Critical Concerns: Evaluating the safety of North Korea's new light water reactor

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4 June 2012
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Abstract

This paper aims to evaluate the various aspects of North Korea’s new light water reactor that will contribute to the overall inherent and operational safety of the plant. While the political discussion generally focuses on weapons and denuclearization, many academic experts emphasize the necessity of an in-depth analysis of the plant’s safety in order to identify the best response and engagement options. My project is the first to present a focused analysis of the likely safety risks associated with this new reactor.

In the absence of complete information regarding the construction and operation of the reactor, I assess North Korea’s potential fulfillment of safety requirements by their adherence to key principles of nuclear safety in this and related projects. Although the DPRK is most likely able to complete a functional LWR of this size, the inherent risks of running it will be intensified by a lack of institutional attention to safety, coupled with unfamiliarity with the technology and the likelihood of dangerous external conditions. In light of the response to the Fukushima-Daiichi disaster, it has become clear that a technical understanding of North Korea’s LWR will be crucial to an appropriate response in case of an accident.

Acknowledgments

I want first of all to sincerely thank my advisor, Siegfried Hecker, for his guidance, his genuine interest in my own enjoyment of this project, and for his truly unfailing patience. I also have his assistant Peter Davis to thank for his constant availability and eagerness to help this next generation of CISAC students.

As for the process of understanding the intricacies of nuclear reactors, risk analysis and politics on the Korean Peninsula, I must thank Chaim Braun, Ed Blandford, and David Straub, as well as Niko Minopolous, for their generous time and willingness to speak with me.

Of course, this amazing program would not have been possible without our advisors Coit Blacker and Martha Crenshaw, Thomas Fingar, and our capable teaching assistant and administrator, David Blum and Dmitry Soustin. The care taken in supporting all of us in our research and writing process made this a truly incredible program.

I'd like also to take a moment to thank my family for their support throughout this process, with a particular shout-out to my sister, Shalina, whose impressive balancing of numerous responsibilities in her first year of college has been an inspiration as I complete my last year. My incredible fiancé, John, has not only given me his endless faith and encouragement, but stayed up with me in the final hours of writing to proof-read my work.

Finally, I have professors Siegfried Hecker and Bill Perry to thank (or blame) for introducing me in my junior year to the complex relationship between technology and national defense – and inspiring what I hope to be a life-long involvement in international security.

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BWR	Boiling Water Reactor
CDF	Core Damage Frequency
DPRK	Democratic Peoples Republic of Korea (North Korea)
ECCS	Emergency Core Cooling System
FSAR	Final Safety Analysis Report
HEU	Highly Enriched Uranium
IAEA	International Atomic Energy Agency
INPO	Institute of Nuclear Power Operations
KEDO	Korean Peninsula Energy Development Organization
LERF	Large Early Release Frequency
LEU	Low Enriched Uranium
LOCA	Loss-of-Coolant Accident
LOPA	Loss-of-Power Accident
LWR	Light Water Reactor
NPS	Nuclear Power Station
NPT	Nonproliferation Treaty
NRC	US Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Analysis
PSAR	Preliminary Safety Analysis Report
PWR	Pressure Water Reactor
ROK	Republic of Korea (South Korea)
SNSRC	State Nuclear Safety Regulatory Commission
SOARCA	State-of-the-Art Reactor Consequence Analyses
TEPCO	Tokyo Electric Power Company
WANO	World Association of Nuclear Reactors
WHO	World Health Organization

Introduction

In November of 2010, North Korea revealed to an American delegation newly started construction on an experimental 100 megawatt thermal (MWt) light water reactor (LWR).[1] As nuclear expert Siegfried Hecker explains in accounts written upon his return from North Korea, Pyongyang intends this reactor to be constructed and operated using purely indigenous material and talent. Moreover, the new LWR will be a prototype for future larger stations meant to provide much-needed electricity to the country.

The reaction in the US to this revelation has been widely varied. On one hand, media coverage has generally questioned the intended use of the reactor, suggesting that its true purpose is the fabrication of more plutonium for North Korea's nuclear arsenal. For example, one *Washington Post* article warns, "North Korea said Wednesday it is making rapid progress on work to enrich uranium and build a light-water nuclear power plant, increasing worries that the country is developing another way to make atomic weapons."[2]

These fears are unfounded – nuclear nonproliferation experts maintain that the pilot facility is indeed intended to generate electricity[3] – but several nuclear experts

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[1] Siegfried S. Hecker, Chaim Braun, and Robert L. Carlin, "North Korea's Light-Water Reactor Ambitions," Journal of Nuclear Materials Management 39-3 (Spring 2011).

[2] Associated Press. "NKorea Claims Progress in Uranium Enrichment, Light-water Reactor, Raising Nuclear Bomb Worry." *Washington Post*. 30 Nov. 2011. In general, media outlets covering the November 2010 trip to the DPRK focused their attention on the other major revelation of the returning travelers: the existence of a brand new uranium enrichment facility at the Yongbyon nuclear site, and the associated security implications.

[3] While von Hippel and Hayes do voice concern about the possibility of fractional increase in uranium enrichment to HEU, a substantial portion of their paper on engagement with North Korea is devoted to explaining why LWRs – especially reactors of the size the North is building, are unsuitable for weapons-grade plutonium production (Von Hippel, David, and Peter Hayes. "Engaging the DPRK Enrichment and Small LWR Program: What Would it Take?" *The Nautilus Institute*. 23 Dec. 2010.) Hayes also compares the proliferation intensity parameters of an LWR to those of a reactor like the DPRK's old 5 MWe gas-graphite

familiar with North Korea voice serious concerns regarding the safety with which Pyongyang can construct and operate an LWR. These worries are exacerbated by the disaster at the Fukushima-Daiichi nuclear power station, which served as a harsh reminder of the complexities and risks involved in ensuring nuclear reactors safety.[4]

Though experts have questioned or doubted the future safety of the new facility, no one yet has undertaken a thorough study examining these questions. Some of the literature presents insights into possible methods of engagement with the DPRK to address LWR issues, but the lack of in-depth investigation results in a poor understanding of the specific issues that must be addressed and the urgency with which the nuclear community should react.[5] Von Hippel and Hayes most clearly convey the need for an comprehensive analysis:

> How well, long, or safely such a reactor would operate are certainly worthwhile questions, particularly for those nations (starting with Japan) likely to be downwind from the reactor site…An assessment of the DPRK's situation with regard to each component of the nuclear energy fuel chain and related institutions, based on an analytical structure…would be expected to help to identify where outside assistance would be of most use to the DPRK in reaching its nuclear power development goals. A result of such an assessment would be an identification of what types of assistance are most likely to elicit desired behavior from the DPRK in terms of addressing the international community's nuclear

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reactor in order to show their relative security (Hayes, Peter. "Supply of Light-Water Reactors to the DPRK." *Peace and Security in Northeast Asia: The Nuclear Issue and the Korean Peninsula*. Ed. Young Whan Kihl. New York: M.E. Sharpe, 1997. 25-52.) Hecker too expresses confidence in his belief that the new LWR is not intended for military purposes and that "Although it is technically possible that the LWR will be used to produce bomb-grade plutonium, such a scenario is unlikely." (Hecker, Siegfried S. "What I Found in North Korea." *Foreign Affairs*. 9 Dec. 2010.)

[4] Hecker, Siegfried S., and Robert Carlin. "North Korea in 2011: Countdown to Kim Il-Sung's Centenary." *Bulletin of the Atomic Scientist* 68.1 (2012): 50-60. Web. http://bos.sagepub.com/content/68/1/50.

[5] See, for example, Hecker, Siegfried S. "A Return Trip to North Korea's Yongbyon Nuclear Complex." *The Nautilus Institute*. 22 Nov. 2010, or Von Hippel and Hayes (2010). These two works argue the LWR is a viable entry-point to communication with the DPRK. Other relevant sources include: Cavazos, Roger. "Not Bad Options for the Six Party Talks." *The Nautilus Institute*. 9 Nov. 2011, and Kim, Duyeon. "2012 Nuclear Security Summit: The Korean Twist." *Korea Economic Institute: Academic Paper Series* (September 2011). This second paper effectively illustrates the inexorable connection between nuclear safety and security that was reinforced forcefully with the accident at Fukushima.

> weapons proliferation and other concerns regarding the North Korean nuclear program.[6]

This paper attempts to fill the gaps in the understanding of nuclear safety concerns and evaluate the relative safety of North Korea's light-water reactor project by identifying specific areas where the DPRK is most likely to fall or to have fallen short of internationally accepted standards.

[6] Von Hippel and Hayes (2010).

