NUCLEAR TECHNOLOGY · VOLUME 207 · iii–xv · SEPTEMBER 2021

DOI: https://doi.org/10.1080/00295450.2021.1941663

The Nuclear, Humanities, and Social Science Nexus: Challenges and Opportunities for Speaking Across the Disciplinary Divides

Aditi Verma[a,b]*

[a]*Harvard University, Kennedy School, Belfer Center for Science and International Affairs, Cambridge, Massachusetts*
[b]*University of Michigan, Department of Nuclear Engineering and Radiological Sciences, Ann Arbor, Michigan*

I. INTRODUCTION

It is my pleasure to introduce and frame this *Nuclear Technology* special issue, "The Nuclear, Humanities, and Social Science Nexus: Challenges and Opportunities for Speaking Across the Disciplinary Divides." This special issue features 13 papers authored by humanists and social scientists who, though each rooted in distinct and rich scholarly traditions, share with each other an interest in the nuclear energy sector. These scholars adopt an intellectually diverse set of theoretical and methodological lenses to examine the work of nuclear energy practitioners and policy makers.

The central aim of this special issue is to explore how research findings and insights from the humanities and social sciences can be used to shape and meaningfully inform the work of practitioners and policy makers in the nuclear energy sector and its corresponding areas of research and practice—all of which presently, in many ways, simultaneously face several challenges and opportunities and find themselves at a crossroads.

Nuclear energy's challenges are frequently (and have long been) described as having a significant "social" dimension. These challenges, as interpreted by nuclear engineers, include failures to site nuclear power plants and used nuclear fuel repositories, or more broadly, to secure support and approval for sustaining or expanding the use of nuclear energy. A negative perception of nuclear energy is frequently cited by nuclear engineers as the source of these challenges. Still other problems are believed to be the result of institutional failures and managerial difficulties. These include delays in construction projects and escalation of plant costs, the slow pace of development and commercialization of new nuclear energy technologies, and failures of regulatory institutions.

In spite of, or perhaps because of, these challenges, organizations in the nuclear energy sector have, since their inception, proved to be rich research sites for scholars in the humanities and social sciences. In a significant and growing base of scholarship, researchers—historians, political scientists, sociologists, anthropologists, and science and technology studies (STS) scholars—have used a diverse, rich, and increasingly sophisticated set of theoretical and methodological approaches to examine the work of practitioners in nuclear organizations.[1–5]

Some concepts developed by social scientists have proved to be pivotal for the work of practitioners in the nuclear sector. For example, the idea of an organization that is capable of rapid and continuous learning—operationalized by the Institute of Nuclear Power Operations and World Association of Nuclear Operators for the nuclear industry—comes from a long line of sociological and management research on "high-reliability organizations."[6,7] Further, the idea that culture can play an important role in ensuring safety also finds its basis in a long tradition of sociological and anthropological research on culture. However, these concepts are often not used as the humanists and social scientists intended or used instrumentally.[8]

They undergo modification in their translation from research to practice, and their uptake and use by practitioners and policy makers in the nuclear sector have largely been serendipitous. Further, while social science scholars have produced a growing and increasingly relevant literature, it has not received significant attention from academic and practitioner nuclear engineers, nor has it really made its way into the intellectual canon of nuclear engineering and its pedagogy. This special issue as a whole, and each of the papers in it, seeks to bridge the intellectual divides between the nuclear sector and the researchers who have long studied its work and practices.

The purpose of this introductory paper is to synthesize the findings across the papers that appear in this special issue, draw connections across them, and point to some potential areas of future collaboration across nuclear engineering, humanities, and the social sciences.

*E-mail: aditi_verma@hks.harvard.edu

II. THIS SPECIAL ISSUE AND ITS CONTRIBUTIONS: REFRAMING FAMILIAR PROBLEMS

The papers that appear in this special issue seek to expand and reframe how we understand familiar problems and areas of work in the nuclear sector ranging from the very design of reactors to the disposition of nuclear waste. The sections that follow begin by laying out our traditional and familiar understandings of work in the nuclear sector and then compare these framings to the ways in which they are described and reframed by the authors of the papers in this special issue.

II.A. Reactor Design

Nuclear engineering recognizes reactor design as a central skill and intellectual output of the discipline. To this end, nuclear engineers, as part of their education at both the undergraduate and graduate level, are trained in the scientific and engineering fundamentals of the field. Reactor physics, thermal hydraulics, structural mechanics, computation, and materials science are all mainstays of a nuclear engineering education. Much less attention, if any, has typically been paid in the discipline's research and pedagogy to the social dimensions of design. How the designers' imagination and expertise, the organizational site of the design work, and the institutional environment all shape the design process and its outcomes are seldom examined or theorized.[9] Elsewhere, a large and growing body of work in the field of STS (Ref. 10) as well as design research[11,12] (a subfield of mechanical engineering) has consistently emphasized the importance of understanding the design process in all its richness and complexity and making sense of the social factors that shape design outcomes. In their papers in this special issue, Tillement and Garcias[13] and Schmid[14] draw our attention to precisely these determinants of design outcomes.

