Stanton Nuclear Security Fellows Seminar

PANEL 4: Looking Ahead

1. Edward Jenner, Texas A&M

Examination of Climate Change's Contribution to Nuclear Weapons Proliferation Risk

What issue are you working on and why is it important?

This research focuses on climate change, nuclear weapons proliferation, and their interaction in future nuclear energy programs. Nuclear weapons proliferation poses a substantial risk to international peace and stability. Climate change is another significant man-made risk to security, but this challenge is still evolving and requires deeper understanding. Nuclear energy is attractive for combating climate change because it produces minimal CO_2 emissions. There are concerns, however, that expanding nuclear energy globally could increase the risk of nuclear weapons proliferation by spreading dual-use technology, materials, and expertise.

At the same time, failing to address climate change could also lead to the spread of nuclear weapons. One potential motivator for weapons proliferation is regime survival, usually described as a way to resolve interstate security threats[1,2]. Research has already established climate change will increase domestic conflict and civil unrest[3], and many policymakers believe that it will threaten international peace and stability as well. For example, former Airforce Chief of Staff David Goldfien argued, "we have to respond militarily very often to the effects of, globally, of climate change"[4]. Former President of UN Security Council Kairat Umarov echoed this sentiment: "The Security Council recognizes the adverse effects of climate change and ecological changes among other factors on the stability of West Africa and the Sahel region"[5]. And former UN Secretary-General Ban Ki-Moon said, "Make no mistake, climate change not only exacerbates threats to peace and security, it is a threat to international peace and security"[6]. If climate change increases interstate conflict, it would increase motivation for weapons proliferation. Thus, mitigating climate change by expanding the use of nuclear energy globally could decrease weapons proliferation risk.

In sum, increased reliance on nuclear energy could raise the proliferation risk due to the greater availability of relevant materials and knowledge or lower it by reducing interstate security threats. The goal of this research is to better understand these two processes. Doing so will elucidate how to pursue both climate change abatement and nuclear weapons nonproliferation.

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

The big question I seek to answer is: how will climate change influence the spread of nuclear weapons? Many studies have previously addressed how the expansion of nuclear energy affects weapons proliferation. The relationship between climate change and interstate conflict is less well understood[7]. I seek to determine what kind of relationship between climate change and interstate conflict is needed such that future peaceful nuclear energy expansion will have a net zero proliferation risk. Addressing this issue will provide insight into how climate change might, if at all, impact the nuclear energy and weapons landscape in the future.

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

To answer the fundamental question above, the project will examine the two competing processes in three separate statistical models of future nuclear energy programs. These models are designed to isolate variables for meaningful analyses. The project will profile currently planned nuclear energy plants from now until 2050 based on their construction timeline, level of knowledge transfer expected, plant capacity, and location. I will not consider in nuclear weapon states, as the dynamics for their decision to further proliferate would likely be more complex.

Model 1 will cover the process of nuclear energy lowering the barrier for proliferation (by increased availability of material, technology, and knowledge). Based on existing literature, I will develop a statistical model that examines the propensity of nuclear energy programs to cause weapons proliferation[8]. I will then use this model to predict the likelihood of future nuclear proliferation events based on expected nuclear power plant development in the coming years. This number of proliferation events will be compared against the predictions generated by two other models (Models 2a and 2b).

Model 2a and 2b will be based on the potential for climate change to drive proliferation, the second process. They will utilize existing projections of climate change based on representative concentration pathways (RCP), which are a function of emissions. These will be combined with research on nuclear energy's ability to lower emissions[9], creating a model between the amount of nuclear energy and difference in climate change intensity. Utilizing existing literature, a probit analysis will identify the relationship between the number of interstate disputes and nuclear weapons pursuit. The number of interstate disputes will be modeled from historical data and rare event statistics. Once sufficiently motivated via conflict, a failure mode and effect analysis (FMEA) on a hypothetical facility will be utilized in a two-person zero-sum inspection game to see if a state develops weapons.

