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SMALL LWR DEVELOPMENT AND DENUCLEARIZATION

Small LWR Development and Denuclearization

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The unveiling of the Democratic Peoples' Republic of Korea's (DPRK's) enrichment and pilot light water reactor program offers another moment for engagement with Pyongyang, another point of leverage over how its nuclear weapons program evolves, and a new opportunity to determine whether it can be influenced to recommit to the global nuclear non-proliferation and disarmament regime.

We believe that it may be possible to slow and even reverse North Korea's nuclear breakout through collaboration that assists Pyongyang in the development of small light water reactors (LWRs) that are safe, reliable, and above all, safeguarded, and that integrates its enrichment capacity into a regional consortium. Engagement could entail some or all of the following steps[1]:

- Immediately deploying a small barge-mounted reactor (possibly Russian) to provide power to a coastal North Korean town;
- Helping the North participate in the production of low-enriched uranium to fuel such a reactor;
- Jointly designing with North Korea a "made-in-the-DPRK" small reactor that meets international safety and manufacturing standards, possibly in a joint project with South Korean firms;
- Undertaking planning for the rational development of a national power grid in the DPRK capable of supporting small reactors over the coming decade;
- Creating a multilateral financing scheme (possibly linked to a regional grid connecting the North with the South Korean, Chinese

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and Russian Far East grids) for the construction of small LWRs in the North, starting with a survey of its manufacturing capabilities that might meet the international standards required for safe, reliable reactor production;

- Creating a regional enrichment consortium involving Japan, South Korea, and North Korea (and other countries) with Pyongyang's enrichment capacities either incorporated into a safeguarded scheme or operated as part of a multinational facility.

In return, North Korea would reveal its enrichment acquisition history and possibly participate in the development of a small reactor export program as part of an inter-Korean nuclear export push as well as a program of training and institutional development to support each of these activities.

Since engagement with the North on nuclear energy issues cannot occur in a vacuum, it should be accompanied by other policy, economic, and humanitarian initiatives. But most importantly, it must be accompanied by engagement on a range of other energy sector issues including electricity transmission and distribution grid redevelopment, conventional power and fuels supply, and the development of energy markets to spur efficiency, renewable energy, and capacity-building. (See Part 2, "Transforming the DPRK through Energy Sector Development.")

The analysis in this article was inspired by the most important (but least covered by mass media) part of Siegfried Hecker's report[2] on the DPRK's uranium enrichment and small light water reactor (LWR) program, namely that this program offers a new entry point for engagement and leverage over the North's nuclear weapons effort. His report was issued after a Stanford University team visited the North in mid-November 2010, and observed a previously undeclared uranium enrichment facility at Yongbyon with about 2000 operating centrifuge units, including what appeared to be modern control facilities. Moreover, the team was told that the North was planning to construct a light water reactor with an estimated size of 20-30 megawatts of electric generating capacity (MWe), and was shown the site where initial work on was underway. Small by global standards, this unit is apparently designed as a pilot project for a fleet of small reactors, each perhaps on the order of 100 MWe.

Though the North Koreans told the Stanford delegation that the DPRK planned to enrich uranium only to about 3.5% U-235, consistent with production of low-enriched uranium (LEU) for LWR fuel, with some reconfiguration the facility could produce highly-enriched uranium (HEU), which might be used to build nuclear weapons. The acquisition by the DPRK of enrichment capabilities of this magnitude immediately raised for the United States and its allies the specter of Iran, where a nominally peaceful enrichment program operating outside International Atomic Energy Agency (IAEA) safeguards has gradually increased its fractional enrichment towards HEU levels. Faced with the possibility that the DPRK could acquire, within a relatively short time, a second path to producing fissile material for nuclear weapons, formulating an effective response is urgent.

Possible Responses

The United States, its allies, and other concerned countries have three plausible options to deal with this situation. One is to contain the program and, eventually, launch a military strike to disable the DPRK's nuclear facilities. Another is to continue with strategic drift, that is, to do nothing to engage the DPRK, thereby allowing the North to further develop its nuclear capabilities and gain greater leverage in dictating any terms of negotiation. A third is to engage the DPRK in negotiations designed to return to a denuclearization trajectory by offering the North something of value while being mindful of its motivations.