Tillement and Garcias observe that a close study of nuclear reactor design projects "from the inside" makes it possible to understand the causes of their successes and failures. Such knowledge may be particularly helpful at a time when nuclear energy is being seriously considered as a low-carbon source of energy in many countries and at a time when a large number of reactor design projects are in relatively early stages of development. In their paper, Tillement and Garcias study the development of ASTRID, a French Generation IV sodium-cooled fast reactor whose development began in 2010 and which was terminated in 2019. The authors studied the development of this reactor from 2015 to 2019 inductively through interviews with the reactor's designers. Through their in-depth case study, the authors explore the causes of the project's termination. In so doing, they draw on the concepts of scale and alignment from the literature on large infrastructures. They find that the failure of this particular reactor project, and its eventual suspension, can be attributed to three forms of scale misalignment—temporal, social, and physical—and more specifically to the increasing complexity and ambiguity faced by the reactor's designers. ASTRID, as an example of a nuclear reactor design project pursued for a substantial period of time and ultimately suspended, does not represent an exception but rather the norm in the nuclear sector. Another recent notable example of a French reactor design whose development was ultimately terminated is the Flexblue small modular reactor (SMR). Across the Atlantic, in the United States, such examples abound. The most notable, though not the most recent, among them perhaps is the Next Generation Nuclear Plant project whose development was halted at the demonstration phase. More recent examples of reactor projects that have been suspended for various reasons after initial periods of sustained effort include the mPower reactor, the Westinghouse SMR, and the Transatomic molten salt reactor, to name a few.

Nuclear reactor design projects are resource-intensive efforts. When pursued to completion they can cost upward of hundreds of millions of dollars in the design and regulatory licensing phases alone and require hundreds of thousands of work hours. Only a handful of reactor design projects, particularly in the recent past, have successfully been pursued from idea to new build.

The causes of failure and termination of reactor design projects are not always clear, are numerous, and are seldom clearly understood even by those who are directly involved in these projects. Further, those involved in the project or in its ultimate cessation may even find that it is in their best interests to misrepresent the causes of the project's failure so as to shift responsibility away from organizations and institutions that must carry on their work well after the project in question has ceased to be. Tillement and Garcias, by inductively developing their theoretical framework of scale misalignment, make an important contribution by proposing a new lens through which to make sense of the successes and failures of reactor design and development projects. Ultimately, for reactor design projects, or for that matter, the design and development of any complex technology to succeed and be seen in society writ large as a success, they argue that scale alignment work is necessary.

In her paper, Schmid asks us to reconsider how we frame the parameters by which design projects are deemed to be successes and failures. Schmid first describes the development of the RBMK reactor design in the Soviet Union. Retrospective narratives of the reactor's development justify the development of the RBMK design in the Soviet Union because of its cost effectiveness. By drawing on archival research, interviews, and trade publications, Schmid shows here and elsewhere[3] that the RBMK was in fact not a cost-effective design even when it was first conceived. A range of other considerations, including the perceived safety and modularity of the design, led to the adoption of the RBMK as the reactor technology to be pursued for standardization and large-scale deployment in the Soviet Union. Schmid writes that technological designs are seldom chosen purely for their techno-economic characteristics. However, these fuller, richer, and often more complicated narratives describing trajectories of technological design and evolution are often forgotten, leaving future generations of designers and engineers with falsely linear narratives of technological evolution and development.

Sociologists and historians of technology have shown that such mechanisms of forgetting the true course of technological evolution may be integral to the process of technology design and development. Technologies, when they are first created, are born under conditions of great uncertainty. Their designs, particularly when they are first of a kind, have significant potential for improvement. As a new technology is developed and evolved by its designers, some of the flaws inherent in the initial designs are addressed in substantive ways as the machines and systems themselves are improved. However, it is seldom possible to exhaustively address every flaw and weakness in a technological design. When this turns out to be the case, weaknesses of the design may be solved partially substantively and partially rhetorically.[10] For example, designers of reactors do not (and cannot) design reactors to be absolutely safe. Many vulnerabilities to accidents, when first identified, may be addressed through changes to designs and nuclear safety regulations. Other vulnerabilities, for a variety of reasons, including the low presumed probability of occurrence or high costs and substantive design changes needed for redressal of flaws, are solved rhetorically. One example of this is the historic treatment of some accidents as being within the "design basis" of a reactor and of others as being beyond design basis.

These rhetorical mechanisms of closure lend stability and credibility to a technology. In the case of complex technologies such as nuclear reactors, these forms of closure may be written more durably into the institutional frameworks, such as nuclear safety regulations, that govern the designs. While such forms of stability and closure may be necessary for bringing (and keeping) new technologies into the world, these closure mechanisms obscure the complex and rich histories of technological development, making it difficult, if not impossible, to learn from past experience. Instead of instituting these sanitized and stripped-from-context stories of technological development, we should, as Schmid implores, acknowledge the socioeconomic, political, and cultural factors that shape the development of new technological designs. Effectively, Schmid calls on designers and developers of nuclear reactor technologies to render visible the scale alignment work that makes it possible to transform paper reactors into real reactors and for those real reactors to work. Indeed, a central contribution of Schmid's paper is to show that a broader awareness of the context in which design choices have been made is likely to illuminate new courses of action—be they in improving an existing design or in the development of future ones.

II.B. Reactor Commercialization: From Design to Market

There has, of late, been a policy turn in engineering schools and departments, and increasingly engineers have become interested in studying policy and developing policy recommendations for the development of new technologies. However, much of our thinking about how to design policies is premised on a linear model of innovation—a model that has many times proven to be false or only partially correct.[15] According to the model, innovation begins with basic research, which then stimulates applied research, development, and finally technological diffusion.

