Stanton Nuclear Security Fellows Seminar

PANEL 3: Nuclear Technology and Nuclear Weapons

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Flagging Dual-Purpose Research in the Physical Sciences

Summary

For a non-proliferation regime, research that is dual-purpose poses significant challenges. How can dual purpose research be recognized and how might it be regulated? I propose two case studies to address the question of what in contemporary research can be of dual intent and raises red flags for future weaponization potential. I will identify the weaponizable characteristics and categorize academic projects specifically developed in universities that recently received grants from the National Nuclear Security Administration in 2022 that do not require direct application of their science to immediate nuclear stockpile maintenance. In parallel, I intend to study the Brazilian nuclear-powered submarine project in the context of Brazilian nuclear development as a case study for how States can develop the necessary technology to pursue projects of possible dual intent in military facilities beyond verification.

Background

The connection between academia, particularly in the physical sciences, and the military has long existed, but sometimes it can be "disguised" as funding for basic science that does not support the development of technologies for military use. In 2019, the International Campaign to Abolish Nuclear Weapons (ICAN) published a list of "schools of mass destruction."[1] The list is comprised of 49 academic institutions that directly contribute to the US nuclear weapons program in different ways. However, the list of academic projects funded by the US Department of Energy's National Nuclear Security Administration (NNSA) in 2022[2] raises the question of what type of research has the potential to contribute to the future of the nuclear

[1] Schools of Mass Destruction. International Campaign to Abolish Nuclear Weapons (2017). Available at https://universities.icanw.org/

[2] NNSA awards $21 million for research grants for science and technology. National Nuclear Security Administration (2022). Available at https://www.energy.gov/nnsa/articles/nnsa-awards-21-million-research-grants-science-and-technology

weapons enterprise. The NNSA controls the nuclear weapon stockpile in the US and some of the national laboratories developing and maintaining them, under the guise of only ensuring a safe, secure and effective performance of US nuclear weapons over time without adding extra capabilities to them. Nonetheless, several of NNSA's recently funded projects are in institutions not mentioned in ICAN's list of schools directly contributing to the American nuclear weapons program, meaning that they are not supposedly aiding in the development and maintenance of nuclear weapons and their research is not necessarily considered to be of dual purpose.

The Carnegie Endowment for International Peace published a report in 2017 called "Toward a nuclear firewall,"[3] which delineates a framework to determine whether a given national nuclear program is for peaceful purposes. This report lists technical indicators of interest when identifying whether a country is starting a nuclear weapons program or further developing an existing one. Nonetheless, the report focuses on technical developments historically known to be linked to nuclear weaponization, such as reactor operations, the control of the fuel-cycle, delivery systems and military structures. However, policymakers need a more specific framework and understanding of how contemporary cutting-edge research in the physical sciences may finally support nuclear weapon development, *e.g.,* the development of new materials and even high-pressure studies of planetary cores.

Case Study #1

As a first case study, I propose investigate the list of "purely" academic projects the NNSA funded in 2022. These projects, funded through the Stewardship Science Academic Alliances (SSAA) Program, are supposedly funded solely for the development of basic science of interest to the nuclear enterprise and training of early-career scientists but with no contracts related to the immediate maintenance or development of nuclear weapons. Given NNSA goals of developing and maintaining the American nuclear weapons stockpile, this list should be a great pool of projects that show what the future of weaponization will look like to produce a framework to evaluate the dangers of basic, recent science. What features of these projects raise weaponization red flags? How can these projects be categorized technically? What is the NNSA prioritizing in terms of weaponization potential now that might be a red flag in the non-proliferation regime in the US and elsewhere?

I intend to analyze papers recently published by the awarded research groups to identify the features or developments that are weaponizable and categorize them according to their unique technical aspects. Finally, this categorization will be used to develop a framework that non-

[3] Toby Dalton, Wyatt Hoffman, Ariel E. Levite, Li Bin, George Perkovich, and Tong Zhao. Toward a nuclear firewall. Carnegie Endowment for International Peace (2017).

proliferation experts can use to evaluate the threat from not only classic signs of weaponization, but also from other types of possibly weaponizable technologies that are currently under development and not historically associated with nuclear weapons. This effort can be extended into a more comprehensive analysis of research funded over several years not only by the NNSA, but also by the DoE and DoD more broadly, as well as other basic research funding agencies like NSF and NASA.