Of these options, the first is untenable. In 1994, when this option was discussed in depth in the Clinton White House, it rapidly became clear that a strike without warning, while technically feasible, was not politically possible. The United States would have to warn its nationals living in the South of pending hostilities, including ordering their evacuation, and the political impact of such an announcement internationally, especially in US-China relations, and domestically in the South would be unsupportable. Even using precision weapons, an attack on the densely-populated Yongbyon complex would likely generate a significant number of civilian casualties and inevitable international backlash.[3] Such a strike deep in DPRK territory would also almost surely provoke a major military response, resulting in full-scale war with widespread destruction and loss of life on both sides of the DMZ. Though a war would probably be concluded in weeks or months, an American public, already fatigued by two long wars and reeling from the effects of the deepest recession in two generations, would be unenthusiastic and pressure on the White House to avoid such an outcome would be enormous—as is clear to everyone including the DPRK. The trillions of dollars it would cost to recover from a full-scale war serves as a further deterrent to a preemptive strike, as does the likelihood that the DPRK has other enrichment components stockpiled elsewhere or even another entire functioning enrichment plant (again, Iran-like) buried deep in a granite mountain somewhere in the rugged spine of Korea.

The second option—attempting to apply additional international pressure—is likely to result in further advances in the DPRK nuclear program, further inter-Korean military skirmishes, and shrill rhetoric on both sides. It also affords more time and incentive for the DPRK to align with nations and sub-national groups bent on the proliferation of weapons of mass destruction or other international mischief. Short of China shutting off the DPRK's oil supply, which it is unlikely to do, the United States has little ability to inflict more pain on the North or its leadership, given how isolated Pyongyang already is. Simply waiting for the North Korean people to literally collapse under the strain of hardships is indefensible from a humanitarian perspective and is likely, in any case, to be a long wait.

This leaves the third option—to engage the DPRK in a way that acknowledges its strategic gains of the last eight years[4]—and attempts to converge on a common goal with its leadership as the country carries out a political transition and nears a milestone year (Kim Il Sung's centenary in 2012).

This approach also assumes that China and other parties would assist in efforts to further integrate the

DPRK economy into the international system, that other political and military steps are taken to reduce tension in Northeast Asia, and that large-scale bilateral and multilateral assistance resumes aimed at benefiting the North Korean people. We have previously described how such engagement should include assistance to the North to modernize its crumbling energy sector to help form the backbone of efforts to stabilize and ultimately transform the DPRK into a "normal" state without the devastation of war or chaotic collapse.

Given these realities, the critical question is if the United States, its allies, and other concerned countries convince the DPRK to trade its enrichment and plutonium programs and weapons for development assistance, would helping North Korea build small LWRs accelerate that exchange and, if so, what can be done to facilitate such an effort?

Why Does the DPRK Want Small LWRs?

Why does the DPRK want nuclear power and why is it now pursuing smaller reactors? Starting in the 1980s, if not before, the DPRK's domestic nuclear power program had the stated goal of using the North's uranium resources to augment existing coal and hydroelectric power plants. Of course, production of fissile material for nuclear weapons (ultimately accomplished with its domestically-built 5 MWe-equivalent graphite-moderated reactor[5]) was a subtext of the nuclear power development program, but the North, like dozens of other countries, also wished to be a member of the nuclear energy club as a badge of its technological accomplishments.[6] Once established, that goal became a point of national pride. The DPRK contracted with the Soviet Union to build two reactors at Simpo on its east coast. The deal stalled, however, over payment for the reactors, but the DPRK only agreed to join the Nuclear Non-Proliferation Treaty (NPT)—under Soviet pressure at American behest—if these plants were built.

Acquisition of the reactors became a moot point when the Soviet Union collapsed. New efforts were launched to acquire LWRs, first in North-South nuclear talks in 1992 and then as part of US-DPRK negotiations to resolve concerns over Pyongyang's nuclear weapons program. Under the terms of the 1994 Agreed Framework, the North agreed to give up its plans to build domestically-built graphite moderated reactors as well as its nuclear weapons program in return for two modern, large (1000 MWe) LWR units, to be built at Simpo by the US-led Korean Peninsula Energy Development Organization (KEDO).[7] At that point, the KEDO reactors, or their equivalent, became the benchmark for energy assistance, all the more so because they had been blessed by Kim Il Sung in his meeting with President Jimmy Carter in July 1994, just before Kim died.