The model is often attributed to Vannevar Bush, who headed the U.S. Office of Scientific Research and Development during the Second World War and was a prominent science advisor in the postwar period. In 1945, Bush wrote about the relationship between basic research or fundamental science and applied research that leads to technological innovation. Economists and management scholars seized on Bush's postulated relationship between science and innovation, developing it into the linear model of innovation as we know it today. The model, though proven to be false through many empirical analyses, nevertheless persists today, in large part because of its simplicity and amenability to statistical analysis.[15] It is important for us to acknowledge, understand, and critique this model because it shapes how we think about technology and policy, including in the nuclear energy sector, and where we direct our attention and resources when we analyze prior policies or set out to create new ones. This linear model of innovation compels us to think about how to progress from one stage of innovation to another, through securing funding or through securing public support. In other words, the model directs our attention to the actions needed to push or pull a technology from one stage of development to another and to quantity of innovation and not to the quality of it. As Tillement and Garcias and Schmid have counseled us, we must open the technological black box at every stage of design and development and subject our own framing, design, and policy choices to greater scrutiny. We must understand how the environments in which we operate as engineers and designers influence our decisions, and whether those decisions, as we make them, are in the best interest of the society we intend to serve through our work. To this end, when we set out to develop new technologies or examine our failures to develop and commercialize prior ones, we must move our diagnosis of commercialization failures, prospective and retrospective, beyond the linear model. In their papers in this special issue, Lehtonen[16] and Iakovleva et al.[17] show us how to do just that.

Nuclear reactor construction projects are arguably the archetypal example of a megaproject and have been prone, particularly in the recent past, to what some scholars have described as "megaproject pathologies."[18] These pathologies frequently manifest as the failures of the projects to meet cost estimates, forecasted schedules, and predefined project prescriptions—sometimes also referred to as the "iron triangle" criteria.[19] Simplistic accounts of innovation grounded in the linear model are unlikely to provide satisfactory explanations for the occurrence of these pathologies. Lehtonen, in service of answering this question, draws on framing theory and megaproject scholarship to examine the megaproject pathologies of nuclear plant construction projects. Specifically, using these theoretical lenses, he examines how the staff of an international agency, in this case the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency, diagnose the causes of the megaproject pathologies. This analysis reveals four frames as well as two meta frames. Lehtonen's interlocutors argue that a vicious circle of inadequate investments, the bureaucratization and contractualization of complex infrastructure projects, broken markets that do not incentivize infrastructure investments, and the complexity and exceptionality of the nuclear sector explain megaproject failures. They further contend that limited support from political leadership and aversion to project risk in Western societies exacerbate the failures of megaprojects. While an analysis of the relative role of these frames is beyond the scope of this paper, Lehtonen's contribution is to propose that the conversational process of frame generation and testing, or "frame reflection" as he calls it, serves an important purpose in that it subjects megaprojects and their failures to an ongoing mode of inquiry that is likely to yield fresh insights on which future projects may build, if they are to be built at all. Lehtonen concludes that the country peer review system frequently used by the OECD agencies, as well as other international organizations, may be a particularly good mechanism of frame reflection as an ongoing diagnostic tool for the nuclear practitioner and policy-making community to evaluate the successes and failures of megaprojects.

Looking to the future, Iakovleva et al. turn to sustainability transition studies to draw lessons for the development of future nuclear reactor technologies, specifically SMRs. Within the body of work they survey as part of their paper, the authors specifically focus on the strategic niche management and technological innovation systems literatures. They study this literature, both technology development case studies as well as review articles, with the specific goal of identifying policy-relevant recommendations that can be applied to scaling SMR designs from prototype to commercial production. The authors conduct this study with a particular focus on SMR development in Canada. This literature yields a number of interesting findings for SMR development having to do with the role of technology roadmaps, incumbents, and intermediaries. For example, technology roadmaps, while important instruments of technology policy and sustainability transitions, are alone insufficient to orchestrate the transitions or the commercialization of a new technology. The authors are of the view that this applies to SMR development in Canada as well. These technologies are unlikely to be deployed unless the political dimensions and obstacles are also addressed. The studies reviewed by the authors also point to the vital role of intermediaries who connect learning processes across niches, facilitate access to investment, navigate the regulatory environment, and connect innovations across both local and global scales. The authors identify publicly owned utilities and regional ministries as two possible intermediaries that might have an important role to play in the Canadian context of SMR development. Finally, the review also reveals a nuanced and potentially early-adopter role that incumbents may be able to play in sustainability transitions and the adoption of new technologies. Additionally, the review also points to the importance of framing (as

Lehtonen does) as well as spatial path dependency in the process of technology development.

Together, these two papers shift our attention away from the linear model of innovation to the intricacies of systems of innovation made up of institutions, actors, and organizations that have national and regional specificities.

II.C. Economics and Financing: From Market to Build

Nuclear plant construction projects are capital-intensive undertakings. Decisions about whether or not to build a new plant necessarily accompany extensive and in-depth economic and financial analyses. Such economic analyses are often mistakenly treated by their audiences (indeed as intended by the authors of such analyses) as objective and impartial. Instead, a significant body of work in the field of economic sociology has found that the results of such analyses are context dependent, and the very act of quantification and analysis may often be carried out as an exercise in persuasion.[20] Saraç-Lesavre[21] and Ialenti[22] urge us to look inside the black box of such analyses instead of reifying them, as is often the case.