Chapter 1: The Light Water Reactor – Basics and Background

This chapter is intended to set the stage for a discussion of safety at the new reactor site. It opens with a description North Korea's history in nuclear energy, providing context for their current ambitions by illustrating the many failed attempts to procure a light water reactor (LWR) through negotiations. It continues on to describe the progress made on the reactor as observed in satellite images, and discusses the preliminary concerns posited by experts as a motivation for exploration of the safety of the LWR. The chapter concludes with a description of LWR design and operation in order to establish a thorough understanding of both the physical requirements and safety considerations incorporated in reactor design, and the complex infrastructure required to safety operate an LWR.

1.1 North Korea's Nuclear Industry: History

Over the past 40-plus years, North Korea has experienced a long but unsatisfactory history with nuclear energy technology. Their first procurement after starting a major nuclear development program at Yongbyon, approximately 100 kilmeters north of Pyongyang, came in the form of a research reactor purchased from the Soviet Union in 1965. At the time, North Korean scientists received training and assistance in operations from the Soviet Union. The Democratic People's Republic of Korea (DPRK) eventually upgraded the unit's power rating from four megawatts thermal (4 MWth) to 8 MWth by reverse-engineering the reactor.[7]

North Korea started construction on its first indigenously built reactor, a five-

[7] Albright, David, and Kevin O'Neill. *Solving the North Korean Nuclear Puzzle*. Washington, D.C.: Institute for Science and International Security, 2000, 146.

megawatt electric (5 MWe) gas-graphite (Magnox) reactor modeled after the 50 MWe British Calder Hall reactor, in 1980.[8,9] Toward the end of the decade North Korea negotiated the sale of a number of LWRs from the Soviet Union, but in the turmoil that accompanied the end of the Cold War and the fall of the Soviet union, the reactors never materialized. When IAEA inspectors visited the DPRK in 1992, they were shown three gas-graphite reactors – the 5 MWe unit and two unfinished reactors of 50 MW and 200 MW. The construction of these facilities were frozen as part of the Agreed Framework (1994-2002), and they were never finished.

In accordance with the Agreed Framework, the US promised Pyongyang two LWRs in exchange for the freezing of their existing nuclear facilities, and the Korean Energy Development Organization (KEDO) was created to coordinate and fund the reactor projects. As per the agreements, two LWRs were started in North Korea, but like the larger Magnox reactors, those have been left unfinished due to the breakdown of the Agreed Framework in 2002, and Pyongyang failed once again to procure modern LWRs.

After the Agreed Framework broke down in 2002, the DPRK restarted the 5 MWe reactor, but the facility was finally shut off for good in 2007 as the result of Six-Party Talk negotiations. Throughout the Six-Party Talks, Pongyang has repeatedly brought up the sale of LWRs but because of stalemates regarding North Korea's denuclearization an

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[8] The term "MW thermal" describes the thermal power output while "MW electric" describes the electrical power output, which is typically one 3rd to one 5th the thermal output. Although the Magnox reactor could be described by either parameter, the North Koreans preferred to use the MWe value to emphasize its usage for electricity-supply uses over its plutonium-producing capacity. The reactor was the main source of heat for the nearby town once US shipments of heavy fuel oil were halted (Hecker, Siegfried S. Statement to Senate Committee on Foreign Relations. *Visit to the Yongbyon Nuclear Scientific Research Center in North Korea*, Hearing, January 21, 2004.). Experts typically refer to North Korea's new LWR in thermal output terms because the electricity generation efficiency is not yet known.

[9] Hayes (1997).

agreement has never been reached.[10]

1.1.1 The Symbolic Importance of the LWR

While the new reactor is intended to provide power to the surrounding community and address the "acute electricity problem" North Korea currently suffers, the LWR also has symbolic importance to the Kim regime.[11] Pyongyang views the acquisition of an LWR as a matter of utmost importance, not only as a solution for its energy needs but also as mark of progress and legitimacy in the worldwide nuclear community. Moreover, in the face of decades of failure to obtain an LWR, the success of a natively conceived reactor would be a major victory for the regime.

The indigenous nature of the undertaking is in perfect keeping with the North's national ideology of *Juche*, which loosely translates to self-reliance. Another advantage is that the ability to provide LWRs rather than purchasing them from nations like the US or South Korea would mean freedom from demands to denuclearize.

Nevertheless, it is apparent that the acquisition of a modern LWR by any means is still high on Pyongyang's agenda: in the mismatched statements that came out of the Leap Day Deal, the North's version state that: "Once the six-party talks are resumed, priority will be given to the discussion of issues concerning the lifting of sanctions on the

[10] "Joint Statement of the Fourth Round of the Six-Party Talks." *U.S. Department of State*. Beijing 19 Sept. 2005. Available at <http://www.state.gov/p/eap/regional/c15455.htm>".
[11] "DPRK FM Spokesman's Statement on Experimental LWR Construction." *KCNA*. 30 Nov. 2011. (This success would be even sweeter because Pyongyang views itself as having been cheated multiple times out of an LWR: "The DPRK made up its mind to build its own light water reactor [LWR] according to its economic development strategy given that there was no prospect for getting LWRs whose delivery was promised from outside.")

DPRK and provision of light water reactors." The statement that came out of Washington made no similar mention. [12]

The success of the reactor is plainly important to Pyongyang, but without insight into the deliberations of the regime, it is unclear whether that importance predicts increased or decreased attention to reactor safety. On one hand, the safety of the facility may be viewed as essential to success. On the other, attention to safety may be lost to a single-minded focus on the completion of the product.

1.2 The New Light Water Reactor

1.2.1 Progress at the Construction Site

Satellite images are taken every couple of months by companies such as Digital Globe[13], Google Earth[14], and GeoEye, and made commercially available. From these images, it is possible to follow the development of the external components that comprise the civil engineering portion of the reactor. Analysis tools such as Google sketch-up have been utilized to create ground-level reconstructions and models of the site in order to verify building heights and sizes.

It is clear from the images that the pace of construction at Yongbyon has been rapid, but not consistent. After the foundation was laid in late 2010, there was little progress made between December 2010 and April 2011, presumably because of winter

[12] "DPRK Foreign Ministry Spokesman on Result of DPRK-U.S. Talks." *KCNA*. 29 Feb. 2012. <http://www.kcna.co.jp/item/2012/201202/news29/20120229-37ee.html>. Compare the language of the North Korean statement on the Leap Day Deal to the language in the American statement at US Department of State. "US-DPRK Bilateral Discussion." Press Release. 29 Feb. 2012. <http://www.state.gov/r/pa/prs/ps/2012/02/184869.htm>

[13] "Light Water Reactor Construction Progressing at Yongbyon Nuclear Site." *ISIS Reports*. Institute for Science and International Security, 5 Mar. 2012. <http://isis-online.org/isisreports/detail/light-water-reactor-construction-progressing-at-yongbyon-nuclear-site1/>.

[14] Milonopoulos, Niko, Siegfried S. Hecker, and Robert Carlin. "North Korea from 30,000 feet." *Bulletin of the Atomic Scientists*. 6 Jan. 2012.

weather conditions; however, much of generator hall and containment building were completed between the following May and September.[15]

According to February 2012 images, the roof of the generator hall has been added, indicating the fast pace of construction from November 2011 to February 2012.[16] Before the installation of the roof, images revealed several components inside the generator hall, including a traveling crane rail and the turbine pedestal. This last aspect indicates that the necessary specs for the turbine have already been worked out such that a pedestal could be built to fit.[17] The dome of the containment building appears to be complete, but lies detached on the ground next to the structure itself; before the containment building can be sealed, the heavy interior equipment of the reactor must be loaded into the reactor by cranes.[18]

Based on the most recent images, experts predict that North Korea is on track to complete the external development mid to late 2012.[19]

Next Steps

Despite the impressive rate of development onsite, the civil engineering aspects of the LWR are the easiest to fabricate. At this time there is no evidence of progress on the mechanical components of the reactor, which will likely be manufactured in specialized factories.

