Illustrative Assessment of the Risk of Radiological Release from an Accident at the DPRK LWR at Yongbyon

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The Nautilus Institute for Security and Sustainability

I. INTRODUCTION

The March 11, 2011 Sendai earthquake and resulting tsunami, in addition to causing tragic loss of life in Japan, triggered a series of events at the Fukushima Dai-ichi nuclear power plant that resulted in the release of radioactive materials in the area around the plant and extending out to sea.[1] But for (mostly) favorable winds, heavily populated areas nearby might have received more significant doses of radioactivity.[2] The slow-motion accident at Fukushima, watched anxiously for months by people around the world,[3] was triggered by the tsunami, but was exacerbated by choices in reactor design and management made, in some cases, many decades before the event. In particular, at Fukushima, the BWR (boiling water reactor) reactor design that placed pools for storing spent nuclear fuel in the same building with and above the reactor vessel, sharing key utilities, and “dense packing” of the spent fuel pools to allow them to accommodate more spent fuel, could have increased both the risk of radiation releases, and the amount of radioactivity ultimately released at Fukushima.[4]

The Fukushima accident induced a wide spectrum of actors around the world, ranging from nuclear plant operators, designers, and managers to government officials, civil society and environmental groups, and the general public, to once again reconsider the safety aspects of nuclear power. As of this writing, all of the nuclear plants in Japan[5] have been shut down pending extensive safety reviews, and several countries, most notably Germany, have markedly shifted their own nuclear power policies. Many nuclear plants in the Republic of Korea (ROK) were at least initially shut down for safety reviews as well, though most ROK plants have subsequently been brought back on line. Even in China, which under virtually any scenario will be building more nuclear power plants than any other nation, and probably more than the rest of the world combined, paused, reviewed, and modified its plan for nuclear power deployment as a result of Fukushima.[6]

In a parallel development, the Democratic People's Republic of Korea (DPRK), after the failure of the Six-Party Talks (and subsequent negotiations) on the DPRK's nuclear weapons program, announced that, in the absence of international assistance to complete a pair of commercial-scale (1000 MW) light-water reactors (LWRs) begun at Simpo in the 1990s, the DPRK was building its own domestically designed LWR. The plan to develop a domestic LWR, and initial work at the site of the plant—the Yongbyon nuclear complex in the northern part of the DPRK— were revealed to Western visitors in late 2010.[7] Satellite imagery confirms that construction on this small LWR has continued through 2012, 2013, and early 2014. Many of the details of the plant's design, however, including the safety, control, and other systems that it will employ, remain unknown.

As a contribution to the global discussion of the safety aspects of nuclear facilities, Nautilus Institute, supported by the MacArthur Foundation and the Carnegie Corporation, has been undertaking a project to examine aspects of radiological risk at nuclear energy facilities in Northeast Asia. As a part of the "Spent Fuel and Reduction of Radiological Risk after Fukushima" project, Nautilus commissioned Gordon Thompson to develop a methodology and underlying information to enable the rapid estimation of the potential releases and dispersion of radioactive materials from nuclear energy facilities (including reactors and spent fuel management facilities) caused by accidents at or attacks on those facilities.[8] As an illustrative application of Thompson's methodology, Nautilus has undertaken a study of the potential radiological releases from the small LWR being built by the DPRK. Given the many unknowns about the DPRK reactor, this study is of necessity quite approximate and indicative in nature, and its results should be considered in that light.[9] Below we provide a summary of what is known (and assumed) about the DPRK's under-construction LWR, followed by a discussion of the other assumptions included in our application of the radiological release methodology. We then present the results of our analysis of potential radiological releases resulting from an accident at or attack on a completed Yongbyon LWR, and conclude with a discussion of potential lessons from, and implications of, the analysis.

We focus herein solely on the small LWR, and do not examine the safety dimensions of operating the co-located small graphite-moderated reactor reportedly restarted in 2013, or possible interactions between the failure of one reactor and the safe operation of the other. Graphite-moderated reactors using magnox fuel cladding are subject to fire should the heat removal fluid (carbon dioxide) be lost in the core, potentially leading to radiological release. There is no reason to believe that the DPRK's graphite-moderated reactor is exempt from this problem—however, it is not the subject of this paper.[10]

Summary Conclusions

Our summary conclusions are four-fold.

First, the radiological risk arising from the DPRK's small LWR should not be overstated, but it also should not be neglected. Should an accident (as opposed to an attack) occur at this LWR, the consequences would not be zero, but due to the technical characteristics of the reactor, they would likely be modest in scale and in scope. If the accident affected only the reactor, and not the spent fuel pool, it seems likely that radiological releases could be very small. The radiological consequences of a concerted terrorist attack on the reactor and associated facilities, however, could be more substantial, in terms of health impacts and damages to property. These impacts, however, are highly uncertain, and will remain so even after such an event due to the unresolved issue of dose-response threshold assumptions made to determine the excess deaths resulting from low-level radiation exposure. Thus, the primary predictable impacts of a radiological release from the DPRK's LWR will be psychological in terms of downwind perceptions and anxiety on the part of exposed or potentially exposed populations, and political, in terms of the policies adopted in anticipation or as a result of such an event.

Second, our appraisal is that the DPRK undertook this project at least in part in order to offset the loss of the KEDO (Korean Peninsula Energy Development Organization) LWRs that were to have been built under the original 1994 Agreed Framework between the US (and its allies) and the DPRK. The completion and operation of the KEDO LWRs would have, in the eyes of the DPRK leadership, brought the DPRK to co-equal status with other regional powers in terms of a complete nuclear fuel cycle—that is, the DPRK's small LWR is a symbolic project aimed at embodying the perceived prestige of the DPRK state in the eyes of its own population and third parties, in accordance with the *juche* principle of self-reliance, and in response to the slight of the United States in cancelling the KEDO project, as well as to fulfill the leadership's long-standing commitment to build a nuclear power reactor, a commitment dating back to the early 1980s. Following the suspension of the KEDO project, the DPRK leadership sees this small reactor as a first step in gaining the experience needed to construct a reactor fleet based on domestic technologies. Nonetheless, the potential utility of the small LWR as a negotiating item, should the parties to the Korean conflict return to talks, cannot have escaped the attention of the DPRK's leadership.

Third, on balance and in light of our net assessment of the stakes involved with a potential incident at the DPRK small LWR leading to release of radiation, we conclude that it is timely for the ROK, the United States, China, Japan, and Russia—all potentially affected states—to engage the DPRK on the issue of nuclear reactor safety, irrespective of the nuclear weapons issue. Although it is difficult to bring the DPRK into the trilateral (Chinese, Japanese, ROK, see Attachment 1) Cooperative Nuclear Safety Initiative while it remains completely isolated due to its nuclear weapons program, the earlier it is engaged on fuel cycle safety issues, the better, and this area is one in which confidence building measures with the DPRK should be undertaken.

Fourth, this analysis should lay to rest any argument that the DPRK's small LWR avails it of a way to lever the United States and its partners to engage it due to the radiological risks posed by the small LWR. Left to itself, radiological release due to technological failure, natural disasters, operating error, or malevolent state or non-state attack on the DPRK's small LWR poses a risk only to North Koreans, and because it is so small, even then it poses only a relatively small risk to North Korean public health due to the high levels of existing risk from disease, malnutrition, and other health risks in the DPRK. This conclusion arises from a careful consideration of the plausible pathways for release of radiation from the DPRK's small LWR and its spent fuel pond, over time, under a wide range of event specification and analytic assumptions, and in no way suggests a low valuation of North Korean lives that would be put at risk irrespective of the initial cause of the release. Rather, it is a statement of fact about the risk posed on populations outside the DPRK, whose welfare is the direct responsibility of external governments.

The only way we can envision a large-scale release of radiation, benchmarked against the release that occurred at Fukushima disaster for example, is deliberate, malevolent attack on the DPRK's small LWR and/or its spent fuel pond. In principle, the power grid connecting to the LWR also could be subject to attacks intended to cut off its power supply to adjacent areas, or to stop it operating for safety or other reasons, which could compound difficulties of maintaining control of the small LWR in the lead up to, during, or after a direct attack. Due to the risk of reciprocal attack, in which case, the ROK is disproportionately vulnerable, readers should note that we are *not* suggesting that US and ROK forces currently target the Yongbyon reactors or grid. Whether such attacks would be legal under international law in any circumstances remains controversial given reactor targeting during the Cold War, Israel's attacks on Iraqi and Syrian reactors under construction, and the International Atomic Energy Agency's 1990 resolution 510 on the "Prohibition Of All Armed Attacks Against Nuclear Installations Devoted To Peaceful Purposes Whether Under Construction Or In Operation".[11] In 1994, US military planners did examine closely the feasibility of attacking the Yongbyon thermal graphite-moderated reactor to disable it, before it could accumulate large quantities of plutonium.[12] Such attacks therefore cannot be discounted.

Of course, the probability of such attack from a state-based actor is controlled by the DPRK's adversaries, not the DPRK itself (except to the extent it attempts to defend the small LWR against external attack—mostly likely with the surface-to-air missiles that defend the entire Yongbyon complex, and their associated radar systems). Today, the United States has low flying stealth aircraft (and in the future, drones) and air-launched cruise missiles able to exploit corridors that evade these radars and would be able to deliver precisely conventional warheads that would disable and destroy the small LWR. In this scenario, significant radiological release could occur, and we have addressed radiological releases roughly consistent with this scenario in our analysis.

The possibility of a reciprocal, retaliatory attack on the ROK's much larger LWRs or spent fuel storage sites, however, is likely to give the United States and its allies pause when considering this option, because the risks to populations and economic losses arising from successful North Korean missile bombardment of ROK LWRs or spent fuel sites are much greater to the ROK (including not only radiological exposure, but prospective loss of large fractions of the ROK's power supply) than the consequences of a successful attack on the DPRK's reactor. In short, the United States and its allies control most of the variables that would result in substantial radiological release from the DPRK's small LWR, but any leverage arising from that dominance is offset by the reciprocal threat posed by DPRK retaliation to ROK LWRs, neutralizing the US-ROK threat from the DPRK's perspective.

Finally, some analysts downplay the risk *of non-state* attack on the DPRK's LWR on the grounds that nuclear security in the DPRK is extremely tight—possibly more so than any other reactor site on Earth. In our view, any assumption that non-state actors are not present or unable to attack radiological facilities in the DPRK is just that—an assumption. Transnational criminal networks operate across borders and reach into the DPRK,[13] as do politically and ideologically motivated networks opposed to the regime. For all these reasons, it is appropriate at a purely analytical level to include state and non-state attacks on the reactor and its supporting infrastructure as possible reason for a reactor accident and radiological release, not only technological failures within the reactor itself.

As to home-grown non-state malevolent attack on the DPRK's nuclear facilities, including its small LWR, the prevailing assumption amongst analysts is that this risk is non-existent so long as the current regime exists, due in part to the related belief that there are no autonomous, non-state actors in the DPRK social system. Based on our experience of working in the DPRK as well as decades of close observation of DPRK decision-making at many levels, we believe that these assumptions and beliefs are wrong, both empirically, and in the underlying theoretical frameworks that shape these external perceptions of the social reality of the DPRK.

This essay is not the place to engage in this debate. We admit that the DPRK has many cross-cutting surveillance and control apparati that provide the leadership with unparalleled means of control over the population.[14] We suggest, however, that fealty and ideological commitment are at the core of compliant individual and group behavior in the DPRK, not surveillance and terror. This issue is hotly contested among scholars of the DPRK's political culture. We believe that there *are* plausible scenarios of collapse and disorder in which insurgent individuals and networks could pose a threat to the regime, albeit of indeterminate probability.[15] In some scenarios in which the regime unravels from the top down, potential insurgent elements could find it useful to create spectacular threats in order to invoke US and ROK intervention. We stress that there is no empirical data on which to make such judgments at this point.

Relatedly, the DPRK was characterized in 2012 as having the worst nuclear security of the thirty states that have access to weapons-usable nuclear materials (based on an index ranking of five material quantity, security and control measures, global norms, domestic commitments and capacity, and societal factors).[16] If, as we suggest above, scenarios of non-state malevolent attack are plausible, then it is prudent for external powers party to the DPRK nuclear conflict to persuade the DPRK to implement its national obligations to control non-state actors in relation to weapons of mass destruction imposed on all states by UNSC Resolution 1540, including reporting to the 1540 Expert Committee. Participation in this regime may enable the DPRK to build confidence that the small LWR and DPRK spent fuel ponds are not vulnerable to non-state actor malevolent attacks, and that by building control systems that meet international standards and are transparent to external actors, and induce the DPRK to participate in the international nuclear security regime in a responsible manner.

II. THE YONGBYON LWR: KEY ASSUMPTIONS

In a visit to the DPRK's Yongbyon nuclear complex in late 2010, a delegation from the United States including Siegfried Hecker of Stanford University were shown an operating uranium enrichment facility previously unknown to international observers, and were told that the DPRK was constructing an experimental Light Water Reactor (LWR), as part of a DPRK effort to develop a domestic nuclear energy source.
Shortly thereafter, Hecker described his visit in a report that also expressed concerns about the potential safety shortcomings of a DPRK reactor. If those safety concerns are realized, the DPRK LWR could, once commissioned, be vulnerable to accidents causing significant radioactive releases.

As described to Hecker[1] by his Korean hosts, and as observed by Hecker and his colleagues, the under-construction DPRK LWR was planned to have (and, we assume, has or will have) the following approximate characteristics:

- Designed heat output: 100 thermal megawatts (MWth)
- Electricity generation capacity: 25-30 MWe (megawatts electric output, by Hecker's estimate). We assume for the sake of this calculation that the output is 25 MWe, implying a relatively low conversion efficiency of 25 percent. A relatively low conversion efficiency would be expected for a first-of-its-kind technology.
- Level of enrichment in U_{235}: 3.50 percent.
- Mass of Uranium in the reactor core: 4 tonnes heavy metal (tHM).
- Implied rate at which the reactor uses fuel per unit output: 40 kg HM per MWth.
- Height of containment structure: 40 meters.
- Diameter of containment structure and reactor dome: 22 meters.

Construction of the DPRK LWR in recent years has not been observed (at least in reports we could find) on site by international visitors, but satellite photos taken over the last two years have shown continuous progress in construction of structures in the area of the reactor. Figures 2-1 shows a photo of the reactor complex area in late 2010, probably about the time that Hecker and his colleagues visited the site. Figure 2-2 shows the site as it was in June 2012, and Figure 2-3 shows a digital rendering of the site from the same time period, from a perspective northeast of the reactor building. Figures 2-4 and 2-5 present images taken, respectively, in approximately late Winter/early Spring of 2013, and in late Spring/Early Summer of 2013. Both show the dome of the reactor containment in place and painted, most or all of the support structure used while building the reactor removed (including the two tower cranes used to put the dome in place) and other site improvements. In the time between when the images in Figures 2-4 and 2-5 were taken, the site was further graded, and several concrete walkways or roadways were completed, including a cap over what seems to be a trench for piping between the reactor and the river. Figure 2-6 shows the site as of early 2014.

