Stanton Nuclear Security Fellows Seminar

PANEL 3: Science, Technology, and Nonproliferation

1. Brian Henderson, MIT NSE

Novel Experimental Nuclear Physics Techniques for Nuclear Security Applications

The large number of nuclear warheads currently in stockpiles (in excess of 10,000 globally[1]) and the abundance of available fissile materials create a host of policy challenges. Ideally, nuclear security policy would address the threats posed by the risk of theft of weapons and materials by providing mechanisms to block the unauthorized transportation of warheads and nuclear materials while also reducing warhead stockpiles as a root cause of such threats. Both of these tasks require overcoming both technical and political challenges. The science of reliably detecting, identifying, and characterizing special nuclear materials links these issues, due to a lack of suitable technical solutions for each. In the case of former, detection of smuggled nuclear materials in commercial cargo requires sensitive yet practicable measurement techniques[2]. The latter presents the difficulty of verifying that warheads presented for dismantlement under any future treaties are legitimate without revealing classified details of the weapons' construction to the inspector[3]. While nuclear materials naturally produce radiation that may be detected to indicate their presence, such passive detection methods provide limited information about the distribution and composition of the source materials. Furthermore, passive techniques may be defeated by shielding the material and are essentially incapable of detecting certain materials such as enriched uranium[4]. Active material interrogation techniques, in which a material is inspected by examining its interaction with externally-produced radiation (similar to a medical x-ray), increase the reliability of measurements and can allow an inspector to take advantage of unique physics signatures of nuclear materials. During my tenure as a Stanton Fellow in the LNSP group at MIT, my work will focus on investigating active material interrogation techniques from experimental nuclear/particle physics as a means of addressing the aforementioned nuclear security challenges. While each of these topics presents unique challenges, they are connected as problems that existing techniques of material inspection have failed to solve satisfactorily. Recent work at LNSP has established new techniques for both of these challenges, providing an opportunity for me to be immediately involved with multiple projects with nuclear security implications and a strong platform to further explore the space of issues that may be approached using physics-based techniques.

The detection of nuclear material, or an assembled weapon, in cargo entering U.S. ports represents an enormously challenging task, given the previously mentioned difficulty of detecting such materials and the volume of cargo traffic (approximately 57,000 containers cross the U.S. border daily at more than 300 ports-of-entry[5]). The probability of any single container posing a nuclear smuggling threat is extremely small, but the consequences of failing to detect an instance of smuggling may be enormous. Any approach to the inspection of cargo for nuclear materials must meet a number of criteria including cost efficiency, ease of implementation, limited radiation dose delivered to the cargo, and both high sensitivity and specificity for detection of nuclear materials[6]. The Cargo Security Initiative[7], established following the 9/11 terrorist attacks, predominantly relies on passive techniques to detect nuclear material, which are relatively inexpensive and involve no radiation dose. These systems, however, may be easily thwarted with shielding of the material and are ineffective for the detection of uranium. Active techniques using broad energy spectrum gamma beams ray beams for transmission radiography often require high radiation doses to the cargo in order to gain sufficient information about the contents. Successful cargo scanning technologies will require novel techniques to overcome these difficulties.

Recent work by the LNSP group has demonstrated that several of the disadvantages associated with broad spectrum radiography may be overcome using monoenergetic gamma ray sources, particularly when several discrete energies are used simultaneously[8]. Such multiple monoenergetic gamma ray beams may be generated using well-known nuclear reactions and available accelerator technology. A radiograph with such a beam takes advantage of the varying strength of interaction between matter and gamma rays as a function of energy to identify materials. Initial experiments have demonstrated that this method shows promise in classifying materials according to their density and approximate average atomic number, which provides an identifier for materials such as uranium and plutonium with high atomic numbers compared to typical cargo. While this represents a significant accomplishment in advancing cargo inspection technology, my work will include expanding the capabilities of the proof-of-concept system to increase its capabilities for real cargo screening scenarios. Areas for improvement include the application of advanced data analysis techniques for maximizing the information learned from the radiographic signal, investigating new detector and accelerator systems that could increase the efficacy and robustness of the system, and the examination of additional physics processes that occur during the exposure of cargo to the beam to extract further information about the cargo contents. Each of these areas of research overlaps significantly with techniques in experimental nuclear/particle physics, providing an opportunity to apply my experience to a definite, pressing issue of national security.