The next phase of production requires significantly more specialized materials

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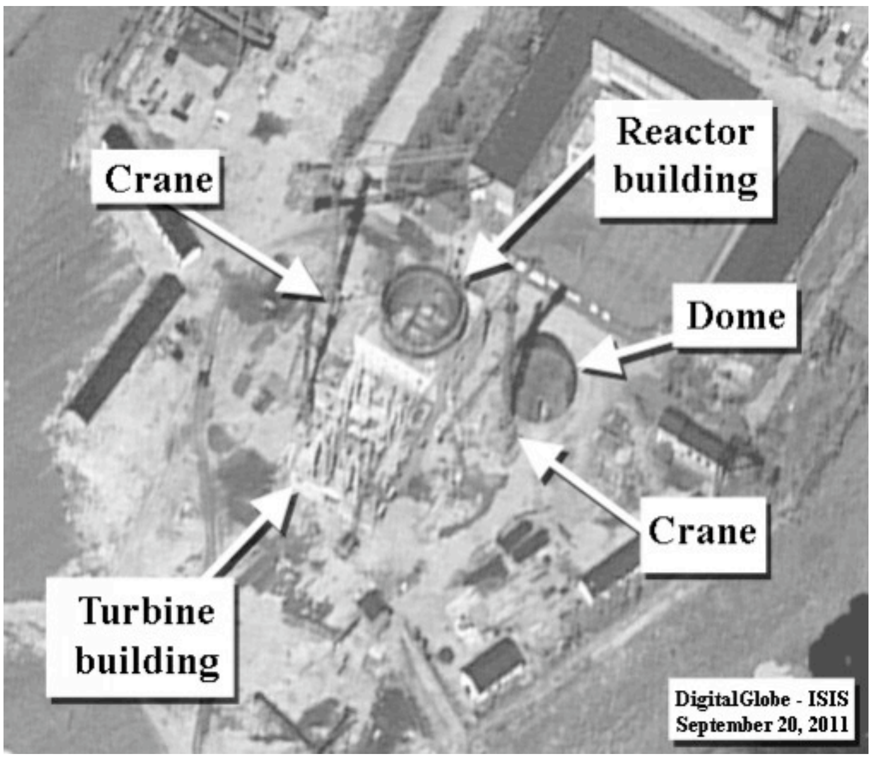
[15] *Ibid.*
[16] ISIS, March 2012.
[17] Milonopoulos et al.
[18] "North Korea Makes Significant Progress in Building New Experimental Light Water Reactor." *38 North*. 14 Nov. 2011.
[19] *Ibid.*

and equipment: custom-made stainless steel components for the core, control rod systems, and pressure vessel; nuclear grade heat exchangers; and an instrumentation and control system that monitors the various parameters of the reactors operation.[20]

Figure 1 Satellite image of the LWR construction site on September 20th, 2011[21]



[20] 38 North.
[21] ISIS, March 2012.

Figure 2 Satellite image of the LWR construction site on November 14th, 2011[22]

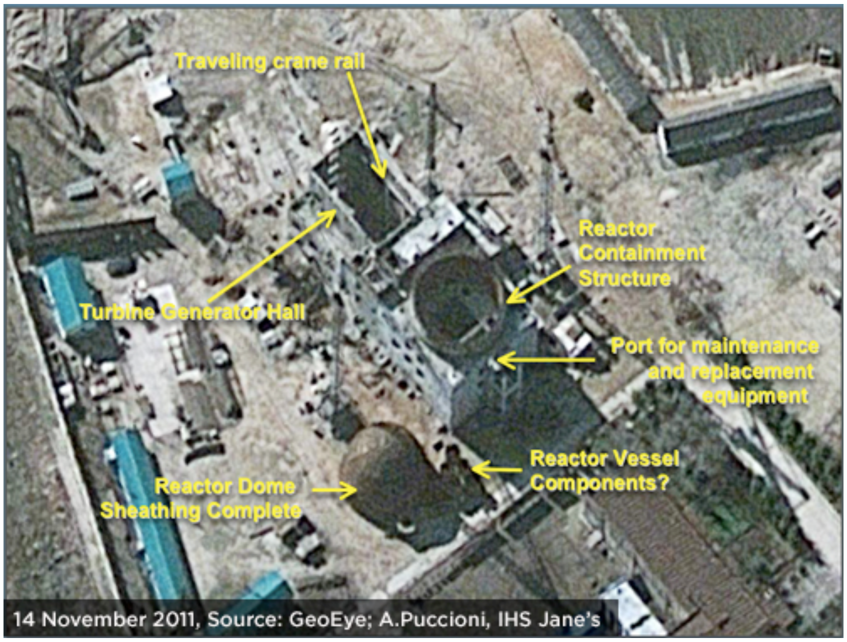
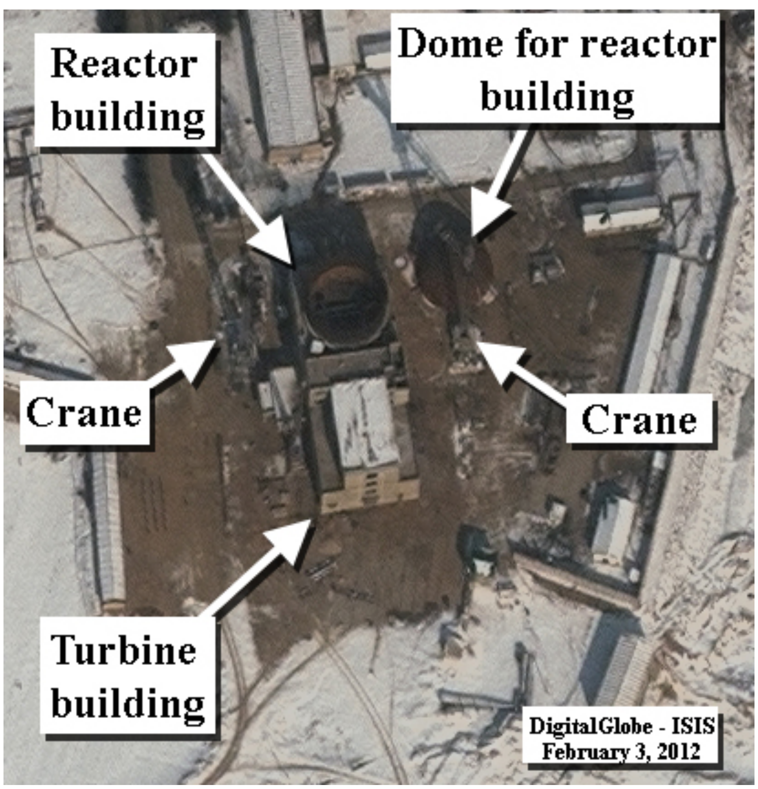


Figure 3 Satellite image of the LWR construction site on February 3rd, 2011[23]



[22] Milonopoulos et al.
[23] *Ibid.*

1.2.2 Initial Safety Concerns

Reports from nuclear experts familiar with the LWR project voice serious concern about the safety with which Pyongyang can install and run the facility, saying that while it is likely they have the materials required for a small reactor, they lack the technical expertise to fabricate many of the elements that require more sensitive engineering or state of the art technologies.

Furthermore, North Korea's complete detachment from the global nuclear safety regime cause for major concern, both because the DPRK cannot benefit from external assistance and because other states do not have access to detailed information about the new reactor. Hecker, Braun and Carlin posit that though the plant may get completed with purely indigenous resources, "without the benefit of external safety consultation and review, we have serious concerns about the design and whether or not NK can operate it safely"[24]. In particular, Hecker explains that "from what little we saw, it also appears that construction practices are not commensurate with international reactor safety standards and practices."[25]

Von Hippel and Hayes of the *Nautilus Institute* agree that North Korea can "almost certainly build a pilot 25 MWe LWR, albeit of unknown safety", specifying that an indigenous reactor would likely incorporate crude electro-mechanical systems rather than modern technologies. The introduction to the DPRK Energy and Minerals Working Group Meeting, held by the *Nautilus Institute* in March 2011, mentions the safety risk

[24] Hecker, Siegfried S., Chaim Braun, and Robert L. Carlin, "North Korea's Light-Water Reactor Ambitions," Journal of Nuclear Materials Management 39-3 (Spring 2011).
[25] Hecker, Siegfried S. "Redefining Denuclearization in North Korea." *Bulletin of the Atomic Scientists*. 20 Nov. 2010.

that the LWR presents to "both North and South Koreas."[26] Though most authors voice some concern, Lewis, Hayes and Bruce are more conclusively pessimistic about the reactor's viability in mentioning the "home-made, unsafe light water reactor currently under construction at Yongbyon".[27]

Finally, the likelihood that the DPRK's nuclear regulatory body has the robustness and independence that is necessary to maintain safe nuclear operations is a central worry.[28] Government oversight of the State Nuclear Safety Regulatory Commission (SNSRC) may vitiate the organization's ability to perform and report accurate inspections, and to take actions to ensure that faults are addressed.

1.3 LWR Design and Operation

Light water reactors are nuclear reactors that use low enriched uranium (LEU) for fuel and water as both the coolant and the moderator.[29] The fuel pellets, densely packet cylinders of UO_2 (uranium dioxide), are packed into cladding rods in order to keep fuel and fission products separated from the coolant. These fuel rods are then arranged in rectangular cross section bundles and the fuel assemblies are placed vertically in the reactor vessel to make up the core. Typically, reactor technicians replace approximately one third of the fuel assemblies every 12 to 18 months.