From there, the two models diverge. Model 2a will be the control, in which climate change has no ability to increase militarized disputes. In Model 2b, however, climate change can increase disputes and thus proliferation risk. This variable risk multiplier will be applied to model 2b and iteratively solved until the difference between model 2a and 2b (as a percent) is equal to the increase in model 1. This value, which would be framed as number of conflicts per ^{o}C, will give insight into how climate change might impact proliferation risk. By design it is necessarily a decrease, but this variable implies existing nuclear power plants could pose a proliferation risk, and their effect is not examined in this project. Because this is the value required to offset the two processes, its value will provide insight into the effect of climate change on proliferation risk. A very small value implies that climate change could easily impact proliferation (as a low number of wars are needed to have a set known increase in proliferation risk), while a large value suggests the opposite.

What is your answer to the question that you are asking, that is what is your argument or conclusion even if it is still tentative at this point?

The expected conclusion is that climate change will have a meaningful impact on nuclear weapons proliferation risk. If left unaddressed, climate change will exacerbate international security threats and increase incentives for additional countries to build nuclear weapons. Expanding nuclear energy globally can reduce this likelihood by mitigating climate change through reduced CO_2emissions. Although the spread of nuclear energy globally lowers the barriers to proliferation, the conflict-reducing effects of this form of energy production are relatively large. The end result of nuclear energy expansion will be a net positive benefit for nonproliferation.

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

One counterargument is that climate change attenuation does not require increasing peaceful nuclear energy. The only renewables that have the same level of energy produced per CO_2 emitted is off-shore wind energy and hydroelectric, both of which are very geographically limited. The most promoted renewables, on-shore wind energy and solar, have significantly less energy generated per CO_2 emissions and also do not load follow. This necessarily requires nuclear energy for global deep decarbonization.

Second, in the United States there exists the argument that climate change could produce some adverse effects, but likely will not generate severe consequences such as interstate conflict. In best case scenarios, this will be true. However, the current trend is far from a best case scenario, and the 'business as usual' path is closer to a worst-case scenario. Projections currently are that we will very likely hit 1.5 ^{o}C warming in 2050, resulting in the loss of arable land, destabilization of fresh water systems, extinction of species, and increased extreme weather events with heightened morbidity and mortality[10].

Third, even if there are adverse effects from climate change, war may not be one of them. There is research supporting both sides, and scholarship has yet to produce consensus on this front. With loss of resources, water scarcity, and increase in intergroup conflict, it is not hard to imagine climate change also causing some non-zero amount of militarized interstate conflict. Further, war is a complex process, and even if research shows climate change does not significantly drive it, that could take years to elucidate, while decisions effecting climate change and nuclear energy need to be made soon, so having some potential understanding of their interaction is beneficial.

Finally, there is an existing debate about whether nuclear energy causes an increase in nuclear proliferation[11]. This specific risk is quantified in Model 1, which is used so the proliferation risk from climate change has a meaningful baseline for comparison. Some might argue that the proliferation risk stemming from nuclear energy expansion is exceedingly large, such that it would swamp any nonproliferation benefits in the form of conflict reduction. Ultimately, I will use the empirical analysis described above to determine if this alternative argument is correct.

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

This research will explore a new dimension of nuclear proliferation for future nuclear energy programs. Though the relation between climate change and interstate conflict is not well understood, this research will contextualize it in understandable terms, as the inherent risk of peaceful nuclear energy is a concept most experts are familiar with. This will yield an increased understanding of how combating climate change with peaceful nuclear energy could also impact nuclear proliferation.

What do you see as your most important contribution?

The most important contribution of this research will be elucidating a new driver of nuclear proliferation that has not been well examined in previous scholarship. Although this does not determine the exact effect of climate change, it frames it via an already studied risk – it is set equal to the proliferation risk of more readily available nuclear techology, material, and knowledge. This allows policy makers and researchers to make reasonable assumptions on what climate change could do to the nonproliferation regime while more quantitative analysis develops.

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

The research aims to make one of two potential policy recommendations, based on the end result of the research. A low value of the required relation between climate change and conflict suggests climate change could meaningfully increase the risk of weapons proliferation. In that case, policymakers should pursue further peace agreements between countries with nuclear energy programs. A high value suggests that substantial climate change will not increase threat of proliferation, thus policy makers could pursue promoting peaceful nuclear energy to abate climate change with confidence of the existing proliferation risk.