Case Study #2

As a second case study, I will analyze the history of Brazilian technical developments that led to the Brazilian nuclear-powered submarine program, a type of project that can be of possible dual purpose. This submarine program[4] stands out because it is a nuclear project undertaken in military facilities in a non-nuclear weapon state. Only one other non-nuclear weapon state in the world, Australia, currently has a nuclear-propelled submarine program. Several questions related to inspection and verification matters arise from these circumstances. Brazil's peaceful history, the fact that it signed and ratified most international treaties in the non-proliferation regime, its bilateral verification agency with Argentina (ABACC), and its own constitutional article forbidding the use of nuclear science for non-peaceful purposes are guarantees that Brazil does not intend to produce a weapon. However, submarine reactors have several technical features that can lead to weaponization, from reactor designs to uranium enrichment.

How did Brazil get to a point in which it could develop its own nuclear-propelled submarine despite embargoes on equipment? How did it develop its own centrifuges with a classified design? I propose to first identify the technical features that can be weaponized. Then I intend to examine the literature that describes how Brazil acquired the initial equipment and knowledge to develop weaponizable features of a nuclear-propelled submarine. From my background literature search, I intend to identify and interview key players to answer a few key questions: 1. What did Brazil already have as resources? and 2. How did it develop the additional technologies that were needed? I intend to visit nuclear sites to understand first-hand what these capabilities are and how they were developed. As an end goal, this project should become a framework for what indicates that a country might end up pursuing a dual-purpose nuclear project in its military facilities beyond inspection.

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[4] Ian J. Stewart. Brazil wants special treatment for its nuclear submarine program—just like Australia. Bulletin of the Atomic Scientists (2022). Available at https://thebulletin.org/2022/06/brazil-wants-special-treatment-for-its-nuclear-submarine-program-just-like-australia/
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Target Audience and Policy Contributions

To reach the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and the Treaty on the Prohibition of Nuclear Weapons (TPNW)'s end goals, existing nuclear weapons programs should end, and new ones should be curtailed before their inception. Hence, finding ways to identify dual-purpose research will become more and more relevant in the future. The projects described above would provide these non-proliferation efforts with a technical framework under which academic research can be evaluated in the physical sciences to identify dual purpose developments in the nuclear weapons field as well as their intended next steps.

Moreover, making scientists aware of the ethical and dangerous implications of the early-stage projects that they are pursuing is the first step towards having them consider their roles in the weaponization of their respective fields. Hence, before even achieving the goal of aiding global non-proliferation efforts, this project's intended audience is scientists working on research similar to what I am examining in my case studies.

2. Simon Adu, Texas A&M

Addressing Nuclear Security and Nonproliferation Concerns in the Introduction of Small Modular Reactors (SMRs) in African Countries

1. On what nuclear security issue are you working and why is it important?

This project addresses the proliferation concerns stemming from the introduction of Small Modular Reactors (SMRs) in Sub-Saharan Africa. The third pillar of the Non-Proliferation Treaty (NPT) encourages states with nuclear energy ambitions to harness this technology only for peaceful purposes without diverting it for nuclear weapons. Most African countries such as Ghana, Nigeria, Egypt, South Africa, Uganda, Kenya, and many more have announced their interest in taking advantage of this initiative to embark on nuclear energy development. Africa is experiencing a growing demand for energy, driven by increasing population, urbanization, and economic productivity. Many African countries consume substantially less energy per person than the global average (IEA, 2019). In July 2015, representatives from ten African countries came together to establish the African Network for Enhancing Nuclear Power Programme Development (ANENP) (WNS, 2022).

With more than 70 Small modular reactor (SMR) designs under development in 17 countries and the first SMR units already in operation in Russia, SMRs are expected to play an increasingly important role in helping the global energy transition to net zero. SMRs have garnered the interest of policymakers as an alternative source of energy. (OECD, 2021, Esam M.A. H., 2020). Nevertheless, the deployment of SMRs in Africa raises concerns about nuclear security and nonproliferation, given the continent's security threats. Increased use of nuclear energy could potentially increase the production of uranium as fuel and the potential availability of nuclear materials in the region. The operation of these reactors will also increase the production of Pu-239 as a byproduct in spent fuel. U-235 and Pu-239 are fissile materials use for manufacturing of nuclear weapons and other related nuclear explosive devices. These materials need to be controlled to ensure that they are not diverted from peaceful use to nuclear weapons (IAEA, 2018).