The LWR in question is a pressurized water reactor; a pressurizer connected to

[26] Imhoff, Arabella, and Scott Bruce. "Introduction: Energy and Mineral Resources in North Korean Security and Sustainability." *The Korean Journal of Defense Analysis*23.2 (June 2011): 149-57. This document is an introduction to the documentation of the DPRK Energy and Minerals Working Group Meeting, which includes analytical assessments of the energy sector and mining industry in North Korea: "DPRK Energy and Minerals Working Group Meeting - Background." *The Nautilus Institute*. 18 Mar. 2011.
[27] Lewis, Jeffrey, Peter Hayes, and Scott Bruce. "Kim Jong Il's Nuclear Diplomacy and the US Opening: Slow Motion Six-Party Engagement." *The Nautilus Institute*. 21 Oct. 2011.
[28] Hecker, "Redefining Denuclearization" (2010).
[29] The function of the coolant is to absorb the heat released during fission. A moderator slows the neutrons in the core to thermal energies in order to make atomic fission more viable.

the reactor vessel prevents the water in the primary coolant circuit from ever boiling. Since LWRs normally operate at upwards of 300 °C, the pressure vessel must consequently sustain pressures of around 2300 psi.[30] The primary coolant travels in a closed loop: upward through the reactor core (parallel to the rods and against the temperature gradient), through the steam generator, and finally into pumps where the cooler water is injected back into the core. Heat is exchanged to feed-water in the secondary cycle in the steam generator. As in any conventional power plant, steam goes through a turbine to generate power for electricity and then through a condenser to be heated again.

The physical construction of a LWR may be thought of as being comprised of four major engineering components: nuclear, mechanical, civil and electrical.

1. The nuclear and materials engineering aspect deals with fuel fabrication, cladding, manufacture of fuel rods and arrangement into fuel assemblies in the core.

2. The mechanical engineering part comprises the heavy industrial engineering aspects of the reactor, including the pressure vessel and pipework that makes up the steam generator.

3. Civil engineering considerations include the integrity of the concrete containment structure and the strength of the foundation to withstand major natural disasters and directed attacks.

4. Finally, the electrical engineering components deal with the measurement instrumentation and control features that are continually running during normal operation. Neutron-absorbing control rods that maintain the core at a safe level of

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[30] *Achieving Nuclear Safety: Improvements in Reactor Safety Design and Operation.* Paris: Nuclear Energy Agency, Organization for Economic Co-operation and Development, 1993, 20.

reactivity function on electrically-driven actuators.

1.3.1 The LWR: Design Safety Principles

In considering the safety of a nuclear reactor, the ultimate goal is to prevent the release of radiation into the surrounding area. For LWRs, the assumption is that this eventuality involves a core meltdown, which can be initiated in several ways. The task is then to minimize the probability of any initial and subsequent failures that could lead to the undesirable consequence.[31] Because safe operation of the reactor depends on the proper functioning of all components and systems, each part of the unit is important to its overall safety whether or not it performs a specific safety function.[32]

Reactor engineers are careful to incorporate safety principles into the design of the reactor. While individual design specifications depend on each component, some general principles apply to the system as a whole. First, redundancy of safety-related parts ensures that other constituents can compensate for the failure of one device. Diversification employs various types of parts for a specific purpose in order to protect against the risk of common-mode failures. Defense-in-depth describes the ability to respond to failure at each stage as an accident progresses.[33] The layered barriers that prevent radioactive release provide a clear example of these safety principles: at the first level, fuel cladding prevents radioactive material from entering the coolant stream. In case it does, the walls of the pressure vessel act as the secondary barrier. In the more extreme case of a core meltdown or other breach of the primary system, the concrete

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[31] "Fact Sheet on Probabilistic Risk Assessment." *US NRC*. 4 Feb. 2011. <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/probabilistic-risk-asses.html>.
[32] "10 CFR Appendix A to Part 50— General Design Criteria for Nuclear Power Plants."*NRC*. 31 Jan. 2012. <http://www.nrc.gov/reading-rm/doccollections/ cfr/part050/part050-appa.html>.
[33] Pershagen, Bengt. *Light Water Reactor Safety*. Oxford, England: Pergamon, 1989. 129-132.

containment structure is designed to completely contain the results of a reactor failure.

Today's nuclear reactors are designed with as many inherent safety features as possible, which are supported by passive and active response systems. Inherent safety features describe aspects of the reactor design that automatically prevent or counteract undesirable consequences. For example, LWRs have a negative temperature and void coefficients, indicating that reactivity decreases in the case of primary coolant evaporation.[34]

Passive safety functions do not require an electrical current to work; if a LWR loses power, an automatic shutdown (scram) occurs. This shutdown includes a passive mechanism whereby the control rods default to a containment position within the core.

The emergency core cooling system is an example of an active response system (i.e. one that requires electricity). In a loss-of-pressure or loss-of-coolant accident, lowpressure sensors activate coolant injection systems and overhead spray systems until the coolant volume or pressure reaches an acceptable level.

For each component, it is necessary to consider the materials used, as well as methods of processing and manufacturing and installation. Individual parts such as valves and pipes are required to reasonably withstand the extreme environment that exists inside a LWR, including high temperatures, extreme pressure, exposure to radiation, and repeated or long-term use. For each system, it is essential to ensure that each constituent is backed-up such that that a single failure does not compromise the function of the entire system.[35]

[34] "Safety of Nuclear Power Reactors." *World Nuclear Association*. 31 Oct. 2011.
[35] 10 CFR Appendix A to Part 50 (NRC).

Nuclear and Materials Engineering

The uranium dioxide pellets must be densely packed to prevent excessive degradation. Besides being able to retain the fuel and fission products (including gaseous products) inside the fuel rods, the cladding material should be non-corrosive. While stainless steel can be used, a zirconium alloy (Zircaloy) is a much better, though more expensive, choice because of its strong resistance to water corrosion and low thermal-neutron cross section; stainless steel tends to lose ductility due to radiation, which can lead to loss of structural integrity.[36] The entire fuel rod should be designed to accommodate expansion of both the pellets and the cladding with increased reactivity and heat.

Mechanical Engineering

The biggest challenge in manufacturing the mechanical engineering components – namely the pressure vessel and steam generator – is to fabricate them to withstand the constant bombardment of highly pressurized water. This is particularly true of the steam generator, which is comprised of many narrower pipes and is exposed to water on both sides.[37] For economic and safety reasons, the reactor vessel is typically constructed of carbon steel with 300-series austenitic stainless steel as internal cladding. This more expensive type of steel contains less carbon, which makes it more resistant to stress-corrosion cracking. Coolant pipes are usually made of stainless steel all the way through. Because pipes are weakest at the joints, high-level, extremely accurate welding and annealing is particularly vital to strength and durability.

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[36] Weisman, Joel. *Elements of Nuclear Reactor Design*. Amsterdam: Elsevier Scientific Pub., 1977, 39-40.
[37] "Nuclear Power Reactors." *World Nuclear Association*. Mar. 2011.

Civil Engineering

Containment buildings for LWRs are constructed out of pre-stressed concrete. While this is not always true, they sometimes support an interior stainless steel lining. The reactor containment should be thick enough and strong enough to prevent release of radioactivity with extremely high confidence. Furthermore, the buildings and foundation of the reactor should have the structural integrity earthquakes of a scale larger than what is known to occur in the area, in order to take into account inadequate information about natural environmental hazards with adequate safety margins. Thick concrete shielding around the primary system compartment separates it from the rest of the vapor containment, providing additional protection against extreme incidents such as falling planes and other missiles.[38]

Electrical Engineering

Because the control rods of an LWR are operated electrically, the reactor requires a dependable source of electricity to work properly. Additionally, the instruments and monitors that facilitate the man-machine interface and allow reactor operates to constantly monitor performance depend on constant electrical power. Consequently, it is imperative that a safe LWR has both reliable onsite and offsite sources of electricity. Moreover, operators of a new LWR should undertake a thorough testing and troubleshooting campaign of the electrical components of the reactor before fuel loading to ensure that all systems are working correctly.

[38] Weisman, 399.

1.3.2 The LWR – The Human Element

The systems and components of a LWR require constant monitoring and periodic testing. Consequently, skillful, attentive operation of the reactor over the course of its lifetime is vital to normal reactor function.

Firstly, sufficient training of reactor operators is critical. In the control room, operators constantly watch instrument read-outs for changes in parameters such as neutron flux, temperature, pressure and mass flow of coolant.[39] Remote operation necessitates constant readiness on the part of the operators – moreover, they must adequately understand the systems they are running and be able to interpret the data from monitoring instruments so they can respond appropriately in case of abnormal conditions.[40]

Secondly, good organization and expertise at the administrative level is paramount. The supporting regulatory infrastructure plays a critical role in assuring diligent practices and maintaining quality control by providing reinforcement and policing of the operator. In order to fulfill this role properly, it must be independent, capable, sufficiently funded and staffed to perform its functions.[41]

A regulatory body also plays a critical role in ensuring the safety of a new nuclear power plant. In a typical case, the utilities company submits a preliminary safety analysis report (PSAR) prior to construction. This report is eventually followed up by a series of approval stages, including the final safety analysis report (FSAR) during construction, pre-criticality tests to check the performance of components and systems before fuel loading, and nuclear tests at low power. Once the plant starts running at full power,

[39] Pershagen, 138.
[40] *Achieving Nuclear Safety*, 56.
[41] Meserve, Richard A. "The Global Nuclear Safety Regime." *Daedalus* (Fall 2009): 100-11.

reactor operators continue to generate regular reports of daily readings and periodic inspections.[42]

The regulatory agency is responsible for ensuring that safe designs of systems and components are actually carried out in construction, fabrication and manufacturing. The safety authority must make sure that the quality of components is high, ensuring adequacy of quality assurance procedures.[43]

Lastly, the importance of the safety culture cannot be overemphasized. Due to the nature of the human-machine interaction of nuclear power plants, the safety of a unit depends heavily on the attitudes of the individuals responsible for it. Therefore, the culture of safety – the "personal dedication and accountability of all individuals engaged in any activity which has a bearing on the safety of nuclear power plants" – is a major contributing factor to the safety of the plant.[44]

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[42] Pershagen, 143.
[43] Pershagen, 130.
[44] Mosey, David. *Reactor Accidents: Institutional Failure in the Nuclear Industry*. Sidcup: Nuclear Engineering International, 2006.