My second research focus involves a considerably different problem of nuclear material inspection, one in which the challenge consists of verifying that the composition and arrangement of material is consistent with a true warhead. Previous arms reduction treaties have required dismantlement of warhead delivery systems, accompanied by verification; but no treaty has directly addressed dismantlement of the warheads themselves. Such verification requires striking a balance between providing enough information to certify a test object as a warhead and sufficiently masking the classified details of the weapon. Past attempts to solve this problem, beginning with Project Cloud Gap in 1963[9], resulted in finding that even non-intrusive methods of inspecting weapons revealed sensitive information. Methods using electronic information barriers, i.e., software or circuitry that deliberately masks information from the inspector[10], suffer from requiring trust between the inspector and inspected that there exist no back-doors to obtain additional information or to manipulate the signal to produce false verifications. As current treaties continue to reduce the number of deployed warheads with the ultimate goal of warhead dismantlement, an agreed-upon method for verifying warheads is apt to become more pressing. Without such a method in place, parties may be hesitant to agree to warhead dismantlement treaties. Given the difficulty that the verification problem has presented over the past five decades, there exists a need for fresh approaches.

Methods in which the means of masking information is physical rather than electronic offer a new approach to the warhead verification problem. Physical information barriers rely on the laws of physics rather than human-implemented barriers to mask information, reducing the risk of one party cheating the system. In such methods, a candidate warhead is interrogated with beam of particles, but the particles that emerge from the candidate interact with another physical system which alters their information content before production of the output signal. If the signal resulting from the total interaction of the beam with an authentic warhead and the masking system is known, then candidate warheads may be verified by testing their spectra against the template case. A proposal from Glaser *et al.* approaches the problem using neutron radiography in which the detector is preloaded with the negative radiograph of the template warhead. The resulting radiographs of candidate warheads measure differences from the template rather than images of the warheads themselves. This results in effectively no leakage of classified information, but may be susceptible to hoaxes in which nuclear materials are replaced with materials that have similar neutron interaction cross sections[11].

LNSP has established the method of physical encryption, in which candidate warheads are interrogated with gamma ray beams and the measurement consists of observing the nuclear resonance fluorescence (NRF) interactions between the beam and the candidate components, which are specific to the type of materials present[12]. The information is effectively encrypted by re-scattering the beam after it passes through the warhead in a foil packet, the contents of which are unknown to the inspector. Only particles which scatter both from the warhead and the foil are detected, causing the foil to act as an encryption key for the final signal. By comparing the combined signal of candidate warheads and a foil with that of a template warhead and the same foil, warheads may be verified without directly observing the spectra of the candidates alone. Initial simulations using relatively simple assumptions regarding the experimental setup and test object geometries indicate that this method shows promise in providing a means of verifying nuclear warhead authenticity without revealing sensitive information. To realize this scheme, however, requires rigorous testing to demonstrate that it provides a sufficiently trustworthy method for consideration in the development of treaties and policy. Additionally, there exist a number of questions regarding the technical implementation of such a protocol that require investigation. My contributions to this project will consist of working to realize a proof-of-concept experiment for the NRF verification measurement, including study and design of technical solutions for various aspects of the scheme and development of advanced simulations to inform the design process, test the method for susceptibility to hoaxes, and examine the information content of the encrypted candidate+foil spectrum for possible leaks of sensitive information.

My goal, which links the two projects discussed and may be expanded to further applications, is to expand the portfolio of technical solutions for nuclear security issues. Due to the fact that the simplest methods have exhibited limited effectiveness in producing solutions to problems such as cargo security and weapons verification, there exists value in exploring new solutions. A foundation of trust can be established in techniques from experimental physics to provide tools for directly addressing longstanding problems. Along these lines, I view the most vulnerable part of my proposal as arising from the challenge of ensuring that I maintain contact and relevance with the related policy issues during my research. There exist a number of political challenges related to these projects that should be considered when developing technical solutions such as the international cooperation required to establish a trusted warhead verification system and the cost and logistics of large scale deployment of cargo scanning systems. Given that my background is technical, I am in the early stages of acquainting myself with the policy issues that surround this topic, and I would be very interested in the panel's feedback on addressing challenges of this nature; i.e., what the panel members view as the primary challenges to implementing technical solutions so that I may work to mitigate such issues as part of my research. Additionally, any suggestions from the panel regarding other issues in nuclear security that may benefit from new technical approaches would also be appreciated as opportunities to further expand my research.

Endnotes:

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4. R. C. Runkle *et al*. “Rattling nucleons: New developments in active interrogation of special nuclear material,” *Nucl. Instrum. Meth.*, vol. A 663. pp. 65–95, 2012.
5. R. Kouzes *et al.*, ed. *Radiation Detection and Interdiction at U.S. Borders*. New York: Oxford University Press, 2012.
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9. U.S. Arms Control and Disarmament Agency. *Summary Report on Field Test 34: Demonstrated Destruction of Nuclear Weapons* (1969).
10. C. Comley *et al*. *Confidence, Security, and Verification: The challenge of global nuclear weapons arms control*. UK Atomic Weapons Establishment (2000).
11. A. Glaser *et al*. “A zero-knowledge protocol for nuclear warhead verification,” Nature, vol. 510, pp. 497–502, 2014.
12. R. S. Kemp *et al*. “Physical cryptographic verification of nuclear warheads,” *PNAS*, vol. 113, pp. 8618–8623, 2016.

