Stanton Nuclear Security Fellows Seminar

PANEL 2: Korean Peninsula Nuclear Issues

1. Naoko Aoki, RAND

Coordination Problems Among the U.S. and Regional Powers over North Korea's Nuclear Program

1. Introduction

The United States and Asian regional powers have used both positive and negative inducements[1] to try to convince North Korea to give up its nuclear weapons. So far, none of the measures have produced the desired outcome. Discussions about these policy tools have largely been focused on which type of inducements and what combinations were more effective. Relatively little attention has been paid to how they were extended, including whether the countries coordinated their actions so that the tools had a good chance of having the intended impact. History shows such coordination was often tenuous. Some countries tried to coerce North Korea into denuclearization while others were trying to pursue the same goal through engagement, creating cleavages that Pyongyang was able to exploit.

My project during the year of my Stanton Nuclear Security Fellowship seeks to identify the factors that led to these uncoordinated approaches by the United States, China, Japan, Russia and South Korea. It will first identify general trends of both positive and negative inducements extended by the five countries from the first North Korean nuclear crisis in the 1990s, and then take a detailed look at four cases in which China, Japan, Russia and South Korea respectively pursued policies that differed from the U.S. position. More specifically, it will ask whether the uncoordinated strategies were due to differences in the countries' policy priorities or their views on what inducements were supposed to achieve. By analyzing why coordination failed in the past, the project will contribute to the debate on ways to improve inducement strategies for North Korea's denuclearization.

2. Existing studies

Researchers have long noted that the United States, China, Japan, South Korea and Russia have not always successfully coordinated their efforts to influence North Korea.[2] For example, Stephan Haggard

[1]In line with the definition in Etel Solingen ed., *Sanctions, Statecraft, and Nuclear Proliferation* (Cambridge: Cambridge University Press, 2012), 5-6, "negative inducements" refers to "international instruments of statecraft that punish or deny benefits to leaders, ruling coalitions, or broader constituencies in a given state, in an effort to dissuade those targets from pursuing or supporting the acquisition of nuclear weapons and is replaceable with "sanctions," while "positive inducements refer to "benefits or rewards" extended to denuclearize.
[2]For example, Solingen ed., *Sanctions, Statecraft, and Nuclear Proliferation* and Stephan Haggard and Marcus Noland, *Hard Target: Sanctions, Inducements and the Case for North Korea* (Stanford: Stanford University Press, 2017).

and Marcus Noland have pointed out that when faced with economic sanctions, North Korea turned to China or South Korea, the most pro-engagement members of that group, to make up for any losses it suffered.[3] Haggard and Noland have also said that positive inducements face the same "weakest link" problem.[4] Meanwhile, others have conducted an empirical study on the many positive and negative inducements that have been extended to North Korea to try to stop its nuclear weapons program.[5] Yet, there has been no systematic study of when the countries did not cooperate and why they did not do so. This study attempts to fill that gap.

3. Framework of research

This research consists of two parts. The first portion lays the groundwork by giving an overview of the positive and negative sanctions extended by the five countries to North Korea since the 1993-1994 nuclear crisis. General trends will be identified, including when the inducements were coordinated by the five countries and when they were not. The countries' preferred approaches and any changes to them will also be analyzed. Data will be collected from databases from the United Nations and think tanks, official announcements by the countries involved, as well as news reports and works by scholars and journalists on the history of the 1994 Agreed Framework and the Six Party Talks in the 2000s, which were the two engagement efforts the United States had with North Korea aimed at denuclearizing the country.

The second part will consist of case studies that analyze the reasons for the uncoordinated actions. It will look at instances when China, Japan, Russia and South Korea respectively announced or implemented policies that ran counter to the U.S. position. Very often, differences in the countries' policy priorities are cited as the reason for such decisions. It is widely acknowledged, for example, that China was reluctant to take harsh measures toward North Korea because Beijing prioritized stability over denuclearization.[6] This project will analyze whether the countries' differing views on the roles of positive and negative inducements also had an impact. For example, did countries believe that positive inducements required a *quid pro quo* on the part of North Korea, or were they aimed at moderating Pyongyang's behavior more generally?[7] Were there other factors that affected their decisions, such as foreign policy issues unrelated to denuclearization and domestic political constraints? The provisional case studies are as follows.

