first one, the fuel would have been in the reactor for eight years, which would imply a higher burn-up. If this is the second core, the fuel would have been in the core since 1989, which also implies a higher fuel burn-up because the reactor is believed to have operated significantly better after 1989.

If the average burn-up of the fuel approaches a maximal value for weapons-grade plutonium production in this type of reactor, the burn-up would be roughly 800 MW_t-d t^{-1}.[6] In this case, the core would contain about 33 kilograms of weapons-grade plutonium (5.6 percent plutonium-240).[6] To produce this amount of plutonium, the reactor would have had to operate at 25 MW_t for a total of about 1,600 full-power days. If this core is the first one, the reactor would have operated at this power for an average of 55 percent of the time from 1986 to 1994. If this was the second core, the reactor would have operated at 25 MW_t for about 85 percent of the period from 1989 until 1994. The latter situation is probably not credible.

At the lower bound for the amount of plutonium in this fuel, an average burn-up of 400 MW_t-d t^{-1} is at the lower end of burn-ups that are typical for this type of reactor when it has been operated to make plutonium for weapons. At this burn-up, the core contains about 17 kilograms of weapons-grade plutonium (about three percent plutonium-240). To produce this amount of plutonium, the reactor would have operated at 25 MW_t for a total of about 800 full-power days. If this core is the first one, the reactor would have operated at this power for an average of 25 percent of the time from 1986 to 1994. If this was the second core, the reactor would have operated at 25 MW_t for 45 percent of the period from 1989 until 1994. Both scenarios appear to underestimate actual reactor performance, and imply that this average burn-up represents a lower bound for the core. The midpoint of these estimates is 25 kilograms (burn-up of 600 MW_t-d t^{-1}, 4.3 percent plutonium-240). The uncertainty in this estimate is about 30 percent.

Reactors Under Construction

200 MW_t Reactor

The North is building a 200 MW_t (50 megawatt-electric) gas-graphite reactor at Yongbyon, although its future is in doubt following the 8 August agreement to replace it and the larger one by light-water reactors. The earliest possible start-up date is late 1995, although Secretary of Defense William Perry stated recently that the reactor will take a few more years to complete.[9] Historically, the pace of construction has varied for many reasons, including the availability of concrete. If the North decided to speed construction; however, Western intelligence agencies believe it could do so.

The reactor building, according to inspectors, is largely finished, although the inside requires more work. According to a U.S. official, the North started installing generating equipment in this reactor just prior to the beginning of IAEA inspections.

Many analysts believe that the North originally intended this reactor to be its main source of plutonium for its nuclear weapon program, while the small reactor would have provided plutonium for only the first few weapons. Using the earlier formula, a 200 MW_t reactor, operated an average of 60 to 80 percent of the year at full-power, could produce about 40 to 53 kilograms of weapons-grade plutonium per year. This amount is sufficient to make eight to ten implosion-type weapons per year. However, this estimate has a high degree of uncertainty.

600–800 MW_t Reactor

The North might also complete a 200 MW_e gas-graphite reactor of the same design at Taechon. The IAEA was told in 1992 that this reactor could be finished in 1996.[9] The thermal power of this reactor is estimated to be about 600–800 MW_t. A mid-point of 700 MW_t is assumed in this discussion. If the reactor were operated to produce weapons-grade plutonium at a capacity factor of between 60 and 80 percent, it could produce about 140 to 180 kilograms of weapons-grade plutonium per year.

However, few believe that this reactor is intended to produce weapons-grade plutonium for nuclear weapons. This reactor is probably optimized to produce electricity, meaning that the reactor would produce plutonium that is not weapons-grade. However, it could serve as a backup production reactor if the other reactors did not produce enough weapons-grade plutonium. If this reactor were optimized for electricity production and had a capacity factor of 60 to 80 percent, it could produce about 90 to 120 kilograms of plutonium (76 percent plutonium 239) per year.[10] The plutonium production rate is lower in this case because the fuel is exposed to many more neutrons, resulting in a significant amount of plutonium fissioning.

How Much Plutonium Could North Korea's Reactors Produce in the Future?

The amount of plutonium that North Korea accumulates in the future depends principally on whether its two larger gas-graphite reactors are completed and operating reliably. The following estimate of future plutonium accumulation assumes that all three of North Korean reactors operate.

The most straightforward projection relies on the earlier equation that calculates annual plutonium production in terms of the reactor power, its capacity factor, and a fixed plutonium conversion factor. In this estimate, a capacity factor of about 60 percent is applied to each reactor. This value is close to the average historical capacity factor for all the worlds' commercial gas-graphite reactors.