An important factor contributing to North Korea's decision to build a small LWR is that 1000 MWe LWR units, such as those promised under the 1994 agreement, are too large to be used on the existing electricity transmission and distribution (T&D) grid. The North's grid, in poor condition, uses substations, switchgear, and control equipment equivalent to 1950s or 1960s vintage devices in the West.

Moreover, decisions on which plants should operate are communicated mostly by telephone and telex rather than computerized control equipment, causing the grid to frequently fail.

Operating a 1000 MWe LWR on the existing grid would have been impossible in the past and still is, in part, because the grid is so unstable that it would trip and thereby cause the LWR to shut down regularly, requiring lengthy restarts, and risking damage to the reactor itself. Also, the DPRK power system, even if functioning perfectly, is simply too small, in terms of generating capacity, to allow the safe operation of a nuclear plant as large as 1000 MWe.[8] It would have taken two large electrical transmission lines (or interties) linking it to other electric grids—for example, two interties connected to the South Korean grid each capable of carrying 1-3 GW of power, or one to each of the Russian and ROK grids—for the KEDO nuclear plants at Simpo to have operated safely.

Why did the North Koreans ask for a large LWR if they couldn't run it on their grid? In fact, they didn't. A senior DPRK power engineer told us that knowing full well there were grid constraints limiting the size of reactors that could be used (the DPRK power engineers had briefed their bosses on this technical reality), the North actually asked for 400 MWe units in 1994, but such units were only made in Russia. When South Korea and the United States refused to supply Russian-made units since there was no financing available for them, DPRK foreign ministry officials negotiating the Agreed Framework agreed to accept the larger (1000 MWe) LWRs, along with supplies of heavy fuel oil until the reactors were operational. Moreover, in subsequent talks under the KEDO framework, the North Koreans pushed for the organization to upgrade its power grid, a request that was soft peddled, at least in the very beginning of the project, given the large-scale costs involved.

Today, the DPRK runs a fragmented grid that we estimate has an average total nationwide generation of about 2000 MWe. Its national electricity consumption, after accounting for losses, is about the same as that of the state of Delaware or New Hampshire, but is used by a population 40-50 times larger. Therefore, smaller reactors make sense from a technical point of view. They could be deployed near demand centers and supported by nearby large hydro- or coal-fired power plants, reducing reportedly considerable transmission and distribution losses, and accommodating the reality of a fragmented grid.

North Korea cannot, however, hope to develop the technologies for modern LWRs in a reasonable time frame (say, less than 20 years) without considerable outside assistance.[9] The list of technologies to be mastered for the different elements of the nuclear fuel cycle, oversight institutions to be built, standards and procedures to be put in place, and, above all, human capacity to be developed to produce and operate a modern LWR is long and daunting. The North can, however, almost certainly build a pilot 25 MWe LWR, which may or may not be safe, using crude electro-mechanical systems rather than modern reactor control technologies and materials. Our guess is that a crash job could be done in two to three years, depending on how much of a head start the North has as of today. How well, long, or safely such a reactor would operate are certainly important questions, particularly for those nations like Japan that will be downwind from the reactor site. Successfully building and safe operation of even a small LWR requires many of the same capabilities and systems needed to operate a modern large reactor, albeit at a different scale.

The North aims to begin operating the plant by 2012 as part of the celebration of Kim Il Sung's 100th birthday. Kim Jong Il has promised North Koreans a "strong and prosperous nation" by then and has exhorted the people to work toward that goal. Having a LWR well under development (if not operating) would be an important symbol for the North's leaders to point to as a totem of national strength as well as an accomplishment that would help reinforce the credibility of Kim Jong Il and his anointed successor, Kim Jong Un, with the populace and the military.