- China's opposition to U.N. sanctions against North Korea that continued until Pyongyang's missile and nuclear tests in 2006.[8]

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[3] Haggard and Noland, *Hard Target*, 8.
[4] Ibid.
[5] Celia L. Reynolds and Wilfred T. Wan, "Empirical Trends in Sanctions and Positive Inducements in Nonproliferation," in *Sanctions, Statecraft, and Nuclear Proliferation*, ed. Solingen.
[6] Eleanor Albert, The China-North Korea Relationship, Council on Foreign Relations, last updated on March 18, 2018, https://www.cfr.org/backgrounder/china-north-korea-relationship.
[7] The typology of engagement strategies is discussed by Miles Kahler and Scott L. Kastner in "Strategic Uses of Economic Interdependence: Engagement Policies on the Korean Peninsula and Across the Taiwan Strait." *Journal of Peace Research* 43, no. 5 (2006): 523–41.
[8] Cheng Xiaohe, "Implementing Sanctions Against North Korea: A Chinese Perspective," The Asan Forum, August 3, 2016, http://www.theasanforum.org/implementing-sanctions-against-north-korea：a-chinese-perspective/.

- Japan's refusal from 2007 to provide funding for fuel aid under the Six Party Talks because of a dispute over the kidnapping of Japanese nationals by North Korea in the 1970s and 1980s.[9]
- South Korea's strategy for deep engagement with North Korea under the progressive governments of Kim Dae Jung (1998-2004) and Roh Moo Hyun (2004-2009).[10]
- Russia's shielding of North Korea after the U.S. discovered Pyongyang's procurement efforts for a highly enriched uranium program in 2002 and Moscow's proposal for a freeze on North Korea's nuclear program in exchange for aid in January 2003.[11]

In addition to the data collection materials cited above, interviews will be conducted where possible.

4. Preliminary findings and policy implications

This project is in the very early stages of development, but preliminary findings confirm that the five countries have often been unable to successfully coordinate their policies in the past. The United States generally preferred to use negative inducements to constrain North Korea, frequently imposing unilateral sanctions and spearheading calls for multilateral sanctions against Pyongyang. China and Russia favored the use of positive inducements, and while they have shown increasing support for sanctions since North Korea's first nuclear test in 2006, their enforcement has been selective.[12] South Korea tended to follow the U.S. lead on sanctions, but the progressive governments from 1998 to 2009 sought broader engagement with North Korea than the United States was comfortable with. Japan increasingly favored a hardline position after the kidnapping issue became a prominent problem in the early 2000s.

While policy priorities explain some of these differences, varying views on the roles of inducements are likely to provide a better explanation for others. South Korea, for example, pursued deep engagement with North Korea under Kim Dae Jung because it believed economic interdependence would moderate North Korea's behavior and promote internal change. The United States, meanwhile, preferred an explicit *quid pro quo* from North Korea for any positive inducement.

A better understanding of why the countries could not successfully coordinate their policies would help improve strategies in the future. An improved approach can test North Korea's intentions to denuclearize more consistently and have a better chance of impacting Pyongyang's decision calculus in the future.