Figure 2-1: DPRK LWR Reactor Site, Late 2010**[2]**

Figure 2-2: DPRK LWR Reactor Site, June 2012**[3]**

Figure 2-3: Rendering of DPRK LWR Reactor Site, June 2012**[4]**

Figure 2-4: Satellite Photo of Yongbyon Reactor, Early 2013**[5]**

Figure 2-5: Satellite Photo of Yongbyon Reactor, Mid-2013**[6]**

Figure 2-6: Satellite Photo of Yongbyon Reactor, Early 2014**[7]**

Not yet described in available reports, however, are other details of the reactor, such as the size, number, and other characteristics of the fuel rods/bundles, though Hecker reported that the North Koreans planned to use uranium oxide (UO_2) fuel. Hecker reports that North Korean engineers have told him that that the LWR is to be a PWR (pressurized water reactor).[8] Our initial assumption was that, because the PWR has a somewhat more complex cooling structure than the boiling water reactor (BWR) design that is the other common LWR variant, it would be preferred by the North Koreans for ease of manufacture, but apparently this is not the case. Many BWR and PWR designs, albeit mostly for larger reactors, would have been available for the North Koreans to use as templates. A BWR only somewhat larger (67 MWe, as opposed to modern BWRs of 1000 MWe or more) than the DPRK unit operated for several decades, first, in the 1960s, as an experimental reactor, and then as a commercial reactor, at a lakeside location in Michigan, USA (see Figure 2-7). Other examples of early, small reactors in the United States include Pacific Gas and Electric Company’s Humboldt Bay reactor in California, a 63 MWe BWR that began operation in 1963 and was shut down in 1976, and the 50 MWe LaCrosse (Wisconsin) plant, also a BWR, which started up in 1969 and was closed in 1987.[9]

We do not know whether the designs of any of these particular reactors were available to the DPRK, but they are examples of designs that DPRK scientists and technicians might have studied in preparing the plans for the Yongbyon unit.

We also assume that the DPRK LWR will use stainless steel cladding for the fuel rods, rather than the Zircaloy (typically 98 or more percent zirconium alloyed with small amounts of other metals)[10] cladding usually used on LWR fuel rods. We make this assumption because we assume that the DPRK would have difficulty with Zircaloy metallurgy, and might have difficulty importing Zircaloy due to international sanctions. In conversations with DPRK nuclear engineers, Hecker was told that a decision had not yet been made as to the composition of the cladding of the fuel for the DPRK LWR. The assumption of the use of stainless steel cladding is of importance in terms of radiological risk because in the presence of oxygen and water vapor at high temperatures, Zircaloy reacts with steam to produce hydrogen, and can also ignite, causing a fire that can spread radioactive materials into the atmosphere. Stainless steel cladding can also evolve hydrogen under similar conditions, but stainless steel’s rates of hydrogen evolution is less, by a factor of two or more, than that of Zircaloy under the same conditions.[11] A comprehensive evaluation of the relative costs and benefits of the two cladding materials from a radiological release and in-reactor performance perspective apparently remains to be done.[12] The United States Nuclear Regulatory Commission has released an extensive review of the potential environmental impacts of different modes of spent fuel storage, in which a discussion of spent fuel pool “fires” is included.[13] A detailed review of this topic is, however, beyond the scope of this paper.

Assumptions and suspicions about the technical parameters and expected operating procedures for the DPRK's LWR aside, it is clearly important for the international community to learn more about this reactor, and the DPRK's plans for it. As noted below, developing opportunities to engage with the DPRK on nuclear issues may offer both access to learn more about what the DPRK intends with regard to the reactor, and opportunities to help to correct safety deficiencies in the reactor design before it is powered up, thus potentially avoiding at least some of the radiological risk associated with the unit.

III. Assumptions Used in Modeling Potential Radioactive Release from the Yongbyon LWR

The methodology developed by Gordon Thompson for estimating release of radioactive materials following an accident or attack includes seven steps:

1. Specify the system

Figure 3-7: Example of Small BWR --67 MWe Big Rock Point, MI, US, Completed early 1960s**[1]**

2. Characterize the spent nuclear fuel in the system
3. Assess the potential for an atmospheric release of radioactive material
4. Estimate the behavior of a radioactive plume
5. Characterize downwind assets
6. Assess harm to downwind assets
7. Assess collateral implications of radiological risk from spent nuclear fuel

For some of these steps, Thompson has provided quantitative tools for estimating key parameters and results, while for other steps—including steps 5 and 7 above—more qualitative approaches or other quantitative tools are likely to be needed.

3.1 CHARACTERIZATION OF SPENT FUEL IN THE SYSTEM

The methodology thus requires, first, a description of the reactor complex—which we have provided (at least approximately) above, and second, an estimate of the inventory of spent fuel in the reactor and in storage at the time of the assumed incident, and an estimate of how much of certain key radioactive species are present in the fuel at that time. In order to estimate these quantities, we assume, for the sake of the radiological risk assessment calculation that:

- The reactor has operated for 1, 3, 5, 15, and 20 years as of the time of this radiological risk calculation. Assuming that the reactor had operated for less time would yield a lower inventory of radioactive products overall, as shown in Figure 3-1. Note that it is possible that the reactor will not, in fact, operate for even 15 years. The DPRK regards this reactor as an experimental unit, meaning that they may plan to shut it down once DPRK nuclear scientists and engineers have learned what they need to about the construction and operation of LWRs, and once the next generation of DPRK reactors has been built. Alternatively, the reactor might be shut down earlier if it performs poorly. On the other hand, if there is a delay in developing next-generation DPRK reactors, this “experimental” 25 MWe LWR may ultimately be used longer than expected or anticipated.
- The reactor operates at an average capacity factor of 80 percent. This is somewhat less than the typical capacity factor for many LWRs worldwide, though in fact not so different than that experienced in Japan during most of the pre-Fukushima years. It is still likely to be an over-estimate of actual performance for the DPRK LWR, particularly in the early years, but is probably in line with DPRK expectations for the reactor.
- Approximately one-third of the reactor’s core is replaced every 1.5 years, consistent with designs of PWRs (and BWRs) in general.[2] Figure 3-2 shows the estimated inventory of Cs-137 in the reactor core, factoring in the cycles of fuel replacement.[3]
- The spent fuel storage pool is assumed to be located, as in other PWR designs, outside of the reactor containment building, near (but not necessarily adjacent to) the containment building, and probably below or at the same level as the reactor core.
- By 15 years after the first operation of the spent fuel pool inventory would be 12 tonnes HM. Note that this assumes that all of the spent fuel produced is not only placed in but stays in the spent fuel pool. It is possible, perhaps more than possible, that the operators would withdraw some of the fuel for reprocessing to extract plutonium for use in weapons,[4] even if doing so would place technicians at risk for radiation exposure. If some of the fuel is reprocessed, the spent fuel pool inventory would decrease, and some of the radioactive inventory that would have remained in the pool will be transferred to another facility at Yongbyon, with some of the radioactivity ending up in high-level wastes from reprocessing.
- We assume that the spent fuel pool capacity (packed at low or standard, not high, density) is approximately five times the core size, or sufficient to accommodate 20 tonnes HM of spent fuel assemblies.[5] Note that although this ratio of pool size to core size is consistent with historical practice in nuclear reactor construction worldwide, the DPRK could choose to build a smaller, or larger, spent fuel pool without markedly changing the cost of the reactor project as a whole.
- We assume that the *design* fuel burn-up at the DPRK plant was intended to average somewhat approximately the representative level of 32 GW-days/tHM, cited by Gordon Thompson for PWRs with enrichment of 3.2 percent U-235, which adjusted for the higher assumed enrichment in the DPRK reactor fuel yields 35.0 GW-days/tHM. We assume somewhat actual average burn-up is

lower than this design level, however, because it will take DPRK technicians some time to become proficient in fuel fabrication and handling. As a consequence, we assume an average burn-up of 28 GW-days/tHM over the reactor lifetime, which implies that the average full-load thermal output is about 85 MWth, rather than 100 MWth, if we continue to assume that the mass of the reactor core is at the as-reported level of 4 tHM. Average burn-up is thus assumed to be 28 GW-days/tHM for spent fuel added to the spent fuel pool during and after the third refueling of the reactor (that is, from 4.5 years after start-up on).

- The average age (after discharge) of spent fuel in the spent fuel pool is 6.75 years (calculated) after the reactor has been operating for 15 years.
- We assume that the DPRK converts to dense racking when or if the amount of spent fuel in the pool plus the amount of fuel in one core plus the amount required for one refueling of the reactor would exceed the capacity (at standard packing density) of the reactor pool. Based on the assumptions above, this would occur after about 17 years of reactor operation.

Figure 3-1: Estimated Cesium-137 Inventory in DPRK LWR versus Years since Reactor Start-up

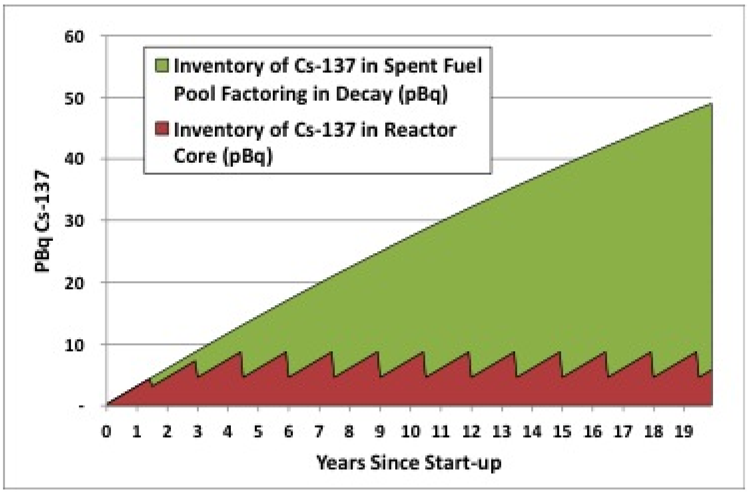
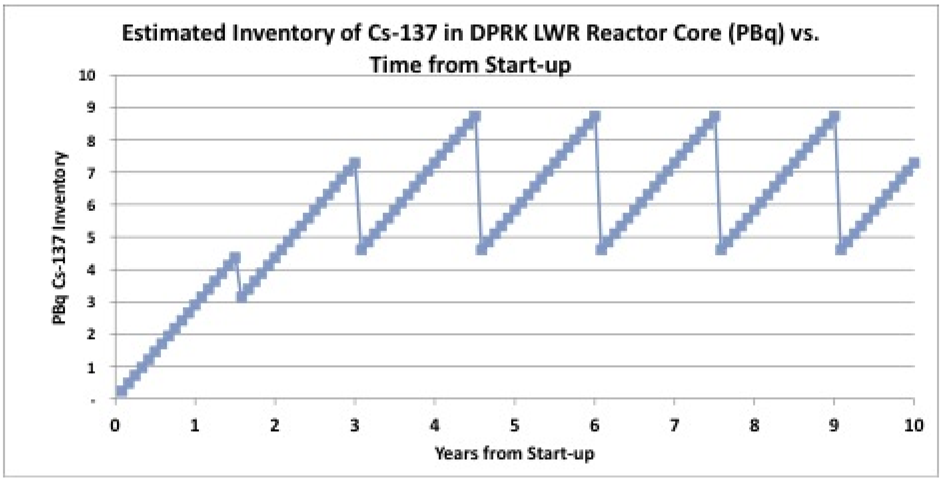


Figure 3-2: Estimated Cesium-137 Inventory in DPRK LWR Rector Core (only) versus Years since Reactor Start-up



By way of comparison, the maximum content of Cs-137 in the DPRK LWR reactor core, as calculated above, is on the order of 3.5 percent of the estimated inventories of Cs-137 in each of the reactor cores of Fukushima Dai-ichi Units 1 through 3 at the time of the accident, and on the order of 1 percent of the Cs-137 in the cores of the three crippled units combined. After 20 years of operation, the approximately 50 PBq of Cs-137 in the core and spent fuel pool of the DPRK LWR (assuming no fuel is removed over time) amounts to about 1.7 percent of the total inventory of Cs-137 in the reactors of Fukushima Dai-ichi Units 1 through 3 and the spent fuel pools of Units 1 through 4.[6]

3.2 ASSUMPTIONS FOR ASSESSMENT OF RADIOLOGICAL RELEASE POTENTIAL

In order to estimate the radiological outcome of an accident at or attack on a reactor and/or spent fuel storage complex, it is necessary to make assumptions about the degree to which each of the sources of radioactivity (specifically, for this estimate, Cs-137) "participate in" an accident or attack. The participation fraction is an estimate of the extent to which the different potential sources of radioactivity at the site are involved in a given event in which radioactivity is released. For those fuel-containing facilities of the reactor complex (reactor core, spent fuel pools, transport casks, and dry casks) that are involved in the event, it is further necessary to estimate a release fraction for the Cs-137 present. That is:

Cs-137 release in a given facility = Inventory of Cs-137 for the facility * the participation fraction for the facility * the release fraction for the facility

The total Cs-137 radioactivity released is the sum of the releases over each facility. We made the following assumptions in applying step 3 of the methodology developed by Gordon Thompson:

- Unlike larger LWRs, including the Fukushima BWRs, the core of the DPRK LWR will be sufficiently small that virtually no plausible accident scenarios related to, for example, technical malfunctions, inadvertent operator error, seismic damage, or industrial accidents can be devised that would lead to significant releases of Cs-137 to the atmosphere. The reason for this is that the core is sufficiently small that in the event of loss of coolant the reactor core would be self-cooling, and releases of Cs-137 would be small, if any. As a result, we assume that the reactor core has a "participation fraction" of **zero** in the event of an accident. In the event of an attack, however, including through the use of explosives or via sabotage (whether carried out by those inside or outside the plants), the reactor core could be breached, thus for an attack scenario, we assume a participation fraction of one. This implies for an incident affecting the Yongbyon LWR, the reactor core is damaged such that a pathway for emissions of radioactive gases is created. An attack on the facility, in this case, is assumed to be a general one by a non-state actor using devices designed to cripple or destroy the facility, or carried out via sabotage, but is not specifically designed to maximize release of radioactive materials.

- The "Participation Fraction" for the spent fuel pool in an accident or attack was assumed to be zero until dense racking is needed. Thereafter, its participation fraction depends on the mode of the accident or attack, as described below. Given our assumptions regarding the number of years of reactor operation before the event, that the spent fuel pool, though it may be damaged in the event, is *not* expected to release any Cs-137 before about 17 years of reactor operation.

- If, as has been reported, the DPRK LWR is a PWR, its spent fuel pool will likely be located outside of the reactor containment in an adjacent building, and at or below grade level (as opposed, for example, to the spent fuel pool location at a level above the reactor core used in the Fukushima BWRs). As such, its potential exposure to conditions that would cause it to release radioactivity to the atmosphere in the event of a reactor *accident*, for example, through a technical failure, operator error, or seismic event,[7] are likely more limited than would be the case for a BWR design. Common-mode failures during an accident where the reactor core was damaged would likely be related to the loss of power for cooling the spent fuel pool. This common mode failure is arguably less probable (or, in any event, easier to recover from) for a PWR than a BWR, given the location of the spent fuel pool in a different building than the reactor.