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 most vulnerable aspect of this research is that it attempts to conjoin several moving parts, which can exacerbate errors and decrease the plausibility of causality. Further, it can be too complicated to derive meaningful results in only a year timeline. Feedback on keeping the research coherent while coordinating these parts, along with any advice on strengthening the stated arguments against the identified alternative arguments in the previous section, would be most valuable.

1) Singh, S. and Way, C. The Correlates of Nuclear Proliferation: A Quantitative Test. *J. Confl. Resolut.* **48**, 859-885 (2004).
2) Dong-Joon, J. and Gartzke, E., Determinants of Nuclear Weapons Proliferation. *J. Confl. Resolut.* **51**, 167-194 (2007).
3) Hsiang, S., Burke, M., and Miguel, E., Quantifying the Influence of Climate on Human Conflict. *Science*. **341** (2013).
4) David Goldfien to United States, Senate, Committee on Armed Services, 4 April 2019.
5) Kairat Umarov, United Nations, Statement by the President of the Security Council, 30 January 2018.
6) Ban Ki-Moon, United Nations, Statement by Secretary-General, 20 July 2011.
7) Sakaguchi, K., Varughese, A., & Graeme, A. Climate Wars? A Systematic Review of Empirical Analyses on the Links between Climate Change and Violent Conflict. *Int. Stud. Rev.* **19,** 622-645 (2017).
8) Furhmann, M., Spreading Temptation: Proliferation and Peaceful Nuclear Cooperation Agreements. *Int. Security*. **34**, 7-41 (2009).
9) IAEA. Climate Change and Nuclear Power. (2018).
10) IPCC. Global warming of 1.5°C: Summary for Policymakers. (2018) [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]
11) Miller, N. Why Nuclear Energy Programs Rarely Lead to Proliferation. *Int. Security*. **42**, 40-77 (2017).

2. Heather Williams, MIT SSP

Asymmetric Arms Control: Emerging Technologies and Nuclear Competition

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

This research project will address three primary questions. 1) Why do states participate in arms control for emerging technologies? 2) What are the implications of these drivers for how future cooperation might unfold? 3) What do arms control agreements of emerging technologies look like in practice, particularly in accounting for strategic asymmetries and their relationship with nuclear weapons?

In principle, arms control is least likely where it is most needed. On the one hand, emerging technologies have the potential to undermine strategic stability and increase nuclear risks, therefore arms control could play an important role in managing those risks. On the other hand, states are unlikely to limit development of an emerging technology while in competition with others, therefore arms control is unlikely to be desirable or achievable.

Understanding this paradox and how it will shape future strategic arms control agreements will require new analytical and empirical tools. These questions are important because technological improvements present new challenges to strategic stability and could incentivize crisis escalation and arms racing.[1] This has been highlighted in recent scholarship, such Acton's work on "entanglement,"[2] Lin's research on cyber escalation[3], and others exploring the impact of emerging technology on strategic stability.[4]

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

Is arms control a valuable tool for preserving strategic stability between strategic competitors as they pursue emerging technologies?

This research takes a broad definition of arms control as a tool for managing weapons and military technology. The project focuses on arms control efforts to limit the deployment or application of a technology, rather than attempts to outright ban an emerging technology altogether.[5] Chris Chyba recently defined an emerging technology as, "one that has not yet been overtly significantly deployed by any nation's military, so that its effects on strategic stability are still largely in prospect."[6] For the purposes of this research, I will be focusing on hypersonics, cyber, and artificial intelligence (AI).

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[1] I use the Schelling and Halperin definition of strategic stability as crisis stability and arms race stability. Thomas Schelling and Morton Halperin, *Strategy and Arms Control* (Boston: Brassey's, 1985 [1960]).
[2] James Acton, "Escalation through Entanglement: How the Vulnerability of Command and Control Systems Raises the Risks of Inadvertent Nuclear War", *International Security*, 43:1 (Summer 2018), pp. 56-99.
[3] Herbert Lin, "Escalation Dynamics and Conflict Termination in Cyberspace", *Strategic Studies Quarterly*, 6:3 (2012), pp. 46-70.
[4] See, for example, Christopher Chyba, "New Technologies & Strategic Stability", *Daedalus*, 149:2 (Spring, 2020), pp. 150-170; and *Journal of Strategic Studies* special issue 42:6 (2019).
[5] For a useful discussion of bans on emerging technology, see Paul Scharre, *Army of None* (London: W. W. Norton, 2018).
[6] Chyba