In addition to the grid and other technical factors mentioned above, from a geopolitical perspective, there are at least two additional reasons for the DPRK to pursue domestic development of small reactors. First, the domestic enrichment program needed to fuel small LWRs offers the North a slow-but-steady second track to producing fissile material (highly enriched uranium) for nuclear weapons, like Iran, while maintaining possession of its existing plutonium stockpiles and nuclear devices to support its bargaining position. Second, the development of a small LWR could be a negotiating ploy that will be used by the North to obtain a large reactor, only this time on its own, rather than the international community's terms, as was the case with KEDO. The DPRK could also see its uranium enrichment program as necessary to "hedge" against the possible failure of its small LWR program and the continued contention with the international community over its nuclear program.

What Can We Do?

Now that the DPRK has revealed a relatively mature enrichment program and is developing a domestic LWR, what should the international community do? The first task is to block the North's independent development of a uranium enrichment program. We recommend that, as a first step towards achieving this objective, dialogue with the North Koreans should be resumed to ensure that its light water reactor program is safe and produces reliable electricity, and to help the DPRK become a member in good standing of the international nuclear energy community once again. Should the DPRK agree to resume such talks, some combination of the following ten steps will be necessary to move forward.

1. ***Deploy a Barge Reactor Immediately:*** One way to demonstrate good faith would be to deploy a ship-based reactor—for example, on a barge—that is able to supply power to shore, perhaps a coastal town. This is easier said than done because small LWRs are not a commercial commodity in the West, though a number of groups have proposed development of them for commercial sale. In the short term, leasing or buying a barge-mounted reactor from Russia or adapting a US military nuclear reactor from a mothballed naval vessel for use as a barge-mounted generator would seem to be the best options.[10] The reactor would be operated under strict IAEA standards by a team of North Korean and foreign technicians who would also serve as operators and trainers to

instruct the North Koreans in safe operations. Using older nuclear technology would help to allay fears that the DPRK would appropriate industrial secrets of reactor design.

2. ***Develop DPRK LEU Fuel for the Barge Reactor:*** This would involve working with the North Koreans to adapt their uranium enrichment program to produce enriched fuel suitable for the barge-mounted reactor. Actual incorporation of uranium from the DPRK enrichment program into fuel rods might or might not be done in the DPRK itself, in part because the North may not have the metallurgical capabilities to produce suitable fuel cladding, but also in part to maintain control over the fuel fabrication process. All of the North's uranium production and enrichment facilities would have to be placed under IAEA safeguards and monitored by the agency.

3. ***Commence Joint Design Negotiations:*** The international community led by the United States could engage the DPRK in the design of a small LWR judged to be safe by international standards. This might also become a standard, "made-in-Korea" small reactor, possibly as a joint North-South product, with capacity in the range of 100 MWe. Such a program would require intensive capacity building in North Korea covering IAEA reactor design and operation safety protocols, development of national institutions to oversee the nuclear power sector, and training on nuclear materials management.

4. ***Plan Small LWR Power Program for the DPRK:*** This would involve working with the North Koreans to design a small 100 MWe reactor program that might be built over a specified time frame in conjunction with grid refurbishment (the latter is likely to cost about $20 billion) and also involve the international community in an effort to determine a financing-investment scheme. The 100 MWe reactors could cost roughly $200-500 million each. This estimate is at the low end of the range and is based on the assumption that a simple, robust, and standardized design is adopted and produced serially, with assembly-line-style manufacture of key components. A plan for reactor deployment would also have to be developed that includes IAEA oversight of all nuclear elements of the fuel cycle in the DPRK, and IAEA/international expert training and manpower development programs in nuclear system planning, regulation, economics, and related disciplines. Reactor deployment would also have to take place in the context of a sensible, overall energy sector and economic development plan.