- It is beyond the scope of this paper to explore all of the possible accident or attack scenarios that could befall the DPRK LWR. Given the technical considerations above, we assume that the range of true *accident* scenarios that would involve a participation fraction significantly above zero for the spent fuel pool is very limited. Such an accident would have to apply to a spent fuel pool using dense packing of spent fuel. This means, given our assumptions, 17 or more years of spent fuel would need to be stored in the pool, which is perhaps unlikely given that the DPRK may remove some fuel for reprocessing and/or choose to store spent fuel elsewhere. In addition, the accident would need to damage the spent fuel pool such that it loses cooling for long enough—likely days or weeks—for the water in the pool to boil away and to heat to the point at which some fuel elements would fail. This would imply a loss of ability to provide auxiliary cooling for a period long enough for the spent fuel to be damaged, which would in turn imply that radiation levels were high enough to keep technicians and emergency personnel from implementing triage cooling measures (such as those employed in the spent fuel pool of Fukushima Dai-ichi Unit #4). Given anecdotal reports (and our own experience) of a lack of an industrial safety culture in the DPRK, the prospect of radiation conditions limiting emergency cooling options would seem less than it would be in Japan or the United States (for example). On the other hand, one could argue that the likelihood of timely availability of functioning pumps, tanker trucks, or other equipment to provide emergency cooling for a damaged spent fuel pool in the DPRK could well be lower than in most nations. The lack of cooling water has also been mentioned as a safety-related problem for both reactors at Yongbyon.[8] All of the above considered, for an *accident* scenario, we suggest that most cases would probably involve a participation fraction of zero for the spent fuel pool, meaning no significant emissions of Cs-137. We do, however, consider as a worst-case scenario, an event in which the participation fraction in the event of an accident is one—due, for example, to a failure causing a large leak in the spent fuel pool under conditions where auxiliary cooling cannot be implemented in a timely fashion. The consequences of this worst-case accident scenario, for modeling purposes, are the same as for a scenario involving an attack designed to breach the spent-fuel pool while crippling the LWR itself.

- Under an *attack* scenario, the “Release Fraction”—that is, the fraction of Cs-137 released to the atmosphere—is assumed to be 0.3 for Cs-137 in the reactor core. Note that this would be higher by about an order of magnitude than the average release fraction estimated for the cores of the Fukushima Dai-ichi units 1 through 3, and thus implies an attack or sabotage (or both) that results in considerable damage to both the reactor vessel and its containment.

- For the spent fuel pool, though as noted above, given the period in operation assumed before an incident, the spent fuel pool is assumed not to be involved in releases of radioactivity until it is dense-packed. At that point, in a worst-case accident scenario or an attack scenario, the release fraction for Cs-137 becomes limited by our assumption of the use of stainless steel cladding for the reactors fuel assemblies. The use of stainless steel cladding renders impossible the ignition of the cladding itself, as could happen with Zircaloy cladding, and thus limits releases of Cs-137 to those caused by failure of the fuel cladding by overheating of fuel elements (“hot gap” ruptures). The heat required to cause these types of ruptures, in turn, is possible only with the most radioactive spent fuel, that is, spent fuel recently removed from the reactor. Emissions from “hot gap” ruptures in the spent fuel pool are estimated at 3 percent of the Cs-137 inventory from spent fuel equivalent to the loading of one-third (that is, the most recent set of fuel elements replaced) of the reactor. As an alternative scenario, also in case of a worst-case accident or attack, we calculate releases of Cs-137 if the DPRK *does* use Zircaloy cladding. In this variant, the release fraction for the spent fuel pool is assumed to be 0.3 for the entire spent fuel pool once dense-racking has begun.

- No dry casks or transport casks are present at the time of the modeled accident, because spent fuel inventories have not yet accrued to the point that they are needed. If such casks were present, their participation fraction would be assumed to be zero, as it is assumed that an attack on the facility by a non-state actor would not involve the highly-targeted, highly skilled types of activities required to penetrate and ignite spent fuel stored in dry casks or transport casks; and that it would be irrational strategically for a state to attack dry casks full of radiological material with unpredictable effects downwind on military operations as well as on neighboring countries including the ROK, Japan, and China.

3.3 ASSUMPTIONS FOR ESTIMATION OF BEHAVIOR OF RADIOACTIVE PLUME

In order to estimate the behavior of a radioactive plume rising from the Yongbyon LWR after an accident or attack (step 4 in the methodology), we make the following assumptions:

- The average wind speed at Yongbyon at the time of the accident or attack is 7 meters per second,[9] and prevailing winds at the time of the incident are out of the North or Northwest. As the prevailing winds on the Korean peninsula are typically from the North (that is, blowing toward the Republic of Korea) in the winter, and from the South (that is, blowing toward China and Russia) in the summer, this assumption is quite important in defining downwind assets.

- We used a 1 cm per second deposition velocity for particles released in the accident or attack. This is assumption is commonly used in the application of the wedge model, and is consistent with typical winter weather and windspeeds in the region of the Yongbyon site.[10]

As noted, the fourth step in Thompson's methodology involves modeling the behavior of the plume of radioactive material released by the accident or attack and through subsequent damage to the reactor and spent fuel stored at the site. A simple "wedge" model is used to carry out this modeling[11] Some of the assumptions made in applying the wedge model for a release of radioactivity from the LWR at Yongbyon include:

- A "Mixing Height" of 1000 meters, representing the height above the ground through which the plume of released materials is assumed to be mixed;

- A "Wedge Angle" of 0.25 radians (about 14 degrees), representing the spread of the plume of material as it travels downwind;

- A "Shield Factor" of 0.33, representing the average degree to which humans in the area of the plume are shielded from radiation;

- An exposure time of 5 years, though this parameter was varied in our application of the model for the purposes of sensitivity analysis;

- Distances for ground contamination and individual dose calculation were varied from 5 to 350 km from Yongbyon (see below);

- Calculations of collective dose were made at four locations, ranging from the immediate area near

Yongbyon outward and southward to Seoul (see below).

3.4 CHARACTERIZATION OF DOWNWIND ASSETS

Based on our assumption of a wintertime event (accident or attack) triggering releases of radioactivity from the LWR at Yongbyon, we reviewed the downwind assets that the plume would encounter. These include (but are by no means limited to):

- The plutonium separation complex at the Yongbyon site, that is, the facilities used to separate plutonium (Pu) from the nominal 5 MWe[12] gas-cooled, graphite moderated reactor at Yongbyon—which was shut down in 2007, but was apparently restarted late in 2013,[13] as well as the reportedly unusable structure of the partially-completed 50 MWe gas-cooled, graphite moderated reactor abandoned as a part of the 1994 Agreed Framework, and other elements of the Yongbyon research area, This complex is located 1 to 2 km due South of the reactor site, as shown in Figure 3-3.

- The Chongchon River, which is 10 to 15 km South of the reactor site, and to which the river flowing past the reactor site (within tens of meters of the reactor) is a tributary.

- A tributary of the Taedong river (which flows through Pyongyang), located about 30 km South of Yongbyon.

- The Pukchang power plant (the largest in the DPRK, with a nominal capacity of 1600 MW, and, probably, a functional capacity of 500 MW or so) about 35 km Southeast of Yongbyon.

- The coal mining area of Anju, about 50 to 60 km to the Southwest of the reactor site. The Anju coal area is the site of one of the major mines in the DPRK.

- A number of cities with populations of 100,000 or greater, and located between 15 and 100 km from Yongbyon, as well as, further afield, the major cities of Pyongyang and Seoul. Table 3-1 provides a summary of the larger cities downwind of the reactor in winter.

Figure 3-3: Towns and Facilities in the Vicinity of the LWR Site**[14]**

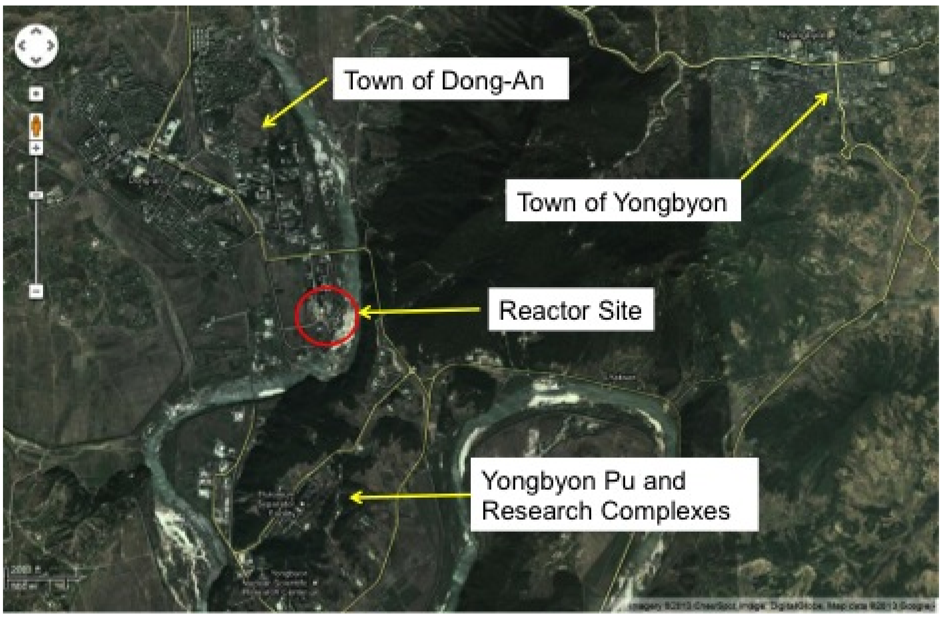


Table 3-1: Major Cities Downwind from Yongbyon in Wintertime**[15]**

	Population (as of 2008)
Kaechon, 15 km South/Southeast	320,000
Anju, 30 km South/Southwest, an imporant coal-mining region	240,000
Sunchon, 50 km south, 10 km east	297,000
Sukchon, 60 km south, 10 km west (rough estimate)	100,000
Pyongsong, 80 km south	284,000
Pyongyang, 130 km south	3,255,000
Kaesong, 250 km south, 70 km east	308,000
Seoul (ROK), 310 km south, 100 km east (metro area)	16,000,000
Seoul (ROK), 310 km south, 100 km east	10,582,000

IV. ESTIMATED RADIOLOGICAL RELEASES, DOWNWIND DEPOSITION, AND HEALTH IMPACTS FROM AN ACCIDENT AT OR ATTACK ON THE YONGBYON LWR

Below we present the results of wedge model calculations carried out using the assumptions presented in sections 2 and 3 of this paper. Before presenting our results, it is crucial that we convey the key caveats associated with this research, viz:

- As noted, there are many uncertainties, for those of us without access to information about the DPRK's plans for the Yongbyon LWR (meaning virtually everyone but a very few researchers and officials in the DPRK itself), about what technologies and safety systems will be used in the reactor. If our assumptions about the reactor are off-base, our analytical results may require revision.

- The wedge model is a convenient tool to obtain an approximate sense of the potential atmospheric transport of radioactive materials emitted as a result of accident or attack, but other available models can provide more detail. Other models, however, require more data, including weather data, to run[1], and in many cases more expertise as well, and are subject to uncertainties of their own. In addition, all atmospheric transport of radioactive (and non-radioactive) materials can vary hugely with local conditions at the time of the incident, including temperature at different levels of the atmosphere, prevailing winds directions and velocities (and changes in same), and precipitation. This means that the results of even the best models may vary considerably from what occurs during an actual release event.

- Our analysis has focused on a single radioactive element, Cs-137, though other radioactive elements released following an accident or attack could also contribute to doses received by nearby populations. One estimate of the relative contributions of the different radionuclides to total doses from the Fukushima accident[2] suggests that 43 percent of the total dose came from cesium isotopes, thus as a rough estimate, Cs-137 might contribute about half of the total dose of radioactivity from an incident at Yongbyon.[3]

- There is a longstanding and ongoing debate about the impact on human health of radiation at very low doses. A body of scientific opinion contends that even small additions of radiation, below the threshold of the radiation background experienced routinely by human populations, contributes to the risk of cancer, or at least that it cannot be proven that it does not do so.[4] This "linear no-threshold" model has been adopted by the U.S. National Academy of Sciences Committee on the

Biological Effects of Ionizing Radiation. Other researchers, however, contend that very low doses of radioactivity cannot contribute measurably to human health impacts, or at least that calculations of the impacts of low doses of radiation should not serve as a basis for public policy[5]. The biological responses to low doses of radiation have been the subject of a long-term US Department of Energy Research program[6]. This program, together with related research, has identified a number of interactions between radiation and biological systems and between biological systems affected by radiation that make it clear that the biological response to low doses of radiation is certainly more complex than had been thought. We acknowledge both sides in this debate, and present our estimates of radiological consequences with the understanding that opinions as to the validity of the "linear no-threshold model" of the impacts of ionizing radiation, at least for policy purposes, remains divided, thus readers will have to reach their own conclusions as to whether the impacts we estimate should affect public policy.

- With the exception of the immediate vicinity of the accident or attack, it is evident that the consequences of radiation released from the DPRK LWR will be far less—likely many orders of magnitude less—significant in terms of public health impact than any number of other environmental and other health stressors, ranging from background radiation to air and water pollution, routine accidents, preventable and treatable diseases, and cancers in the general population. This is also true with respect to the impacts this posited LWR accidental release would have in the ROK, and though little direct information is available on the overall state of public health in the DPRK, is likely to be at least as true in the DPRK as well.

4.1 POINT OF COMPARISON: THE FUKUSHIMA ACCIDENT

Before presenting estimates of the potential release of radioactivity due to an accident or attack on the Yongbyon LWR, it is helpful to review, as a point of comparison, existing estimates of emissions of Cs-137 and what is currently known about the health and environmental consequences of the nuclear reactor accident most current in the minds of policymakers and the public, namely, the accident at the Fukushima daichi power plant initiated by the tragic March 11, 2011 Sendai earthquake and tsunami. Such a comparison is, of course, by its nature out of scale, as the four Fukushima reactors affected by the accident are together two orders of magnitude larger, in terms of power output, than the Yongbyon reactor will be.

A wide range of estimates have been published for the "source term" of the Fukushima accident, that is, for the total releases of radioactive materials to air and water as a result of the accident. Focusing on Cs-137, these estimates range from 7 to 130 Petabecquerel (PBq)[7] of emissions to the atmosphere as a result of the accident.[8] The estimates vary with respect to mode of calculation and the period of emissions included. Within this range, central estimates include those prepared by ZAMG, at 36 PBq,[9] and Stohl et al (range of 20.1 to 53.1 PBq, with an average of 36.6),[10] both of which used a period extending a month of more after the original accident. We use 36 PBq as the Fukushima source term in the comparisons below.