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

The big question that this research seeks to answer is: to what degree will the adoption of SMRs in West African (Nigeria and Ghana) countries increase the risk of nuclear weapons proliferation?

This overarching question encompasses several key sub-questions:

a. How fast can state actors manufacture a nuclear weapon using an SMR if they decide to sprint towards a bomb following a political shock, like a military coup.

b. What are the design issues with SMRs that might lead to proliferation or security concerns? What are the proliferation risks related to refueling, particularly in the African context, and how can they be effectively managed?
c. Are the existing international legal instruments concerning nuclear security, nonproliferation, and civil liability adequate and applicable to the introduction of SMRs in Africa, or do they require refinement or adaptation?

Answering these questions will provide a comprehensive framework for addressing the complex issue of introducing SMRs in Africa, considering the unique energy, security, and proliferation challenges faced by the continent.

3. How are you going to answer your question?

To address this question, a multi-faceted approach will be employed:

1. Estimation of Pu-239 and U-235 buildup of the reactors over a period. Monte Carlo N-Particle code MCNP6, will be used to calculate the build-up of Pu-239 and U-235 over a period to know how much material would be produced. A proliferation risk will then be estimated using the following variables:
    - The likelihood that the country will go into weapon production.
    - Will there be a significant quantity to be used for the weapons production.
    - Will there be available competencies for enrichment?
2. Two common deigns likely to be deployed in Africa, the Nuscale and Rosatom designs, will be analyzed as to which design could be weaponized quicker, considering the security threat in the region.
3. Comparative analysis of SMRs and large traditional reactors in terms of proliferation risk will be performed. This will be based on their designs, number of fuel rods, their enrichment levels and the refueling process. It will also account for the frequency of refueling and whether the spent fuels will be on-site.
4. Interviews with experts in nuclear energy, non-proliferation, and security studies to gain insights into the potential risks and best practices for mitigating them.

4. What is your answer to the question you are asking?

The tentative argument is that the speed at which countries can manufacture a nuclear weapon from SMRs depends on various factors, including the design of the SMR, the availability of fissile material, and the technical expertise of the actor involved. It is crucial to consider safeguards, security measures, and international monitoring mechanisms to mitigate this risk. Design issues with SMRs that might lead to proliferation or security concerns could include factors like the accessibility of certain components, the potential for covert weaponization, or the presence of features that could facilitate weapons production. Refueling processes also present a potential proliferation risk, as they involve handling fissile materials. Risk management strategies might involve stringent security protocols, international oversight, and advanced reactor designs that minimize proliferation risks. Existing international legal instruments, such as the NPT, participating in a 123 agreement, the Foundational Infrastructure for the Responsible Use of Small Modular Reactor Technology (FIRST) initiative, and various regional and bilateral agreements, play a crucial role in regulating nuclear activities. However, the specific applicability of these instruments to the introduction of SMRs in Africa would need to be carefully assessed. Refinements or adaptations may be necessary to address any unique challenges posed by SMR technology in the African context.

Overall, addressing these questions will be essential for developing a comprehensive framework for the introduction of SMRs in Africa, while ensuring that energy needs are met without compromising security and nonproliferation objectives. This will likely require close collaboration between experts, policymakers, and international organizations.

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

The United States has engaged most African countries embarking on the adoption of SMR technology under the US Department of State's FIRST program. This program is designed to provide capacity-building support to partner countries, ensuring that they develop their nuclear energy programs in adherence to the highest international standards for nuclear safety, security, and non-proliferation. Most of these countries may consider U.S. SMR technology, raising important implications for U.S. nonproliferation polices and arms control. The estimation of uranium and plutonium build up during the operations will determine the degree of proliferation risk associated with SMRs. This will influence the nuclear security and nonproliferation policies.

The policy implications of the work are:

a. Advocate for African countries to develop robust nuclear security, nonproliferation p olicies specific to SMR designs and how this technology will impact on proliferation a nd arms control.
b. Encourage international cooperation and support for capacity building in African nati ons to enhance their ability to manage nuclear security and nonproliferation effectiv ely.
c. Promote adherence to international nuclear security and nonproliferation agreemen ts while recognizing the unique challenges and capacities of African countries.