5. Limitations and caveats

This project looks only at how positive and negative inducements were extended to North Korea. While it can reveal lessons for increasing the impact of the inducements, whether they would ultimately have

[9] Emma Chanlett-Avery, "North Korea's Abduction of Japanese Citizens and Six-Party Talks," CRS Report for Congress, March 19, 2008, https://fas.org/sgp/crs/row/RS22845.pdf.
[10] Stephan Haggard and Marcus Noland, "Engaging North Korea: The Efficacy of Sanctions and Inducements," in *Sanctions, Statecraft, and Nuclear Proliferation*, ed. Solingen.
[11] Christina Chuen, "Russian Responses to the Nuclear Crisis," Middlebury Institute of International Studies at Monterey, August 24, 2010, https://www.nonproliferation.org/russian-responses-to-the-north-korean-crisis/.
[12] Haggard and Noland, "Engaging North Korea," 232-260.

been effective for convincing North Korea to give up its nuclear program is beyond the scope of this study.

One of the limitations of this study involves data collection. The data for positive and negative inducements that will be gathered involves only those that were announced or reported. For example, if a country took a punitive action against North Korea but chose not to publicize the measure and it remained undetected, it would not be included in the study,

Another challenge will be to analyze whether a country took a certain action because of its policy priorities or because it preferred a certain approach. Whether a country refused to take harsh measures against North Korea because the country prioritized stability or because it believed engagement was a better way to convince Pyongyang to denuclearize may be observational equivalents.

2. Rachel Carr, MIT NSE

New Options for Cooperative Threat Reduction in North Korea: Leveraging Techniques and Partnerships from Basic Physics

On what issue are you working and why is it important?

I am working on new options for cooperative threat reduction in North Korea. In particular, I am working to apply techniques originally developed in basic research on neutrinos, very weakly interacting particles emitted by nuclear reactors. This project is a collaboration with physicists from South Korea, China, Japan, Europe, and the US.

The value of this project is twofold. First, neutrino-based methods for reactor monitoring offer unique technical benefits for future treaty verification. Neutrino emissions carry detailed information about reactor power and fuel evolution (including whether plutonium has been diverted from a reactor core), and they can be monitored from well outside the reactor building. Particle physicists have recently demonstrated the ability to capture these signals in moderate-size, moderate-cost detectors.

Second, neutrino physics is a hot topic in international research, particularly in East Asia, and the opportunity to join this high-tech community may be appealing to North Korea and its scientists. At the Yongbyon reactor site, North Korean scientists could lead interesting fundamental physics measurements using the same neutrino detectors deployed for reactor monitoring. Since the Cold War, this kind of peaceful scientific engagement has helped to stem the spread of nuclear know-how and to reshape relations between adversaries. Policy experts have stressed the value of cooperative science in future agreements with North Korea.

What is the big question that you are seeking to answer about that issue?

Can techniques from neutrino physics play a useful role in nuclear negotiations with North Korea and eventually help to verify an agreement, keep nuclear scientists and engineers peacefully employed, and build relations between North Korea and the rest of the world?

How are you going to answer your question? What methods will you use and what evidence or cases will you explore?

I recently started a working group of neutrino physicists from South Korea, China, Japan, Europe, and the US (we are working to involve at least one physicist from Russia). So far, we have met by phone, scheduled an in-person meeting for October, and made a plan to publish our main paper the end of 2018. That paper will present policymakers with realistic options for using neutrinos for reactor monitoring and cooperative science in North Korea. We are drawing from previous studies in neutrino applications, our own experience as neutrino experimentalists, and case studies of cooperative threat reduction in the former Soviet Union and other countries.

Over the next year, we intend to produce three publications and a policy memo, each intended for a different audience:

- **Main publication**: For policymakers with science backgrounds and for the broad scientific community, we are writing a concise article on options for neutrino-based reactor monitoring and science in North Korea (target journal: *Science*).
- **Policy memo**: Once we have a draft of the international proposal, I will work with my US collaborators to write a policy memo proposing this concept to the U.S. State Department. Collaborators from other countries may choose to approach their own diplomatic agencies.
- **Outreach publication**: Depending on the State Department response, we may circulate the idea within the policy community through an article in, e.g., *Arms Control Today*.
- **Technical publication**: To provide technical details for the physics and engineering communities, we are writing a comprehensive review of nuclear security applications of neutrino physics (journal: *Reviews of Modern Physics*).