2. JI Yeon-jung, Belfer

Scientists in India's Nuclear Policy-Making (1948–1974)

Objective

This research examines scientists' influence in India's nuclear policy-making (1948–1974). In particular, it seeks to explore the process by which scientists' influenced India's peaceful nuclear explosion in 1974. For this purpose, this project studies three aspects: 1) How nuclear scientists established a scientific advisory system in pursuit of India's nuclear program; 2) How this system worked to defend the interests of nuclear scientists; and 3) Whether and to what extent India's decision regarding the peaceful nuclear explosion in 1974 was advanced by this system.

Overview

Nuclear scientists in India penetrated the bureaucratic decision-making process by the establishment of an independent scientific advisory system. Their objectives in setting up this system were 1) To institutionalize and legalize their autonomy; 2) To maintain the credibility of scientific advice; and 3) To stabilize autonomous institutional practice in the long term. The motivation for the institutional establishment emerged from the scientists' calculated desire to rebuff the interference of external actors (politicians and bureaucrats) on continuing a dual-purpose nuclear program. The shared goal among nuclear scientists first led them to coalesce as an interest group, and then caused technocrats to guard India's nuclear program against any external interference.

The first goal of nuclear scientists was to set up the "hardware," with the legalization and institutionalization of a scientific advisory system. The Atomic Energy Act (1948) and its amendment (1962) provided legal grounds to constitute advisory institutions, such as the Atomic Energy Commission (AEC, 1948) and Department of Atomic Energy (DAE, 1954). These two main bodies governing the nuclear program thus came under a single leadership with a handful of scientists who formulated a coherent decision-making process. The same group also formed committees under other ministries, such as the Defense Science Advisory Board in the Ministry of Defense, the Electronics Committee under inter-departmental ministries, and the Board of Research on Atomic Energy in the Council for Scientific and Industrial Research, targeting the propagation of a collective view on the necessity of India's nuclear program. Other irregular meetings at sub-committee level or personal ties with political leaders facilitated the acquisition of extensive political and financial support further where there were conflicts of interest with other ministries. In competition with other ministries requesting grants for other economic and social welfare sectors, scientists prioritized the systematic communication of their policy deliberations to prime ministers to acquire larger investments from the government.

Second, scientists also invested efforts to foster "software" to buttress the system. From its inception, scientists appeared to have coherent scientific policy deliberations, ranging from the development of the nuclear program to nuclear diplomacy. While the former falls exclusively into the domain of scientists', the latter was a deliberate target of a core group of scientists advocating a robust nuclear program in India. Those affiliated with the AEC and/or DAE, in particular, provided a consistent policy view on all aspects of India’s nuclear policy: threat perception on its nuclear neighbor; an interpretation of nuclear deterrence; India’s approach to the nuclear nonproliferation regime and nuclear safeguards, and international cooperation in peaceful applications of nuclear science. Scientist’s perception and policy preferences were conveyed at the highest level of decision-making through this scientific advisory system and thus into the nuclear policy-making process. The continuing development of India’s technological capability and the feasibility of a nuclear explosion was pushed by scientists in a coherent manner.

Despite an abundant literature on this scientific leadership as a dominant factor in India’s nuclear discourse, rather little attention has been paid to tracing the system-building process through which the scientists endeavored to develop their authority in the decision-making apparatus. Unlike a leadership analysis− that attributes the determination of India’s nuclear discourse to a leaders’ charisma and personal connections with (other) political leaders, this research contends that India’s nuclear policy was conducted within the scope of a coherent science policy view delivered through scientific advisory system.

Research Design

In order to examine the scientists’ influence on India’s nuclear policy, this research will take a two-dimensional approach, focusing on the application of the “hardware” and “software” of the scientific advisory system to India’s nuclear policy. The hardware of the system was established and expanded by stages containing several organizational and legal reforms, while the software incorporated the context of India’s nuclear policy options and preferences largely as designed by the scientists. Therefore, the course of research will entail an analysis of 1) the evolution and development of scientific advisory bodies on India’s nuclear program, 2) the process of producing coherent policy suggestions by the scientific enclave, and 3) the communication of their policy deliberations to the prime minister and its influence on policy outcomes from 1948 to 1974.

In order to devise an alternative explanation rather than contribute to the leadership literature, this research will borrow from macro organizational theory the idea that organizational change and adaptation increases the reliability and accountability of the collective opinions of experts (in this case nuclear scientists). The organizational structure and function largely comprise the scientific advisory system. The same members in different organizational structures aggregated the sum of sub-organizational activities to enable cohesive policy perspectives among nuclear scientists. This allowed the organizational inertia that protects the common interests of nuclear scientists to expand or maintain its influence in nuclear decision-making. Finally, to investigate this course, I will draw on declassified archival documents collected from the archives of India, the US, and the UK as primary sources, in addition to secondary literature.