5. ***Undertake Manufacturing, Construction, and Deployment of Small LWRs:*** This would involve working with the DPRK to build one to five 100 MWe reactors after 2012, roughly a five to ten year long project. It would be crucial early on to determine which manufacturing plants in the North are capable of producing nuclear and non-nuclear components of sufficient quality to meet standards required for safe reactor operation. For example, required manufacturing capacities would include high-strength concrete work, very large castings for pressure vessels, electronics for control facilities, and the machinery for lifting, moving, and placing heavy pieces of equipment. Of particular importance is determining what ability exists or needs to exist to make reactor

-grade heat exchangers, steam generators, pressurizers, coolant pumps, valves, and control rod drive mechanisms.[11] A review of DPRK manufacturing capabilities may yield some positive surprises. For example, the North has a 10,000 tonne forging press at the Chollima Steel Complex near the city of Kangson.[12] The few such presses that exist elsewhere in the world are used for making large, heavy pieces of equipment, including reactor components such as pressure vessels.

6. ***Create a Safety Culture:*** The North is known for its appallingly bad occupational health and safety practices, especially with respect to the risks taken in improvising responses to the extreme scarcity of spare parts and material. These bad practices are also due to its culture of politically- and ideologically-imposed speed construction campaigns with insufficient attention to quality control. In the 1970s, South Korea was beset with similar problems in its construction and engineering culture, leading to collapsed bridges and shortcuts in the construction of its early reactors. The international community will need to work with the DPRK to develop a regulatory and safety framework capable of overseeing a nuclear sector under IAEA safeguards, perhaps even learning from the South's problems early in its light water reactor program.[13] This program would be launched concurrent with the review of manufacturing needs and capabilities.

7. ***Create a Regional Enrichment Consortium:*** This would involve working with the DPRK and other countries in the region to develop, by the time the 100 MWe reactors are ready to be deployed, a regional enrichment consortium also involving South Korea, Japan, possibly China, and maybe Russia. Enrichment would be carried out in North Korea or other locations under IAEA safeguards and perhaps with the LEU produced by the consortium owned by the agency. Under such a scenario, the IAEA, or the enrichment consortium, would pay the DPRK for uranium and enrichment services. The selling of fissile materials by the DPRK to the South is not far-fetched. North-South discussions were held under the rubric of the Six Party Talks in late 2008 and early 2009 for the purchase of North Korean fresh fuel rods. And recently, the North proposed such a purchase to former New Mexico Governor Bill Richardson during his visit to Pyongyang.[14]

   This type of consortium, with the accompanying prestige of being the member of an enrichment club with major nuclear energy users, might induce the DPRK to put all of its enrichment cards on the table in a way that persuades the US and other countries that they do not have an on-going monitoring and verification problem. Under this scheme, the North would also be required to tell the international community about its sources of nuclear technologies, burning bridges with suppliers, but also allowing the international community to check whether the DPRK is acting in good faith.

8. ***Develop a Small Reactor Export Program:*** In conjunction with design and deployment of small LWRs, work with North and South Korea to develop a Korean "for export" 100 MWe reactor, thus hooking the DPRK wagon to the South's LWR export train. This effort would include training for technology export controls, market development, and other support functions.

9. ***Develop a DPRK Nuclear Waste Disposal Strategy:*** Like all states with nuclear reactors, the DPRK will increase its existing stock of radioactive waste if it operates small LWRs. This is a problem shared with other states in the region. A possible solution would be to develop "deep borehole" direct disposal in the granite-mountains of North Korea either for its own, or for an inter-Korean deep disposal strategy that might be part of a regional scheme.[15] Such a scheme, also under consideration by Mongolia, could earn significant revenues for the North. Depending on its geology, the DPRK nuclear test site may be a good place to begin deep borehole disposal activity for existing sludge as part of a nuclear weapons disablement package.

10. ***Undertake Other Nuclear Dismantlement:*** At the same time the above steps are enacted, we will need to consider the political and denuclearization steps that would go in lockstep with them over a ten-year period, leading to a DPRK uranium enrichment industry that is under international safeguards and supervision, and presumably not a proliferation threat. At minimum, at the outset, the LWR-enrichment cooperation scheme must be accompanied by the immediate and verifiable freeze of the DPRK's plutonium production program. In the near-term, the North would remain a "nuclear armed" state but would not be recognized as such. The DPRK would be required not to sell its plutonium or related technology to other countries, nor to produce or separate additional plutonium (except during the use of safeguarded LWR spent fuel). These steps would be required, along with the North placing its enrichment under full safeguards, in order for the United States, South Korea, and others to agree to the small LWR engagement scheme.