How does your work fit into the existing work on your subject?

The idea of using neutrinos to monitor reactors was proposed 40 years ago by physicists in the Soviet Union. At that time, the technology to carry it out did not exist. Physicists worldwide have continued to study the idea, including possibilities in North Korea, and to demonstrate detector prototypes. Serendipitously, the most important experimental work comes not from these applications studies but from fundamental research into neutrino properties. In the last year, scientists searching for new kinds of neutrinos have demonstrated detectors which, incidentally, would work well for monitoring reactors.

What alternative arguments or explanations exist and why is your answer superior?

There are other methods for monitoring reactors, especially looking for waste heat emission. These methods cannot observe the fuel evolution or track power levels as precisely as neutrinos can. Furthermore, existing surveillance methods are not natural opportunities for cooperative engagement. Realistic neutrino detectors would need be deployed within a few kilometers of the reactor site, so cooperation would be important. Another special advantage of neutrinos is that two of the world's strongest programs in reactor neutrino physics are led by North Korea's neighbors, South Korea and China.

How does your work add to or change our understanding of the issue you are studying?

One important aspect of this project is that our collaboration is international. International collaborations are very common in particle physics (e.g., for collider experiments and large neutrino experiments in the US and China), but so far reactor neutrino applications have mainly been pursued within in individual countries. Previous discussions of neutrino applications in North Korea have come from all-US or all-European groups of scientists. Our project is the first time physicists from many countries, including South Korea and China, have worked together on these applications.

Another important feature is that we are focusing on a single policy issue (North Korea's nuclear program) and restricting ourselves to demonstrated technology. Physicists have tended to discuss neutrino applications in a generic nonproliferation context and have often mixed discussions of actual and hypothetical technologies. Consequently, it has been hard for policymakers to make the leap to a

real-world situation. This project explicitly makes that connection, so policymakers can see exactly what is available for realistic use in North Korea.

What do you see as your most important contribution?

The most important contributions are the two elements discussed above: (1) that this proposal comes from an international team, including East Asian physicists, and (2) that this proposal is specific to North Korea and includes only realistically deployable technologies.

What policy implications flow from your work? What concrete recommendations can you offer to policymakers?

From the outset, this project demonstrates that physicists from South Korea, China, Japan, Europe, and the US are ready, willing, and able to work together on cooperative threat reduction for North Korea. This itself may be useful for policymakers to know. Additionally, as discussed above, we will present specific options for neutrino applications in North Korea.

An initial recommendation is for policymakers is to start talking about neutrino opportunities in discussions on North Korea. From North Korea's perspective, these ideas may be among the more attractive elements of a treaty verification discussion, because they show positive regard for the state's technical capabilities (toward peaceful ends) and offer a chance for international leadership in science. If negotiations with proceed, policymakers from both sides should seriously consider cooperative deployment of neutrino detectors in North Korea.

What do you think is the weakest or most vulnerable aspect of your study and what sort of feedback would be most useful to you?

As a proposal for cooperative activities, this project can only proceed past the proposal stage if the political opportunity for cooperation arises. The collaboration and papers will have some value even if no detectors are ever built, but their impact will be lower.

I would value advice on how to maintain momentum in this effort even if the political process is stalled. Once we complete our papers, how can we keep enthusiasm and relationships within our collaboration alive, in case an opportunity occurs later? How can we encourage policymakers to keep these ideas in mind for the future, even if there is no chance to use them immediately?

3. Se Young Jang, MIT SSP

Nuclear Re-proliferation and Reversal: The Change of South Korea's Nuclear Strategy during the U.S. Carter and Reagan Administrations

Project Objectives and Questions

The broad purpose of this project is to better understand the history of nuclear diplomacy between the United States and South Korea (Republic of Korea: ROK) in the late 1970s and the early 1980s under the U.S. Jimmy Carter and Ronald Reagan administrations. In particular, the project aims to examine three major themes in nuclear proliferation and de-proliferation through a historical case study: motivations behind nuclear re-proliferation, a patron state's counter-strategy on its client's nuclear re-proliferation, and key determinants of nuclear de-proliferation.

