A U.S. team earlier this month was unable to determine whether North Korea has an atomic ace in the hole or is bluffing. Verifying any future freeze of its nuclear programs will require scientific sleuthing—and a leap of faith.

North Korea’s Nuclear Shell Game

Late in the afternoon on Thursday, 8 January, Siegfried Hecker and four other members of an unofficial U.S. delegation were huddled in a chilly conference room at the Nuclear Scientific Research Center in Yongbyon, 100 kilometers north of Pyongyang. They had just finished a tour of the crown jewels of North Korea’s nuclear program: a 5-megawatt electric (MWe) reactor and a nearby Radiochemical Laboratory, a massive facility for extracting plutonium from spent uranium fuel rods, said to be the second largest such facility in the world. Hecker, a plutonium expert and former director of the Los Alamos National Laboratory, had confirmed that the reactor was operating normally and, by all appearances, could accumulate in its fuel rods 6 kilograms of plutonium a year—enough for a nuclear bomb. He also confirmed that 8000 spent fuel rods removed from the reactor in 1994 were no longer in a cooling pond. The Radiochemical Laboratory, meanwhile, was “in good repair,” Hecker testified at a 21 January hearing of the U.S. Senate Committee on Foreign Relations.

But the North Koreans were saving their best for last. They claimed to have finished reprocessing all 48 tons of spent fuel last June and brought a metal case into the conference room that afternoon. Nested inside was a wooden box with two glass jars, one of which contained a greenish powder and the second a thin-walled funnel, about 5 centimeters wide at its base and 3.8 cm tall. Inside the first jar, the North Korean scientists claimed, was plutonium oxalate powder. Inside the second: 200 grams of plutonium metal, the raw makings of a bomb.

“I tried to get a feel for the density and heat content of the alleged plutonium metal by holding the glass jar in a gloved hand,” Hecker said. The jar was heavy and slightly warm—“it was definitely not cold as was everything else” in the building. And both the metal and the powder were radioactive. However, he noted, “the bottom line is that with the rather primitive tools at hand, I was not able to definitively identify the purported metal and the powder as plutonium.” And without sophisticated isotopic measurements, they had no way to confirm that it came from the spent fuel rods that the North Koreans claim to have reprocessed last year.

Such ambiguities have kept the world guessing about how far North Korea has traveled on the road to nuclear statehood. Western intelligence agencies have publicly concluded that it possesses one or two fission bombs. But North Korea hasn’t yet announced its membership in the nuclear club with a detonation, so there’s no guarantee its bombs would work—if it has them. Then there’s the question of whether the country has a viable program for enriching uranium, a potential alternative to plutonium as a source of nuclear explosive. According to U.S. officials, North Korean officials admitted pursuing enrichment after Assistant Secretary of State James A. Kelly confronted them with unspecified evidence during talks in October 2002, precipitating the present crisis. North Korea has since denied the existence of an enrichment program, however.

Hecker’s group, led by Asia scholar John Lewis of Stanford University, traveled to North Korea to try to resolve some of the ambiguities about North Korea’s program as part of an effort to end the current standoff. Earlier this month, North Korea said it would freeze its nuclear program in exchange for security concessions and economic aid from the United States, an offer that U.S. Secretary of State Colin Powell called “a positive step.” This offer is expected to be on the table when the United States, North Korea, South Korea, China, Japan, and Russia reconvene “six-party talks” as early as next month. But the talks could founder on a crucial issue: how a freeze could be verified and facilities monitored—especially centrifuge enrichment plants, which are notoriously difficult to detect. The United States and Japan are taking a hard line. “We will have to assume 100% cooperation from North Korea authorities. Otherwise any inspection and verification would be insufficient,” Mikio Mori, a member of Japan’s delegation to the talks, told Science.

From Russia with know-how

There’s little doubt that North Korea has had nuclear ambitions for half a century. North Korean scientists and engineers started training at the Joint Institute for Nuclear Research in Dubna, near Moscow, in 1956. Although the North Koreans could rub shoulders with top talent there, “the Soviet Union treated them like junior partners,” says Tetsuya Endo, vice chair of Japan’s Atomic Energy Commission. Science could find no evidence that North Korean scientists had ever visited the Soviet Union’s elite, closed nuclear weapons cities. Nevertheless, they “did acquire basic
knowledge," says Endo. "They are very capable and shrewd." Several South Korean defectors in the 1950s and '60s who had studied nuclear physics in Japan apparently also helped build the program, says Mori, director for multilateral nuclear cooperation in Japan's Ministry of Foreign Affairs.

North Korea established its nuclear research center at Yongbyon in 1962 and in 1965 started running fission experiments on a subcritical assembly purchased from the Soviet Union 2 years earlier. North Korea opted for a "very scaled-down version" of the U.K.'s Calder Hall reactor, says Robert Alvarez, a former senior policy adviser to the U.S. Department of Energy (DOE) now at the Institute for Policy Studies in Washington, D.C. This carbon dioxide–cooled reactor, more effective at generating plutonium than a water-cooled reactor, was central to the United Kingdom's weapons program in the 1950s.