In her paper, Saraç-Lesavre examines the process through which nuclear investments are valued and revalued. Specifically, she studies the process through which different groups of analysts have sought to place a value on electricity generated using open versus closed fuel cycles. She identifies two styles of revaluation invoked to calculate the levelized cost of electricity for closed fuel cycles in the United States during the George W. Bush administration and the early years of the Barack Obama administration. Saraç-Lesavre argues that each of these styles of revaluation seeks to quantify different moral values and that they are used by analysts with different audiences in mind. The first style of revaluation, which Saraç-Lesavre terms "monetary figures of dissent," is intended for an audience of policy makers. This style translates moral and political values inherent in the fuel cycle technologies into numerical estimates. Under the second "return on investment" style of revaluation, whose intended audience is investors, the profitability of investments takes center stage. Technology designers and policy analysts frequently may choose instrumentally from among these (and other) styles of revaluation depending on the intended audience, thus, at least in part, carrying out a performative analysis as a way to achieve an intended policy decision goal. Saraç-Lesavre's analysis suggests that while such styles of revaluation are undoubtedly extremely useful, their continued usage as a basis for policy making should be accompanied by making their implicit logics and values explicit. Instead of seeking to make technology policy decisions on the basis of neat numerical values that the use of any single style alone may yield, decision makers should use a broader repertoire of styles, make sense of the assumptions and values inherent in each, and make their decisions on the basis of a more complete set of analyses, thus using them with greater transparency and humility.[23]

Ialenti examines the logics of nuclear energy infrastructure financing for the specific case of the Finnish nuclear energy companies known as mankalas. Mankalas, a Finnish organizational innovation, have long been associated with trust, cooperation, social cohesion, and transparency. These not-for-profit cooperatives bring together a diverse range of organizations, including energy- and nonenergy-based Finnish companies as well as municipal energy providers, to jointly own, finance, and purchase the output of energy-generating facilities. The unique corporate form of the mankala aligns organizational, institutional, and societal motives, creating a conducive set of conditions for building, owning, and operating large infrastructure projects, thus mitigating the megaproject pathologies described in Lehtonen's paper. In his paper, which is based on nearly three years of ethnographic fieldwork in Finland, Ialenti describes how political and economic uncertainties have destabilized the Finnish mankala model, thus having far-reaching implications and repercussions not only for Finnish energy companies but also reactor technology suppliers beyond Finland. Ialenti's central contribution is to show that an anthropological analysis of the intricacies of corporate form and project financing can yield insights that may inspire institutional innovation in the nuclear sector.

Collectively, Saraç-Lesavre's and Ialenti's papers call on us to look beyond what is an objective facade of techniques of financial valuation and to examine how implicit values and variations of corporate and institutional form shape the valuation of technologies.

II.D. Producing New Knowledge for Regulation and Nuclear Safety

A central and oft-repeated tenet in the nuclear sector is that nuclear power plants, once built, must be operated with the utmost attention to safety. Different practitioners, researchers, and policy makers, be they reactor designers, operators, or regulators in the sector, have their own unique ways of thinking about safety. This repertoire of approaches for measuring and observing safety includes its treatment as a byproduct of organizational and cultural practices (safety culture), its embeddedness in reactor design philosophy (defense in depth), and its treatment as a numerical quantity expressed as a probability of failure (probabilistic risk assessment).

Within this last category, safety as a property is frequently equated with risk, which in turn, particularly in the nuclear sector, is defined quantitatively as the product of the probability of an accident or a disaster and its consequences. Such a quantitative metric, though one measure of safety, is by no means the only possible measure or indicator of it. As reactor designers, regulators, and operators have acknowledged, especially in the aftermath of major nuclear reactor accidents, safety takes many other forms, and its presence or absence, though not easily quantifiable, is indelibly shaped by the organizational, institutional, and cultural environment in which the human and machine parts of reactor systems operate. Each major nuclear accident has made nuclear safety regulators attentive to the nonquantifiable aspects of safety. In their papers, Wellock[24] and Gisquet et al.[25] describe the pursuit of these new forms of knowledge concerning nuclear safety by two nuclear safety regulatory organizations in the United States and France, respectively. These papers are especially interesting because their authors are embedded researchers in the very organizations and institutional frameworks they seek to study. Wellock is the historian of the U.S. Nuclear Regulatory Commission (NRC). Gisquet and her coauthors work at the Institut de radioprotection et de sûreté nucléaire (IRSN or the Radioprotection and Nuclear Safety Institute) in France. The IRSN acts as a technical support organization to the French nuclear safety regulator, Autorité de sûreté nucléaire (ASN or the Nuclear Safety Authority). In their papers, Wellock and Gisquet et al. reflect not only on the pursuit of these new forms of safety-related knowledge within their organizational milieus but also the difficulties encountered in working that knowledge into organizational practice.

Wellock writes about the pursuit of organizational factors research at the NRC in the aftermath of the 1979 Three Mile Island (TMI) accident. Paradoxically, Wellock's work shows that no other nuclear safety regulator has been both more supportive and more skeptical of integrating social science research into its organizational practices. For the NRC, these reservations stemmed from its traditional emphasis on regulating "power plants not people."[24] The NRC regarded oversight of the former as regulation and therefore as lying within its purview, and the latter as management and therefore the responsibility of the plant management and staff. This principle of regulating plants and not people was, however, called into question following the 1979 TMI nuclear accident, in which, nuclear engineers generally concurred, human and organizational failures had compounded with design flaws to lead to a partial core meltdown. In the aftermath of the TMI accident and worrying events at other plants in the country, the NRC, in collaboration with behavioral experts, sought to develop methodologies to evaluate organizational culture as a proxy for safety. These research efforts, though far-reaching and well-funded, faced significant resistance from the nuclear industry and were suspended in the mid 1990s. However, the Davis-Besse vessel head erosion incident in 2002 led to a renewed emphasis on organizational culture as an indicator of and proxy for safety and as a tool for regulatory oversight, leading to a resumption of the organizational factors research that had been abandoned in the previous decade. Wellock writes that ultimately, folding the insights of behavioral theorists into the reactor oversight program granted it a stability that had long been missing.