Each of the ten steps listed above must also be matched by clear milestones with regard to the dismantlement of the DPRK's nuclear facilities as well as of its nuclear weapons and related infrastructure. The purpose would be to create a process based on the incremental and verifiable implementation of measures to denuclearize North Korea. Its return to the NPT and the IAEA would be built into this process.

Now may not be viewed as the right moment to engage the North on the issue of nuclear weapons security due to tensions after the recent North-South military clashes and the desire of other countries to avoid any appearance of acknowledging the DPRK as a nuclear weapons state. Nevertheless, we believe that any serious movement towards incremental disarmament should also include detailed discussions with the North on issues of command and control, security, and reassurance mechanisms that need to be established to manage its plutonium weapons and fissile material. Such issues include the development of a declaratory and operational doctrine for fissile materials that accords with standard practices, along with the adoption of a raft of non-proliferation controls required to ensure that the DPRK plutonium and dual-use technologies do not "leak" overseas.

What Would It Cost, and Would It Work?

It is possible, though far from certain, that the offer of a "made-in-the-DPRK" small LWR, plus the other diplomatic and security steps necessary to implement that program, would induce the North to put its enrichment program under IAEA safeguards. Would the DPRK accept a "KEDO Mark 2" package (that is, an international consortium like KEDO, only this time to design and build small LWRs) at this point? It's possible, particularly if the near-term use of a small nuclear reactor serves its domestic needs as a symbol of national progress. But the DPRK would have to be convinced that the international community would follow through on the small LWR commitment, given its previous negative experience with KEDO.

The estimated "value" to the DPRK of the two KEDO LWRs is about $1.25 billion in net present value terms.[16] A package of significantly lower perceived value will likely not induce the DPRK to freeze or abandon its nuclear weapons program. Based on this preliminary estimate, the $1.25 billion present value might be enough to fund a program that includes the startup of a small reactor industry in the DPRK plus two to three prototype/commercial demonstration units over five to ten years. Because some components might prove hard to produce, such a program might have to be pursued with the participation of other countries, such as South Korea.

The engagement strategy outlined above might also result in the establishment of a North-South joint venture to manufacture and market small LWRs. An international market for small reactors may well develop on its own in the coming years, and certainly a number of nuclear industry and research groups have presented concepts for their deployment.[17] Small LWRs produced by a North-South consortium would probably find buyers, particularly among countries not now using nuclear energy.[18]

A variant to the small LWR engagement strategy that would be less complex but perhaps, at this point, less attractive to the DPRK, would be to restart the now-defunct KEDO LWR program. Construction could resume on one or both of the reactors and arrangements would be made for the DPRK to sell most or all of the power from those units to the South over a purpose-built transmission intertie connecting them to the ROK grid. The Simpo LWRs would be operated under IAEA safeguards with fresh fuel imported from international suppliers and spent fuel removed for storage or disposal outside the North. Capacity-building for DPRK technicians and officials would still be included, but would be less extensive than in the small LWR engagement strategy, reflecting the more limited role that the North will have in managing the nuclear fuel cycle associated with the large reactors. If this path is taken, it would be preferable to build only the first Simpo unit, reserving half of the LWR "value" to pay for either the small LWR engagement strategy, or preferably, a package of non-nuclear energy sector assistance.

A phased, varied package of energy sector assistance to the DPRK—including such steps as legal, institutional, and market reforms, energy efficiency, renewable energy, coal sector rehabilitation, transmission and distribution systems and power plant upgrading—with intense, small, on-the-ground pilot projects that would bring outside experts into contact with North Koreans seems the best way to approach engagement on the inextricably linked issues of DPRK energy sector modernization and elimination of the North's nuclear weapons.[19] Such a program would be an essential condition for the institutional and practical transformation of the DPRK energy sector that is needed—especially for creating small light water reactors and deploying them in the DPRK. The task of producing a home-built reactor is a daunting challenge that already must be confounding the DPRK's best-and-brightest nuclear engineers. To the extent that the group tasked with producing an LWR can communicate the difficulties in doing so to those involved in international negotiations, the urgency of the task may increase the probability that engagement on a small LWR program (and related energy sector issues) becomes something to which North Korean negotiators can say "yes."