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

Various studies have analyzed the nuclear security implications of SMRs. Abdula et al. examined the potential deployment of SMRs, with a specific emphasis on assessing the feasibility of the technology (Abdulla, 2014). M.V Ramana et al. delved into the cultural and political factors influencing the global proliferation of SMRs. Glaser et al. conducted a study investigating the consequences of large-scale SMR deployment, including an initial analysis of proliferation risks using Markov-Chain methodology (Glaser et al., 2013). Additionally, Dany et al. (2023) compared the proliferation resistance of Light Water Reactors (LWRs) and pebble bed reactors (Mulyana & Chirayath, 2023).

My research builds on prior work by assessing how quickly and feasibly a potential proliferator could weaponize an SMR deployed in a developing country such as Ghana or Nigeria, while considering the security threats within and surrounding these nations. The research addresses a crucial aspect of nuclear non-proliferation by examining the introduction of SMRs in Africa. This is particularly relevant considering the security challenges that the continent faces and the need to ensure that the technology will not be diverted for nuclear weapons. The study acknowledges the dual-use nature of nuclear technology and seeks to provide insights into how to balance the need for increased energy access with concerns about non-proliferation and nuclear security. The USA is actively engaging in efforts to prevent the spread of nuclear weapons and materials. This includes supporting international agreements like the NPT and working to strengthen international safeguards. This study complements existing research on nuclear non-proliferation in the United States by providing a specialized emphasis on Africa, particularly considering the potential increase in SMR deployment in the region [4]. It broadens the discussion to include the shared design features that could influence proliferation and security concerns. Additionally, it investigates the potential ramifications of increased SMR deployment on the national and regional security as well as arms control policies of the technology-exporting country. By analyzing nuclear security policies, assessing proliferation risks, and evaluating legal frameworks in the African context, this work provides a valuable perspective that can inform both regional and global efforts to ensure responsible and secure deployment of SMRs.

In sum, this work will contribute to the broader field of nuclear non-proliferation by offering a focused examination of the African context and providing practical recommendations for the responsible deployment of SMRs in the region. It adds a nuanced perspective to the existing body of research and policy discussions surrounding nuclear energy and non-proliferation.

7. **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?**

The potential weakness will be the availability and reliability of data in the African context, especially in countries embarking on nuclear energy. Feedback that could be useful includes suggestions for mitigating data gaps, such as alternative sources.

8. References

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3. Jake Hecla, MIT NSE

Technology, Signatures, and Applications of Aircraft Nuclear Propulsion

I. Project Summary

Though aggressively pursued from the 1940s-1960s, nuclear-powered flight has long remained an elusive goal, having consumed billions of dollars without a single nuclear-powered take-off. The story of the nuclear airplane is therefore often framed as a tale of Cold War military extravagance: a predictable failure resulting from atom-mania running far ahead of technical realities. While this assessment may have been accurate in that era, the technology may be poised for a re-emergence. Key advancements in material science and innovations in uncrewed systems may have removed many of the enduring barriers to developing nuclear-powered flight. In 2019, five Russian scientists lost their lives in a nuclear accident involving the flight-testing of the *Burevestnik,* a system claimed to be a nuclear-armed, nuclear-powered cruise missile. Patent and publication activity in Russia, as well as in other states, indicates work on endo-atmospheric nuclear propulsion is at a level of activity not seen since the 1950s.

Despite the apparent resurgence of interest in endo-atmospheric nuclear propulsion, little work exists in the open literature exploring the fundamental technology, potential defense applications or deterrence impacts of this novel power source. In response to the limitations of the literature, I intend to develop a research project with a focus on understanding the physical characteristics of air-breathing nuclear engines (including exhaust products), evaluating potential roles for nuclear propulsion in future arsenals, and understanding the impact such systems may have on deterrence and stability.

This technology may pose unfamiliar challenges to both military planners and policymakers.

Advancements in high-temperature nuclear fuels, radiation-tolerant circuits and turbine technology may allow diverse applications that go far beyond the cartoonish “doomsday missile” under development in Russia. Among other applications, air-breathing nuclear engines may be useful in creating indefinite-endurance systems for intelligence gathering, emergency communications and radar. The fundamentally different scale of energy density available in nuclear propulsion suggests that these systems may have no conventional analogues.