This projection assumes that the 200 MW_t reactor under construction will start operation in 1997, and the 600–800 MW_t reactor will start in 1998. In both cases, these start-up dates are somewhat later than those the North has provided to the IAEA. During their first three years of operation, their power is assumed to increase linearly to full power.

For the 25 MW_t and 200 MW_t reactors, the grade of the plutonium is assumed to be weapons-grade. At a 60 percent capacity factor, the two reactors would produce 5 and 40 kilograms of weapons-grade plutonium, respectively, each year at steady state. The largest reactor is assumed to have an average power of 700 MW_t and to produce reactor-grade plutonium. This reactor would produce about 90 kilograms of reactor-grade plutonium per year at steady state.

Table 1 shows that through the year 2010, North Korea could produce

Table 1: Estimated cumulative North Korean production of plutonium in three gas-graphite reactors.[a]

Year	25 MW_t (5 MW_e)	200 MW_t (50 MW_e)	700 MW_t (200 MW_e)	Cumulative total
	kg	kg	kg	kg
end 1994	25[b]	—	—	25
1995	30	—	—	30
1996	35	—	—	35
1997	40	13	—	53
1998	45	40	30	115
1999	50	80	90	220
2000	55	120	180	355
2001	60	160	270	490
2002	65	200	360	625
2003	70	240	450	760
2004	75	280	540	895
2005	80	320	630	1,030
2006	85	360	720	1,165
2007	90	400	810	1,300
2008	95	440	900	1,435
2009	100	480	990	1,570
2010	105	520	1,080	1,705

a. This table estimates total plutonium production. The 25 MW_t and 200 MW_t reactors are assumed to discharge weapons-

b. Ignored is any plutonium discharged prior to 1994.

about 1,700 kilograms of plutonium. If only the two smaller reactors are considered, they could produce a total of about 625 kilograms of weapons-grade plutonium through 2010, or enough plutonium for about 125 nuclear weapons.

PLUTONIUM SEPARATION

Producing plutonium is only the first step in making a nuclear weapon. The plutonium must be chemically separated from the irradiated fuel. During processing, some fraction of the plutonium is lost in waste. The North has worked on separating plutonium for many years, and its knowledge of plutonium chemistry appears extensive.

Early Efforts

IAEA Director Blix told the U.S. House of Representatives' Committee on Foreign Affairs on 22 July 1993 that the North did "experiments quite a number of years ago in which they identified plutonium." U.S. officials say the North's early lab-scale plutonium separation was done in "hot cells," which are lead-shielded rooms with remote handling equipment for examining and processing radioactive materials. The Soviet Union supplied the hot cells during the 1960s or 1970s as part of a deal to supply an IRT research reactor. According to IAEA officials, the North orally declared to the IAEA that it separated grams of plutonium from irradiated fuel from its IRT reactor in 1975. This campaign occurred before the IAEA applied safeguards to the IRT reactor in 1977.

North Korea told the IAEA during its initial visit in May 1992 that it had shifted from laboratory experiments to an industrial-scale plant without building a pilot plant. North Korea told the IAEA that it has often followed such a course of action in its industrial development. Although Western officials believe that North Korea could have jumped from hot cells to industrial-scale production, questions remain about the developmental history of North Korea's plutonium separation program. In particular, some believe that the North operated a pilot separation plant which the IAEA and intelligence services have not discovered.

Radiochemical Laboratory

The plutonium-separation plant under construction at Yongbyon is sizable—180 meters long and six stories high. U.S. officials estimate that this facility could theoretically process up to several hundred tons of spent fuel per year when fully operational. Its eventual capacity is believed sufficient to handle all the spent fuel from the three gas-graphite reactors.

The North is suspected of having obtained important technology abroad. Basic knowledge about reprocessing technology and chemistry is reported to have come from Russia and perhaps China many years ago. An inspector stated that the Radiochemical Laboratory looked similar to the Eurochemic reprocessing facility that operated in Belgium from 1966 until the mid-1970s. Information about this plant has been largely declassified.

Some reprocessing chemicals are reported to have come from abroad. In addition, The Washington Post reported on 2 April 1994 that the North obtained stainless steel tanks from Japan. North Korea is also thought to have imported leaded glass for its hot cells and zirconium for its fuel cladding.