Estimates of the ultimate impact of the Fukushima accident on human health and the environment vary as well. A 2013 World Health Organization study concluded that "for the general population inside and outside of Japan, the predicted risks are low and no observable increases in cancer rates above baseline rates are anticipated", and that in the most contaminated parts of Fukushima prefecture, "the estimated increased risks over what would normally be expected" are 4 to 7 percent, with the risk of thyroid cancer increased "up to 70% in females exposed as infants (the normally expected risk of thyroid cancer in females over lifetime is 0.75% and the additional lifetime risk assessed for females exposed as infants in the most affected location is 0.50%)".[11] A 2012

Stanford University team “found a range of possible death tolls, from 15 to 1,300, with a best estimate of 130. A wide span of cancer morbidities was also predicted, anywhere from 24 to 2,500, with a best estimate of 180”, noting that only 19 percent of the radioactivity released to the atmosphere in the Fukushima accident was released over land.[12] Other health and environmental consequences of the Fukushima accident, including contamination of food and water in Japan and of North Pacific marine life and seafood, have also been noted.[13]

An additional point of comparison for any radiological accident is, of course, the 1987 Chernobyl reactor accident. Even 15 years after that accident, a United Nations report found that “[v]ery considerable uncertainty remains over the possible long-term health effects of the accident”.[14]

4.2 ESTIMATED RELEASE OF CS-137 FROM ACCIDENT OR ATTACK AT YONGBYON LWR

As described in section 3.2, above, we quantitatively explored three different incident scenarios involving the DPRK LWRs. These scenarios can be summarized as follows:

- In the first scenario, which we characterize as "Worst-case Accident" (referred to also as "S1" below), the reactor itself is assumed to be highly unlikely to suffer a meltdown due to its small size. The spent fuel pool is assumed to suffer a loss of coolant, likely by suffering a major rupture.

- For the second scenario, which we characterized as "Worst-case Attack" (or "S2"), we assume that as a result of sabotage of reactor controls/components and/or an explosion that breaches the containment dome and reactor vessel, sufficient damage is caused that the cladding in the fuel in the reactor fails, and the cesium in the spent fuel is heated to the point that a portion of it is released to the atmosphere. In this scenario, the spent fuel pool cooling system also fails and/or there is a major rupture in the pool (the pool is also targeted by the attackers), leaving it vulnerable to overheating and eventual rupture of the cladding in the most radioactive fuel elements.

- For the final scenario, which we call "Worst-case Attack/Zircaloy cladding" (or "S3"), again, as a result of sabotage of reactor controls/components and/or an explosion that breaches the containment dome and reactor vessel, sufficient damage is caused that the cladding in the fuel in the reactor fails, and cesium is released to the atmosphere. In addition, in this scenario, the spent fuel pool cooling system also fails (it is also targeted by the attackers) but, different from S2, in this case the use of Zircaloy cladding is assumed to have been used by the DPRK, meaning that coolant loss results in a cladding fire if the pool is dense-packed.

These three scenarios, of course, do not begin to exhaust the universe of possible scenarios of damage and subsequent release of radioactivity that could result from different types of accidents or attacks on the DPRK LWR. Knowing as little as we do about the ultimate technologies to be used on the LWR, and with a wide range of different modes possible for a terrorist attack on the plant, we have chosen what we view to be illustrative “worst-case” scenarios in order to provide an upper bound possible emissions (the lower bound being zero).

Table 4-1 presents estimated atmospheric emissions of Cs-137 for each of these three scenarios for incidents occurring at different times after reactor start-up. An accident scenario—and again, there are many possible scenarios that could be devised—would likely not result in significant emissions until after the spent fuel pool began to be dense-packed, at a minimum 17 or so years into the future, and at that point, the assumption of stainless steel cladding would limit emissions of Cs-137 to about 0.1 PBq, a fraction of a percent of estimated emissions from Fukushima. In the other two scenarios, an attack on the LWR yields Cs-137 emissions to the atmosphere of about 2 PBq, or about 5-10 percent of total Fukushima emissions, with the exception being an attack on the reactor and spent fuel pool when the spent fuel pool is dense-racked **and** if Zircaloy is used as the cladding material for the reactor fuel. In this worst of worst cases we have explored, emissions would rise to about 15 PBq, on the order of half of atmospheric emissions from Fukushima as estimated to date.

Table 4-1: Estimated Cs-137 Emissions to the Atmosphere by Incident Scenario[15]

	Atmospheric Emissions of Cs-137 (PBq) for an Incident Occuring				
Scenario	1 year after start-up	3 years after start-up	5 years after start-up	15 years after start-up	20 years after start-up
S1: Worst-case Accident	-	-	-	-	0.1
S2: Worst-case Attack/Stainless Steel Cladding	0.9	2.2	1.7	2.6	1.9
S3: Worst-case Attack/Zircaloy Cladding	0.9	2.2	1.7	2.6	14.7

4.3 ESTIMATED GROUND CONTAMINATION AND INITIAL EXTERNAL DOSE FROM RADIOLOGICAL RELEASE

Figure 4-1 presents our estimates of ground contamination, at a range of distances from the reactor site, following the release of radiation from the Yongbyon LWR under the modeling assumptions presented above, for releases occurring 1, 3, 5, and 15 years after reactor start-up for scenarios 2 and 3. No significant emissions are likely during this period for Scenario 1, again because it involves only the reactor. Note that the results for years 3, 5, and 15 are quite similar as all involve releases only from the reactor core, and thus vary only based on the timing of the refueling cycle (with releases in year 3, in fact, being greater than in year 5). Figures 4-2a through c show the same result for each of the three scenarios for a release occurring 20 years after reactor start up, at a time when the spent fuel pool is assumed to be dense-packed, and thus vulnerable to releases of radioactivity through failure or, when Zircaloy cladding is used, ignition of the cladding and fuel. Again, however, the assumption that the spent fuel pool would be dense-packed due to rising inventories of spent fuel may prove incorrect if, as is certainly at this point conceivable, the DPRK decides to attempt to reprocess some of the spent fuel from the LWR, and/or if some of the spent fuel is removed for storage elsewhere. Note that the scales on Figures 4-2 a through c are different from each other, and are different from that in Figure 4-1. As such, the results at any given distance from the reactor are different in the four figures, with the contamination levels in Figure 4-2a about 5 percent of that in Figure 4-1, the contamination levels in Figure 4-2b similar to those in Figure 4-1, and the contamination in Figure 4-2c at any given distance about six times as severe as those shown in Figure 4-1. Figure 4-3 presents estimates of the external dose after deposition for the attack scenarios 2 and 3 for an incident occurring one to 15 years after reactor start-up, again at a range of distances from the site of release. The accident scenario (scenario 1) is assumed to yield no significant emissions, and thus no dose, for an accident occurring up to 15 years after reactor start-up.

Assuming, based on USEPA recommendations, at 20 mSv (millisievert) threshold for the first year dose that would trigger abandonment of lands[16], the radius of land area contaminated to a dose threshold of 20 mSv would be about 3 kilometers, encompassing at least some of the Pu production facility and related areas at Yongbyon. Note that the threshold that DPRK authorities would use to trigger abandonment of an area would likely be different, and likely higher, than 20 mSv, but we could find no reference to an official DPRK threshold value, and thus use the EPA value. Under attack scenarios 2 and 3, for a release after 3 to 15 years of operation (and after 20 years of operation in scenario 2), the area contaminated to the 20 mSv dose threshold would be on the order of 1 square km; a release after one year of operation would contaminate a slightly smaller area. In scenario 3, increasing the reactor's time in operation to 20 years, as shown in Figure 4-4, increases the contaminated radius under scenario 3 to approximately 20 km, and the contaminated area to about 40 square km, making the consequences of the release much more serious both near to and far from the reactor site. The reason for this significant increase in risk is as noted above: the assumed requirement to move to dense racking in the spent fuel pool used by the LWR could put the spent fuel, which is assumed in this scenario to have Zircaloy cladding, at risk. In scenario 1, an accident after 20 years of operation involving the spent fuel pool leads to a limited release of Cs-137, with an area contaminated to a level of 20 mSv on the order of a few thousand square meters. As noted, the DPRK's plans and approach for racking of spent fuel in the LWR pool at Yongbyon is unknown. If the DPRK builds the LWR with a spent fuel pool that is smaller than we have estimated, a more serious release could occur in an earlier time frame. If, on the other hand, a bigger spent fuel pool than we have assumed is built for the DPRK LWR, or fuel is moved out of the pool before dense racking is needed, the date at which emissions risks related to the spent fuel pool come into play could be delayed for years or indefinitely.[17] Also, as noted earlier, if this experimental reactor is shut down (having, presumably, fulfilled its mission as a facility that the DPRK uses to gain experience in nuclear energy technologies) before the spent fuel pool is dense-racked, the 20-year outcomes in Figures 4-2a through c would be avoided.

As shown in Figure 4-3, the first-year radiological dose received in the vicinity of the nearest medium-sized city south of Yonbyon, the city of Anju, would be about 3 mSv per year for releases occurring 15 years or less after start-up, well below the EPA's guideline dose for abandonment of contaminated lands. By way of comparison, these doses are similar in magnitude to those estimated for the areas closest to (but outside of) the restricted and evacuation areas associated with the radiological releases from the Fukushima accident.[18]

As indicated above, there is, due to the nature of the methodology used to prepare these results, a decidedly non-linear relationship between time from the initiation of reactor operation and the time of the incident causing a release of radioactivity, and the amount of radioactivity released. Our assumption that a third of the reactor core will be replaced every 1.5 years implies that the Cs-137 inventory in the reactor core during steady-state operation will be at its maximum just before refueling after 4.5 years and every 1.5 years thereafter, and at its minimum just after refueling (at, by definition, about two thirds of the maximum value). In the shorter term, after, say, 3 years, the Cs-137 inventory in the reactor core would be on the order of 50 percent of the maximum (see Figure 3-2). What this means is that for an accident or state or non-state attack that occurs basically any time between 3 and 16 years from the initiation of reactor operations, the radiological release would be on the same order of magnitude as that shown below. After 16 years, however, the capacity assumed for the spent fuel pool is such that dense racking of the pool becomes necessary, and as a result, the potential for spent fuel to fail or ignite (depending on the cladding material assumed) increases markedly.[19] At that point, the participation fraction of the spent fuel pool rises from zero to 1 (that is, to 100 percent), and the resulting level of release of radioactivity, ground contamination at any given distance, and dose at any given distance all rise by a factor of about six in scenario 3 (which assumes Zircaloy cladding), but only slightly in scenario 2 (with stainless steel cladding).

Figure 4-1: Ground Contamination Results for Attack Scenarios (2 and 3)

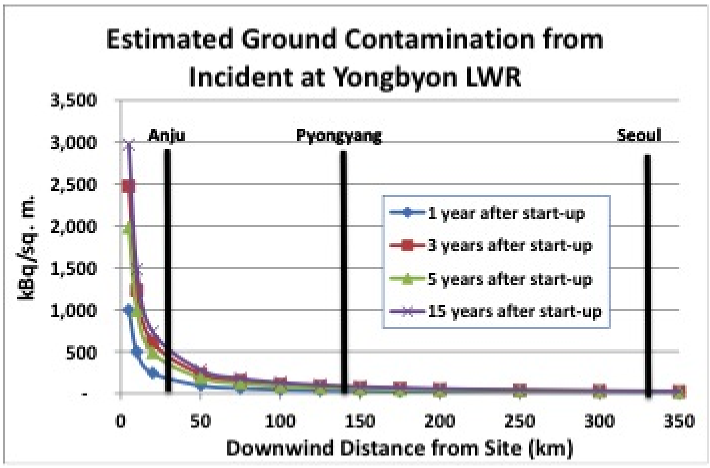


Figure 4-2a: Ground Contamination Results for an Incident 20 Years after Reactor Start-up

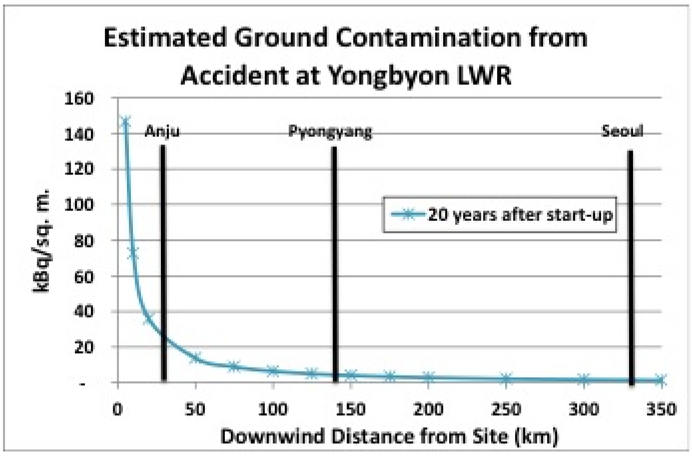


Figure 4-3b: Ground Contamination Results for Attack Scenario 2 for an Incident 20 Years after Reactor Start-up

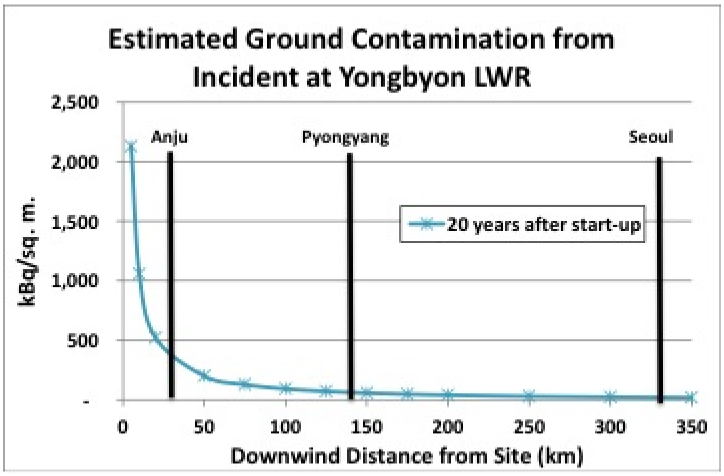


Figure 4-4c: Ground Contamination Results for Attack Scenario 3 for an Incident 20 Years after Reactor Start-up