Conclusion

The DPRK has a nuclear explosives program based on plutonium and has just revealed a remarkably mature uranium enrichment effort with the stated goal of fueling domestically-produced, small LWRs, raising fears of a second North Korean path to the bomb. As has always been the case, the options for the United States, other concerned countries, and the international community in dealing with this problem are remarkably limited. The most commonly conceived are a military attack with devastating consequences for the entire peninsula, reliance on international sanctions in the vain and historically contra-indicated hope of DPRK regime implosion, and engagement.

Only the last option, however unappealing, is tenable. The DPRK's desire to produce a home-grown nuclear reactor, intended to be ready for the Kim Il Sung centenary in 2012 (but not likely to be operable then), offers an opportunity to engage the DPRK in the design and implementation of small reactors. Starting with the provision of a small reactor on a barge providing power to a port city, that opportunity could be expanded to include not only reactor design, production, and operation, but also safeguards, oversight of enrichment facilities, and DPRK participation in regional nuclear fuel cycle cooperation activities such as waste disposal. All of these activities would proceed in parallel with a comprehensive program of non-nuclear energy sector assistance and matched on the DPRK side by progressively more restrictive limits on its nuclear weapons program.

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[1] This article has been abstracted and adapted from the Nautilus Institute Special Report Online, *Engaging the DPRK Enrichment and Small LWR Program: What Would It Take?,* by David von Hippel and Peter Hayes, http://www.nautilus.org/publications/essays/napsnet/reports/engaging-the-dprk-enrichment-and-small-lwr-program-what-would-it-take.

[2] Siegfried S. Hecker (2010), *A Return Trip to North Korea's Yongbyon Nuclear Complex*. NAPSNet Special Report, November 22, 2010, http://www.nautilus.org/publications/essays/napsnet/reports/a-return-trip-to-north-korea2019s-yongbyon-nuclear-complex. The fact that the DPRK chose to reveal this facility specifically to a group of visitors almost uniquely suited to appreciate its significance and to be listened to with respect when they returned to the US surely says something about the DPRK's feel for its international audience.

[3] See, for example, satellite images shown in Siegfried S. Hecker (2010) "Redefining denuclearization in North Korea," *Bulletin of the Atomic Scientists*, December 20, 2010, http://www.thebulletin.org/web-edition/features/redefining-denuclearization-north-korea-0.

[4] Specifically, since the October 2002 visit to the DPRK in which US Assistant Secretary of State James Kelly confronted his North Korean counterparts with allegations of its pursuit of uranium enrichment capabilities.

[5] The 5 MWe reactor at Yongbyon never actually generated electricity. The 5 MWe rating was nominal, based on the estimated amount of power that could be generated by the heat (about 25 thermal megawatts) that the plant produced, if the reactor were hooked up to a turbine and generator.

[6] With reasonably ample supplies of coal and hydroelectric potential, and low reliance on imports (except of oil, which is largely unrelated to debates over nuclear power), the DPRK cannot claim the same need for nuclear power as an energy (supply) security strategy that has been used to justify investments in nuclear power by Japan, South Korea, and Taiwan (for example). It can, however, claim a need for nuclear power on the same grounds that many other countries have been using in recent years, that is, that nuclear power development is needed to reduce emissions of greenhouse gases as well as of local and regional air pollutants.

[7] The KEDO LWR project was terminated in 2006, but documents from the project remain available at www.KEDO.org.

[8] See J. Bickel (2001), "Grid Stability and Safety Issues Associated with Nuclear Power Plants." Prepared for the Workshop on Power Grid Interconnection in Northeast Asia, Beijing, China, May 14-16, 2001, http://www.nautilus.org/projects/asian-energy-security/workshop-on-power-grid-interconnection-in-northeast-asia/papers/Bickel.pdf/at_download/file.