Despite these imports, the North is unlikely to have depended significantly on imports to build its gas-graphite reactors or plutonium separation capabilities, as countries such as Iraq have done. The North values self-reliance and suffers a severe shortage of funds.

First Line

In 1992, the Laboratory had one operating "line" which included equipment to dissolve the fuel, extract the plutonium, and purify the plutonium. According to one inspector, as of the end of 1992 the facility's waste reduction processing section was not finished.

There is little information on the current capacity of the first line to process spent fuel, but most believe that the capacity is large enough to have processed all the fuel in the core of the small reactor before inspections started. A preliminary estimate of this line's nominal annual capacity can be derived by assuming that the first line is sized to process all the fuel from the 25 MW_t and 200 MW_t reactors. As part of defining a nominal or maximal capacity for the first line, the following are assumed:

- the reactors produce weapons-grade plutonium;
- the reactors achieve a capacity factor of 80 percent; and
- the reprocessing line is large enough to handle the situation where the fuel burn-up is only 400 MW_t-d t^{-1}, corresponding to a maximum spent fuel output of the reactors.

In this scenario, the line would need to be able to process on average about 160 metric tons of fuel per year.[11] If this estimate is accurate, the first line could reprocess the recently discharged 48 tonnes of spent fuel from the 25 MW_t

reactor in as little as 3.5 months. This estimate represents the shortest time to reprocess this fuel. The actual throughput of this plant could be considerably less, in which case the plant would require more time to process a given quantity of fuel.

If the expected fuel burn-up is 600 MW_t-d t^{-1}, the nominal throughput of the first line would be 110 tonnes a year. In this case, the line could reprocess all the recently discharged fuel in about five months.

No plutonium separation process is 100 percent efficient. Although the North declared that it separated about 90 grams of plutonium, it also declared that it had lost about 40 grams of plutonium to the various waste streams. A loss rate of 30 percent is high, but possible when first starting a plant. The operators, however, should have been able to reduce the plant's plutonium losses. Only a 10 percent loss rate is therefore applied to the plutonium processed in the Radiochemical Laboratory under the above worst-case estimates.

The Second Line

The IAEA first learned about the second line during its initial inspections in 1992. During an IAEA inspection in March 1994, inspectors were surprised to see a nearly completed second separation line at the Radiochemical Laboratory.[12] The North had not allowed inspectors to adequately inspect the Radiochemical Laboratory since the spring of 1993. Nevertheless, IAEA inspectors had not thought that significant construction activity was happening.

According to IAEA officials, at the time of the March inspection, steel components had been installed, but the instrumentation had not. U.S. intelligence officials said in the summer of 1994 that plutonium separation had not occurred in the second line.

This line is nearly identical to the first line, and, therefore when finished, would roughly double the capacity of the separation plant, sufficient for the 600–800 MW_t reactor. Alternatively, the second line could be a backup to the first line, in case it fails. Such redundancy is common in newer plutonium separation plants.

HOW MUCH PLUTONIUM DOES NORTH KOREA HAVE?

Plutonium from a Possible Core Unloading in 1989

A lower bound on plutonium separation would equal the North's declaration of 100 grams of separated plutonium. The most credible upper-bound estimate is roughly 7 to 14 kilograms of weapons-grade plutonium that may have been discharged from the core of the 25 MW_t reactor in 1989. In this case, the fuel would have been processed during 1989 to 1991, and most of the plutonium extracted. If 90 percent of the plutonium was recovered, a total of 6 to 13 kilograms of separated plutonium would have been recovered.

A nuclear weapon can require up to 10 kilograms of separated weapons-grade plutonium. This quantity is about double the amount needed in the device because plutonium is lost at each step in the manufacturing process. However, most of this plutonium can be recovered. The North might have enough separated plutonium for one and perhaps two nuclear weapons.

Plutonium from the Spring 1994 Core Unloading

Regardless of whether North Korea unloaded more fuel than it declared to the IAEA, the spent fuel unloaded in spring 1994 contains an estimated 25 kilograms (±30 percent) of weapons-grade plutonium.

North Korea may have enough plutonium in this spent fuel for four or five nuclear weapons. This plutonium, however, is in irradiated fuel and must first be separated before it could be used in nuclear weapons. As of late September 1994, the IAEA and several governments were satisfied that this has not happened.