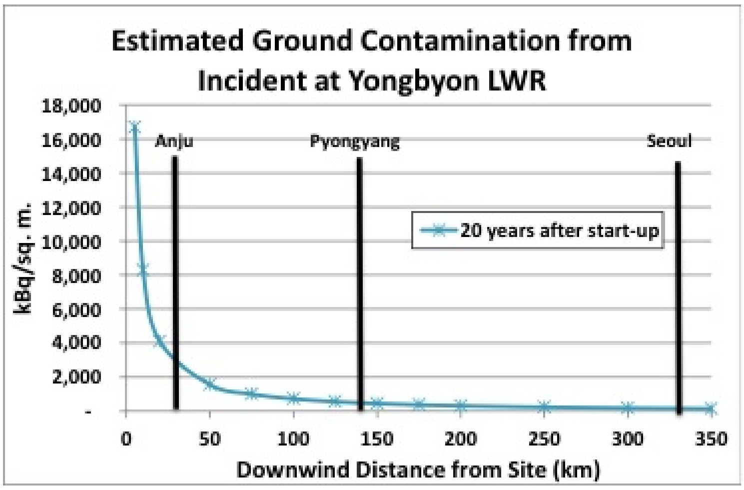


Figure 4-3: Estimated External Dose, Scenarios 2 and 3

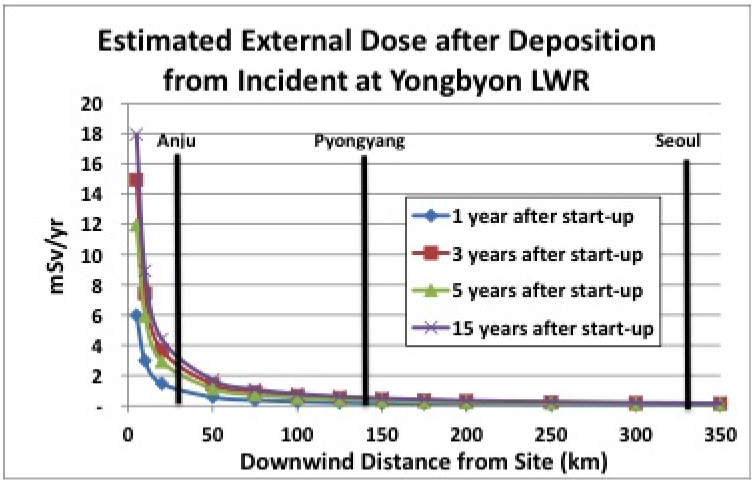
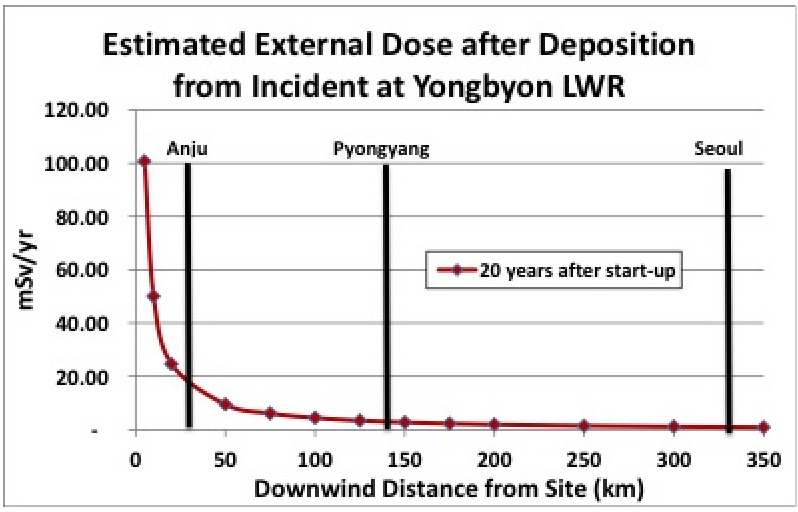


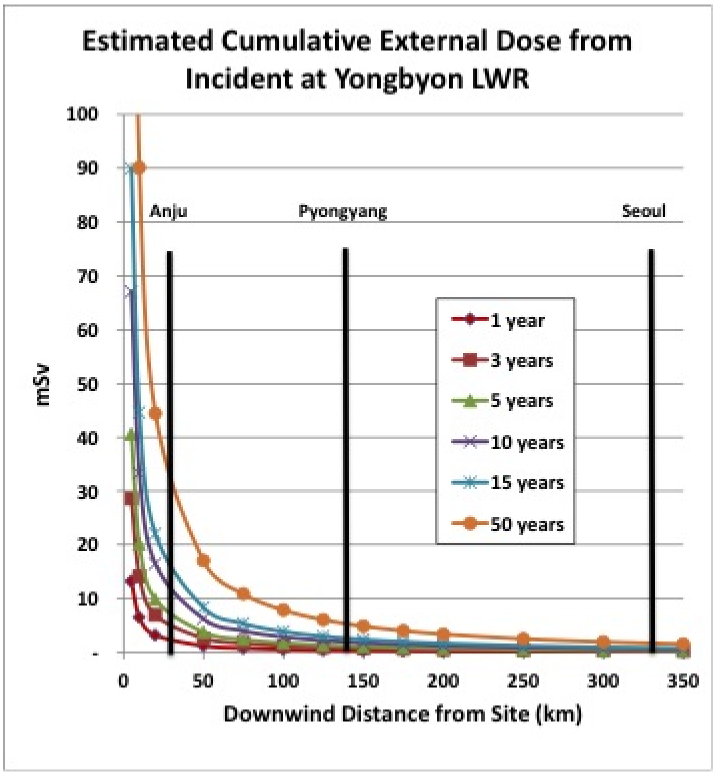
Figure 4-4: Estimated External Dose, Scenario 3, for an Incident 20 Years after Reactor Start-up



4.4 ESTIMATED CUMULATIVE AND COLLECTIVE DOSE FROM RADIOLOGICAL RELEASE

Following on from Figures 4-3 and 4-4, Figure 4-5 presents the estimated cumulative external dose from radiation release at Yongbyon under scenarios 2 and 3 at a range of downwind distances from the site, and over time periods ranging from 1 to 50 years, for a release occurring after 15 years of reactor operation. As shown and described above, had we chosen to do this calculation for a release after only 3 years of reactor operation, the results would have been qualitatively the same—about 16 percent less for each point than we show for an accident at the 15-year mark. Assuming the USEPA's guideline that the cumulative 50-year dose to an exposed individual should not exceed 50 mSv[20], no medium or large cities in the DPRK would be within the cumulative exposure threshold area for a release not involving the spent fuel pool, though contamination at some smaller cities closer to Yongbyon could cross the long-term exposure threshold.

Figure 4-5: Estimated Cumulative Dose, Scenarios 2 and 3



Tables 4-1 through 4-3 present estimates of the excess deaths implied in each of four locations, at varying distances from the release of radioactivity, for releases after 3, 15, and 20 years of LWR operation, respectively, and assuming an exposure time of 10 years. These cities are examples of locations along potential southward downwind emission paths, and thus in interpreting the results in these tables, three issues must be kept in mind. First, using the wedge angle that we applied, the cloud of emissions would not, without a very discrete mid-incident shift in the wind, pass over both Pyongyang and Seoul. As a consequence, the rows in these tables cannot be summed to an overall value. A larger wedge angle could be used in the analysis, implying southerly winds that shift back and forth over time, but using a wedge angle that was, for instance, doubled (implying radioactivity would be dispersed over a wider area) would imply Cs-137 deposition and related results one-quarter of those shown. Second, the example cities listed are only some of the possible population centers along any given southerly downwind path, thus the sum of the impacts of listed cities that *are* within a given wedge angle from the Yongbyon source is not the sum of all of the affected individuals or impacts within the arc modeled. Third, though some general wind directions at specific times of year are more probable than others, many wind directions are possible at the specific time of an incident, meaning that the probability of any given city, particularly one far from Yongbyon, being affected may be small. Each calculation assumes an exposure time of ten years.

As noted above, this calculation assumes that a linear dose-response relationship between excess deaths from solid cancers and radiation dose can be extrapolated linearly to zero for both dose and effect. As Tables 4-1 through Table 4-3 include only selected population centers between Yongbyon and Seoul (and beyond), the indication is that on the order of several hundred early cancer deaths might arise as a result of the radiation released from an accident at or non-state attack on Yongbyon for releases occurring between 3 and 15 years after start-up, rising to on the order of perhaps a few thousand for a release 20 years after start-up. It should be stressed that in this context "early" may mean death occurs just minutes earlier than it might have in the absence of the additional radiation, and thus essentially indiscernible from deaths caused by background radiation. If, rather than using a no-threshold dose-response relationship, we count those individuals receiving a dose greater than approximately the USEPA's guideline (that a cumulative 50-year dose to an exposed individual should not exceed 50 mSv), the number of early cancer deaths falls to a few hundred for radiation releases between 3 and 15 years after start-up, with the number of people exposed to doses of that level on the order of a few hundred thousand.[21]

In the very worst case, for a radiation release at 20 years after start-up and for scenario 3, which includes substantial emissions from the spent fuel pool because it assumes a Zircaloy cladding fire, neglecting those exposed to a dose less than 50 mSv suggests early cancer deaths numbering in perhaps the low thousands out of a population of a million or so exposed beyond the EPA's guidelines. In both cases, all of those individuals would be in the DPRK.

Table 4-1: Calculation of Collective Dose at Selected Locations along Southward Deposition Paths from Yongbyon for Release 3 years after Reactor Start-up, Attack Scenarios 2 and 3

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Yongbyon	0	2	2,000	100
Kaechon	13	17	20,000	1,500
Pyongyang	120	140	5,008	1,600
Seoul	315	335	4,185	1,000

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Yongbyon	300	1,000	1.400	10
Kaechon	5,500	300,000	0.090	300
Pyongyang	5,900	3,255,000	0.010	300
Seoul	3,700	6,800,000	0.003	200

Table 4-2: Calculation of Collective Dose at Selected Locations along the Southward Deposition Path from Yongbyon for Release 15 years after Reactor Start-up, Attack Scenarios 2 and 3

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Yongbyon	0	2	2,000	100
Kaechon	13	17	20,000	1,800
Pyongyang	120	140	5,008	1,900
Seoul	315	335	4,185	1,200

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Yongbyon	300	1,000	1.700	17
Kaechon	6,600	300,000	0.110	330
Pyongyang	7,000	3,255,000	0.010	330
Seoul	4,400	6,800,000	0.003	200

Table 4-3: Calculation of Collective Dose at Selected Locations along the Southward Deposition Path

from Yongbyon for Release 20 years after Reactor Start-up, Attack Scenarios 3

	Diameter (km)		Population Density	Initial Collective Radiation Dose
Location	Inner	Outer	persons/km^2	person-Sv/yr
Yongbyon	0	2	2,000	500
Kaechon	13	17	20,000	9,900
Pyongyang	120	140	5,008	11,000
Seoul	315	335	4,185	7,000

	Cumulative Collective Radiation Dose	Exposed Population	Percent Excess Deaths	Implied Number of Excess Deaths
Location	person-Sv	People	%	
Yongbyon	1,900	1,000	9.700	100
Kaechon	37,000	300,000	0.630	1,900
Pyongyang	39,000	3,255,000	0.060	2,000
Seoul	25,000	6,800,000	0.019	1,300

4.5 ECONOMIC DAMAGES

Several types of economic damages could arise due to the release of radioactivity following an accident or attack on and LWR.   These include:

- Economic damages related to premature human deaths due to the effects of radiation exposure;
- Direct economic impacts related to the loss of generating capacity in the DPRK due to the impacts of the accident or attack on the reactor (that is, to the loss of the reactor as a functional asset);
- Direct economic impacts related to the need to clean up the reactor site following an accident or attack;
- Economic damages related to the loss of use of areas (including the farms, homes, mines, and other assets in those areas) downwind of the reactor that are contaminated past a threshold of tolerance by radioactive materials as a result of the accident or attack, and/or the costs of decontaminating those areas sufficiently that they can be used again.

These types of damages are discussed below.

Damages Related to Premature Human Deaths

There is a substantial literature related to the valuation of premature human deaths—essentially, the valuation of a human life.[22]   That literature applies a variety of valuation approaches and produces a wide range of results, including results varying by several orders of magnitude between countries. Below (Tables 4-4 through 4-6) we present estimates of the value of the premature deaths indicated in Tables 4-1 through 4-3 based on two estimates of the “value of a statistical life” compiled in a review of a number of studies, one of which is for the United States (about $10 million per person in 2012 dollars) and one of which is for the ROK (about $1.1 million per person).[23] Applying these estimates—and remembering that these calculations include both the extrapolation of the calculation of excess deaths to very low doses of radioactivity *and* the application of the value of a statistical life, each of which involves assumptions about which there is considerable debate—yields values in the range of $1 to perhaps $15 to 20 billion for events before 16 years after reactor start-up, and perhaps $10 to $100 billion for events after that point, for loss of life caused by a radiological release from the Yongbyon LWR, in both cases roughly factoring in population areas that the plume of material released will encounter that are not included explicitly in Tables 4-4 through 4-6. Note, however, that the range of values per excess death that has been used here is adopted with no attempt to adapt it to DPRK conditions or practices, although the bulk of early cancer deaths would occur in the DPRK. Attempting to estimate such a parameter for the DPRK is beyond the scope of this paper. In addition, when and if the point is reached where (non-DPRK) policymakers are called upon to develop and implement approaches to engagement with the DPRK based, in part, on radiological risk, it seems reasonable to assume that those policymakers will be obliged to weigh the lives of all Koreans equally.

Conversely, considering *only* those individuals exposed to cumulative doses higher than the EPA's guidelines based on the dose threshold response hypothesis reduces these estimates of excess death by a factor of about 3 for releases up to 16 years after reactor start-up, and a factor of about 2 after that point.

It is important for readers to keep in mind that the range of excess deaths and value thereof is enormous in this sensitivity analysis due to the combination in the calculations of high-low dose response assumptions with high-low estimated values of excess deaths. As we noted above, these possible impacts in the DPRK itself should be evaluated in the context of other energy-related public health impacts from coal mining and use, especially residential coal and wood use including, in some cases, carbon monoxide poisoning and particulate inhalation from use of traditional "ondol" Korean home cooking-heating systems and other coal and biomass-fired cooking and heating devices. Although good data for DPRK public health are notoriously scarce,[24] we believe that these energy-related health impacts are relatively much larger than those associated with the operation of a small LWR in the DPRK, or the radiologically-induced health impacts in the case of a hypothetical accident at or attack on the DPRK's small LWR.

Damages Related to Loss of Generating Capacity in the DPRK

An accident at or attack on the Yongbyon LWR would in all likelihood render the reactor (and probably much of the site around it) unusable. Replacement of the capacity of the LWR with fossil-fueled or hydroelectric power would likely involve on the order of $30 to $70 million in capital costs, and an additional $6 to $8 million annually in fuel costs if the generators are fueled with coal—costs would be perhaps 2 to 3 times higher if replacement fuel is oil or gas.

Damages Related to Required Clean-up of the Reactor Site

We do not know if the DPRK's nuclear law contains an indemnity provision related to Table 4-4 Calculation of the Value of Excess Deaths at Selected Locations along the Southward Deposition Path from Yongbyon for Release 3 Years after Start-up, Attack Scenarios 2 and 3

	Exposed Population	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US)	
Location	People		Lower Estimate	Higher Estimate
Yongbyon	1,000	10	$ 10	$ 100
Kaechon	300,000	300	$ 320	$ 3,000
Pyongyang	3,255,000	300	$ 320	$ 3,000
Seoul	6,800,000	200	$ 210	$ 2,000

Table 4-5: Calculation of the Value of Excess Deaths at Selected Locations along the Southward Deposition Path from Yongbyon for Release 15 Years after Start-up, Attack Scenarios 2 and 3

Location	Exposed Population People	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US) Lower Estimate	 Higher Estimate
Yongbyon	1,000	20	$ 20	$ 200
Kaechon	300,000	300	$ 320	$ 3,000
Pyongyang	3,255,000	300	$ 320	$ 3,000
Seoul	6,800,000	200	$ 210	$ 2,000

Table 4-6: Calculation of the Value of Excess Deaths at Selected Locations along the Southward Deposition Path from Yongbyon for Release 20 Years after Start-up, Attack Scenario 3

Location	Exposed Population People	Implied Number of Excess Deaths	Value of Excess Deaths, $ million (US) Lower Estimate	 Higher Estimate
Yongbyon	1,000	100	$ 110	$ 1,000
Kaechon	300,000	1,900	$ 2,000	$ 19,000
Pyongyang	3,255,000	2,000	$ 2,100	$ 20,000
Seoul	6,800,000	1,300	$ 1,400	$ 13,000

damages resulting from the operation of (or accident at) nuclear facilities in the DPRK. Wherever the liability lies, a clean-up of some sort (whether extensive enough to provide the opportunity for re-use or simply sufficient to stabilize facilities for long-term isolation) will be required. This clean-up will likely cost on the order of $100 million, perhaps more, given experience in other countries. It seems likely that the ROK would ultimately end up paying the bill for this effort following eventual reunification.