Expected Results and Final Product

The preliminary research draws a tentative conclusion that India’s moves toward a peaceful nuclear explosion in 1974 were the result of a continued push by scientists. The changes in political leadership made the timing of a nuclear explosion uncertain, yet the nuclear program required a hefty investment of national resources that could be continued due to the scientists' collective opinion effectively delivered to the prime minister, various ministries, and also bureaucrats through a multi-layered channel in advisory system.

This research will form the basis of my book project. Before expanding to a book manuscript, the research outcome will be at least one journal article in a peer-reviewed academic journal.

Target Audience and Policy Contribution

The structural change of the scientific advisory system and its contents holds important lessons for both research scholars and policy-makers. India's nuclear policy often invites different interpretations regarding its motivation and process that analyze the speed and intensification of the nuclear weapons program and policy direction to India's peaceful nuclear explosion in 1974. Creating additional layers of explanation from the collective interest of scientists contributes to offer an alternative of India's nuclear discourse. The institutional arrangement of scientific advisory system in India reveals not merely national style of India nuclear policy-making but also is instructive with respect to the complicated nature of interface between science and politics.

3. Farzan Sabet, CISAC

The Iranian nuclear program, U.S. policy, and the nuclear nonproliferation regime, 1968-1978

Q1(a). On what issue are you working?

My project is on the Iranian nuclear program under the Shah from 1968 to 1978, with a focus on the goals of the Iranian program, how US nonproliferation policy shaped it, and what this history can tell us about the emerging global nuclear nonproliferation regime.

Q1(b) Why is it important?

The Iranian nuclear program is important because, despite its pertinence as an international security and scholarly topic, its history remains poorly understood. The Shah's nuclear program, which covers just over one third of the Iranian program's entire lifetime to date, remains especially understudied despite the amount of recently declassified archival documents and former policymakers willing to speak on the record. The Iranian nuclear program under the Shah is also an important episode in the story of the final chapter of U.S.-Iran relations before the Iranian Revolution of 1979, the arc of U.S. nuclear nonproliferation policy, and the global nuclear nonproliferation regime during the 1970s. This history may shed light on the Iranian nuclear program under the Islamic Republic and adds to our store of knowledge of nuclear programs and the range of strategies governments pursue, specifically in regard to the question of nuclear hedging and latency.

Q2. What is the big question that you are seeking to answer about that issue?

The big questions I seek to answer about the Iranian nuclear program under the Shah are as follow: What were the goals of the Iranian nuclear program under the Shah between 1956, when it began, and 1978, when it effectively ended, and what strategies did the Iran pursue to achieve them? How did US nonproliferation policy affect the Iranian program? How did the US-Iran nuclear relationship affect the emerging global nuclear nonproliferation regime and how was it in turn affected by the regime?

Q3. How are you going to answer your question? What methods will you use and what evidence or cases will you explore?

I answer these questions through an inductive historical case study that draws on the existing historiography, archival documents, oral histories, and newspapers and interviews with former policymakers that I have conducted myself. I have outlined a nearly comprehensive list of my primary sources below.

DOCUMENT ARCHIVES: National Archives and Records Administration (College Park, Maryland); State Archiving System Central Files 1973–1979 (SAS)(RG 59) (online); Central Intelligence Agency Library, President's Daily Brief 1969-1977 (online); Nixon Presidential Library & Archive; Gerald R Ford Presidential Library & Museum; Jimmy Carter Library; Ronald Reagan Presidential Library; Hoover Institution Library & Archives (Includes Persian-language documents); Booth Family Center for Special Collections, Georgetown University; MIT Libraries Institute Archives & Special Collections; United

Kingdom National Archives; Institute for Iranian Studies, University of St Andrews; Archives nationales de France (presidential archives); Archives diplomatiques français; Library and Archives Canada (online)

ORAL HISTORY PROJECTS: Harvard University Iranian Oral History Project (online); Foundation for Iranian Studies, Oral History Program (online); Frontline Diplomacy Oral History Collection (online)

NEWSPAPERS: TimesMachine (New York Times archive) (online)

Q4. 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?

My preliminary answers to the questions I have posed at the outset of my project are as follow. The nascent Iranian nuclear program had two primary goals. First, it was part of an energy policy which sought to use nuclear energy as an alternative for petroleum to free up the latter for export at ever higher prices during the 1970s in light of projected “peak oil” by the 1990s and rising domestic energy demand due to rapid industrialisation. Second, the program sought to put Iran a screws turn away from a nuclear weapon, with the aim of having the capability to build nuclear weapons should other regional states acquire them. The Shah pursued these goals through a strategy that procured nuclear technology and services from vendors from over a dozen countries as a means to diversify sources of supply and to create political support for the program. It was hoped that eventually all or most of the program would become indigenous.