North Korea's effort hit its stride in the mid-1980s. In 1984 it started work on its Radiochemical Laboratory. Two years later the 5-MWe reactor was started up, and construction had begun on a 50-MWe version; in 1989 ground was broken on a 200-MWe reactor in Taechon. If all three reactors were put into operation, North Korea could produce enough plutonium for more than 50 weapons a year (see table).

But North Korea's intellectual link to the Soviet Union was fraying. Soon after the Soviet Union unraveled in 1991, says a former Russian government official, "the North Koreans expressed great interest in high-energy physics and invited our specialists for long-term visits." They were so persistent, the official says, that "we had to take administrative measures to stop our nuclear physicists from traveling to North Korea." He insists that the measures worked.

Today "we cannot make a definitive judgment on how much technological expertise they have," says Mori. "My sense is that they could have obtained sufficient training in Russia—or on their own." He estimates that Kim Il Sung University and Kim Chaek University of Technology together produce about 300 nuclear science graduates a year.

The perils of plutonium

In spite of this growing nuclear program, the Democratic People's Republic of Korea (DPRK), as the country is formally known, signed the Nuclear Nonproliferation Treaty (NPT) in 1985 and so had to submit to inspections by the International Atomic Energy Agency (IAEA). The agency conducted six inspections between June 1992 and February 1993. The North Koreans "got increasingly hostile as the inspections became more and more invasive," says Alvarez. In late 1992, IAEA inspectors found evidence that North Korea had reprocessed more than the roughly 90 grams of plutonium-239 it had disclosed. Their environmental sampling at Yongbyon had revealed varying ratios of americium-241, a decay product of plutonium-241, suggesting that reprocessing had occurred on multiple occasions, an IAEA official told Science. "The IAEA was able to prove the North Koreans were lying, but not by how much," says Matthew Bunn, a nonproliferation expert at Harvard University.

As the Radiochemical Laboratory was still being outfitted, attention was focused on several "hot cells"—lead-lined glove boxes for handling highly radioactive materials—imported from the Soviet Union. "They were probably taking small batches and doing separation in the hot cells," says Alvarez. How much North Korea might have separated between 1986 and 1992 is unknown; estimates range from 5 to 26 kilograms.

When IAEA officials in 1993 asked to inspect the Radiochemical Laboratory and a nearby waste-storage facility, "the DPRK freaked out," Alvarez says. North Korean officials refused and announced their intention to withdraw from the NPT. In May 1994 North Korea shut down the 5-MWe reactor to refurbish the entire core, spurring an IAEA request to sample the fuel before removal.

Only a diplomatic breakthrough by former President Jimmy Carter in Pyongyang that June averted further escalation of tensions. In the Agreed Framework signed in October 1994, North Korea said it would freeze and eventually dismantle its graphite reactors. In exchange, a U.S.-led consortium, the Korean Peninsula Energy Development Organization (KEDO), pledged to finance a $5 billion deal to supply a pair of light-water reactors and annual shipments of fuel oil. KEDO suspended construction of the reactors last month.

Alvarez and a team of U.S. experts arrived in Yongbyon in November 1994 to hash out implementation of the Agreed Framework. They got a surprise. The fuel rods just removed from the reactor lay submerged in a 6-by-15-meter cooling pond that was choked with algae and an opaque suspension of magnesium oxide—rust from magnesium cladding eroding in the warm water. It looked "like a diluted form of Milk of Magnesia," Alvarez wrote in the July/August 2003 issue of the Bulletin of the Atomic Scientists. Further erosion threatened to lay bare the uranium metal, which can react with water to form hydrogen gas and uranium hydride. Because uranium hydride ignites spontaneously in air, removing such unstable fuel rods from the pool could have sparked an explosion.

In a $20 million, 18-month project funded by the U.S. government, each spent fuel rod was laboriously cleaned and bundled into stainless steel canisters filled with argon, an inert gas, to retard the generation of hydrogen. Each canister was placed under IAEA seal and returned to the cooling pond.

Since North Korean officials threw IAEA inspectors out of Yongbyon on 31 De-

North Korea's Plutonium-Related Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Plutonium production per year (kilograms)</th>
<th>Weapons per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-megawatt electric (MWe) reactor</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>50-MWe reactor (under construction)</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>200-MWe reactor (under construction)</td>
<td>220</td>
<td>44</td>
</tr>
<tr>
<td>Reprocessing facility</td>
<td>220– to 250-ton throughput, enough for the fuel produced annually from the 5- and 50-MWe reactors</td>
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Nagging fears. The U.S. group confirmed that North Korean technicians had removed spent nuclear fuel from this cooling pond, but whether its plutonium was extracted is an open question.
December 2002, speculation has focused on the fate of the spent fuel. But North Korea's claims that it has reprocessed the fuel haven't been verified. U.S. spy planes should have been able to detect gases, especially telltale krypton-85, waiting for the Radiochemical Laboratory if reprocessing had indeed occurred there. "You have a good chance of detecting those once they went up the stack," says Bunn. "We have observed elevated krypton," acknowledges a senior Bush Administration official, "but it doesn't seem to have come from Yongbyon."