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

The project will first develop two sets of hypotheses. First, it will hypothesize that states pursue arms control of emerging technologies for different reasons from established technologies (e.g. economic factors are a more prominent driver in arms control of emerging technologies). Second, it will hypothesize that arms control of emerging technologies will look different from arms control of established technologies (e.g. states prefer more flexible arms control agreements, such as limited verification, of emerging technologies).

To test these hypotheses I will apply two frameworks to historical cases of arms control of emerging technologies and contemporary cases wherein emerging technologies have the potential to upset strategic stability, drawing on secondary sources. Historical case studies include the1899 and 1907 Hague Conventions, 1922 Washington Naval Treaty, and efforts to control the neutron bomb. These case studies were selected because there are relatively few historical examples of arms control incorporating emerging technology, but these capture variation in geopolitical context, number of members, and arms control format. Contemporary cases include NATO-Russia, US-China, and India-Pakistan as three strategic competitions between nuclear possessors that are poised to be impacted by emerging technologies

The first framework to be applied to the cases will consider the security, economic, and ethical drivers of arms control of emerging technologies. These drivers were selected based on classical arms control theorists, such as Schelling and Halperin[7], Bull[8], and Brodie[9], who explored why states engage in arms control not only for security reasons, but also for economic and ethical ones. The second framework, asymmetric arms control, will identify how states account for emerging technologies' impact on strategic stability. I first published this framework in 2019 in the *Journal of Strategic Studies*,[10], which identified arms control options to include asymmetry of reductions (one side must reduce more than another, e.g. New START); asymmetry of ceilings (one side has a higher limit than another, e.g. SALT); and asymmetry of domains (a non-like-for-like exchange of one capability for another). The framework will identify the design of historical arms control cases and options for contemporary ones.

What is your answer to the question you are asking?

Although arms control of emerging technologies is challenging for the reasons outlined at the outset, states can still benefit from arms control for economic reasons. States decisions' to engage in arms control of emerging technologies, therefore, depends on whether or not these economic benefits outweigh the challenges and potential risks to strategic stability of limiting technologies which are intrinsically difficult because many of these technologies cannot be "counted", their impact remains unknown, and verification would be particularly challenging.

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[7] Schelling and Halperin, *Strategy and Arms Control.*
[8] Hedley Bull, "Arms Control and World Order", *International Security*, 1:1 (Summer, 1976), pp. 3-16.
[9] Bernard Brodie, "On the Objectives of Arms Control", *International Security*, 1:1 (Summer, 1976), pp. 17-36.
[10] Heather Williams, "Asymmetric arms control and strategic stability: Scenarios for limiting hypersonic glide vehicles", *Journal of Strategic Studies*, 42:6 (2019), pp. 789-813.

Arms control of emerging technologies will not lead to arms race stability as states will continue to compete within the confines of an agreement. Additionally, arms control of emerging technologies will not necessarily lead to crisis stability because of the increasingly complex nature of crises due to technological innovation. Asymmetric arms control *can* strengthen crisis stability, but it must also keep arms control in the broader geopolitical context, as argued by Trachtenberg.[11]

How does your work fit into the existing work on your subject? What alternative arguments or explanation exist and why is your answer superior?

This work aligns with recent scholarship by Cameron[12] and Green[13] that demonstrates states continued to pursue strategic competition within the constraints of the ABM Treaty and SALT process. It builds on recent research by Coe and Vaynman into impediments to arms control, whereby verification may prove particularly challenging for emerging technologies and therefore could undermine confidence in compliance.[14] It will also draw upon recent research into arms control drivers and design, such as Kreps,[15] by arguing that arms control of emerging technology is driven by economic factors, which have received relatively less attention in scholarship.

An alternative explanation would be that normative factors are the primary driver of arms control of emerging technologies and arms control agreements should be designed to strengthen norms.[16] My approach is more holistic, wherein norms are captured in ethical drivers, and accounts for variance in states' motives.