[9] See, for example, L.J. Droutman et al (1979), *International Deployment of Commercial Capability in Nuclear Fuel Cycle and Nuclear Power Plant Design, Manufacture, and Construction for Developing Countries*, Oak Ridge National Laboratory report, ORNL/Sub-7494/4, October 1979, http://www.nautilus.org/publications/essays/napsnet/reports/summary-international-deployment-vonhippel, for a summary of the issues that developing country would face as it builds a nuclear industry.

[10] Different naval reactors (including US, Russian, and French units) use fuel with different levels of enrichment. Some apparently use HEU, and many use fuel more highly enriched than typical land-based LWR fuel. This higher level of enrichment could be a concern for an application involving North Koreans.

[11] L.J. Droutman et al, *op cit*.

[12] This press, commissioned with Kim Il Sung present in 1989, has been mentioned in the DPRK press a number of times over the years (for example, KCNA, June 14, 1984; October 9, 1989; and October 13, 1989; *Choson*, January 12, 2006).

[13] S. Levy (1982), *Update Review of Safety Aspects of Nuclear Power Program in Republic of Korea,* prepared for World Bank/UNDP, April 1982, http://www.nautilus.org/publications/essays/napsnet/reports/summary-update-review-vonhippel. Salomon Levy, in this 1982 review for the World Bank of the worrisome safety shortcomings of the early ROK LWR program, noted the need for a "…strong, independent, and competent nuclear regulatory function as well as associated Korean safety laws, regulations, criteria, codes, and standards."

[14] J. Pomfret and C. Harlan (2010), "North Korea makes gestures toward calm after South's drills," *Washington Post*, December 21, 2010, http://www.washingtonpost.com/wp-dyn/content/article/2010/12/20/AR2010122005890.html.

[15] See D. von Hippel and P. Hayes, *Deep Borehole Disposal of Nuclear Spent Fuel and High Level Waste as a Focus of Regional East Asia Nuclear Fuel Cycle Cooperation*, NAPSNet Special Report, December 13, 2010, http://www.nautilus.org/publications/essays/napsnet/reports/Deep%20Borehole%20Disposal%20von%20Hippel%20-%20Hayes%20Final%20Dec11-2010.pdf; and J. Kang, *An Initial Exploration of the Potential for Deep Borehole Disposal of Nuclear Wastes in South Korea*, NAPSNet Special Report, December 16, 2010, http://www.nautilus.org/publications/essays/napsnet/reports/JMK_DBD_in_ROK_Final_with_Exec_Summ_12-14-10.pdf.

[16] Authors' calculations. Key assumptions include a DPRK discount rate of 15%/yr (nominal basis), reactor cost of $2500 per kW, sales of most of the electricity from the reactors to South Korea at a price of 6 US cents per kWh, and North Korea pays for other costs of running the reactors out of the proceeds of its power sales to the South.

[17] See, for example, "Mini Nuclear Reactors, Thinking Small," *The Economist*, December 9, 2010; and research groups/companies such as Hyperion Power, which offers a (non-LWR) 25 MWe nuclear module unit for $50 million (though it is not immediately clear what other major system components, such as the steam turbine or generator, are included in that cost), with initial deliveries "slated to begin in the second half of 2013" (http://www.hyperionpowergeneration.com/product.html).

[18] The sale of many small reactors is not necessarily a positive development, as it would lead to many more different nations having access to nuclear materials, as well as the existence of many more different nuclear materials locations and transport

pathways for the international community to secure, monitor and safeguard. If deployment of small reactors in many countries comes tightly bundled with a stringent international regime of safeguards, especially if coupled with fuel supply/take back arrangements in all countries, some of the risk associated with large-scale deployment of small reactors can be reduced. Some of the key difficulties associated with nuclear power, most notably the generation of radioactive wastes that must be managed nearly indefinitely, will be unavoidable.

[19] D. von Hippel and P. Hayes (2009), "DPRK Energy Sector Assistance to Accompany Progress in Denuclearization Discussions: Options and Considerations," produced as part of the project "Improving Regional Security and Denuclearizing the Korean Peninsula: US Policy Interests and Options," organized by Joel Wit of Columbia University's Weatherhead East Asian Institute and the US-Korea Institute at the Johns Hopkins University School of Advanced International Studies, http://www.nautilus.org/DPRKPolicy/vonHippel.pdf.