Chapter 2: Methodologies of Evaluating Safety

The evaluation of risk and safety at nuclear power stations is a science that has been developed over several decades of research. This chapter opens with an introduction to the safety concepts driving modern risk assessment methodologies (RAMs). It will explain how a lack of information about and access to North Korea's LWR severely limits the extent to which we can employ modern techniques of safety analysis and propose that the safety of the reactor can be analyzed by examining the DPRK's capacity to abide by the principles of reactor safety in other endeavors and arenas.

2.1 Modern Risk Assessment Methodology for LWRs

Modern methods of reactor safety analysis utilize probabilistic risk calculation techniques. Aided by high-powered computer modeling programs, analysts can input relevant parameters and scenarios in order to assess the probability of severe damage to a reactor and compare its risk rating to internationally accepted standards. It is evident that current-day RAMs require extensive and detailed quantitative information regarding reactor design and operation.

North Korea's isolation from the international nuclear community means that potential analysts have almost no concrete information about the facility. So, far from knowing extensive technical specifications of the LWR, almost nothing is known about the specifics of the new facility. Consequently, probabilistic techniques of safety analysis have no chance of working for North Korea's new LWR.

2.2 Adapting Safety Assessment to North Korea

In order to give structure to the assessment regarding the safety of the new LWR, this section will first establish basic safety principles and describe likely safety paradigms then examine North Korea's ability and willingness to abide by those safety principles in a general sense.

Accepted assessments at nuclear facilities include Probabilistic Risk Assessments (PRAs). PRAs conceive of severe accidents as a series of failures that occur in stages, eventually resulting in a large uncontrolled release of radiation into the atmosphere that causes injury and economic damage to the surrounding community.[45] Within this model, the probability of a major disaster is associated with the risk of failure at three successive stages in the accident scenario. The first stage is termed the Core Damage Frequency (CDF), and describes the probability of damage to the radioactive material within the reactor. The second, Large Early Release Frequency (LERF), represents the magnitude and timing of radioactive release once the reactor has experienced core meltdown. Finally, the PRAs also account for established disaster mitigation procedures in their evaluation of risk.

It is evident that minimizing the chance of failure at each stage depends heavily both on inherent safety and operational safety. Inherent safety aspects comprise physical features of the reactor that contribute to or detract from the overall safety of the plant. The materials, fabrication and construction techniques, and physical situation of the

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[45] For a clear and understandable explanation of PRAs, see either of the U.S. NRC's sites explaining these concepts: "Fact Sheet on Probabilistic Risk Assessment." *US NRC*. 4 Feb. 2011, <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/probabilistic-risk-asses.html.>. or "Probabilistic Risk Assessment (PRA)." *US NRC*. 29 Mar. 2012, <http://www.nrc.gov/about-nrc/regulatory/risk-informed/pra.html>.

facility all affect its inherent safety. Operational safety is dictated by the infrastructure and practices surrounding operation of the reactor. A recent study by the U.S. Nuclear Regulatory Commission (NRC) characterizing the potential consequences of severe accidents, found that well-established resources and procedures for accident management could significantly reduce the impact of an accident at a nuclear reactor. This emphasizes the role of a robust safety regime that combines inherent and operational safety.[46]

In order to address impact of safety during all stages of an accident, this paper will consider several key safety principles as they relate to the DPRK's new facility.

- North Korea's technical capability to design, construct, and maintain an LWR
- Pyongyang's nuclear regulatory organization and administrative infrastructure
- North Korea's emergency response capabilities
- The safety culture within North Korea

Throughout the discussion it will be important to keep in mind the particular challenges and stringent requirements of building and running an LWR in order to put observations into perspective and get a clear idea of what they signify for the new project.

2.3 Resources for assessing safety in North Korea

Sources of direct insight into the progress of the new LWR are remarkably scarce: Such information originates in part from the testimonies of individuals, such as Siegfried Hecker, who have personally visited Yongbyon since the start of construction. Satellite images taken of the site between September 2010 and February 2012 give additional insight into North Korea's progress on the construction of the LWR.

In general, information directly relating to the LWR itself is limited, and there are

[46] "State-of-the-Art Reactor Consequence Analyses (SOARCA)." *U.S.NRC*. 29 Mar. 2012. Web. <http://www.nrc.gov/about-nrc/regulatory/research/soar.html>.

many crucial aspects of fabrication and operation relating to safety that cannot be observed directly. Satellite images only give spotty information about the exterior, civil engineering portion of the entire facility, while personal accounts of this project are limited to a single visit shortly after the beginning of construction.

Therefore it is crucial to study North Korea's performance record in other nuclear and non-nuclear undertakings to obtain an understanding of safety prospects at Yongbyong. Examples to be examined include the manufacture and operation of the 5 MWe reactor, the KEDO partnership during the Agreed Framework, and the DPRK's disaster management record during floods that have struck the country. It will also be necessary to analyze several external factors that can exacerbate the risk to the plant, particularly the reliability of the DPRK's power grid. The Magnox reactor constitutes a suitable comparison to the LWR because, like this new project, it was presumably designed and built within the DPRK. Nevertheless, the inherent dangers of each reactor type are dissimilar: in general, LWRs demand more stringent safety features and quality control of components, while gas-graphite reactors are more forgiving. KEDO negotiations constituted one of the few instances that the U.S. has had interaction with the nuclear regulatory body of the DPRK.

Finally, we will take a closer look at last year's disaster at the Fukushima-Daiichi nuclear power station in Japan. Familiarity with this incident is not important because the two reactors are comparably similar, but analysis of factors leading to the disaster has recently brought to light several particularly important aspects of nuclear safety pertinent to North Korea's situation. Additionally, the differences between North Korea's and

Japan’s experiences in nuclear engineering put Pyongyang’s situation into perspective with respect to modern international standards.

Chapter 3: Inherent Safety at the Light Water Reactor

Chapter three evaluates aspects of inherent safety of the Light water Reactor (LWR), addressing North Korea's technical and engineering capabilities. In the beginning, observations that impact the civil, mechanical, nuclear and materials scope components are discussed as well as off-site influences. The reader will find that there are few definite answers regarding North Korea's capabilities regarding the new LWR, rather, inferences based on particular observations that imply a level of particular competency and adherence to standard safety protocols.

3.1 Civil Scope Components

Hecker, Lewis, and Carlin expressed concerns about the methods the DPRK was using to lay down the concrete foundation of the reactor. In particular, they note that this foundation pad was "quite thin", and that the concrete of the containment shell appeared to be poured in small batches. In order to assure proper curing, it is necessary to pour the concrete continuously in large batches.[47] These worries regarding the simplest stage of reactor construction are underscored by previous comments about the old plutonium reprocessing building at Yongbyon (known in North Korea as the Radiochemical Laboratory): the concrete structures of the separation plant appeared too thin to be safely used for reprocessing.

The rapid pace of construction progress since the initial visit is evident from satellite images. While the speed indicates that the North has "impressive manufacturing

[47] Siegfried S. Hecker, Chaim Braun, and Robert L. Carlin, "North Korea's Light-Water Reactor Ambitions," Journal of Nuclear Materials Management 39-3 (Spring 2011).

capabilities", it is simultaneously alarming when considering the "safety concerns associated with building and operating an LWR", [48] Since proper planning of construction is a lengthy process that requires thorough seismic analysis of the site and multiple iterations of the safety analysis report, the speed of construction implies that preliminary precautions were not adequately addressed.

"What is especially troubling", Hecker explains, "is that this is a new endeavor for North Korea and its technical specialists have not been part of the global nuclear safety community."[49] The prospect of a hasty construction job in a situation where there is no prior experience with the type of project at hand is an alarming one. Problems such as haste and failure to recognize dangerous problems, as well as ignorance about LWR best practices, can introduce intrinsic risk factors to reactor that make core damage and subsequent large early release of radiation more likely than is acceptable by international standards.