Q1: Why did South Korea reverse its earlier decision to suspend its nuclear weapons program and reconsider a military nuclear option as the form of "hedging" when President Carter took power?

This question will lead to my analysis of motivations behind South Korea's nuclear re-proliferation. Existing nuclear demand-side scholarship has thoroughly examined a variety of motivations, but less attention has been given to the cases of nuclear re-proliferation since the number of cases is limited. As one of the very few cases that resumed its nuclear efforts after suspending, my analysis of South Korea's nuclear pursuits in the late 1970s will identify the conditions under which the ROK government was forced or willing to put itself in a risky path of nuclear proliferation again.

Q2: How did the Carter administration respond to its close ally's revived nuclear ambitions?

This question will shed light on the change and consistency of U.S. nuclear nonproliferation strategy. Some literature has explained why President Carter failed to fulfil his campaign pledge to withdraw U.S. forces from South Korea, but again, little attention has been particularly paid to the nuclear angle of U.S.-ROK confrontation during the Carter years. Did Washington adopt the same tactics which had been already used in 1975 and 1976 to South Korea even in/after 1977? If so, were the same tactics successful again? Or if not, why did Washington under Carter's presidency adopt different approaches?

Q3: Why did South Korea finally abandon its nuclear hedging strategy in the early years of the Reagan administration?

South Korea massively downsized in nuclear research during the early 1980s and completely shifted towards civil uses of nuclear technology for electricity production. This abrupt shift makes us speculate that the death of President Park (assassinated in 1979) and the new military dictatorship's necessity for being recognized by the United States were the main causes for the termination of South Korea's nuclear hedging efforts. However, little empirical/historical research has been conducted on this subject, and thus this project will be one of the first historical analyses of domestic and external determinants of South Korea's abrupt change of nuclear strategy in the early 1980s.

Project Background and Overview

Nuclear weapons have played a critical role in the history of U.S.-ROK relations. In 1945, U.S. atomic bombings on Japan led to the liberation of Korea from the Japanese colonial rule, opening up a new era for U.S.-ROK alliance. As the Korean War broke out in 1950, the Truman administration considered the option of atomic bombings to defeat the Chinese and North Korean forces, but opted against using these weapons. Not long after the war ended, Washington started deploying tactical nuclear weapons to the Korean Peninsula. In a broader sense, the nuclear build-up in South Korea was part of the Eisenhower administration's "New Look" initiative and "Massive Retaliation" doctrine. At the same time, the deployment of those weapons to South Korea contributed to strengthening the concept and role of U.S. extended deterrence in Northeast Asia.

Later in the 1970s, the bilateral relations between Washington and Seoul underwent a severe downturn due to South Korea's attempts to develop nuclear weapons (*Project 890*) amidst President Richard Nixon's disengagement strategy from Asia (*Guam Doctrine*). A series of military provocations from North Korea in the late 1960s, not meeting strong military reactions from the United States, had already stirred up the ROK leadership's deeply-rooted anxiety over the patron's possible abandonment of its ally. President Nixon's 1970 announcement of his decision to withdraw a third of US forces stationed in South Korea, without any prior consultation with Seoul, drove a nail into this anxiety and led to President Park Chung-hee's decision to pursue a military nuclear option.

Under the strong pressure from Washington, South Korea's contract with France to acquire a nuclear reprocessing facility was canceled in 1976, and this "first" nuclear crisis between Washington and Seoul appeared to be resolved. However, history tells us that it was only a temporary success for U.S. nuclear nonproliferation policy. When Jimmy Carter took power in 1977, his plans to remove U.S. tactical nuclear weapons and withdraw all the U.S. forces from South Korea reignited the temporarily-dead nuclear conflict between the two allies. President Park reconsidered a nuclear option and secretly pursued several ways to develop relevant nuclear and missile technology. Although South Korea adopted a less assertive way of pursuing its nuclear option through "hedging" at this time, it still concerned U.S. policy makers and affected their ways of dealing with South Korea.