Damages Related to Loss of Use in Areas Affected by the Plume

Areas contaminated by radiation past an acceptable level will need to be either abandoned or decontaminated up before they can be reused. Given the many complexities involved in the calculation of related damages (what does the DPRK consider an acceptable radiation threshold? What land values should be ascribed to assets downwind? Exactly what assets are downwind near the site?), we do not attempt to estimate a value for this loss-of-use. It seems likely that the DPRK's tolerance for contamination might be higher, perhaps far higher, than that in the US or ROK, in part because, it has been suggested, the DPRK sees itself at war, and thus may view risks of radiological exposure to its citizens that would seem excessive elsewhere as acceptable under the circumstances. One facility that will likely need to be abandoned—the plutonium production facility at Yongbyon—poses an interesting case, as it may actually have a very high implicit value to the DPRK, whereas the ROK would consider the forced abandonment of the facility a significant benefit. At any rate, as with clean-up of the reactor site itself, it will likely be the ROK that will need to determine either the degree to which contaminated lands must be quarantined or invest in cleaning them up.

4.6 IMPACTS OF AN INCIDENT DURING A PERIOD OF WINDS FROM THE SOUTH

In the previous paragraphs we have focused on an incident that takes place during a time when prevailing winds near Yongbyon are from north to south, as is typical in the winter. We have done so largely to limit the required scope of the quantitative and qualitative analysis. Looking North from Yongbyon, however, in the direction of winds that prevail on the peninsula in the summer, there are a number of fairly large cities to the North and Northwest in China—Shenyang, Liaoyang, Benxi, and Tonghua, for example—but most are as distant from Yongbyon as Seoul, and much farther away than Pyongyang. The Russian cities of Vladivostok and Nakhodka, to the Northeast, are even further away. Although there are a number of significant cultural (for example, Mount Paektu) and environmental (for example, key avian flyways) resources located to the North of Yongbyon, areas of high population density, and (probably) of high economic importance are generally further away than toward the South. This is not to say that the prospect of an atmospheric release of radioactivity heading north from Yongbyon should be ignored—an in fact the political consequences of same are somewhat unpredictable—just that a full consideration of such an event is beyond the scope of this paper.

V. INTERPRETATION OF RESULTS

The calculations described above—again, only rough estimates of what the radiological implications of an incident at the LWR being constructed by the DPRK at Yongbyon, indicate that there would be likely be a relatively small radiological impact away from the reactor site in the event of an *accident* at the plant, due mostly to the fact that a reactor as small at that at Yongbyon would be self-cooling in the event of an accident. A concerted *attack* on the reactor and spent fuel pool by terrorists could lead to a much more significant radiological release, but there would still be relatively modest radiological impacts away from immediate area of the reactor, due in part to the small size of the reactor, even if some of the cesuium-137 in the spent fuel pool adjacent to the reactor were released during the event. Even adding to an already worst-case attack scenario the assumption that Zircaloy cladding is used for the reactor fuel, rather than stainless steel (the latter seems the more likely choice for the DPRK at present), only after about 17 years of operation would an attack scenario lead to radiological impacts even approaching those of the atmospheric releases of Cs-137 currently estimated to have resulted from the Fukushima Dai-ichi accident.

These estimates notwithstanding, it is arguably the case that the truly significant results of an event resulting in the release of a significant portion of the radiation inventory from the Yongbyon reactor would be the social and political impact in the Republic of Korea once the general public learns of the release. The emotional impact on the ROK public of the news of an oncoming cloud of radiation, no matter how diffuse, is not to be underestimated, and might well even result in more economic dislocation than the direct impacts of the radiation release could ever have. We would suggest that one likely impact of a radiological release from Yongbyon, particularly if caused by a terrorist attack, would be a re-focusing by the South Korean public on the future of nuclear power and related nuclear fuel-cycle related activities in the ROK. Where this renewed scrutiny would lead is hard to say—possibilities include increased security at nuclear facilities, including an emphasis on securing spent fuel, reconsideration of the current emphasis on the part of the ROK nuclear industry on a future including the development and use of pyroprocessing and fast reactors,[1] and/or reconsideration of the future of nuclear power in general, as has occurred (and is ongoing) as a result of the Fukushima accident.

As such, there are good reasons for the ROK and others to seek to reduce radiological risks, both real and perceived, though engagement of the DPRK on its LWR project in order to improve the reactor's safety systems at the outset. We have previously written about options for engaging the DPRK on LWR and related technologies[2], including among other options, education of DPRK nuclear experts in international standards for reactor safety, jointly designing with North Korea a made-in-DPRK small reactor that meets international safety and manufacturing standards, possibly in a joint project with ROK LWR manufacturing firms, and undertaking a program of power system planning for the rational development of a DPRK national grid capable of supporting a fleet of small LWRs over time.

As precursors to (or as a part of initial steps in) such an engagement, the international community (and the ROK) will need to improve its understanding of DPRK's existing plans for the Yongbyon reactor (to the extent possible), and revise analyses like the one above accordingly, undertake a deeper review of the technical options to reduce risk, and of the available engagement options that could contribute toward eventual implementation of technical and non-technical risk reduction strategies, and try to understand and develop opportunities for engaging both the ROK and DPRK on the issue of radiological risk.

Finally, the radiological risk arising from an incident the DPRK's small LWR should not be overstated, but it also should not be neglected. Should an *accident* occur at this LWR, the consequences would not be zero, though they seem unlikely to have much of an effect beyond the immediate area of Yongbyon. Impacts resulting from an *attack*, including a non-state attack using explosives, internal sabotage of the plant, or a combination, could, under admittedly worst-case conditions, be substantial, in terms of health impacts and damages to property. These impacts, however, are highly uncertain, and will remain so even after such an event due to the unresolved issue of dose-response threshold assumptions made to determine the excess deaths resulting from low-level radiation exposure. Thus, the primary predictable impacts of a radiological release from the DPRK's LWR will be psychological in terms of downwind perceptions and anxiety on the part of exposed or potentially exposed populations; and political, in terms of the policies adopted in anticipation or as a result of such an event.

In this regard, the DPRK's leaders may believe that they obtain political leverage from the likely unsafe status of their small LWR, and that this lever may enable them to force open a crack in the closed door of US and ROK policy on nuclear weapons-related issues. We do not, however, view this possible rationale, if it exists, as the primary motivation for the DPRK building a small LWR. Nor do we view the construction of the DPRK's small LWR as solely driven to produce electric power, although with sufficient grid support, this reactor is scaled more realistically with respect to the size of the DPRK power grid than were the KEDO reactors, as the latter could never have operated while connected directly to the DPRK national grid Further, we do not believe that the small LWR is particularly useful for the DPRK's nuclear weapons program; the DPRK has other, easier ways to produce weapons-grade plutonium (which it has already embarked upon by restarting the 5 MWe graphite-moderated reactor, and reportedly by accelerating its uranium enrichment program).

Rather, our appraisal is that the DPRK undertook this project at least in part in order to offset the loss of the KEDO LWRs that were to have been built under the original 1994 Agreed Framework between the US (and its allies) and the DPRK. The completion and operation of the KEDO LWRs would have, in the eyes of the DPRK leadership, brought the DPRK to co-equal status with other regional powers in terms of a complete nuclear fuel cycle—that is, the DPRK's small LWR is a symbolic project aimed at embodying the perceived prestige of the DPRK state in the eyes of its own population and third parties, in accordance with the *juche* principle of self-reliance, and in response to the slight of the United States in cancelling the KEDO project, as well as to fulfill the leadership's long-standing commitment to build a nuclear reactor, a goal dating back the early 1980s. In that context, building this small LWR can be seen, from a DPRK perspective, as a logical first step designed to gain the experience necessary to launch a fleet of small, domestically-built reactors aimed at helping to address the DPRK's electricity shortage. This logic notwithstanding, the potential utility of the small LWR as a negotiating item should the parties to the Korean conflict return to talks, cannot have escaped the attention of the DPRK's leadership. However, this study suggests that the DPRK does not gain much leverage by posing a reactor safety hazard, even if its leaders were to think that is the case.

VI. CONCLUSIONS: POSSIBLE APPROACHES TO MITIGATE RADIOLOGICAL RISKS, WHILE GRASPING ENGAGEMENT OPPORTUNITIES

On balance, we conclude that it is timely for the ROK, the United States, China, Japan, and Russia—all potentially affected states—to engage the DPRK on the issue of nuclear reactor safety, irrespective of the nuclear weapons issue, although we acknowledge that the likelihood of engagement is very slim in the absence of any steps by the DPRK to address concerns about its nuclear weapons program.

There are precedents (United States with Pakistan and India) for providing assistance on nuclear power safety issues to nuclear-armed states outside of the NPT, possibly using the US Nuclear Regulatory Commission as the point of a-political contact, and it is possible to do so without assisting the DPRK' s nuclear weapons program in any material manner. Technical discussions with regard to safety measures such as, for example, filtered vents for the LWR containment, as are being installed in Japan, or increasing the size of the spent fuel pool, could be entered into with little risk, and could lead to engagement on other issues.

Also, a trilateral framework already exists for such discussions that could be expanded to include the DPRK. At their May 22, 2011 summit, Japanese Prime Minister Naoto Kan, Chinese Premier Wen Jiabao and ROK President Lee Myung-bak committed each country to help each other "especially at times of disaster and adversity" and to increase cooperation on nuclear safety.They also "agreed to facilitate joint programs on renewable energy and energy conservation to avoid excessive dependence on nuclear power"[1].

In fact, the top nuclear regulators of China, Japan, and the ROK have met annually since 2008 under the rubric of disaster response.[2] The inaugural statement committed the three regulators "to discuss the exchange of useful information for common issues and technologies related to nuclear safety improvements, and to improve and strengthen nuclear safety cooperation in Northeast Asia."[3] The May 22, 2011 summit was followed by the 4th Top Regulators meeting on November 29, 2011. (The text of this declaration is provided below in Attachment 1).China, South Korea and Japan established a framework in which to quickly exchange information in a nuclear emergency at a December 4, 2013 meeting in China.[4] As a potentially downwind as well as upwind state, the DPRK should be considered as a possible participant in this framework.

As Sharon Squassoni has outlined, a process of discussions with the DPRK on the topic of its LWR could begin with mere talks about nuclear safety, best practice, and information sharing on accident pathways and impacts analysis. The IAEA could send safety missions; and states (especially China and Russia) could host bilateral nuclear reactor safety study tours and trainings. The DPRK could be briefed about the need for it to sign and ratify the Convention on Nuclear Safety, the Code of Conduct on Safety of Research Reactors, and the Code of Conduct on the Safety and Security of Radioactive Sources, and supplementary Guidance on the Import and Export of Radioactive Sources. It could also be briefed on the need for the DPRK to file a national report on its actions to implement UNSC Resolution 1540 on controlling non-state actors in relation to smuggling nuclear materials and dual use commodities and knowledge, and trainings could be offered to the DPRK either bilaterally or in a regional context at the new Chinese regional center of excellence on nuclear security.

The DPRK's small LWR may also hold the political key to unlocking the uranium enrichment safeguards barrier to a denuclearization of the DPRK. The small LWR will use low enriched uranium, presumably obtained from the DPRK's uranium enrichment plants, and fabricated into fuel rods as explained above. One possible formula is for the DPRK and the ROK to cooperate in replacing the small LWR at Yongbyon with a jointly built "reunification reactor" based on the ROK 90 MWe SMART reactor design,[10] as we suggested in 2010.[11] In turn, this approach would be the political and technical basis for it to be logical for the DPRK to enter into an enrichment consortium such as that proposed by the ROK in relation to the renewal of its 123 Agreement with the United States. The *quid pro quo* for such a deal would be the verified dismantlement of the DPRK's enrichment facilities, preceded by a prior declaration of the location and details of such facilities, supplemented by an acceptable level of inspections in the DPRK in a regional context.

In this regard, we suggest that a regional nuclear weapons-free zone is likely to provide the right, enduring regional institutional framework for such cooperation on nuclear fuel cycle issues, including the DPRK small LWR program and other related issues.[12]

VII. ATTACHMENT 1: NORTHEAST ASIAN NUCLEAR SAFETY MEETINGS

Cooperative Nuclear Safety Initiative of Japan, The People's Republic of China, and The Republic of Korea[1] Based on the Summit Declaration of Japan, the People's Republic of China, and the Republic of Korea on May 22, 2011, where the leaders of three countries confirmed the commitment to strengthening cooperation in the field of nuclear safety, we, the top nuclear safety regulators of the three countries, confirmed to take the trilateral initiative on nuclear safety as follows: 1. Cooperative Framework - To make the Top Regulators' Meeting (hereinafter referred to as TRM) as a practical and tangible framework of cooperation; - To establish working groups on specific fields of common interests as agreed by consensus; 2. Harmonized Approach - To develop a harmonized approach to nuclear safety and regulation within the three countries, with reference to the IAEA safety standards where appropriate; - To promote exchange of experience and learning from best practices of each country; 3. Cooperative Leadership in Regional and International Cooperation - To maintain a network of nuclear safety regulators in Northeast Asia and promoting international cooperation in the Asian region; - To enhance the effective implementation of international conventions as well as bilateral arrangements on nuclear safety; 4. Action Items - To implement the action items decided by consensus among the three countries and included in the Annex of this initiative; - To review the action items on a regular basis to check the status of implementation and to amend when agreed also by consensus;

VIII. ANNEX

List of Action Items 1. Revising the existing MoC (Memorandum of Cooperation for TRM) and preparing ToR (Terms of Reference) to establish a practical and tangible framework of cooperation; 2. Establishing an information exchange framework to actively share experiences of construction and operation including lessons learned from the accident at the TEPCO Fukushima Dai-ichi Nuclear Power Station; 3. Enhancing cooperation in regulatory responses to external events and severe accident management; 4. Enhancing cooperation in establishing and strengthening an effective, independent and authorized regulatory framework while securing appropriate expertise and promoting an effective nuclear safety culture; 5. Promoting international nuclear safety cooperation encompassing the whole of the Asian region utilizing existing regional activities and enhancing the effective implementation of international conventions such as the Convention on Nuclear Safety, as well as bilateral arrangements on nuclear safety; 6. Developing a harmonized approach to nuclear safety and regulation in a manner consistent with the IAEA safety standards; 7. Maintaining high level of emergency preparedness and response capacity to mitigate the effect of nuclear accidents and enhancing cooperation in capacity building in emergency response; 8. Enhancing cooperation on research and development of nuclear safety technology; 9. Acknowledging importance of transparency of information in case of nuclear incident and enhancing cooperation in public relations; 10. Encouraging cooperation among TSOs.