During the Ford administration U.S. nuclear nonproliferation policy sought to use nuclear cooperation negotiations with Iran as a demonstration of American resolve to pursue nonproliferation, even at the expense of Cold War alliances and commercial opportunities, during the Nuclear Supplier Group meetings in London. These negotiations continued under the Carter administration, which also emphasised nonproliferation. The cumulative effect of these two successive administrations’ effort from 1974 to 1978 contributed to the ultimate failure of the nuclear cooperation negotiations and hurt the U.S.-Iran bilateral relationship.

While the Shah sided with the United States on most global issues, nuclear nonproliferation became a zone of both cooperation AND contention between the United States and Iran, especially over the question of the rights and benefits endowed by the nonproliferation treaty. Leading up to the failure of the negotiations, Iran became a rallying point for many nuclear suppliers and consumers dissatisfied with U.S. nonproliferation policy.

Q5(a). What will your research add?

My research will be among the first comprehensive and thoroughly research historical works on the Iranian nuclear program under the Shah, drawing extensively on newly available archival material and incorporating interviews with former policymakers with new insights on the program. It will show that Iran under the Shah was an important part of the debate over nuclear nonproliferation during the 1970s. For example, my research will be the first to highlight the extent of the Shah’s nuclear technology acquisition efforts, including seeking plutonium reprocessing technology and rights from West Germany and France and entering into nuclear cooperation negotiations with the Soviet Union. My research will also be the first to show that Iran under the Shah was pursuing a nuclear weapon design and that this likely contributed to the failure of U.S.-Iran nuclear cooperation negotiations. This study adds to the list of cases on states that had nuclear programs but did not produce nuclear weapons, thereby expanding our understanding of how the NPT and the nonproliferation regime has developed.

Q5(b). Why will you answer be useful?

My answer will be the first to comprehensively and accurately shed light on what actually happened in this historical episode and allow scholars to better judge the evolution and efficacy of U.S. and global nuclear nonproliferation efforts during this period.

Q6. How does your work fit into the existing work on your subject?

The existing work on my subject is either incomplete, covering only narrow aspects of what I discuss, or lacks historical rigour in terms of grasp of the academic literature and sources. For example, high quality historical works like the chapter on U.S.-Iran nuclear cooperation negotiations in the book “Nixon, Kissinger, and the Shah” by Roham Alvandi and the Diplomatic History article “The Nuclearization of Iran in the Seventies” by Richard Darwin Hamblin are limited in scope. Meanwhile, more comprehensive works like “Nuclear Iran: The Birth of an Atomic State” by David Patrikarakos and “The Trajectory of Iran's Nuclear Program” by Michele Gaietta suffer from a failure to sufficiently utilise available archival sources and oral histories as well as deeply flawed analysis. My work is thus both comprehensive and deploys rigorous historical methods including a knowledge of the historiography, archival sources, and oral histories, and draws what I contend are more accurate conclusions than existing works.

My work will also complement studies of U.S. nuclear nonproliferation policy following the Indian “Smiling Buddha” peaceful nuclear explosion, such as Or Rabinowitz’ “Bargaining on Nuclear Tests: Washington and its Cold War Deals”, as well as works on the nuclear programs of Middle Eastern states, such as Malfrid Braut-Hegghammer’s “Unclear Physics Why Iraq and Libya Failed to Build Nuclear Weapons.”

Q7(a). What alternative arguments or explanations exist and why is your answer superior?

Below I have given a small selection of examples of alternative arguments or explanations that exist to the questions I ask and why my answers are superior. “The Trajectory of Iran's Nuclear Program” does not give a coherent historical narrative but is largely descriptive. “Nuclear Iran: The Birth of an Atomic State” takes a broadly constructivist approach to explaining the goals of the Iranian nuclear program under the Shah, arguing that the chief objective was “royal glory” (prestige). While prestige may have been one goal of the program, archival record and interviews not used by the author show there were other, arguably more important, goals. “Nixon, Kissinger, and the Shah”, which looks at why U.S.-Iran nuclear cooperation negotiations failed, attributes this failure to President Carter’s decision to treat the Shah like a client, rather than a partner. I show that the reasons behind the failure were far more complex, and likely included the discovery that the Shah had ordered his atomic energy organisation to work on a nuclear weapon design. In summary, my answers are superior because they are both comprehensive in their treatment of the topic and utilises sources to which these other works did not have access.

Q7(b). How does your work add to or change our understanding of the issue you are studying?

My research will be among the first comprehensive and thoroughly research works on this topic, drawing extensively on all of the available historiography, archival material, and interviews with relevant figures, and will will add to and change our understanding of the issue in at least three important ways. First, my work will emphasise the greater continuity, rather than change, between the nuclear program under the Shah and the Islamic Republic. Second, my research highlights the importance of the nascent Iranian nuclear program to the evolution of both U.S. nuclear nonproliferation policy and the global nuclear nonproliferation regime during the 1970s. Finally, I will bring to light new revelations, such as how the Shah was pursuing a nuclear weapon design, the discovery of which appears to have contributed the failure of U.S.-Iran nuclear cooperation negotiations.