Methods and Sources

This project is primarily a historical research based on primary sources. The transformation of South Korea's nuclear strategy has not been fully explored yet in existing literature, and there is a gap in the research on primary sources from both the United States and South Korea. In particular, U.S.-ROK nuclear diplomacy in the period from the Carter administration onwards has not been a major subject of research mainly due to the difficulty of accessing primary sources. The Foreign Relations of the United States (FRUS) only covers documents on South Korea until the year 1976 thus far, but a significant number of documents from the Carter administration are becoming accessible at the Carter Presidential Library and the National Archives and Records Administration (NARA) in College Park. In addition, there is still a much lower, but steadily growing number of documents from the Reagan administration being

currently declassified. South Korean archival sources are also accessible, if declassified, mostly up to the ones produced by 1986 under the 30-year rule. The accessibility to those once classified primary sources will make my project timely and significant in advancing current scholarship on U.S.-ROK nuclear diplomacy.

Thus, I plan to look into those declassified U.S. government and legislative documents at the NARA, the Carter and Reagan Presidential Libraries, and the Library of Congress. Some State Department telegrams with U.S. Embassies in Seoul and other capitals until 1979 have been digitalized and accessible online. With regard to South Korean primary sources, Korea's foreign ministry documents, which are accessible in the form of microfilm at Harvard Yenching Library, will be a major source for examining Korea's nuclear policy during the Park Chung-hee and Chun Doo-hwan administrations. Former U.S. officials having worked for the Carter and Reagan administrations will be also useful sources for addressing U.S. nuclear nonproliferation policy towards South Korea in those periods. A series of interviews with those former officials involved in U.S.-ROK nuclear diplomacy will be thus conducted upon availability.

Target Audience and Policy Contributions

The main audience for this project is primarily academics in history/international relations/security studies and policy makers working on U.S.-ROK relations and nuclear diplomacy. I plan to write and publish a couple of academic articles in history, security, or Asia-related journals. In the long term, the outcome of this project will be included in my future monograph on South Korea's nuclear pursuits during the Cold War, which I am currently working on.

I also intend to offer the general public with some historical insights on current policy debates related to nuclear controversies surrounding U.S.-ROK alliance. These include nuclear deterrence, civil nuclear cooperation (pyro-processing), South Korea's growing interests in acquiring nuclear-powered submarines (SSNs) and domestic pro- and anti-nuclear sentiments. By writing up op-eds and analytic pieces on those issues, I would like to inform the public of how closely nuclear history relates to contemporary policy discussions and what historical implications we can learn.

4. Sherzod Kurbanbekov, Texas A&M

Investigation of High-Enriched Uranium Stockpile in North Korea

- **On what issue are you working and why is it important?**

  One of the greatest threats to world peace and security is the prospect of nuclear weapons in the wrong hands. Although the likelihood of a large-scale military conflict with nuclear weapons seemingly decreased with the end of the cold war, the threat posed by nuclear proliferation continues to persist. Indeed, nuclear proliferation remains a critical global problem that challenges vital national security interests of the United States (U.S.). This is partly due to the fact that the proliferation of nuclear weapons may endanger armed forces and military bases outside the U.S., threaten allies and friendly states of the U.S. and also complicate - if not undermine - the possibility of U.S. military intervention abroad. North Korea's nuclear program poses particularly acute threats to the U.S. and its allies in East Asia.