3.2 Mechanical Scope Components

Off-site fabrication of heavy internal components makes it impossible to directly track their manufacturing process or assess their quality, but the pace of construction implies that mechanical scope components are undergoing fabrication as well. According to Chaim Braun, an expert in nuclear power and nonproliferation at Stanford University's Center for International Security and Cooperation (CISAC), major construction could not have been initiated without knowledge of internal specifications:

> While we have no idea whether all the requisite nuclear steam supply system's and turbine generator system's equipment items can be manufactured domestically

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[48] Hecker, Siegfried S. "Can the North Korean Nuclear Crisis Be Resolved?" Conference on "Rethinking Nuclear Issues in Northeast Asia" Seoul. 21 Mar. 2012. Prepared notes for speech.
[49] *Ibid*

> in the DPRK, the fast-paced progress in civil works construction implies that the mechanical scope equipment items have already been designed (thus determining the dimensions of the various buildings), and these items are likely now under fabrication.[50]

Braun's remarks are further echoed by a late 2011 *Washington Post* article asserting that the "accelerated pace of construction… lends credence to Pyongyang's claim that it has the materials and know-how to build nuclear plants on its own."[51]

It should be noted that recent March, 2012 satellite images show that the external construction is very near to complete, but completion of the exterior depends on delivery and installation of heavy parts components, including the turbines, steam generator and reactor pressure vessel. However, this is not evidence of any structures where the completed modules might be stored on-site prior to welding.[52]

Welding

North Korea can most likely can fabricate major equipment, but welding has been a major concern because of the specialized requirements necessitated by the high pressures in the reactor vessel and pipes .[53] To evaluate welding capabilities observations at the Magnox reactor were taken into account. Previous U.S. visitors recounted that the quality of welding appeared, understandably, to depend on the importance of the weld; for example, steam lines running from the plant to the turbine building were well not done. At the same time, there was no evidence of any inspection program of any

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[50] Email correspondence between Chaim Braun and Siegfried Hecker, Nov. 13, 2011. The email was passed along to me on Nov. 15, 2011 by Hecker's assistant, Peter Davis.

[51] Harlan, Chico. "N. Korea Makes Rapid Progress on Nuclear Plant." *Washington Post*. 14 Nov. 2011.

[52] Email correspondence between Chaim Braun and Siegfried Hecker, Nov. 13, 2011. The email was passed along to me on Nov. 15, 2011 by Hecker's assistant, Peter Davis.

[53] Heavy manufacturing is a national strong industry, and we know of facilities in the DPRK, Like the Chollima Steel Mill, that are equipped to make the reactor's internal parts (Ho, Park In. "Kim Jong Il Inspected New Chollima Steel Mill." *Daily NK*. 26 Dec. 2008. <http://www.dailynk.com/english/read.php?cataId=nk01700&num=4399>.)

assurance program confirming the sufficient quality of each weld from spot to spot on the reactor. [54] When a US team worked on a welding job together in 2007 with the North Korean nuclear workers, they found that their site contacts were unfamiliar with modern welding equipment such like the TIG (tungsten inert gas) welder. [55] In the face of the advanced welding requirement of LWR construction, it is worrisome that only a few years ago the North Korean reactor operators were completely unfamiliar with modern welding technology.

3.3 Nuclear and Materials Scope Components

Accounts from the two visits of international inspectors to the Magnox reactor reveal several issues related to the internal workings and performance of the plant. Firstly, it appeared that North Korea encountered problems with basic operations at the plant for quite a long time, especially toward the beginning of the reactor's lifetime. The Koreans experienced acute start-up issues for about the first five years of operation, causing the power output to be less than 15 MWth, compared to the nominal value of 25 MWth.[56] Additionally, the reactor was plagued with fuel failures due to its operation with many of the control rods partially inserted; the resulting skewed neutron flux caused uncharacteristically high temperatures in the fuel. It was not until the early 1990's that performance began to improve, and even then the power output never exceed 20 MWth.

While the North Koreans were successful in making the plant run, they never completely mastered its operation or achieved consistent power production. Albright and O'Neill explain that in general the reactor underwent a "very unusual operation" regime,

[54] Former U.S. Inspector in North Korea. "Observations on North Korea's 5 MWe Reactor." Message to the author. 2 Apr. 2012. E-mail.
[55] "Interview with Previous US Visitor to North Korea's 5 MWe Reactor." Telephone interview. 3 May 2012.
[56] Albright and O'Neill (2000), 96.

characterized by isolation from the use of modern controls and instrumentation and a keen focus on getting the reactor to operate rather than on maintaining a steady operating regime[57]

After the breakdown of the Agreed Framework, the reactor was loaded with new fuel and restarted in 2003. It functioned intermittently for the next three years and evidently experienced several fuel cladding problems that "limited full-scale operations."[58]

3.4 Maintenance of Safety Features

3.4.1 Cooling Water Concerns

In some instances, the development at Yongbyon has raised questions about how the DPRK is going to address certain obstacles that affect will affect the safety of the power plant. One such issue is the intended supply of water. Light water reactors require a reliable source of water for cooling and steam production, but the Kuryong River, from which the LWR plans to draw water, does not provide a consistent flow of water. In the winter it freezes over, while in the summer water levels are often low enough to expose sandbars.[59] While pipes installed across the river in order to draw from deeper parts of the river, the water supply may not remain adequate throughout the year.[60]

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[57] *Ibid.* Other U.S. visitors to the plant also give accounts of shoddy instrumentation: "The instrumentation generally appeared old and poorly maintained. No calibration stickers were observed. Site operations staff mentioned that the several methods for measuring core power did not provide consistent measurements" (Former U.S. Inspector in North Korea. "Observations on North Korea's 5 MWe Reactor." Message to the author. 2 Apr. 2012. E-mail.)

[58] Hecker, Siegfried, and William Liou. "Dangerous Dealings: North Korea's Nuclear Capabilities and the Threat of Export to Iran." *Arms Control Today*. Arms Control Association, 28 Mar. 2007. <http://www.armscontrol.org/act/2007_03/heckerliou>.

[59] 38 North.

[60] According to 38 North, the trenches in which the pipes were placed were covered up by September 2011. These may contain part of a sophisticated intake and discharge cooling system.

3.4.2 North Korea's Power Grid

The reliability of the DPRK's power grid is a critical concern because nuclear power plants, and especially LWRs, require reliable electrical grid because of their active cooling needs. Risks of an unreliable grid are significant. Peter Hayes explains that the combination of "primitive technology and materials", along with an unstable grid, can lead to a reactor scram and the "very real possibility of a loss-of-control and meltdown".[61]

The power grid in the DPRK is notoriously bad; the 5 MWe plant underwent "frequent blackouts" such that a loss of off-site power would have been fairly common.[62] In town, visitors at the guest house in Yongbyon got at best a couple hours of power power each day, and even then there would be drastic voltage fluctuations. [63]

Clearly, constant voltage fluctuations, along with numerous power outages, would be a major problem for the LWR.

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[61] Hayes, Peter. " **Nuclear Safety and Security After 3-11.**" *The Nautilus Institute*. 22 Mar. 2012. The world witnessed exactly this scenario at the Fukushima-Daiichi plant last year. Significantly, it was the it was the availability of off-site power that saved the nearby Fukushima-Daini plant (A. Omoto, "Fukushima Accident: An overview", ICAPP 2011, 3 May 2011.)

[62] Albright and O'Neill (2000), 238.

[63] "Interview with Previous US Visitor to North Korea's 5 MWe Reactor." Telephone interview. 3 May 2012.

Chapter 4: Operational Safety at the Light Water Reactor

Chapter four examines several issues associated with operational safety, emphasizing the human element of nuclear safety. North Korea's safety culture and extent of disaster preparedness are explored, as well as what we can discern about the nuclear regulatory body and administrative framework. The chapter concludes with an examination of the Fukushima-Daiichi incident, looking at the operational and organizational factors at play and drawing connections back to the experience of the DPRK.

4.1 Safety Culture

As David Mosey phrases it, the safety culture of a nuclear reactor "refers to…the personal dedication and accountability of all individuals engaged in any activity which has a bearing on the safety of nuclear power plants". A strong safety culture is characterized by training and education of staff and nuclear workers that emphasizes the motivations behind safety practices and elucidates the real-life consequences of failures in individual performance.[64]

At the Magnox reactor, operation appeared to be the priority. Albright and O'Neill describe the DPRK's operation of the Magnox reactor as "very unusual" compared to modern day practices and standards. Instead of using modern controls and instrumentation, North Korea focused on making sure the reactor was operating.[65] This neglect of instrumentation was accompanied by a similar lack of data recording – when IAEA officials requested records of operation during their trip to North Korea in 1992,

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[64] Mosey, David. *Reactor Accidents: Institutional Failure in the Nuclear Industry*. Sidcup: Nuclear Engineering International, 2006.
[65] Albright and O'Neill, 96.