It's more likely, says Alvarez, that the North Koreans "surreptitiously put [the fuel rods] in barrels of water and hauled them off in the middle of the night," along with the hot cells, for reprocessing outside Yongbyon. Japanese experts have come to a similar conclusion. "If they don't care about radiation exposure, the reprocessing itself is straightforward chemistry," says Endo. The Administration official declined to say whether remote detectors are sensitive enough to catch reprocessing in hot cells. The answer, he said, is "classified."

In the meantime, North Korea has refueled and restarted the 5-MWe reactor, as Hecker's team confirmed.

**Bombs away?**

As bad as it sounds, experts say, it's not too late to put North Korea's plutonium genie back in the bottle. "We have frozen and verified the plutonium program very effectively, so we know how to do that," says Kenneth Luongo, who as director of DOE's Office of Arms Control and Nonproliferation in the mid-1990s managed the process of canning the spent fuel rods.

IAEA inspectors can track nuclear materials entering and leaving a facility if they have access to accurate records and an understanding of a facility's architecture, says Jon Wolfsthal, North Korea nuclear analyst at the Carnegie Endowment for International Peace in Washington, D.C. But Yongbyon would largely be a black box, forcing inspectors to rely on extensive sampling of equipment and the local surroundings for stray particles of nuclear material.

Putting a lid on uranium enrichment—the cause of the recent contretemps—would be even more difficult. Even confirming that North Korea has an enrichment program would be a huge challenge.

As early as 1998, when Alvarez was a senior DOE official, "we were aware that something was going on between North Korea and Pakistan" in gas centrifuges, he says. In such a centrifuge, uranium hexafluoride gas, composed primarily of the isotopes uranium-238 and weapons-grade uranium-235, is spun at twice the speed of sound. Intelligence reports suggested that Pakistan was giving designs for these sophisticated machines to North Korea in exchange for ballistic missiles. Concerns grew in 2000, when the United States discovered that North Korea was attempting to import high-grade aluminum, possibly for the manufacture of centrifuge components.

The centrifuges must be linked in a cascade to obtain significant quantities of fissile uranium. To accumulate enough for several bombs, Alvarez says, "they would have to produce thousands of centrifuges." Just where North Korea might have squirmed away so many centrifuges is an enduring mystery. Sources in the Japanese and U.S. governments have told Science that they have not uncovered any solid information on where North Korea may be enriching uranium. That's not surprising, says Bunn: "Verifying the dismantlement of the facilities you're told about isn't too bad. It's confirming that there aren't any others hidden away somewhere that is the real bear." The size and power requirement for a centrifuge facility that could produce a bomb's worth of uranium-235 per year, he says, "is about the same as that for a typical Safeway in the United States." Experts agree that hundreds of centrifuges could stay hidden underground in a relatively small facility.

But one technique might be able to unmask a clandestine laboratory, according to nonproliferation expert Fred McGoldrick of the consulting firm Bengelsdorf, McGoldrick and Associates. Gas centrifuges operate at a higher frequency than power stations provide, requiring frequency converters. These would "reflect a distinct signal back into the line that can be detected," especially in North Korea's frail electrical grid, McGoldrick argues in a recent working paper from Carnegie and the Nautilus Institute for Security and Sustainability.

In 2000 a trading company in Japan called Meishin attempted to export such converters to North Korea. "At that point we became quite sure that North Korea was pursuing uranium enrichment," says Osamu Moriya, director of security export control in Japan's Ministry of Economy, Trade, and Industry. Then last April, Japanese officials allege, Meishin tried to send three of the devices by boat to North Korea via Thailand. On a scheduled stop in Hong Kong, customs agents seized the contraband. The incident was a lesson, says Moriya: "North Korea's procurement activities are becoming more cunning."

Like most analysts, Alvarez believes that the technical hurdles "make uranium enrichment much less of a threat than the DPRK's plutonium production capability." But negotiators are expected to insist that a freeze on all facets of North Korea's nuclear program be adequately verified. The Bush Administration official told Science that the U.S. will demand measures that are more stringent and intrusive than typical IAEA inspections, including everything from interviewing scientists to installing krypton-85 sensors on North Korean soil. It's not clear, says Bunn, whether North Korea would accept that level of scrutiny. Indeed, the Administration official acknowledges that intrusive verification could delay arrival at any agreement by months—and perhaps even "torpedo any deal."

The biggest question of all is whether North Korea already possesses a legitimate nuclear arsenal. In its latest unclassified assessment, released last August, the CIA concluded that North Korea has concocted "one or two simple fissile-type nuclear weapons and has validated the designs without conducting yield-producing nuclear tests." Others are not so sure. "A plutonium bomb is easy to make but hard to explode," says Endo. "They might have a nuclear device, but it might not work as a nuclear weapon."

As a result, there's considerable uncertainty going into the next round of talks. "We don't have a clear picture of what happens next in the six-party talks," admits Mori. "We just are not sure of North Korea's final objective: whether they intend to strengthen their 'nuclear deterrent' or if they are just bluffing." If the former, "time is on their side," notes Endo, as the latest stalemate enters its second year.

—Richard Stone