Gisquet et al., in their paper, revisit the very notion of safety culture and propose a new cultural framework for the management and oversight of safety. New safety policies and organizational infrastructures are frequently introduced by nuclear safety regulators. How can it be known or anticipated ahead of time whether these organizational changes will in fact promote safe plant operation (as intended) or whether they may have deleterious consequences for the plant's culture, therefore negatively impacting safety? In service of answering this central question, the authors develop a three-level cultural analysis framework and illustrate its utility through a case study of the introduction of a safety management system at a French nuclear facility.

The three-level framework is composed of macro, meso, and micro levels. At the macro level it attends to the economic, political, and regulatory context within which an organization and its practices—new and old—are embedded; at the meso level it attends to the structures, systems, and tools that are used within an organization; and finally, at the micro level it examines the forms of social life and relations within the organization and how a new system or practice may impact them. The authors describe their framework as a "socio-comprehensive" approach to safety that can be used to assess how new organizational systems and practices might impact safety.

These two papers, in addition to making important empirical and theoretical contributions, also demonstrate the vital role that embedded researchers—humanists and social scientists—can play in shaping the work and practices of organizations in the nuclear sector. For these cross-disciplinary collaborations to be truly fruitful, humanists and social scientists must be invited into these organizational settings as equal partners of their scientist and engineer colleagues.

II.E. Learning from Accidents

The periods in the immediate aftermaths of accidents are inevitably times of epistemic crisis for the individuals, organizations, and institutions who have created and work with and within the technological systems in question that have experienced an accident.[26] Accidents upend or destabilize existing organizational and institutional structures as well as everyday practices and norms. Such periods of intense inquiry and sense-making continue until the "root causes" of an accident are identified and a new equilibrium of organizational and institutional forms (and indeed corporate forms) is achieved. Closer inspection of these periods of inquiry and sense-making in the aftermath of accidents reveals flaws not only in the processes of inquiry but also in the new post-accident equilibrium. Indeed, such flaws may be inevitable because post-accident learning proceeds rapidly so that the organizations and institutions may return to business as usual.[27] As a result, these hastened processes of sense-making create pressures to identify a circumscribed set of root causes, when in fact the causes of an accident may be numerous, diffuse, and systemic in nature.[28] Post-accident analyses, while leading to real learning and organizational change, can also efface the new knowledge generated by an accident, leading to the unlearning and forgetting of important lessons.[29]

In their papers, Juraku and Sugawara[30] and Kanamori[31] draw our attention to precisely such circumscribed and flawed forms of learning as they unfolded in Japan following the 2011 Fukushima Daichi accident.

Juraku and Sugawara uncover flawed learning mechanisms by using a sociological lens to examine post-accident controversies surrounding nuclear safety and emergency preparedness as they unfolded in Japan. Their paper, structured as three case studies of the use of probabilistic risk assessments, safety goals, and the System for Prediction of Environmental Emergency Dose Information, examines how each of these concepts or methodologies were used in Japan before and after the accident in 2011. The authors find that a tendency in Japan to avoid critical conflicts, a preference for automated decision making, and the overlooking of "uncomfortable knowledge" collectively characterize a form of structural ignorance in the organizational and institutional nuclear safety infrastructure in Japan. These structural forms of ignorance, as have previously been noted by other Japanese scholars,[32] cannot be separated from the social and historical contexts but must nevertheless be remediated in order to prevent and anticipate future accidents.

Kanamori, in her paper, critiques the accounting of responsibility in the aftermath of the Fukushima accident through an empirical analysis of TEPCO's accounts and post-accident business plans, as well as the documentation from the Japanese Ministry of Economy and the Nuclear Damage Compensation and Decommissioning Facilitation Corporation. This study is situated in the intellectual tradition of sociological studies of quantification (or economic sociology) as well as an accounting literature on economizing.

She argues that the economic and financial accounting of the accident's responsibility obscures the social and moral responsibility of the organizational actors involved in the accident, in this case TEPCO, thus curtailing the ability of that organization to learn from the accident.

While the empirical material on which these studies are based is drawn from Japan, the findings presented in these papers are profound and far-reaching in nature. Practitioners in the nuclear sector must work constantly, as they already do, to prevent the onset of structural ignorance and to ensure design organizations and institutions acknowledge the full range of their responsibilities, including both financial and moral.

II.F. Management of Nuclear Waste

The disposition and management of nuclear waste is typically described and understood by nuclear engineers as a technically solved problem. Though numerous viable technological solutions exist for the long-term disposition of nuclear waste, they are yet to be applied at scale in practice because the ethical, social, and political dimensions of the problem of waste management—with a limited number of exceptions—remain largely unresolved in most countries. In their papers, Kaiserfeld and Kaijser[33] and Parotte[34] examine these social dimensions of the nuclear waste problem.

In their paper, Kaiserfeld and Kaijser describe a case study with a positive outcome. The focus of their study is the Swedish Nuclear Waste System (SNWS) which had, until the 1980s, been the near-exclusive domain of scientists and engineers. The authors, through a historiography of the SNWS, describe how it underwent a change in its system culture. The change was brought about by the introduction of humanist and social scientific expertise as a result of the creation of a new advisory board, the KASAM (Samrådsnämnden för kärnavfall in Swedish), which was specifically charged with the task of widening the perspectives that had, until that point, informed the management of nuclear waste in Sweden. KASAM brought in social scientific and humanist perspectives to the SNWS by convening workshops at which scientists and engineers engaged with scholars from the humanities and social sciences. These cross-disciplinary discussions elevated the importance of the social and ethical dimensions of nuclear waste management, elements which hitherto had been underappreciated by the nuclear scientists, engineers, and decision makers. The authors posit that KASAM's activities had a tangible and durable impact on the work of the SKB (Svensk Kärnbränslehantering Aktiebolag in Swedish), the Swedish organization charged with the long-term management of nuclear waste. Increasingly, SKB began to engage meaningfully with the potential host communities of a nuclear waste repository. The growing focus on community engagement and consent ultimately led, in the early 2000s, to the identification and selection of a host community for a Swedish nuclear waste repository. This particular case demonstrates that enfolding humanist and social scientific perspectives into the work of nuclear organizations can suggest new courses of action and the resolution of long-standing challenges. However, as demonstrated by Kaiserfeld and Kaijser for the Swedish case, the shift in perspective brought about by the integration of new expertise can only be achieved through a period of sustained work and interdisciplinary collaboration, not sporadic one-off engagements.