North Korea could have reprocessed this fuel almost as soon as it was discharged from the reactor, since this fuel does not have a high burn-up. Ideally, they would wait two to three months to allow the short-lived radionuclides to decay. Otherwise, the processing of the fuel could pose a radiation risk to the workers and the people in the surrounding area. However, governments sometimes disregard this risk. For example, in 1949 the United States processed fuel from the Hanford weapons-grade plutonium production reactors five days after the fuel was discharged from the reactor. The authorities decided not to inform the surrounding population about the radiation releases.

HAS NORTH KOREA BUILT NUCLEAR WEAPONS?

The CIA could not confirm or deny that North Korea had a nuclear explosive device, but they felt sure that North Korean scientists had not received any training in nuclear weapon technologies from Russia or China. The CIA has estimated that the North could have only a first-generation implosion design. It estimates that the mass of a device within the North's capabilities would probably be greater than 500 kilograms but less than 1,000 kilograms.

Although there is little direct evidence, U.S. intelligence officials believe that North Korea has clandestine nuclear weapons manufacturing sites, and several indicators support this opinion.

One indicator is North Korea's high-explosives testing at Yongbyon. North Korean officials explained to the IAEA that they were using high explosives to shape metals. This is plausible because several countries are pursuing this technique with metals that cannot be shaped conventionally. However, the North has also reportedly shown an interest in acquiring instrumentation for conducting nonnuclear tests associated with a nuclear weapon program. Usually these tests involve high explosives.

Little is known about how North Korea might deliver a nuclear device. Delivery by aircraft is possible, but air defenses in North Asia are substantial and would pose a serious threat to any North Korean aircraft. However, the North could deliver a nuclear device by ship or truck.

According to CIA assessments, a North Korean device would not fit on a SCUD missile, but it could fit on the Rodong missile which the North is currently developing. This missile, which was first flight-tested in late May 1993, has an estimated range of over 1,000 kilometers. However, this missile is reported to be a few years from deployment.

CONCLUSION

Based on intelligence reports and IAEA inspections, North Korea may have separated enough plutonium for a nuclear weapon. Regardless of whether this is true, there is no doubt that North Korea has enough weapons-grade plutonium in spent fuel to make four or five nuclear weapons. But it cannot turn this plutonium into nuclear weapons unless it separates the plutonium from the spent fuel. Preventing the North from separating any more plutonium must remain a global priority. The IAEA must also be able to verify North Korea's past nuclear activities and determine the amount of plutonium North Korea may have diverted in the past.

NOTES AND REFERENCES

1. See, for example, John J. Fialka, "North Korea May Be Developing Ability to Build Nuclear Weapons," Wall Street Journal, 19 July 1989, p. A16.

2. See Joseph S. Bermudez, "N. Korea—Set to Join the Nuclear Club?", Jane's Defence Weekly, 23 September 1989, pp. 594–597; and Joseph S. Bermudez, "North Korea's Nuclear Programme," Jane's Intelligence Review, September 1991, pp. 404–411.

3. IAEA, "Transcript from the Press Briefing by Dr. Hans Blix, Director General of the IAEA," Beijing Hotel, Beijing, 16 May 1992.

4. Agreed Statement Between the United States of America and the Democratic People's Republic of Korea, Geneva, 12 August 1994.

5. So Yong-ha, "Capacity for Nuclear Weapons Development," [in Korean] Hoguk (Seoul), July 1989, pp. 119–122. English translation in Foreign Broadcast Information Services, FBIS-EAS-89-148, 3 August 1989, pp. 23–26; and "Transcript from the Press Briefing by Dr. Hans Blix," op. cit.

6. S.E. Turner et al., Criticality Studies of Graphite-Moderated Production Reactors, report prepared for the U.S. Arms Control and Disarmament Agency, SSA-125 (Washington, D.C.: Southern Sciences Applications, January 1980).

7. The North Korean gas-graphite reactors are similar in design to the British Calder Hall reactors. Each of these reactors had an initial design power of 180 MW_t and used off-line refueling. Each reactor had two discharging and two charging machines, and refueling took six weeks [IAEA, Directory of Nuclear Reactors: Vol 1. Power Reactors (Vienna: IAEA, 1959), pp. 125–130]. The core contained 127 tonnes of natural uranium in about 10,200 fuel rods where each fuel rod was about 100 centimeters long and 3 centimeters in diameter. Based on this information, each Calder Hall discharging machine could remove about 1.5 tonnes of fuel each day, or about 120 rods per day. Assuming a similar fuel rod unloading rate for the North Korean discharge machine, the North would have needed about 65 days to unload all 48 tonnes of fuel (a rate of 0.75 tonnes per day). It takes longer to unload the North Korean reactor according to this estimate, because the North Korean reactor is assumed to have had only one fuel unloading machine in 1989 and has about 80 percent as many fuel rods as a Calder Hall reactor. If the North had only one machine in 1989, the core would have been reloaded with this same machine. Assuming that reloading took from half as long as long as unloading, the North could have changed the core in about 100 to 130 days. If the 1989 shutdown lasted 70 days, roughly one-half to two-thirds of the core could have been changed. Without more specific information about the North Korean discharge machine, however, this estimate is highly uncertain.