  Several studies have been conducted to understand North Korea's nuclear weapons assets and capabilities. Based on the information available on their nuclear facilities [1], it is expected that North Korea has two types of nuclear weapons based on plutonium and uranium. The stockpile of plutonium was investigated by D. Albright and P. Brannan in 2007 [2]. This report presented the estimated operating histories of nuclear facilities such as nuclear reactors and radiochemistry laboratories that were used for producing plutonium. The expected plutonium stockpile in 2007 was between 46 to 64 kilograms. Between 28 to 50 kilograms of that were separated and available for use in nuclear weapons [2]. An updated assessment by Albright in 2015 estimated that North Korea has between 30 to 34 kilograms of usable plutonium [3]. A decrease of expected stockpile from 2007 to 2015 is probably caused by the nuclear tests on May 25, 2009 and February 12, 2013.

  The expected uranium stockpile was also investigated. The stockpile of high-enriched uranium (HEU) was estimated and reported in 2015 based on two different scenarios [3]. The first scenario assumed two centrifuge plants operating the first plant operated with a capacity of 2000-3000 P2-type centrifuges between 2005 and 2010 to produce HEU and second plant with 2000 P2-type centrifuges until 2014 produced LEU, which could have been misused to produced HEU after 2014. The second scenario is when North Korea operated 2000 P2-type centrifuges between 2010 and 2011 to produce LEU but subsequently misused to produce HEU. The median value for the first scenario is 240 kg and for the second scenario is 100 kg [3]. According to a report published by the Center for International Security and Cooperation at Stanford University [1], around 6,000 centrifuges were operated in 2015 in North Korea. Based on this information, approximately 100 kilograms of the HEU could be produced per year. Then, by 2017, an additional 2,000 centrifuges are estimated to be clandestinely installed. With this addition, the total expected yield of HEU will be between 130 to 150 kilograms per year.

  The estimated HEU stockpiles have varied widely due to the accessibility to the data such as installed number of centrifuges and their associated Separative Work Unit (SWU) capacity Therefore, in this study, the expected HEU stockpile will be reevaluated in the case of North Korea based on new information

available in literature. The results of this study could help U.S. policymakers achieve better outcomes in future negotiations with North Korea.

- **What is the big question that you are seeking to answer about that issue?**
  Based on the thoughts explained in the previous answer, the questions for this study can be summarized as follows:

  1) How can we evaluate the expected quantity of HEU stockpile in North Korea using theoretical methods and open source information?
  2) What is the expected quantity of HEU as a function of enrichment?
  3) How do our assessment change if we assume the existence of other covert enrichment plants in North Korea?
  4) How much natural uranium is available in North Korea?

- **How are you going to answer your question? What methods will you use and what evidence or cases will you explore?**
  The gas centrifuge is the main technology for enrichment of uranium in the world. The production of HEU in North Korea is based on this technology. To determine the expected stock of HEU in North Korea, we will use the uranium enrichment cascade theory. The basic task of the enrichment cascade involves separating natural uranium (with 0.711 wt% of uranium-235) in a gas centrifuge into two streams such as enriched uranium-235 (typically more than 90 wt% for weapons use) product and depleted uranium (tails). The relationship among these three streams including feed is given by the material balance equations for the single centrifuge [Eqs. (1) and (2)]. The parameters in Eqs. (1) and (2), F, P, and W are expressed as the mass of uranium in the feed, product, and tails, respectively. X_F, X_P, and X_W are the weight fractions of uranium-235 in the feed, product, and tails streams respectively.

$$F = P + W \tag{1}$$

$$Fx_F = Px_P + Wx_W \tag{2}$$

  In these equations, the values of P and X_P are determined by desire of operators. X_F is given by the uranium-235 content of natural uranium. F, W and X_W can be set by optimizing the operation of the enrichment plant. Multiple gas centrifuges are connected in parallel form an enrichment stage. A group of stages connected in series is declared as a cascade. Finally, the mathematical formula to evaluate a product flow rate with desired isotopes' enrichment (uranium-235) as a function of a stage number can be developed using formulations given by Benedict et al [5]. Therefore, based on the investigation of information (open sources) for enrichment facilities installed in North Korea, the expected mass of HEU as a function of the enrichment level will be evaluated and a contour plot will be developed.