Parotte, in her paper, examines the problem of nuclear waste management from a different perspective. She examines how the naming and classification of nuclear waste ultimately impacts how it is managed. She comparatively studies the nuclear waste classification systems of the International Atomic Energy Agency, France, Canada, and Belgium and does so by drawing on theoretical frameworks from the STS literature. She finds that the classification of nuclear wastes often leads to a prescription for how they should be managed. Yet, nuclear waste classification systems also create several "blurred" categories that include, for example, spent mixed-oxide nuclear fuel. The top-down waste classification systems that are widely used are unable to prescribe how these blurred categories of wastes ought to be managed. Parotte suggests that the existing logic of naming and classifying wastes is an inefficient approach and that it creates considerable ambiguities about how several categories of wastes (as named by these classification systems) ought to be managed. In a reversal of the extant logics, she suggests that classification systems could be developed based on a particular disposal option, instead of vice versa. This fresh approach would avoid the creation of blurred categories and corresponding dilemmas of wastes for which no clear disposal options exist.

II.G. Pedagogy

The papers in this special issue describe a number of ways in which practitioners and researchers in the nuclear sector can approach familiar, often "wicked problems"[35] with fresh perspectives. Many, if not all, of these new conceptual lenses could be brought into the training of future nuclear engineers such that they are better able to make sense of how their work and technologies are situated in society, how to grapple with the ethical, moral, political, and social challenges posed by the development and use of nuclear technologies, and having understood these challenges, how to frame the development of new technological designs and the management of existing ones in more nuanced ways that are attentive to the desires and concerns of the society we seek to serve through our work.

In an important paper that closes out this special issue, Marshall[36] describes how she has brought humanist and social scientific perspectives into a course on the practices surrounding the development and use of energy technologies. As part of the course, which is offered through the study abroad program in Engineering, Science, Technology and Society at North Carolina State University, students learn about both the social and technological dimensions of resource extraction for energy generation, the production of energy, its consumption, and the management of its byproducts. Given the interconnected nature of global nuclear industries and supply chains, this course suggests a template that instructors across nuclear engineering departments may wish to emulate.

III. STEPPING BACK AND LOOKING FORWARD

III.A. Illuminating the Path Not Taken

The papers in this special issue problematize some of the received wisdom and the taken-for-granted ways in which we in the nuclear sector approach our work and pedagogy, and even how we frame some of the central challenges that our field and our technologies face today. These challenges, to name a few, have to do with the management of nuclear waste, ensuring the safe operation of nuclear facilities, commercializing new kinds of reactor designs, and designing reactors that can be built on time and on budget. These problematizations and reframings by social science and humanities researchers of our practices and our challenges may be a significant opportunity for academic or practitioner nuclear engineers, to the extent that we are willing and able to see it as such. This reframing of our familiar problems might change the imagination of the practitioner and policy-maker nuclear engineer, opening up other possibilities for action, i.e., innovation, both technological and institutional. The authors of the papers in this special issue lay out several such opportunities for institutional and technological innovation.

Tillement and Garcias[13] show us how we can, as individual designers or design organizations and collectively as a nuclear engineering community, learn from reactor projects that are not pursued to completion. Juraku and Sugawara[30] and Kanamori[31] show us how the nuclear sector should learn from accidents to build more robust and vigilant organizations and institutions that do not fall into the trap of structural ignorance or the evasion of ethical and moral responsibility. Wellock[24] as well as Gisquet et al.[25] show how nuclear safety regulatory organizations, by inviting in the perspectives from the humanities and social sciences, build new conceptual lenses for the oversight and improvement of nuclear safety. Kaiserfeld and Kaijser[33] also show us the value of introducing new disciplinary perspectives for the resolution of some of the nuclear sector's most pressing challenges. In their paper, Kaiserfeld and Kaijser show us how the introduction of humanist and social scientific perspectives shifted the system culture of the Swedish nuclear waste management system, leading ultimately to the development of new siting approaches and the identification of a site for a long-term nuclear waste repository. Each of the papers in this special issue demonstrates the value of expanding the canon of academic and practitioner nuclear engineering to make our field more intellectually expansive so that we, as nuclear engineers present and future, are better able to meet and respond to the challenges faced and created by nuclear technologies.

III.B. Identity and Language as Two Main Causes of the Disciplinary Divides

A theme that becomes evident as one reads the papers in this special issue is that the different intellectual identities and traditions represented and on display across the papers each have their own distinct languages and jargon. For example, while terms such as "social construction," "coproduction," "sociotechnical imaginary," "megaproject pathology," "scale alignment," and "economization" (to name a few) may be familiar to many humanist and social scientific researchers, they may be unfamiliar to an audience of engineers (or even to social science and humanities researchers who may not be familiar with the work of their colleagues from specialized disciplines). The intellectual identities of researchers are often bound up in the use and development of these local discipline-specific languages and jargon. It is my hope that one of the ways in which this special issue and the papers within it help intellectually bridge nuclear engineering with the humanities and the social sciences is by introducing this once-jargon into the lexicon of the nuclear engineer. This, however, is only an initial effort. We will have to continue to learn each other's languages and jargon (and likely produce smaller quantities of new jargon!) if our communities of research and practice are to continue to engage with each other fruitfully. These future engagements may be in the form of jointly organized conferences and workshops, future special issues, new roles for social scientists and humanities researchers in nuclear sector organizations, and funding opportunities to jointly work on research projects. This is but an initial list of possible future collaborations that are likely to be mutually beneficial for our respective disciplines.