Q7(c). What do you see as your most important contribution?

My dissertation significantly expands the revision of the historiography of U.S.-Iran relations under the Shah and helps paint a better picture of the resistance of nuclear supplier and consumer states from within the NPT to U.S. nuclear nonproliferation policy during the 1970s.
Q8. What policy implications flow from your work? What concrete recommendations can you offer to policymakers?

Graham Allison and Niall Ferguson in a recent op-ed in The Atlantic called on policymakers to take greater account of historical knowledge when contemplating pressing issues. With this in mind, there are important insights one can glean from comparing the nuclear negotiations between the United States and the Shah versus those with the Islamic Republic, respectively. Despite important distinctions, U.S. policymakers faced many of the same dilemmas in both of these negotiations.

One important question was how the nature of the ruling regime in Iran should be taken into account in the U.S.-Iran nuclear cooperation negotiations (1974-1978). Both the Ford and Carter administrations faced pressure to be more lenient with the Shah in regards to nuclear nonproliferation safeguards because he was an important Cold War ally, but both largely ignored these pressures, cognisant that their decision could also be seen as precedent setting by others, especially when it came to imposing restraints on other nuclear suppliers. This turned out to be a correct decision when it was later discovered the Shah had a serious interest in having the capability to build nuclear weapons, which was seen as contrary to U.S. and global nuclear nonproliferation interests at the time.

The nature of the ruling regime is thought to have been incorporated in a different way in P5+1-Iran nuclear negotiations (2012-2015). Key nuclear nonproliferation provisions of the resulting agreement, the Joint Comprehensive Plan of Action, are temporary and expire within 15 years of the date of implementation. Part of the assumption behind making these provisions temporary by U.S. policymakers appears to have been the hope that in the intervening years the regime in power in Tehran will be more "moderate" and friendly toward the United States and agree to a more binding and permanent follow-up agreement. However, history suggests that the Iranian pursuit of a nuclear weapon option transcends any particular regime and that even a regime that is more friendly toward the United States may not necessarily agree to more restrictions on its nuclear program.

Q9. 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?

I do not sufficiently engage with the non-historical academic literature on nuclear nonproliferation which could help better frame my work or provide useful insights in areas where I am lacking concrete historical evidence. I am also interested in learning more about other similar cases from the period to compare and contrast with that of Iran under the Shah.

4. Eva Uribe, CISAC

Proliferation Risks of Thorium Reactors

The Central Question and its Importance

Since their conception in the 1950s, thorium reactors have been promoted as a promising technology for nuclear energy generation, though they have not yet been successfully commercialized. Proponents of thorium reactors argue that they are safer, produce less waste, and are proliferation-resistant, compared with uranium-fueled light water reactors used around the world today. The central question guiding this research concerns the final claim. *Is the thorium fuel cycle more resistant to nuclear weapons proliferation than the traditional uranium fuel cycle?*

Because of promises of increased safety and reduced waste production, a number of countries around the world have explored commercializing thorium reactors. India possesses over 13% of the world's thorium reserves.[1] The relative abundance of thorium as compared with uranium in India motivates India's long-standing national policy of commercializing thorium technology. India has proposed a three-step program to achieve a self-sustaining, U-233 breeding thorium reactor fleet. In the first step, heavy-water reactors are used to generate plutonium. Plutonium fuel will then be irradiated in fast-breeder reactors that will contain either uranium or thorium "blankets" for the production of more plutonium or uranium-233, respectively. Currently, India is working on commissioning their first fast breeder reactor, which is projected to become operational in 2016.[2] Finally, the U-233 will be used to power self-sustaining thorium reactors. India is not alone in its quest to harness thorium power. The most popular conception of thorium reactors is the molten salt reactor, which is currently being pursued in Canada, China, and, most recently, Indonesia.[3,4]

As other scholars have argued, the proliferation risks of thorium reactors depend on the design and operation of the reactor.[5] As more countries both inside and outside the Nonproliferation Treaty consider thorium reactors, it is critical to develop appropriate safeguards for fissile materials in these reactors and associated fuel cycle facilities. Initially, this research will identify proliferation pathways unique to neutron-irradiated thorium, particularly those involving the separation of protactinium, and will determine key areas where nuclear facilities in the thorium fuel cycle need to be safeguarded. This

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[1] While thorium is approximately three times more abundant in nature than uranium, thorium reserves are not as abundant as uranium reserves. Englert, M., Krall, L., Ewing, R. C., "Is nuclear fission a sustainable source of energy?" *Materials Research Society Bulletin*, 37 (2012): 417-424.