- **What is your answer to the question you are asking? That is, what is your argument or conclusion even if it is still tentative at this point?**
  This project will assess the HEU production capacity in North Korea and identify possible bottlenecks in the expansion of these capacities. Expert assessments are used to identify and determine the reserves of

HEU presented in the introduction. We will use the theoretical cascade method to calculate the reserves of HEU in North Korea using snippets information available in literature.

- **How does your work fit into the existing work on your subject?**
  - **What alternative arguments or explanations exist and why is your answer superior?**
    As mentioned in the previous question, the expected stockpile of HEU was 100 to 240 kilograms in 2014 [3]. Moreover, the expected yield of HEU will be 130 to 150 kilograms per year by a report published in 2017 [1]. The quantity of HEU can be varied with respect to the enrichment of uranium-235. Therefore, in this study, the possible ranges of HEU stockpile as a function of a level of enrichment will be investigated.

  - **How does your work add to or change our understanding of the issue you are studying?**
    The expected stockpile of HEU in North Korea from this study will be compared to that of other previous studies. If a difference is observed, the reasons for this will be analyzed. These procedures would help which uncertainty sources prohibit to expect the stockpile of HEU not only for North Korean but also other states clandestinely attempting to produce HEU.

  - **What do you see as your most important contribution?**
    A thorough understanding of North Korea's HEU stockpile will help U.S. officials better understand the country's capabilities and potentially benefit Washington in negotiations with Pyongyang. The results of expected HEU stockpile in North Korea can be utilized as a reference data by the U.S. policy makers.

- **What policy implications flow from your work? What concrete recommendations can you offer to policymakers?**
  According to experts, North Korea can produce HEU in sufficient quantities. However, the expected stockpile of HEU in North Korea have varied, since it is not clear when and in what quantities the appropriate capacities were put into operation in North Korea. There is a strong assumption that by early 2015 this country could have produced up to 200 kilograms of weapons-grade HEU. Results of the calculations from this proposed study will inform policy makers of the considerations that need to be taken while assessing HEU stockpile not only in North Korea but also at the global level.

- **What do you think is the weakest or most vulnerable aspect of your study and what sort of feedback would be most useful to you?**
  Instead of the detailed information of enrichment facilities in North Korea, we will be able to use only the published or online accessible data, which is a weak point of this study. For example, how many gas centrifuges they have, and how long they have operated gas centrifuges, and what are the design parameters including a separation factor for gas centrifuges are crucial information. However, we will use parametric variation for the different inputs to produce a confidence interval on the accuracy of data produced out of this study on HEU stockpile data in North Korea. We will also explore how our conclusions might change if we assume the existence of additional secret enrichment plants.

References

[1] Chaim Braun, Siegfried Hecker, Chris Lawrence, Panos Papadiamantis, North Korean Nuclear Facilities After the Agreed Framework, 2016. http://cisac.fsi.stanford.edu/sites/default/files/khucisacfinalreport_compressed.pdf.

[2] D. Albright, P. Brannan, The North Korean Plutonium Stock Mid-2006, DIANE Publishing, 2007.

[3] D. Albright, North Korean Plutonium and Weapon-Grade Uranium Inventories, ISIS Report, Washington DC, 2015. http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf.

[4] Hecker S. Comments at the Korean Economic Institute, November 23, 2010. The International Atomic Energy Agency estimates the amount of HEU needed to make a nuclear explosive device ("significant quantity") is 25kg of uranium enriched at 20 % or more /Siegfried Hecker // IAEA Scientific and Technical Publications : website. URL: http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/

[5] M. Benedict, T.H. Pigford, H.W. Levi, Nuclear Chemical Engineering, 2nd ed., McGraw-Hill Book Company, New York, 1981.