8. According to an IAEA official, North Korea started unloading the fuel about 10 May and finished unloading the bulk of the fuel by 15 June. A few of the fuel rods were stuck in the reactor channels, and these rods took several more days to unload.

9. Transcript from the Press Briefing by Blix, op. cit.; and "Remarks by Secretary of Defense William Perry to the Asia Society: U.S. Security Policy in Korea," National Press Club, Washington, D.C., 3 May 1994.

10. This estimate assumes a burn-up of 4,000 MW_t-d t^{-1} and a plutonium conversion factor of about 0.6 grams plutonium per MW_t-d. Under these conditions, the reactor would discharge on average about 40 to 50 tonnes of fuel each year.

11. This estimate is derived by dividing the average burn-up into the total annual energy output of the two reactors, where the capacity factor is 80 percent. The equation is: $[(200\ MW_t + 25\ MW_t) \cdot 365\ \text{days} \cdot 0.8] / 400\ MW_t\text{-d}\ t^{-1}$.

12. M. Hibbs, "Second, Hidden Reprocessing Line Feared Opened at Yongbyon Plant," Nucleonics Week,24 March 1994.

SIDEBAR: DATING PLUTONIUM SEPARATION

To verify North Korea's statement in its initial safeguards declaration that it had separated plutonium in the Radiochemical Laboratory only during one short period in 1990, the IAEA adopted a new safeguards tool that had been developed for use in Iraq after the Gulf War. This analysis of particles can detect extremely small quantities of fissile materials, down to several femtograms (10^{-15} grams) of plutonium.

In North Korea, the approach involved taking "smear" or "swipe" samples in the Radiochemical Laboratory that processed freshly separated plutonium. These areas of the plant contain "glove boxes." Inspectors took samples from inside glove boxes (where workers convert the liquid plutonium into an oxide compound) and from areas adjacent to these glove boxes. The samples were sent to member countries for analysis

The verification technique exploits the radioactive properties of plutonium-241, which undergoes beta decay with a 13.2 year half-life. Its decay product, americium-241, has a half-life of 458 years. The amount of americium-241 in the plutonium can date the plutonium separation process. The amount of plutonium-241 expected in a sample from the North Korean reactors would be small because they would produce plutonium with less than 0.5 percent plutonium-241. Well over 90 percent of the plutonium would be plutonium-239, and a few percent would be plutonium-240.

Below, we show the calculations for estimating the date of plutonium separation.

The total amount of plutonium-241 at the time of separation should equal the number of grams of americium-241 added to the grams of plutonium-241. The time since separation, t, can be found by solving the following equation which describes the radioactive decay of the plutonium-241:

$$y = (x + y)e^{-\lambda t}$$

where λ is the decay constant for plutonium-241, or 0.053 per year.

Solving for t gives:

$$t = -\frac{1}{\lambda} \ln \frac{y}{x + y}$$

The estimated date of plutonium separation is found by subtracting t from the date, T, when the sample was analyzed. If North Korea's declaration is correct, this date should correspond to T_0, the date North Korea said its separation occurred in 1990.

However, after analyzing samples from the reactors, the IAEA concluded that the North had conducted a broader range of separation activities than they declared. IAEA measurements were consistent with plutonium separations in 1989, 1990, and 1991.

We should note that IAEA results are not incontrovertible because this type of analysis can be confounded by cleaning procedures. The North Korean operators used solvents to clean the inside of the glove boxes after precipitating plutonium nitrate to plutonium oxide. Theoretically, these solvents could have preferentially removed plutonium or americium isotopes, altering the isotopic makeup of the samples taken from the glove boxes. However, the IAEA also took and analyzed samples from nearby areas where solvents were never used. These samples also showed the same type of inconsistencies.

Overall, the IAEA is confident that more separation campaigns occurred than the North has declared, and the IAEA will continue to seek out more information about these additional separations, despite North Korea's refusal to cooperate.