Pyongyang insisted that no such records existed. Negotiators for KEDO (the Korean Peninsula Energy Development Organization) also noted that while the DPRK had some experience with safety evaluations for the Magnox reactor, this experience was definitely "limited" compared to current-day safety procedures.[66]

The DPRK's inattention to safety and the rigors of safety practices stands out as a significant concern when applied to the LWR because ensuring the safety of the LWR depends on constant and diligent attention to safety at all levels of operation and governance. In fact, Albright and O'Neill note, "building and ensuring the safe operation and maintenance of LWRs is a highly complex task. The negotiators of the Agreed Framework, particularly the North Koreans, appear to have had little appreciation for the immense problems that would develop".[67] This lack of understanding translates to a poor safety culture within the DPRK's reactor community.

Gaps in safety thinking are evident in accounts of understaffed facilities. One inspector present during the shutdown of the reactor in 2007 notes several alarming observations:

> Standard radiological practices (such radiological area postings, clear barriers between contaminated areas and clean areas, the use of dosimeters by all staff members.) were not observed. It was common to see site security personnel and site engineers/managers enter high contamination areas (~300,000 dpm/100cm^2) wearing street clothes. PPE [Personal Protective Equipment], when used, were often reused. There was no observable lock/tag program, and site staff regularly worked on energized equipment.[68]

To put these observations into perspective, it is important to understand that inattention of individual safety was not the product of incompetence or evil, but the significant resource limitations and funding shortages suffered by reactor operators that

[66] *Ibid,* 237.
[67] *Ibid,* 353.
[68] "Interview with Previous US Visitor to North Korea's 5 MWe Reactor."

precluded the luxury of ensuring the safety of all individuals.[69] Furthermore, the only exposure the North Korean reactor community would have had to a nuclear safety regime was that of the Former Soviet Union's, responsible for the incident at Chernobyl.

Alarming news concerning accidents and incidents at other industrial facilities incites doubt about the appreciation for safety and quality generally in the DPRK. In November of 2011, approximately one year after North Korea began construction at Yongbyon, South Korean media came out with stories that hundreds of North Korean college students, enlisted in the construction of a new hotel and a number of apartment buildings in the capital, had been killed in construction-related accidents.[70] These buildings were part of a government campaign to achieve significant progress by 2012, a highly political year for the North because it is the centenary of Kim Il Sung. Pyongyang has promised North Korean citizens a "strong, prosperous nation" by 2012. In its push to make advances, Pyongyang appears to have forsaken quality and safety. Besides alarm over the recent accidents, observers also worry that these hastily-built apartments may collapse in the coming years. Evidence like this of hurried work with little thought as to the quality or durability of the final product raises alarm bells for the LWR, particularly because the reactor holds significant political significance.

4.2 Nuclear Regulatory Body

During the KEDO partnership, the US and other executive member countries worked with the North Korean nuclear compliance group in preparing to construct the two light water reactors. Through interactions with the North Koreans, it

[69] *Ibid.*
[70] "Pyongyang's Construction Drive Said to Kill Hundreds of College Students." *Yonhap News*. 29 Nov. 2011.

became evident that the quality of the North Korean nuclear regulatory authority was below the national standards of the other member nations.[71] Other member countries were worried that North Korea's compliance body lacked a culture of safety even though its job was to ensure reactor safety. When North Korea was required to approve a preliminary safety analysis report (PSAR) in 2000 as part of issuing the construction permit to KEDO, they did have some experience with safety evaluations for their gas-graphite reactors. Their familiarity was severely limited compared to modern safety practices; the 18 volume, 6 month review that comprised the safety analysis was far more in-depth than North Korea had ever had experience with.[72]

The poor quality of North Korea's regulatory body meant that their role in the KEDO partnership was not well delineated. It was unclear whether the regulatory body was prepared enough to do jobs like monitoring, supervising, or regulating the construction and operation of the two reactors. In order to ensure safe operation of the reactors once the reactors were turned on, North Korea was tasked in 2000 with updating their construction capabilities and quality assurance programs, learning and absorbing a number of modern technologies, creating a "modern nuclear reactor safety culture", and training personnel for reactor staffing.[73] Since the partnership all but terminated two years later however, cooperation between the North and other member states ended and it is still unclear

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[71] Albright and O'Neill (2000). 194
[72] *Ibid,* 237.
[73] *Ibid,* 237.

how much the Korean compliance group actually had a chance to learn and development from working with KEDO.

4.3 Emergency Preparedness

North Korea is woefully unprepared to deal with natural disasters that can not only put the functionality of the reactor at risk but severely damages the civil infrastructure that makes emergency mitigation of a nuclear reactor accident possible. In 2006 and 2007, they DPRK suffered torrential rains and heavy flooding in the South Pyongan, North Hamgyong, Kangwon, and North Hwanghae provinces that not only washed away thousands of homes and acres of crops, but left roads unpassable and washed out.[74] In 2006, the mid-July flooding washed away 100 kilometers of roads, along with over 30 railways and 70 bridges.[75] Siegfried Hecker, who happened to be visiting North Korea during the heavy rains in 2007, describes in his reports that washed-out roads made getting to and from the reactor complex very difficult. Stories abounded in the news that attempts provide aid were hampered by damage to roads and railway tracks, and that many of the worst-hit areas were impossible to reach.[76]

Infrastructural damage like that sustained in the two summers of flooding would render accessibility to the nuclear reactor and the surrounding area difficult, if not impossible, in times of a flood. As a consequence, efforts to evacuate the population or to bring in necessary repair equipment for the reactor may be impossible. Considering the

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[74] "Democratic People's of Korea." *International Federation of the Red Cross*. <http://www.ifrc.org/docs/appeals/rpts10/MAAKP002overallFS01.pdf>.

[75] "Democratic People's of Korea: Floods." *Information Bulletin No. 2/2006*. International Federation of the Red Cross and Red Crescent Societies, 25 Jan. 2006. <http://www.ifrc.org/Docs/Appeals/rpts06/KPfl25070602.pdf>.

[76] See, for example, Watts, Jonathan. "Flooding Devastates North Korea." *The Guardian*. Guardian News and Media, 15 Aug. 2007. <http://www.guardian.co.uk/world/2007/aug/16/naturaldisasters.weather>.

weakness of the civil infrastructure, a natural disaster could simultaneously be the cause of a nuclear reactor accident and a significant factor in obstructing accident mitigation.

Even without flooding, rough weather conditions can seriously hinder mobility. Katherina Zellweger notes, in a panel discussion about challenge and opportunities on the Korean peninsula, that during a typical North Korean winter the roads are icy and driving is particularly dangerous; the only road crews she witnessed were small work forces picking away at the ice.[77] Dangerous conditions such as these would make disaster management very difficult, especially if roads were practically impassible.

Exacerbating the problem of reduced access and mobility are likely to be the issues of damage to public facilities such as clinics, as well as to telecommunications. A report from the Red Cross pertaining to the 2006 flooding states that “access to affected locations and communications are further constrained by extensive damage sustained by telephone networks.”[78]

4.4 A Look at the Fukushima-Daiichi Disaster

As Ed Blandford explains, “The events at Fukushima Daiichi were due to a series of failures, including failures in plant defensive actions, mitigation efforts, and emergency response.” Although there were possible mitigating actions that could have been taken, “human error and design limitations quickly compounded the impact of the loss of power.”[79,80]

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[77] Shin, Gi-Wook, Joon-woo Park, Katharina Zellweger, David Straub, and Daniel C. Sneider. "The Korean Peninsula After Kim Jong Il: Challenges and Opportunities." Lecture. Shorenstein APARC Panel Discussion. Stanford University, Stanford. 18 Jan. 2012. *The Freeman Spogli Institute*. Web. <http://fsi.stanford.edu/events/the_korean_peninsula_after_kim_jong_il_challenges_and_opportunities/>.

[78] "Democratic People's of Korea: Floods." (IFRC).

[79] Fairley, Peter. "What We Learned About Nuclear Safety from Fukushima." *Technology Review*. MIT, 7 Mar. 2012. Web. <http://www.technologyreview.com/energy/39867/>.

An independent investigation into response to the power loss at the reactor found a number of flaws and mistakes. For example, one of the primary reasons for the failure of functionality of the off-site response centers was the lack of communication about delegation of responsibility between the NERHQ at the President's office (nuclear emergency response headquarters) and local NERHQ at the reactor. The local NERHQ needed notifications delegating them the authority to take certain actions, which they had to carry out in a timely manner. Consequently, delays in communication translated to costly delay in actions. These failures underscored the importance of obtaining and transmitting information quickly in an emergency: "the collection of accurate and most up-to-date information is a prerequisite for prompt and exact decision-making"

A lack of technical understanding also played a role in exacerbating the problem. Issues with the status display on the control panel in Unit 1 caused shift operators to assume that the isolation condensers in the reactor were operating normally when in fact that was not the case. While the instrumentation may have been misleading, there were other signs that indicated the failure of isolation condensers; shift operators and staff members at the emergency response centers showed a lack of understanding of the condensers by failing to recognize the problem. The result of their misjudgment was that they missed an opportunity for earlier core cooling.