IX. REFERENCES

[1] David von Hippel may be contacted at: dvonhip@igc.org Peter Hayes may be contacted at: phayes@nautilus.org The authors thank Bob Budnitz, Neil Chapman, Steve Fetter, Sig Hecker, Jungmin Kang, Lee Sigal, and Frank von Hippel for their reviews of an earlier draft of this essay. We have incorporated many of their comments in this text, but not all, and this text is solely the responsibility of the authors.

[2] See, for example, Mark Holt, Richard J. Campbell, and Mary Beth Nikitin (2012), *Fukushima Nuclear Disaster*, U.S. Congressional Research Service, dated January 18, 2012, available as http://www.fas.org/sgp/crs/nuke/R41694.pdf.

[3] See, for example, Jeff McMahon (2011), "Ocean Absorbed 79 Percent Of Fukushima Fallout", *Forbes*, dated 10/29/2011, available as http://www.forbes.com/sites/jeffmcmahon/2011/10/29/ocean-absorbed-79-percent-of-fukushima-fallout/

[4] The final chapter of the Fukushima accident, in terms of direct radiological impacts, is still to be written as of this writing, as water bearing radioactive compounds continues to leak from the plant into the Pacific. See, for example, Quirin Schiermeier , Jay Alabaster and Nature magazine (2013), "Government Urged to 'Step In' to Halt Fukushima Plant Leaks", *Scientific American* , 8-29-2013, available as http://www.scientificamerican.com/article.cfm?id=government-urged-to-step-in-to-halt-fukushima-plant-leaks.

[5] See, for example, David Wright (2013), "How Vulnerable are the Pools that Store Spent Nuclear Fuel at U.S. Reactors?", Union of Concerned Scientists, dated March, 2013, and available as http://www.ucsusa.org/publications/ask/2013/spentfuel.html. See also Gordon R. Thompson (2013), *Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel*, dated January 31, 2013, published as a Nautilus Institute NAPSNet Special Report, and available as https://nautilus.org/wp-content/uploads/2013/05/SNF-Risk-Handbook-Rev-1.pdf. Note, however, that it remains unclear, even as of this writing, nearly three years after the Fukushima Dai-ichi accident, to what extent emissions from the damaged spent fuel pool in Unit #4 have contributed to the overall emissions of radioactivity to the atmosphere from the plant, or if there have been substantial emissions from the spent fuel pool at all.

[6] See, for example, Akira Nagano (2012), "Current Status and Efforts in Japan after Fukushima Accident", JAIF International Cooperation Center (JICC), June, 2012, available

as http://www.iaea.org/NuclearPower/Downloads/Infrastructure/meetings/2012-06-18-20-TM-Vienna/10.Status_and_Efforts_after_Fukushima.pdf; and World Nuclear Association (2014), "Nuclear Power in Japan", updated 17 February 2014, and available as http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan/.

[7] Liu Xuegang (2012), *China's Nuclear Energy Development and Spent Fuel Management Plans*. Nautilus Peace and Security (NAPSNet) Special Report, dated October 16, 2012, and available as https://nautilus.org/napsnet/napsnet-special-reports/chinas-nuclear-energy-developme-t-and-spent-fuel-management-plans/#report.

[8] Siegfried S. Hecker (2010), *A Return Trip to North Korea's Yongbyon Nuclear Complex*. NAPSNet Special Report, dated November 22, 2010, and available as http://www.nautilus.org/publications/essays/napsnet/reports/a-return-trip-to-north-korea2019s-yongbyon-nuclear-complex.

[9] Gordon R. Thompson (2013), *Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel*, dated January 31, 2013, published as a Nautilus Institute NAPSNet Special Report, and available as https://nautilus.org/wp-content/uploads/2013/05/SN--Risk-Handbook-Rev-1.pdf.

[10] This essay updates our earlier analysis of the DPRK small LWR in D. von Hippel, P. Hayes, "*Engaging the DPRK Enrichment and Small LWR Program: What Would It Take?, NAPSNet Special Report* December 23, 2010, at: https://nautilus.org/napsnet/napsnet-special-reports/engaging--he-dprk-enrichment-and-small-lwr-program-what-would-it-take/#axzz2jbioAuWt

[11] J. Ryall, "North Korean nuclear reactor work 'could end in catastrophe,' *The Telegraph*, September 12, 2013 at:http://www.telegraph.co.uk/news/worldnews/asia/northkorea/10304233/North-Korean-nuclear-reactor-work-could-end-in-catastrophe.html For an historical example involving the UK's Calder Hall graphite moderated reactor and fire, see: S. Reid, "Britain's nuclear inferno: How our own Government covered up Windscale reactor blaze that's caused dozens of deaths and hundreds of cancer cases," *Mail Online*, March 19, 2011, at: http://www.dailymail.co.uk/news/article-1367776/UK-Government-covered-nuclear-reactor-blaze-caused-death-cancer.html#ixzz2jc7EYGXg

[12]For discussion of the legal dimensions of attacking nuclear facilities, see D. Joyner, "Can the U.S. or Israel Lawfully Attack Iran's Nuclear Facilities?" Arms Control Law (blog), August 7, 2012, at: http://armscontrollaw.com/2012/08/07/can-the-u-s-or-israel-lawfully-attack-irans-nuclear-facilities/ and, International Atomic Energy Agency, "Prohibition Of All Armed Attacks Against Nuclear Installations Devoted To Peaceful Purposes Whether Under Construction Or In Operation," Governing Council resolution 533, GC(XXXIV)/RES/533, October 1990, at: https://www.google.com/url?q=http://www.iaea.org/About/Policy/GC/GC34/GC34Resolutions/English/gc34res-533_en.pdf&sa=U&ei=hhF3UuXFK-SujALfkIH4BQ&ved=0CAcQFjAA&client=internal--ds-cse&usg=AFQjCNFr4CI35gSvcCEZFdsOki4vHS0pWQ

[13] As recounted by A. Carter, W. Perry, *Preventive Defense, A New Security Strategy for America*, Brookings Institution, 1999, Washington DC, p. 129.

[14]J. Hastings, “The economic geography of North Korean drug trafficking networks,” University of Sydney, January 2014, at: http://jvhastings.files.wordpress.com/2014/01/ripe-article-north-korea-release.pdf

[15] Oh Jae-hwan, “Security Agencies of North Korea under the Kim Jong Un Regime,” *The Korean Journal of Defense Analysis,* 26:1, March 2014, pp. 117–131

[16] Peter Hayes, "Thinking About The Thinkable: DPRK Collapse Scenarios Redux", NAPSNet Policy Forum, September 24, 2013, https://nautilus.org/napsnet/napsnet-policy-forum/thinking-about-the-thinkable-dprk-collapse-scenarios-redux/

[17] Nuclear Threat Initiative, *NTI Nuclear Materials Security Index, Building a Framework for Assurance, Accountability, and Action*, January 2012, pp. 7, 14, at: www.ntiindex.org/static/pdfs/nti_index_final.pdf

[18] Source: "Redefining denuclearization in North Korea" by Siegfried S. Hecker, 20 December 2010, *Bulletin of the Atomic Scientists*, available http://thebulletin.org/redefining-denuclearization-north-korea-0.

[19] From “North Korea Makes Significant Progress in Building New Experimental Light Water Reactor (ELWR)”, *38 North*, 14 November 2011, http://38north.org/2011/11/elwr111411/. In addition, and relevant to Figure 2-2, Choe Sang-Hun (2012), “Progress Is Cited on New Reactor in North Korea”, *New York Times*, dated, August 21, 2012, and available as http://www.nytimes.com/2012/08/22/world/asia/progress-on-new-nuclear-reactor-in-north-korea.html includes the following related to construction of the DPRK LWR: “Allison Puccioni, a satellite image analyst at IHS *Jane’s Defence Weekly*, said Tuesday that North Korea had completed a major step in the construction by placing a 69-foot dome on the reactor building. She based her conclusion on images taken by the GeoEye-1 satellite on Aug. 6.”

[20] From *Update on North Korean Light Water Reactor Construction Project*, By David Albright and Robert Avagyan, Institute for Science and International Security, *ISIS IMAGERY BRIEF*, dated August 14, 2012.

[21] From Siegfried Hecker (2012), “Nuclear developments in North Korea”, prepared for the 18th Pacific Basin Nuclear Conference, Busan, Republic of Korea, March 20, 2012, available as http://iis-db.stanford.edu/pubs/23658/HeckerPBNCfinal.pdf.

[22] From Google Maps. Photo showing dome of reactor building now installed and painted. Crops in nearby fields suggest that the date is approximately late March or April, 2013.

[23] From Google Maps. Photo showing additional site work since the image in Figure 2-4 was taken including additional roadways or walkways near the reactor and over placement of what appears (in Figure 2-4) to be a ditch for water pipes between the reactor and the river (concrete strip heading southeast from the reactor building. Vegetation and water level in the river suggest that the image was taken in approximately May or June, 2013.

[24] From Google Maps. Photo showing most elements of site looking similar to how they appear in image in Figure 2-5. Photo taken in January or early February of 2014 (extracted 2/12/2014).

[25] S. Hecker, personal communication, 1/19/2014.

[26] B. Budnitz, personal communications, 11/7/2013.

[27] See, for example, C.L. Whitmarsh (1962), *Review of ZIRCALOY-2 and ZIRCALOY-4 Properties Relevant to N.S. Savannah Rector Design*, Report ORNL-3281, UC-80 - Reactor Technology, TID-4500 (17th ed.), apparently dated July 9, 1962, and available as http://web.ornl.gov/info/reports/1962/3445605716311.pdf; and Atom.com (2012), "Zircaloy-4(Alloy Zr4) (UNS R60804)", updated: Jun 11, 2013, and available as http://www.azom.com/article.aspx?ArticleID=7644.

[28] L. Baker, Jr. (1983), "Hydrogen-Generating Reactions in LWR Severe Accidents", prepared for International meeting on light-water reactor severe accident evaluation; Cambridge, MA (USA); 28 Aug - 1 Sep 1983, and available as http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/15/003/15003080.pdf.

[29] Zircaloy has advantages as a cladding material over stainless steel in terms of its in-reactor performance, leading to reactor fuel cost advantages, but the authors and experts we have asked are unaware of studies that fully document the tradeoffs between the two cladding materials.

[30] United States Nuclear Regulatory Commission (NRC, 2013), *Waste Confidence Generic Environmental Impact Statement: Draft Report for Comment*, Report # NUREG-2157, dated August 2013, and available as http://pbadupws.nrc.gov/docs/ML1315/ML13150A347.pdf.

[31] From http://www.jalopyjournal.com/forum/showthread.php?p=7569043, captioned "CHARLEVOIX MI 1961 Big Rock Point Nuclear Power Plant". This plant, initially run as an experimental reactor, was the fifth commercial nuclear plant in the US, and served (apparently very well) until decommissioned in 1997.

[32] See, for example, Nuclear Energy Institute, "Costs: Fuel, Operation, Waste Disposal & Life Cycle", undated, but probably 2013, available as http://www.nei.org/Knowledge-Center/Nuclear-Statistics/Costs-Fuel,-Operation,-Waste-Disposal-Life-Cycle.

[33] The calculated Cs-137 inventory in the reactor core shown in Figure 3-2 omits as negligible the decay of the isotope while the fuel is in the core.

[34] Reprocessing of LWR fuel at the plutonium production facility in Yongbyon would require reconfiguring of the portion of the production facility dedicated to taking in, breaking down, and processing spent fuel, but such reconfiguration is thought to be within the DPRK's capabilities.

[35] See, for example, R. Alavarez (2011), *Spent Nuclear Fuel Pools in the U.S.: Reducing the Deadly Risks of Storage*, Institute for Policy Studies, released May 24, 2011, and available as http://www.ips-dc.org/reports/spent_nuclear_fuel_pools_in_the_us_reducing_the_deadly_risks_of_storage.

[36] Fukushima Cs-137 inventory estimates are taken from Stohl, A., Seibert, P., Wotawa, G., Arnold, D., Burkhart, J. F., Eckhardt, S., Tapia, C., Vargas, A., and Yasunari, T. J. (2012): "Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition", Atmospheric Chemistry and Physics, 12, 2313-2343, doi:10.5194/acp-12-2313-2012, 2012.

[37] Yongbyon is located in an area of relatively low historical seismic activity. See, for example, Wenjie Zhai et al., "Research in historical earthquakes in the Korean peninsula and its

circumferential regions", *Acta Seismologica Sinica*, Vol.17, No.3, p.366-371, May 2004, as cited in Jungmin KANG (2010), *An Initial Exploration of the Potent ial for Deep Borehole Disposal of Nuclear Wastes in South Korea*, dated December 13, 2010, and available as https://nautilus.org/wp-content/uploads/2011/12/JMK_DBD_in_ROK_Final_with_Exec_Summ_12-14-102.pdf.

[38] M. Pennington, "Institute: Water Woes Endanger NKorea Reactor," Associated Press, Washington DC, April 8,
2014,
http://abcnews.go.com/Politics/wireStory/report-water-woes-endanger-nkorea-reactor-23229473

[39] No direct weather data was immediately available for the Yongbyon area. As an approximate value, we assume 7 meters per second based very roughly on estimated values for the area around Yongbyon from a map developed by 3TIER (2011), "Global Mean Wind Speed at 80m", available as http://www.3tier.com/static/ttcms/us/images/support/maps/3tier_5km_global_wind_speed.pdf.

[40] Although a rough estimate of deposition velocity was adequate in this case, when more precision is required, guidance for choosing deposition velocities under different Pasquill-Gifford categories of atmospheric stability is provided as Figure II.4-2 in Thompson's *Handbook*; original source, J. Rishel and B. Napier (2012), "Atmospheric Dispersion Modeling in Safety Analyses: GENII", viewgraphs for display at DOE Workshop to Discuss Issues Regarding Deposition Velocity, 5-6 June 2012, accessed on 31 January 2013 from:
http://energy.gov/downloads/maccs2deposition-velocity-workshop. Definitions of the Pasquill-Gifford categories of atmospheric stability can be found in, for example, US Environmental Protection Agency (2005) "Lesson 6: Plume Dispersion and Air Quality Modeling" [part of a set of online course materials], Table 6-1, available
as
http://yosemite.epa.gov/oaqps/eogtrain.nsf/b81bacb527b016d785256e4a004c0393/c9862a32b0eb4f9885256b6d0064ce2b/$FILE/Lesson%206.pdf.

[41] Thompson (2013, ibid) refers to the source of the wedge model as Lewis et al (1975), H. W. Lewis (chairman) and eleven other members of the APS Study Group, "Report to the American Physical Society by the study group on light-water reactor safety", *Reviews of Modern Physics,* Volume 47, Supplement Number 1, Summer 1975.

[42] This reactor, based on the British Calder Hall reactor design and used to produce plutonium, is typically referred to as the "5 MWe reactor", though there is little evidence that it ever actually produced electricity, though it did, apparently, produce heat for processes and buildings in the Yonghyon complex.

[43] See, for example, Bill Chappell (2013), "North Korea Has Restarted Nuclear Reactor, South Korea Says", NPR.org, dated October 08, 2013, available
as
http://www.npr.org/blogs/thetwo-way/2013/10/08/230439644/north-korea-has-restarted-nuclear-reactor-south-korea-says.

[44] Source: Google Maps, accessed 5/2\013.