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

The majority of scholarship on emerging technology focuses on risks to strategic stability. This project is intended to improve our understanding of ways to manage those risks, specifically their impact on arms race stability and crisis stability. Additionally, risks of emerging technologies are typically treated in isolation and focus on a single technology or platform; whereas I will focus on the intersection of these technologies and nuclear weapons.

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

The research will inform future arms control efforts, such as a follow on to the New Strategic Arms Reduction Treaty (New START), trilateral arms control, and multilateral efforts to manage nuclear risks, such as in the Nuclear Non-Proliferation Treaty. At least three policy recommendations can be anticipated. First, the United States, Russia, and China should enter into an arms control agreement to ratio limits on

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[11] Marc Trachtenberg, "The Past and Future of Arms Control", *Daedalus*, 120:1 (Winter, 1991), pp. 203-216.
[12] James Cameron, "What History Can Teach", *Daedalus*, 149:2 (Spring, 2020), pp. 116-132.
[13] Brendan Rittenhouse Green, *The Revolution that Failed* (Cambridge: Cambridge University Press, 2020).
[14] See, also, Andrew J. Coe and Jane Vaynman, "Why Arms Control is So Rare", *American Political Science Review*, 114:2 (May 2020), pp. 342-355.
[15] Sarah Kreps, "The Institutional Design of Arms Control Agreements", *Foreign Policy Analysis*, 14:1 (January 2018), pp. 127-147.
[16] See, for example, Nina Tannenwald, "Life beyond arms control: Moving toward a global regime of nuclear restraint and responsibility", *Daedalus*, 149:2 (2020), pp. 205-221.

their means of nuclear delivery (asymmetric ceilings), to include hypersonic glide vehicles, cruise missiles, and ballistic missiles. Second, competitors should focus on developing crisis communication channels rather than formalized arms control of emerging technologies, particularly for cyber and AI. Third, an international commission should be established to identify the most dangerous applications of emerging technologies, similar to the Hague Conventions.

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 planned to rely on secondary sources, but are there any primary sources, such as archival work or interviews, that might be valuable and which I can do remotely?
- What does this mean for crisis stability? On the one hand, states might pursue arms control for economic benefits, which might create channels of communication and transparency to promote crisis stability. On the other hand, they will still be engaging in competition so first strike incentives might still exist.
- Arms control typically takes time to negotiate and finalize, but technology is moving at such a rapid pace that arms control might struggle to keep up. I believe arms control needs to become more flexible and dynamic, but I'm not sure what that looks like in practice just yet.

3. Aditi Verma, BCSIA

Nuclear safety, risk and epistemic inclusivity: Towards a new taxonomy for expert-public discourse for informing technology and policy design

Premise: the need for epistemic inclusivity in technology and policy design

Nuclear energy has, since its inception, posed significant moral dissonances with the socio-economic contexts in which it is embedded and generally had a tumultuous relationship with society writ large.

Despite the moral dissonances it poses, nuclear energy is nevertheless increasingly held up as a promising contributor in global efforts to radically reduce greenhouse gas emissions, with practitioner and policymaker efforts chiefly directed at developing new technologies and securing public acceptance through outreach and education efforts. The premise of this work is that future nuclear energy technologies and their institutional infrastructures, whatever they may be and if they are at all, must be designed in collaboration with publics such that they are democratic, justice-oriented and epistemically inclusive.

Central argument: codifying the expert's privately held understandings of risk

The lack of epistemic inclusivity in the processes for designing nuclear technologies can be attributed to the antagonizing expert-public divide which, particularly within the nuclear field, leads experts to falsely view themselves as perfectly rational, optimizing agents and exclusively value their own views while construing the public as irrational and public views as not worthy of being included in design processes of technologies and institutions. I argue in this work that the ways in which experts conceptualize risk do not differ so greatly from those of the publics'[i] and that examining and codifying the experts' privately held, nuanced and thus far uncodified understandings of risk is a first essential step towards achieving epistemic inclusivity in the designs of technologies and their governance institutions.