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[80] Blandford, Edward. "Deconstructing the Nuclear Accident at the Fukushima-Daiichi Plant: What Went Wrong and What Are the Prospects of Recovery?" Goldschmidt Conference 2011. Prague. 16 Aug. 2011. Presentation.

A third issue concerning response to the disaster was that the government had not fully prepared for an evacuation once a nuclear disaster had occurred. The events at Fukushima highlighted the importance of several key safety considerations, including defense-in-depth and the allocation of resources for protection, mitigation and emergency response. Addition, the significance of an independent regulatory body and clear chain of command, as well as the critical necessity of clear communication, were highlighted.

Based on findings of the post-accident investigation, the interim report identified specific needs crucial to an effective nuclear safety infrastructure and emergency response. For example, the independence and transparency of the nuclear regulatory organization must be ensured. This means it requires sufficient personnel, authority and financial resources to remain autonomous. Additionally, organizational preparedness for prompt response to emergencies must be established via thorough preparations in times of normalcy. The regulatory body should create partnerships and familiarity with related government departments and local government institutions.[81]

In order to fully understand the significance of Japan's difficulties and misjudgments in properly addressing a severe reactor accident, it is crucial to put the experience of the two countries into perspective. Japan has a massive advantage over North Korea. Firstly, it has decades of experience modern nuclear reactors, since 40% of the country's electricity comes from nuclear energy; the units that comprised the Fukushima-Daiichi plant were built by Westinghouse, one of the world's large nuclear reactor companies, and had been operating since the late 1960's. The reactor was

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[81] "Executive Summary of the Interim Report." *Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company*. 26 Dec. 2011. Web. <http://icanps.go.jp/eng/interim-report.html>.

deliberately designed to probabilistically-determined design basis standards. Unlike in the DPRK, the Japanese nuclear industry is incorporated into the international nuclear community and enjoys cooperation with other countries. Finally, although post-incident report shows the Japan's nuclear compliance organization made missteps, Japan still has a much more robust regulatory body coordinates with the national government and the plant's power company when something goes wrong.

In comparison to Japan, North Korea appears to be alarmingly isolated, unprepared, and unorganized. At every stage the DPRK faces the challenges of ignorance and a lack of resources that increase the risk to the reactor. The incident at Fukushima made evident the vulnerabilities of a country whose nuclear industry functioned completely within the scope of international standards, which makes the fact that North Korea is attempting to "go it alone", with no past experience and no external aid, all the more alarming.

Conclusion

General Conclusions about Safety

Based on North Korea's past achievements in the face of major limitations and challenges, they most likely have the adequate technical ability to build a functioning 100 MWth light water reactor (LWR); however, their technical ingenuity outpaces their appreciation and preparedness for the risks intrinsic to operating an LWR. The DPRK already faces a disadvantage having no prior familiarity with LWR operation. This setback is compounded by their isolation from the world reactor community: consequently they have neither the familiarity with technology nor the benefit of shared knowledge and external consultation. Furthermore, the weak safety culture in North Korea, the absence of a well-established regulatory body to ensure the safe construction and operation of the reactor, and the fact that Pyongyang is ill-prepared to deal with a severe accident, vitiate the safety at all three stages of accident progression. And on top of this, it appears that Pyongyang plans hook the new reactor up to an unreliable power grid, where constant blackouts put will put the reactor in constant danger of a station blackout.

The events at Fukushima are a harsh reminder of how deeply entrenched safety principles must be in the governance of the nuclear industry in order to work as they are intended to. Japan enjoyed all the advantages of modern technology, decades of reactor operating experience, international cooperation, and reactor designs based on probabilistic risk assessments. Nevertheless, the system was still subject to failures caused by incomplete understanding of the technology and complications of disaster management procedures. By contrast, North Korea is far less prepared for an accident than Japan.

Potential Consequences

In order to get a good idea of the physical consequences of a severe accident at this LWR, it is necessary to consider the reactor's physical parameters and location. North Korea's LWR is very small: once complete, the power output will be approximately one tenth that of one of the units at the Fukushima-Daiichi power station, containing a small source term inventory.[82] Despite the relatively small size of the reactor, a major disaster at the new LWR – that is, one in which radioactivity escapes the barriers of the plant and is released into the environment – would still have far-reaching consequences, both physically and politically.

Firstly, there is the surrounding population to consider: The ten thousand residents of the nearby town of Yongbyon who are in closest proximity to the reactor will by hardest hit by the release of radioactive contamination. Prevailing winds at the time of the accident would dictate the direction that radioactive fallout is pushed. During the winter, winds from the north would send fallout south, over the capital city of Pyongyang 100 kilometers away and eventually toward Seoul on the northern border of South Korea. In the case of a summer accident, radioactivity would blow north, toward China.[83]

Politically, a major incident would complicate the already rocky relationship with North Korea. Additionally reactor accidents elicit a global backlash against the use of

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[82] Hayes, Peter. " **Nuclear Safety and Security After 3-11.**" *The Nautilus Institute*. 22 Mar. 2012.
[83] Robinson, Colin, and Stephen H. Baker. "Stand-off with North Korea: War Scenarios and Consequences." *Center for Defense Information*. 1 May 2003. <http://www.cdi.org/northkorea/north-korea-crisis.pdf>.

nuclear energy itself, as the world has witnessed in the responses to the accident at Three Mile Island in 1979 and more recently after the meltdown at Fukushima, a phenomenon that in turn affects energy security in many regions. Meserve explains that "every nation's reliance on nuclear power is to some extent hostage to safety performance elsewhere in the world"; a nuclear accident in one location will have significant consequences everywhere because of its impact on public opinion and perceptions of nuclear energy.[84]

Is There Room for Engagement?

As North Korea continues with the construction and eventual operation of its light water reactor, the U.S. and greater international community will be faced with the options of either allowing Pyongyang to proceed on its own or assisting the nation despite its insistence on keeping nuclear weapons. The choice is a difficult one: taking no action means accepting the dubious safety standards and practices of the DPRK while providing assistance compromises current UN sanctions.[85]

In the meantime, more extreme policy measures on either end of the spectrum – the provision of a modern LWR or a military strike against the North – are not realistic considerations. Firstly, a strike against Pyongyang is untenable due to fear of retribution against Washington's ally, South Korea.[86] On the other end of the spectrum, there is no chance of an LWR-provision agreement without major concessions from North Korea

[84] Meserve, Richard A. "The Global Nuclear Safety Regime." *Daedalus* (Fall 2009): 100-11.
[85] Hecker, Siegfried S., and Robert Carlin. "North Korea in 2011: Countdown to Kim Il-Sung's Centenary." *Bulletin of the Atomic Scientist* 68.1 (2012): 50-60. <http://bos.sagepub.com/content/68/1/50>.
[86] Straub, David. "The Obama Administration's North Korea Policy: An Assessment." Lecture. Shorenstein APARC Seminar Series. Stanford University, Stanford. 10 Feb. 2012. *The Freeman Spogli Institute for Internaional Studies at Stanford University*. <http://iis-db.stanford.edu/evnts/6953/North_Korea_Policy_Assessment.pdf>.

over denuclearization, and such a proposal is unlikely to get congressional approval because there is very little faith or trust in the DPRK.[87] In addition, the U.S. is generally constrained from making moves that appear too concessionary since Seoul may view them as a sign that the U.S. has given up on denuclearization of the Korean peninsula.[88]

While the U.S. faces few realistic options for engagement, China may be a more successful candidate. Over the past few years China has drastically expanded its relations with the DPRK, "with Chinese work and investment on key infrastructure projects in the North growing, and high-level political and economic exchanges proceeding at an impressive clip", and their ties are stronger now than at any time in history.[89] The DPRK is willing to engage with China because they view Beijing as having delivered on its promises, while the U.S. has not.[90] China's top priority is maintaining peace and security on the peninsula, so the threat of a volatile reactor in its neighborhood may increase its willingness to cooperate with North Korea.

Whatever actions or in-actions the international community chooses to take, the situation at Yongbyon presents a unique problem that forces the U.S. and its allies to weigh the need to address safety risks of the LWR through engagement against current security-driven policies that isolate North Korea.

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[87] There is also the possibility of that Pyongyang will opt to prove that they possess the requisite capacity to build one indigenously (Hecker, Siegfried S. "Can the North Korean Nuclear Crisis Be Resolved?" Conference on "Rethinking Nuclear Issues in Northeast Asia" Seoul. 21 Mar. 2012. Prepared notes for speech.

[88] Straub (2012).

[89] Hecker, Siegfried S., and Robert Carlin. "North Korea in 2011: Countdown to Kim Il-Sung's Centenary." *Bulletin of the Atomic Scientist* 68.1 (2012): 50-60. Web. http://bos.sagepub.com/content/68/1/50.

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