III.C. More than One Kind of Divide as Well as Unexpected Bridges

A close reading of the papers in this special issue may lead the reader to ponder the causes of the disciplinary divides (after which this special issue is named). While, as noted previously, discipline-specific language and intellectual identity are two causes of the divides, it may be worthwhile to lay out a broader taxonomy of the divides and their causes. Another example of a disciplinary divide, for example, is normative. Nuclear engineers, and for that matter engineers from other disciplines as well, have historically been reluctant to engage with humanists and social scientists who study their work and practices. This reluctance stems perhaps from the fact that many engineering disciplines, including nuclear engineering, have built their intellectual cores around the design, development, and use of a particular technology. Over time, the success of the technology has come to be equated with the success of the field and discipline.[37] Critiques of the technology and its workings, as put forth by humanist and social scientist researchers, are therefore sometimes incorrectly perceived as threats to the discipline and sector itself. However, to the degree that these critiques are well informed and the product of intellectual rigor, it may ultimately be in the interest of engineering disciplines to embrace such critical stances. Embracing such a critical stance is not only likely to make the field more reflexive and intellectually diverse, but it may also improve its longevity. By becoming both proponents and critics of our technologies, our work, and our practices, we are likely to imagine, design, and build better technologies in service of the outcomes we hope to achieve in society.[9]

On the other side of the disciplinary divide, humanists and social scientists have often been reluctant to engage with engineers because they have not historically been treated as equal partners and collaborators.[38] Engineering research projects and engineering organizations have sometimes brought on a token humanist or social scientist as a perfunctory way to achieve intellectual diversity. The approach to including these researchers in the work of engineering organizations has been instrumental, and humanists and social scientists have been expected to produce research findings that might help secure public buy-in for a technology or policy support for it. While in some or even in many cases such outcomes may in fact be achieved, their pursuit should not constitute the foundation for interdisciplinary conversations and collaborations. Instead, these interdisciplinary engagements should be seen as opportunities to examine what it means to design socially useful technologies and practices, and how the preferences and imaginations of the public can be accounted for across the phases and stages of the engineering design process.[39]

While there are some very real linguistic, identity-based, and normative disciplinary divides, there are also already many unexpected bridges across our disciplines in the form of intellectual border crossers. For example, several of the authors of the papers featured in this special issue have such dual backgrounds, having trained as scientists and engineers and also as humanists and social scientists. These individuals and others like them have an important role to play in intellectually fording our disciplines. Our systems of education and professional development ought to encourage the continued emergence of such individuals.

Finally, the very existence of this special issue and its making, which involved reviews of each paper by both engineers as well as humanities and social science researchers, is proof positive that novel and meaningful research transcends disciplinary divides.

III.D. Role of Pedagogical Practices in Perpetuating or Transcending the Disciplinary Divides

In large part, the inability to communicate effectively across disciplines can be attributed to the pedagogical and intellectual practices at institutions of higher learning. Disciplines typically valorize their own ways of knowing and give students little flexibility and opportunity to explore the epistemologies of other disciplines. Given the increasing interest nuclear engineers have been taking in the social and policy challenges of nuclear technologies, both in the United States and elsewhere, a shared project of curricular reform across several institutions could now be extremely timely. My own conversations with both undergraduate and graduate students in the field from across several nuclear engineering departments suggest that there is a real student interest in the expansion of nuclear engineering education to include concepts and theories that would better equip future nuclear engineers to think about the role, purpose, and implications of the use of nuclear technologies—energy and otherwise—in society.

While there is certainly interest in such coursework from nuclear engineering students, students in the humanities and social sciences, in particular those with an interest in studying the work and practices of the nuclear sector, may also wish to take such courses with their nuclear engineering colleagues. In fact, these courses could be co-taught by nuclear engineers along with their colleagues from the humanities and social sciences.

Curricula that include interdisciplinary courses (particularly those across intellectually distant disciplines) and allow students greater flexibility in taking courses outside their home departments would be helpful in training both future researchers and practitioners who are able to see and respond to a whole problem from the world versus only the parts of it that are valued by a particular discipline. While the purpose of an engineering education—undergraduate or graduate—is to build technical depth in a particular area, an engineering education ought also to build intellectual breadth for thinking about the role and implications of engineering and technology in society. A very concrete way in which this aspiration can be introduced into a nuclear engineering education (besides through the addition of coursework) is by the inclusion, in every nuclear engineering thesis, of a chapter in which the author considers the social dimensions and implications of their area of research or technology design.

IV. CONCLUSION: WHITHER NUCLEAR TECHNOLOGY AND NUCLEAR ENGINEERING?

I hope the readers of this special issue, especially the nuclear engineers, enjoy the rich diversity of theoretical and methodological lenses used by the authors of these papers to thoughtfully and rigorously study the work and practices in the nuclear sector. Few other technology sectors have received such sustained and detailed attention from humanities and social science researchers as the nuclear sector has. I personally have approached this already large and growing body of scholarship with a sense of curiosity and gratitude for being shown new ways in which to think about my field.