Towards inclusive design practices

While these problems of excluding public views from the design processes of technologies and institutions are not unique to nuclear energy, they are especially acute for the nuclear field. Designers of technologies and policies rarely, if ever, consider who gets to do design, who these artifacts and institutions are being designed for, whether mechanisms of accountability are enfolded in the design process and what values are encoded in the artifacts and institutions that are being designed (Costanza-Chock 2018). This lack of inclusivity in the nuclear field is especially jarring because, in other fields of engineering, these questions are increasingly being considered in the process of design of a range of artifacts and systems in order to place publics and users at the center of the design and governance of material and non-material artifacts and make design a more collaborative, open, inclusive and participatory process (Muller and Kuhn 1993; Friedman 1997; Costanza-Chock 2020). While these intellectual premises are relatively novel and still-evolving, they have so far received little traction within the nuclear field.

Nuclear energy and the origins of the expert-public divide

The origins of the expert-public divide, particularly in the nuclear energy field can be traced to the earliest psychometric studies of risk whose launch coincided with the development of the earliest nuclear energy technologies. In a seminal study published over 50 years ago, Starr examined which risks society was willing to bear and which risks would be unacceptable (Starr 1969). Starr's findings suggested that the risks from nuclear accidents, being involuntary, were much less acceptable to the public[ii] than risks over which the public had greater control. He suggested that risky technologies could secure public acceptance either through the design of significantly safer technologies or by creating a public awareness of the benefits of the risky activity – effectively educating the public. The US, and to a large degree, the global nuclear industry, chose the second, epistemically exclusionary approach, and these early psychometric studies of risk perception motivated the development of probabilistic risk assessments as tools for the assessment of reactor safety (Wellock 2017). However, repeated attempts by practitioners and policymakers to educate the public using quantitative estimates of risk have met with very limited success.[iii] Recent writings on risk suggest that public mistrust of risky technologies is likely the result of mistrust of experts. Thus, direct attempts by experts to gain public trust are unlikely to succeed (Kahan et al. 2011). Another line of work suggests that a policy response to the amplification of risk or the neglect of probability in the public consciousness ought to be to reduce risks below levels suggested by cost benefit analyses (Sunstein 2002). Within the broader literature on risk, authors have frequently called for a greater attention to both the qualitative as well as quantitative dimensions or 'cultures' of risk analysis (Jasanoff 1993).[iv] The nuclear energy field, particularly academic nuclear engineering, nevertheless continues to reify the purely quantitative treatment of risks, while having intellectually severed itself from the broader field of risk studies which has evolved significantly since the 1970s – which is the iteration that academic nuclear engineering still largely and, often exclusively, draws on. The nuclear field has, in other words, has created an analytical monoculture of risk premised on the false assumption that an ex-ante determination of best practices is possible. As Bronk and Jacoby (2016) argue, it is dangerous for experts to have their behavior and analysis structured by an identical set of norms and conceptual grids, particularly under conditions of uncertainty when high correlations in unforeseen errors and analytical blind spots can lead to systemic instability.[v]

The irrational expert?

In my doctoral dissertation work, on which this project builds, I studied the design practices of contemporary (1980-2015) nuclear reactor designers in the US and France across 32 distinct nuclear reactor design projects. This work drew on theoretical and methodological resources from sociology and history of technology (Hecht 2009; Schmid 2015) as well as design studies (Schon 1983; Dorst and Dijkhuis 1995). As part of this work I traced the design histories of these 32 projects through in-depth semi-structured interviews, patent filings, technical reports, journal articles, company websites and publications in the trade press. Although nuclear reactor design is recognized as an essential skill and intellectual output of academic nuclear engineering, little attention has been paid within the discipline to the structure of the reactor design process and factors influencing design outcomes. This work, which marked the first systematic study of nuclear reactor design practices, showed the diverse ways in which reactor designers make decisions about risk and safety in the earliest stages of technology design and repudiated five central myths long held within academic nuclear engineering. These are:

1. Design is a linear process of quantitative problem-solving
2. Design is a strictly rational and analytical process in which designer identify, situatedness and affect play no part
3. Experts, including designers of nuclear reactors, are perfectly rational, optimizing agents
4. Experts and publics think differently about risk and safety and the expert conceptualization of risk is the correct one
5. A homogenous analytical culture of and single definition of safety must exist, is desirable, and should be aimed for via epistemic and institutional convergence (often referred to as "harmonization")