[2] "First Fast Reactor Coming Up at Kalpakkam," *The Hindu*, 10 January 2016, accessed online on 21 August 2016.

[3] "Thorium Energy Report," International Thorium Energy Organization, accessed January 15, 2016 http://www.thoriumenergy report.org

[4] In October 2015, the Indonesia Thorium Consortium agreed to commission the first molten salt thorium power plant by 2021. "Indonesia Exploring Liquid Fuel Nuclear Power Plants to Cut Reliance on Coal," ThorCon Power, accessed January 11, 2016 thorconpower.com/library/announcements/indonesiaexploringliquidfuel

[5] Kang, J., von Hippel, F. N., "U-232 and the Proliferation Resistance of U-233 in Spent Fuel," *Science and Global Security* 9 (2001): 1-32

preliminary work will be in support of a larger project to examine the proliferation risks of the thorium fuel cycle more broadly.

Overview of the Thorium Fuel Cycle

The most abundant thorium isotope, Th-232, cannot sustain a fission chain reaction; however, it is a fertile isotope.[6] Upon neutron capture, Th-232 forms Th-233, which undergoes radioactive decay through protactinium-233 to uranium-233 (Figure 1). The proliferation concern is the production of U-233. U-233 is *fissile* and can sustain a nuclear chain reaction in either a reactor or a weapon. U-233 is not found in nature; it is produced when thorium is irradiated with neutrons. Most thorium based reactor designs involve the initial use of fissile material produced elsewhere. In the absence of an already existing thorium-based reactor, this is not U-233, but low-enriched uranium.[7] Over time, as the fuel is irradiated, the quantity of U-233 would increase sufficiently to sustain a fission chain reaction, and U-233 becomes both the fuel and irradiated product. The nuclear properties of pure U-233 make it a potential fuel for nuclear weapons along with U-235 or Pu-239. Like U-235, U-233 has a low spontaneous fission rate, which allows for simple weapons designs. U-233 also has a low critical mass, similar to Pu-239, meaning that less material is required for a weapon. Additionally, the neutron absorption cross-section is higher for Th-232 than U-238, resulting in higher production of U-233 as compared with Pu-239 in reactors of similar neutronic design.[8]

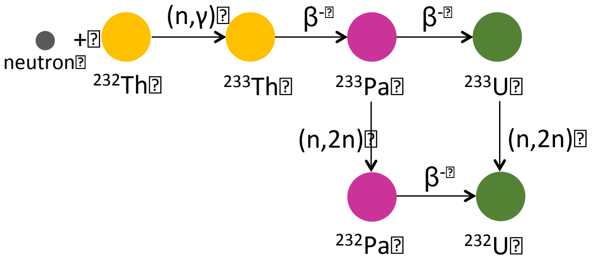

Figure 1. Decay chain of neutron irradiated Th-232. The notation (n, 2n) indicates the capture of one neutron followed by the emission of two neutrons.

Alternative Arguments

Despite the nuclear properties of U-233, advocates for a thorium fuel cycle argue that thorium reactors are more resistant to proliferation than conventional uranium-fueled reactors. First, thorium reactors do not use or produce weapons usable plutonium once they are running on a self-sustaining Th-232/U-233 cycle. However, as India's three-step plan demonstrates, achieving a self-sustaining Th-232/U-233 cycle

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[6] *Fertile isotopes* can become fissile isotopes upon neutron capture and subsequent nuclear decay.

[7] Low-enriched uranium contains less than 20% of the fissile isotope U-235. Pu-239 could also be used.

[8] The thermal neutron absorption cross-section of Th-232 is 7.4 barns, while that of U-238 is 2.7 barns. Kang, J., von Hippel, F. N., "U-232 and the Proliferation Resistance of U-233 in Spent Fuel," *Science and Global Security* 9 (2001): 1-32.

may require (or justify) stockpiling large amounts of separated plutonium.[9] Second, many argue that U-233 is "self-protected" by high-energy gamma rays emitted by daughters in the U-232 decay chain. U-232 is created by the irradiation of thorium (see Figure 1). U-233 containing sufficient U-232 is highly radioactive, which complicates all handling and reprocessing procedures. However, the dose from U-232 from a typical reactor (13 rem/h at 1 meter) is far less than the standard set by the IAEA for reduced physical protection (100 rem/h at 1 meter).[10] Thus, while the presence of U-232 may make the handling of U-233 more difficult, it clearly does not render thorium reactors "proliferation resistant."

To decrease the proliferation risk from U-233, several proposed thorium reactor designs use "denatured" fuel that is diluted with natural or depleted uranium.[11] U-233 denatured with U-238 is like low-enriched uranium and cannot be used to make a weapon.[12] Yet even thorium reactors that use denatured fuel do not adequately decrease their proliferation risk. Proliferation pathways for the thorium fuel cycle can occur with the build-up of Pa-233 from the irradiation of Th-233. Pa-233 has a 27-day half-life, and over time an appreciable amount accumulates. If protactinium is chemically separated from the reactor fuel and isolated from further neutron irradiation, it decays to pure U-233, without U-232 and U-238, making it as dangerous as highly enriched U-235.