[45] Source: *Wikipedia*, "List of cities in North Korea ", based on DPRK Census, available http://en.wikipedia.org/wiki/List_of_cities_in_North_Korea. Distances are approximate, based on measurements by the authors using Google Maps.

[46] Gordon Thompson, personal communication (2013). Examples of other types of models

applicable to the analysis considered here include Gaussian Plume models (see, for example, some of the tools listed by the Oak Ridge National Laboratory's Radiological Safety Information Computational Center in https://rsicc.ornl.gov/Catalog.aspx?key=133; and tools included in the HotSpot Health Physics codes" assembled by the National Atmospheric Release Advisory Center of Lawrence Livermore National Laboratory, https://narac.llnl.gov/HotSpot/HotSpot.html). Gaussian Plume models such as HotSpot would likely be the next step up from the wedge model in terms of fairly straightforward applicability to an analysis such as the one presented in this paper.

[47] Institut de Radioprotection et de Sûreté Nucléaire (IRSN, 2011), *Assessment on the 66th Day of Projected External Doses for Populations Living in The North-West Fallout Zone of the Fukushima Nuclear Accident*, Report # DRPH/2011-10, available as http://hps.org/documents/irsn_fukushima_report.pdf

[48] Note that for some radioactive isotopes, particularly those of iodine, ingestion pathways and thus doses relative to deposition may vary widely from place to place, depending, for example, on whether there are dairy farms nearby, and if so, what measures are taken to reduce milk consumption from contaminated areas.

[49] See, for example, Gordon Thompson (2012), "Unmasking the truth: The science and policy of low-dose ionizing radiation," *Bulletin of the Atomic Scientists*, 2012 68:44 (May, 2012), available as http://bos.sagepub.com/content/68/3/44.

[50] For example, a December 2012 statement by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to the Fukushima Ministerial Conference on Nuclear Safety stated "In general, increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation. This is because of the uncertainties associated with the assessment of risks at low doses, the current absence of radiation-specific biomarkers for health effects and the insufficient statistical power of epidemiological studies. Therefore, the Scientific Committee does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels" (Supplement No. 46. Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. Fifty-ninth Session. (21-25 May 2012)). A portion of this quite is available in Wolfgang Weiss on behalf of UNSCEAR (2012), " Speech on behalf of the United Nations Scientific Committee on the Effects of Atomic Radiation to the Fukushima Ministerial Conference on Nuclear Safety", 15 – 17 December 2012, Fukushima, Japan, available as http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/statements_m68.pdf). Reviews of the literature on the topic appeared as B.F. Wall, G.M. Kendall, A.A. Edwards, S. Bouffler, C.R. Muirhead, and J.R. Meara (2006), "What are the risks from medical X-rays and other low dose radiation?", in *The British Journal of Radiology*, 79 (2006), 285–294, available as http://bjr.birjournals.org/content/79/940/285.full.pdf; A. P. Møller, T. A. Mousseau (2012), "The effects of natural variation in background radioactivity on humans, animals and other organisms", *Biological Reviews*, 2012; and Leon Mullenders, *et al*, (2009), "Assessing cancer risks of low-dose radiation", in *Nature Reviews Cancer* 9, 596-604 (August 2009).

[51] See, for example, A. L. Brooks (2012), *A History of the United States Department of Energy (DOE) Low Dose Radiation Research Program: 1998-2008*, dated September, 2012, and available as http://lowdose.energy.gov/pdf/albRoughDraft/doeHistoryComplete09262012.pdf.

[52] A petabecquerel, or 10^{15} Bq, represents a rate of radioactive decay equal to 1 disintegration per second. 37 billion (3.7 x 1010) Bq equals 1 curie (Ci). See, for example, US Nuclear Regulatory Commission (2013), "Becquerel (Bq)", available

as http://www.nrc.gov/reading-rm/basic-ref/glossary/becquerel-bq.html. .

[53] See, for example, the compilation prepared by The Fukushima Project (2013) and presented as “Fukushima Daiichi Source Term” at http://www.fukuleaks.org/web/?page_id=9317.

[54] ZAMG (2012), *Fukushima, Auswirkungen des Kernkraftwerksunfalls*, (German) dated March, 2012, and available as http://www.zamg.ac.at/docs/aktuell/20120417_Fukushima_Bericht.pdf

[55] Stohl, A., Seibert, P., Wotawa, G., Arnold, D., Burkhart, J. F., Eckhardt, S., Tapia, C., Vargas, A., and Yasunari, T. J., “Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition”, *Atmospheric Chemistry and Physics*, 12, 2313-2343, doi:10.5194/acp-12-2313-2012, 2012.

[56] A summary of the WHO report is provided as “Global report on Fukushima nuclear accident details health risks”, dated 28 February 2013, and available as http://www.who.int/mediacentre/news/releases/2013/fukushima_report_20130228/en/

[57] The Stanford study is summarized by Max McClure (2012) in “Stanford researchers calculate global health impacts of the Fukushima nuclear disaster “, dated July 17, 2012, and available as http://news.stanford.edu/news/2012/july/fukushima-health-impacts-071712.html

[58] See, for example, Alex Rosen (2012), “Effects of the Fukushima nuclear meltdowns on environment and health”, dated March 9, 2012, and available as http://www.ippnw.de/commonFiles/pdfs/Atomenergie/FukushimaBackgroundPaper.pdf

[59] See, for example, the United Nations (2002) report, *The Human Consequences of the Chernobyl Nuclear Accident: A Strategy for Recovery,* commissioned by UNDP and UNICEF with the support of UN-OCHA and WHO, dated 6 February, 2002, and available as http://chernobyl.undp.org/english/docs/strategy_for_recovery.pdf; and The Chernobyl Forum/International Atomic Energy Agency (2006), *Chernobyl’s Legacy: Health, Environmental and Socio-economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine*, revised edition dated April, 2006, and available as http://www.iaea.org/Publications/Booklets/Chernobyl/chernobyl.pdf.

[60] Note that in this table, as for other results below, although results are sometimes presented, for convenience, with two or three significant figures, the many unknowns and uncertainties involved in the calculations that underlie these estimates mean that the actual precision of the calculations is likely to be no more than one significant figure.

[61] Gordon Thompson (2013, ibid) describes the EPA’s threshold value as follows: “In its guidance manual for nuclear incidents, the US Environmental Protection Agency (EPA) recommends that the general population be relocated if the cumulative 1st-year dose to an individual at a radioactively-contaminated location is projected to exceed 0.02 Sv. EPA states that the projected dose should account for external gamma radiation and inhalation of re-suspended material during the 1st year, but should not account for shielding from structures or the application of dose reduction techniques.” (Note (f) for Table II.6-6.) The description refers to the US Environmental Protection Agency document, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents* (Washington, DC: EPA, Revised 1991, Second printing May 1992).

[62] Of course, if the DPRK does remove fuel from the spent fuel pool for storage elsewhere or reprocessing, an entirely different set of potential scenarios for release of radiation from that

component of the spent fuel as a result of accident or (especially) attack could come into play.

[63] Kouji H. Harada, Tamon Niisoe, Mie Imanaka, Tomoyuki Takahashi, Katsumi Amako, Yukiko Fujii, Masatoshi Kanameishi, Kenji Ohse, Yasumichi Nakai, Tamami Nishikawa, Yuuichi Saito, Hiroko Sakamoto, Keiko Ueyama, Kumiko Hisaki, Eiji Ohara, Tokiko Inoue, Kanako Yamamoto, Yukiyo Matsuoka, Hitomi Ohata, Kazue Toshima, Ayumi Okada, Hitomi Sato, Toyomi Kuwamori, Hiroko Tani, Reiko Suzuki, Mai Kashikura, Michiko Nezu, Yoko Miyachi, Fusako Arai, Masanori Kuwamori, Sumiko Harada, Akira Ohmori, Hirohiko Ishikawa, and Akio Koizumi (2014), "Radiation dose rates now and in the future for residents neighboring restricted areas of the Fukushima Daiichi Nuclear Power Plant". *PNAS*, published online February 24, 2014, available as www.pnas.org/cgi/doi/10.1073/pnas.1315684111.

[64] Here the assumption that the DPRK would use stainless steel cladding for its fuel rods is an important one, as stainless steel cladding will not ignite and thus be less likely to fuel releases of Cesium, though the ultimate impact of the choice of cladding materials on release of radioactivity from damaged spent fuel pools has not, to our knowledge, been thoroughly investigated. In addition, it is quite possible that the DPRK does have access to technology that would allow it to use Zircaloy cladding for its LWR fuel. In "Yongbyon Fuel Fabrication Plant", by the Nuclear Threat Initiative (NTI, 2012, available as http://www.nti.org/facilities/771/) it is noted that the DPRK's Yongbyon fuel fabrication plant "was capable of producing Magnox fuel rods with both magnesium-aluminum cladding (used in the 5 MWe reactor), and magnesium-zirconium cladding." This suggests that the DPRK had, and thus may still have, technology to produce more advanced cladding materials, but, as noted by S. Hecker (personal communication, 1-19-14), the amount of Zr in the cladding used in the Magnox fuel rods is very small, and is unlikely to have helped the DPRK very much in mastering the metallurgy of Zircaloy cladding.

[65] As described by Gordon Thompson (2013, ibid).

[66] The USEPA has recently drafted new guidelines for protecting the public in the event of a radiological emergency. See, for example, World Nuclear News (2013) "Update to US emergency guidelines", dated 16 April 2013, and available as http://www.world-nuclear-news.org/RS_Update_to_US_emergency_guidelines_1604121.html.

[67] See, as example of a considerable literature on the topic, W. Kip Viscusi (2005), *The Value of Life*, ISSN 1045-6333, Harvard John M. Olin Center for Law, Economics and Business, Discussion Paper No. 517, dated 06/2005, available as http://www.law.harvard.edu/programs/olin_center/papers/pdf/Viscusi_517.pdf; US Environmental Protection Agency (2013), "Frequently Asked Questions on Mortality Risk Valuation", available as http://yosemite.epa.gov/ee/epa/eed.nsf/pages/MortalityRiskValuation.html; Jie He and Hua Wang (2010), *The Value of Statistical Life: A Contingent Investigation in China*, World Bank Policy Research Working Paper #5421, dated September, 2010, and available as http://elibrary.worldbank.org/docserver/download/5421.pdf?expires=1378489210&id=id&accname=guest&checksum=9645DAE7FCF86BFF07E23197FDC2BB49; and Maureen L. Cropper and Sebnem Sahin (2009), Valuing *Mortality and Morbidity in the Context of Disaster Risks*, World Bank Policy Research Working Paper #4832, dated February 2009, and available as http://www.gfdrr.org/docs/WPS4832.pdf.

[68] ROK value from p. 27 of W. Kip Viscusi and Joseph E. Aldy (2003), "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World", *The Journal of Risk and Uncertainty*, 27:1; 5–76, 2003, one version of which is available as http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0483-09.pdf/$file/EE-0483-09.pdf. The US

value roughly of $10 million per premature death from solid cancer corresponds to the high end of a range cited in Gordon R. Thompson (2013), *Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel*, and is used in the Methodology set out in the Handbook.

[69]World Health Organization, “Health Statistics, Democratic People's Republic of Korea,” at: http://www.who.int/countries/prk/en/

[70] Pyroprocessing is a variant of the reprocessing of spent nuclear fuel to remove plutonium for reuse in nuclear power generation, and fast reactors are touted as a means of making more efficient use of uranium and reducing radioactive wastes. Both proposed technologies have both advantages and disadvantages, the latter including arguably increased risks of proliferation of nuclear weapons due to additional needs to handle and process nuclear materials, among other considerations.

[71] D. von Hippel and P. Hayes "Engaging the DPRK Enrichment and Small LWR Program: What Would It Take?" *op cit.* CNN “Japan, China, South Korea vow joint work on nuclear safety,” May 22, 2011, at: http://www.cnn.com/2011/WORLD/asiapcf/05/22/japan.summit/

[72] See summary reports at the Trilateral Cooperation Secretariat at: http://www.tcs-asia.org/dnb/board/list.php?board_name=3_1_3_disaster&search_cate=Northeast+Asian+Top+Regulators+Meeting+%28TRM%29+on+Nuclear+Safety

[73]From: http://www.tcs-asia.org/dnb/board/view.phpboard_name=3_1_3_disaster&view_id=20&search_cate=Northeast+Asian+Top+Regulators+Meeting+%28TRM%29+on+Nuclear+Safety

[74]The agreement reportedly requires each country’s nuclear regulators to provide information via phone or email on all accidents at or above Level 2 on the International Nuclear and Radiological Event Scale as well as Level 1 accidents of an interest to the public. They will also safety plans. Information on military use of nuclear power is not covered. See M. Itawa, “Japan, South Korea and China Agree on Nuclear Safety Network,”*Dow Jones Institutional News*, December 4, 2013, at: http://online.wsj.com/news/articles/SB10001424052702303497804579237423810359150[20] S. Squassoni, “Nuclear Safety & Security in the DPRK,” Asan Institute workshop, The 2012 US-North Korea Nuclear Deal and A Comprehensive Approach to the Denuclearization of North Korea, Seoul, March 22, 2012, p. 8, at: http://csis.org/files/attachments/120322_NuclearSafetyandSecurityinDPRK.pdf

[75] See http://www-ns.iaea.org/conventions/nuclear-safety.asp

[76] See http://www-pub.iaea.org/books/IAEABooks/7380/Code-of-Conduct-on-the-Safety-of-Research-Reactors

[77] See http://www-ns.iaea.org/tech-areas/radiation-safety/code-of-conduct.asp

[78] Xinhua, “Construction on China-U.S. nuclear security center begins,” October 29, 2013, at: http://news.xinhuanet.com/english/china/2013-10/29/c_132841259.htm

[79] W.J. Lee, “The SMART Reactor,” 4th Annual Asian-Pacific Nuclear Energy Forum, June 18-19, 2010, at:

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCkQFjAA&url=https%3A%2F%2Fsmr.inl.gov%2FDocument.ashx%3Fpath%3DDOCS%252FSMR%2Btechnologies%252FWon_Jae_Lee_KAERI_Pres.pdf&ei=HtR3UoT3KciZiQKn64HgAQ&usg=AFQjCNE-8yYzVJqblGuFiCLSQFpcJiw50A&bvm=bv.55819444,d.cGE&cad=rja

[80] D. von Hippel, P. Hayes, "*Engaging the DPRK Enrichment and Small LWR Program: What Would It Take?* *op cit.*

[81] See the papers from the New Approach to Security in Northeast Asia: Breaking the Gridlock Workshop, October 10, 2012, at: https://nautilus.org/projects/by-name/korea-japan-nwfz/workshops/gridlock/papers-presentations/#ixzz2jhK7HRA7 including D. von Hippel, "Regional Nuclear Fuel Cycle and Energy Security Cooperation in Support of a Regional NWFZ," at https://nautilus.org/wp-content/uploads/2012/10/Von-Hippel-2-pager-Sep28-20121.pdf

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X. NAUTILUS INVITES YOUR RESPONSES

The Nautilus Peace and Security Network invites your responses to this report. Please leave a comment below or send your response to: nautilus@nautilus.org. Comments will only be posted if they include the author's name and affiliation.

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