Instead, through this work, I observed that designers, while generating ideas for nuclear reactor designs broadly and safety systems specifically, conceptualized safety qualitatively rather than quantitatively. These conceptualizations of safety were contingent on the type of design setting and the designers' own backgrounds. Further, the designers' accounts of the design process suggested that it was precisely these qualitative ways of thinking about design that led them to novel design ideas and ultimately to achieving advances in safety in their respective designs. Additionally, the varied and diverse accounts of safety held by the designers which were documented in this work bore striking similarities to the views of publics and non-experts as reported in the literature on risk perceptions.

An especially salient example from this work is about how reactor design practices changed in the aftermath of the Fukushima Daiichi accident. I find that American reactor designers in particular, working in relative isolation from each other and not having a coherent design community, had individual experiences and interpretations of the causes of the 2011 Fukushima accident such that the accident made a different set of flaws salient to each designer in unique ways, and in seeking to remedy those flaws, the designers adopted diverging technological responses to the accident, thus imagining multiple ways of creating and thinking about 'safety' (Verma 2018).

Proposed work

Collectively the findings above suggest an opportunity for an expert-public dialog based on more epistemically inclusive conceptualization risk that transcends the long-held and exclusive emphasis on irts quantitative dimensions. A more collaborative dialog among expert and publics could be helpful not only for folding the public's risk imaginaries and preferences into policies for the governance of risky technologies, but further, the public's understandings of risk could be used to develop more participatory and inclusive design processes for technologies and institutions.

As part of my dissertation work I interviewed designers from 27 American and 5 French reactor design projects. In addition to several secondary sources, the over 500 pages of interview transcripts were the primary source of data for my work. For this project, I propose to add to these interview records, and code the interview transcripts using a grounded theory approach (Glaser 1992; Charmaz and Belgrave 2007) to generate a taxonomy for describing nuclear safety as understood by the nuclear reactor designers themselves. The purpose of this taxonomy would be to illustrate to the experts – the reactor designers – how their conceptualizations of risk, particularly when they are most consequential in the early, foundational stages of design, already transcend the quantitative dimensions and that reactor designers do not in fact think of risk as a product of consequence and probability particularly when they are making the most significant design choices. In later stages of this work, design and survey experiments will be used to explore the efficacy of this taxonomy for creating heuristics for framing design work, for its inclusion in nuclear engineering pedagogy and the potential for its use in dialogs among experts and publics.

Impact and Policy Implications

Engineering pedagogy, practice and technology policy have traditionally privileged, even reified, quantitative measures of risk for risk-related decision-making, thus creating an analytical monoculture of risk and an antagonizing expert-public divide. This project proposes that that a new taxonomy of risk that codifies the experts' tacit understandings of risk may help reveal that experts and publics do not think so differently about risk and that this shared epistemic ground could become the basis for more inclusive and participatory design of technologies and governance institutions.

Endnotes

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[i] I say "publics" and not "public" because the public is itself not a homogenous whole.

[ii] Starr treats the public as a homogenous whole.

[iii] The US Atomic Energy Commission initiated the Reactor Safety Study expecting that probabilistic risk assessments, once developed, could be used to demonstrate to the public that reactors were safe. The executive summary of the Reactor Safety Study (NRC 1975) which compared the risks of nuclear reactor accidents to other hazards, and which drew wide criticism was modeled after and inspired by the psychometric risk perception studies (Wellock 2017).

[iv] For a compilation of these studies see (Krimsky and Golding 1992). Risk analysts, including authors of the early risk perception studies have, in their recent work, called for a shift in emphasis from policy and practice deriving from the measurement of risk, to the broader questions about understanding how societies construe what makes for an acceptable technology (Otway and Von Winterfeldt 1982; Slovic et al. 2004). For a broader treatment of the subject of risk and responsibility see (Giddens 1999).

[v] These ideas are echoed in studies of law and more broadly in the political science literature that calls for plurality of institutional forms. These authors make the case the homogenous analytical cultures are undesirable especially because they often inform the designs of critical institutions (Ewick and Silbey 2002; Ostrom 2009; Sabel and Zeitlin 2008).

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