Method – Case Studies of Specific Thorium Reactors and Fuel Cycles

The initial goal of this research is to address the proliferation pathway based on chemical separation of protactinium for several thorium reactors and fuel cycle facilities, a topic that is largely neglected in the large body of literature on thorium reactors. This research will focus on both solid thorium oxide-fueled reactors and molten salt thorium reactors. *The primary contribution of this research is to estimate how much protactinium accumulates over time for a given reactor, and to determine how easily the protactinium can be separated from the core.*

The chemical properties of protactinium, thorium, and uranium are all very different. In principle, it is possible to design a separation scheme to achieve the isolation of protactinium from thorium and uranium for any type of reactor design and any type of fuel medium. Researchers at Cambridge estimate

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[9] The International Panel on Fissile Material estimates that as of 2014, India has 0.57 metric tons of weapons-grade plutonium, and an additional 5.1 metric tons of plutonium separated from unsafeguarded heavy water reactors that serve as a strategic reserve. Once India's prototype fast-breeder reactor, which is not safeguarded, comes online, they will increase their annual production capacity of weapons-grade plutonium from 30 kg to 140 kg. Alexander Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security* 15 (2007): 85-105

[10] The 13 rem/h dose rate given is for a 5 kg sphere of U-233 from a reactor with a burnup of 70MWd/kg, 1 year after chemical separation. At this burnup, the U-233 contains approximately 0.4 percent U-232. For low burnup fuels, the amount of U-232 can be reduced to several parts per million. Kang, J., von Hippel, F. N., "U-232 and the Proliferation Resistance of U-233 in Spent Fuel," *Science and Global Security* 9 (2001): 1-32.

[11] Uranium is considered "denatured" if it contains less than 20% U-235 and less than 12% U-233. The chemical properties of two isotopes of the same element, for example U-233 and U-238, are essentially identical. The only way to separate them is through isotopic separation, which is much more challenging than conducting a chemical separation of two different elements, whose chemical properties are distinct.

[12] The disadvantage of these reactor types is that Pu-239 will be produced from neutron capture by U-238. However, these reactor types can be configured to produce less plutonium than a typical light water reactor. Ali Ahmad, Edward B. McClamrock, and Alexander Glaser, "Neutronics calculations for denatured molten salt reactors: Assessing resource requirements and proliferation-risk attributes," *Annals of Nuclear Energy* 75 (2015): 261-267.

that it would take less than a year and 1.6 metric tons of thorium metal irradiated in a typical reactor to produce the 8 kg of pure U-233 needed to make a weapon.[13]

In addition, the chemistry of protactinium will make safeguarding aqueous nuclear reprocessing facilities technically challenging. Protactinium readily hydrolyzes to form insoluble hydroxides and polymeric species, even under highly acidic conditions, and Pa tends to adsorb to any solid surface.[14] Because of these properties, strict material accountability of bulk material may be very difficult. *A second contribution of this research will be to identify key areas in the thorium fuel cycle that would be vulnerable to nuclear proliferation despite safeguards and to make specific recommendations for development of adequate safeguards in these key areas.*

Policy Implications and Opportunities for Improvement

This research has the potential to impact policy in two specific ways. First, the analysis will provide policymakers with tools for the comparison of the proliferation risks of the uranium and thorium fuel cycles so that they can make technically-informed decisions. Second, I will identify potential proliferation pathways inherent to the thorium fuel cycle, as well as areas where stronger safeguards may be needed.

The strength I bring to this research is my knowledge of the chemical separations involved in reprocessing spent nuclear fuel. However, my weakness is that I lack a background in nuclear reactor physics. Additionally, Stanford University does not have a nuclear engineering department. Therefore, I plan to collaborate with others who have expertise in reactor physics, including Ron Fleming at the University of Michigan, M. V. Ramana at the Program on Science and Global Security at Princeton University, and Per Peterson and Massimiliano Fratoni at the University of California, Berkeley. For additional expertise in actinide separations I will consult with Gordon Jarvinen and David Clark at Los Alamos National Laboratory. For help with protactinium chemistry, I will consult Richard Wilson at Argonne National Laboratory. Ultimately, collaboration with these experts will strengthen this research.

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[13] Stephen F. Ashley et al., “Thorium fuel has risks,” *Nature* 492 (2012): 31-33.

[14] *The Chemitsry of the Actinides and Transactinide Elements*, ed. by Lester Morss, Norman Edelstein, Jean Fuger, 3rd Ed. Vol. 1. See also R. Wilson, “Peculiar protactinium,”*Nature Chemistry*, 4 (2012): 586.