In addition to providing power for flight, a nuclear powerplant would enable significant energy budgets for sensors. This may expand the mission space of uncrewed aircraft, as previously energy-prohibitive, high-mass and high value payloads could be deployed over great distances. Applications may include antisubmarine warfare, persistent ELINT collection and early warning systems. In some cases, it may even be possible to deploy assets that would otherwise be space-based on nuclear-powered aviation platforms. Once realized, these systems may proliferate due to their utility in carrying heavy, energy-hungry sensor payloads on protracted missions.

Deployment, basing and operation of nuclear-powered aerospace assets additionally poses a unique array of policy problems. Given the risk of radiation exposure or radioactive release, interdiction or shoot-downs of even un-armed nuclear-powered systems may be impossible in many scenarios. Further, these systems may pose risks to ground crews even if successfully forced to land. Limitations on the basing and use of such systems have yet to be seriously discussed, as the technology has remained relatively unknown and poorly understood.

Given these challenges, the proliferation of such systems is far from guaranteed. Despite the potential advantages of indefinite range and energy budget, states may judge them too risky to invest in. The promises of nuclear flight come at the cost of deploying a minimally-shielded reactor (likely fueled by HEU) aboard a system which may crash or be forced down. This may violate norms regarding fissile material use and pose an unacceptable risk to third parties. Due to the potential consequences of a shootdown, hack or accident, these systems may remain relegated to niche strategic roles or may simply never be developed beyond the *Burevestnik*. Understanding the physical characteristics of such reactors and the manner in which states evaluate risks associated with aerospace nuclear propulsion is therefore a critical step to quantifying the threat they may pose.

II. Research Plan

This project contains a technical element focused on understanding engine characteristics and exhaust products, followed by a policy-focused element seeking to understand the roles in which nuclear propulsion may be used. The latter portion of this project will also seek to understand what conditions may favor or disfavor the development of this technology by various states.

To build a strong fundamental understanding of the technology, I have begun by reviewing GE and Pratt & Whitney documents related to the development of the first nuclear jet engines, including the HTRE reactors, the XMA-1 and the R-1 powerplants as part of the US Aircraft Nuclear Propulsion program (ANP). Much of the ANP documentation is available online or in private collections, though some will require travel to review. These documents provide insight into the unique challenges of developing reactors which can operate under flight conditions, and turbomachinery which can operate under radiation conditions. In addition to these documents, I have obtained access to unique records at the Mound Science and Energy

Museum and the University of Cincinnati relating to these programs. These documents describe design studies, test results and product evaluations, all of which shed light on engine limitations which may be improved or side-stepped using modern gas turbine technology. This work will culminate in the development of basic models of direct- and indirect-cycle nuclear powerplants which characterize mass, footprint, and radiation signatures. This portion of the project will include informal consultation with the MIT Gas Turbine Lab to assure the technical soundness of my conclusions.

To better understand exhaust products and detectability, I will be working with both archival documents and modern literature on atmospheric radiochemistry and aircraft exhaust products. This portion of the project will include simulations of core conditions in both direct and indirect cycle nuclear powerplants (using OpenMC), and investigations of activation products and radiosynthesis of various chemical species which may occur in the exhaust plume. Particular attention will be paid to differences between conventional jet exhaust chemistry and that resulting from combustion-free compression and irradiation. This portion of the project will require consultation with experts in atmospheric chemistry and radiochemistry.

The policy portion of this project will focus on the development of a high-level study of missions that may benefit from nuclear propulsion, and factors that favor or disfavor continued development of these systems. To understand the application space for air-breathing nuclear propulsion, I am engaging with public GE, Pratt & Whitney and military studies of nuclear aircraft applications spanning the late 1940s to early 1960s. Additionally, I will be reviewing more modern studies of high-altitude, long-endurance (HALE) and submarine-hunting aircraft designs which may benefit from indefinite-range power sources.

This portion of the project will include consultation with an aircraft configuration expert, as well as subject-matter experts in intelligence, surveillance and reconnaissance (ISR) systems. Further investigation of application studies may redirect these efforts as new application niches are identified.

Finally, to better understand how states may evaluate the risks associated with the deployment of such systems, I will investigate how non-weapons military uses of HEU (such as space reactors) were evaluated in terms of risk to third-party states, and how states weigh these concerns against the benefits of the technology. This will likely involve reviewing US policy discussions regarding RTGs, as well as discussions of liability for accidents involving such systems, such as the Kosmos 954 accident.