Nuclear technologies and nuclear engineers have faced significant headwinds since the inception of the field. Nuclear technologies have long been the subject of fierce and often unproductive debates that have tended to entrench divisions about the purpose and role of us as engineers and of the technologies we design in society.[37] We have equipped ourselves, often on the fly, with the tools with which to grapple with the technical, ethical, social, moral, and policy challenges in which our technologies have been mired, more so than have engineers from other disciplines. We, as a sector and as a discipline, now find ourselves at an inflection point of sorts, poised either for a significant expansion or a significant decline in the use of the technologies we have thus far been designing. Whatever the outcome of this moment of decision turns out to be, we have the chance now to reflect on both the opportunities and the challenges that lie ahead for us as an academic discipline and an engineering profession. It is my hope that one outcome of this collective reflection will be a remaking of sorts of our field such that in the not-distant future we train nuclear engineers who are not only technically deep in their chosen area of specialization but also have intellectual breadth for thinking about the social problems of nuclear energy. These are questions and imperatives with which other fields of engineering are also grappling, and by answering these questions for our own discipline, nuclear engineering can perhaps lead the way in rethinking and remaking the engineer of the future.

APPENDIX

A NOTE ON THE STRUCTURE OF THE WORKSHOP

The papers featured in this special issue were selected from among those presented at an international workshop hosted at the OECD Nuclear Energy Agency in December 2019. This brief note on the structure of the workshop and some of its outcomes is included here for those who might wish to replicate or improve upon our efforts and host such a workshop or conference of their own in the future. The central aims of the international workshop were to (1) map the current state of humanities and social science research with a focus on nuclear energy and the implications of the findings from this research for practice, (2) explore the development of a methodology (or a set of methodologies) for translating research (especially qualitative research) into lessons and recommendations for practitioners, (3) identify "best practices" for and challenges encountered in adopting these recommendations in practitioner settings, and (4) identify possible opportunities for institutional innovation in the nuclear energy sector by surveying current research on innovation and regulation.

The call for papers for the workshop was issued in June 2019. A total of 65 abstract submissions were received. The abstracts were reviewed by a scientific committee made up of 24 members, including social science and humanities researchers as well as nuclear engineers. In all, 34 papers were selected for presentation at the two-day workshop. An additional six papers were presented at an early career researcher colloquium held on December 11 preceding the workshop. Over 100 participants attended the workshop on December 12 and 13, 2019. These participants had a diverse range of backgrounds and included social science and humanities researchers, academic and practitioner nuclear engineers, as well as policy makers from the nuclear sector. The workshop was structured as nine plenary sessions, a keynote lecture, and a concluding session.

The nine plenary sessions were themed according to the empirical subjects of the papers clustered in each session. The nine sessions were about (1) policy, (2) publics, (3) reactors, (4) waste, (5) safety and culture, (6) learning after crisis, (7) pedagogy, (8) organizational and institutional innovations, and (9) research and praxis. Although the papers presented at the workshop had several thematic, empirical, and methodological commonalities, they were clustered thematically (as laid out previously) to make the plenary sessions accessible to those who did not have backgrounds in the humanities and social sciences. Each session featured three to four papers as well as two discussants (typically a nuclear engineering researcher or practitioner as well as a humanist or social scientist) and a session chair. In the papers and talks, the presenters described not only their main research findings, but also what those findings might imply for the work of practitioners and policy makers in the nuclear sector.

A recurring theme at the workshop was that participants felt that future dialogs across the disciplinary divide could be organized around themes or areas that are sources of intellectual disagreement or conflict. The discussions at the workshop suggested that these disagreements primarily have to do with normative stances on nuclear safety, nuclear waste, and the possible role of nuclear energy in the energy systems of the future. Both social scientists as well as nuclear engineers felt that they personally, as well as their home disciplines broadly, would benefit from such dialogs organized around the sources of conflict or disagreement.

The workshop participants displayed a real appetite to continue to engage with each other both through events such as future iterations of the workshop as well as through collaborative programs of research and action. The social scientists and humanities researchers as well as the nuclear engineers acknowledged that their interdisciplinary research projects often include only the token representative of the other discipline. All parties agreed that going forward, this needed to change and that researchers should include their colleagues from other disciplines in the early stages of the grant writing process. The workshop participants also expressed a keen interest in exploring opportunities for research collaborations that might grow out of the workshop. Specifically, participants felt that ongoing public and policy debates about the future of energy systems worldwide would especially benefit from findings that might arise from inter- and transdisciplinary programs of research. Participants felt that these ongoing debates must be informed by economic analyses and the details of the engineering attributes of the technologies that may be mobilized, as well as the publics' visions for the future. These data are generally the result of separate and independent analyses and ought instead to be produced through interdisciplinary inquiry.

Acknowledgments

A number of people played important roles in the making of this special issue. At *Nuclear Technology*, I am grateful to Andy Klein and the editorial board for welcoming this first-of-a-kind effort to publish research by humanists and social scientists in a nuclear engineering journal. I am especially grateful to Sama Bilbao y León for her visionary idea that we undertake such an effort. I hope that we have created a template that others will seek to replicate in the future. At the OECD Nuclear Energy Agency, I wish to thank Clément Bonnay, Danielle Zayani, and Markku Lehtonen, my former colleagues, who played a central role in the organization of the workshop where the initial iterations of these papers were first presented in December 2019. At *Nuclear Technology*, David Strutz, and more recently, Mary Tong, have helped shepherd each of these papers through a rigorous review process. I am extremely grateful for their important contributions and support.

I am also especially grateful to the scientific committee I convened as part of the 2019 OECD Nuclear Energy Agency workshop. Many of these generous individuals went on to review the papers that appear in this special issue, and their constructive and thoughtful input has played a vital role in shaping the papers.

To conclude, a disclaimer: The papers that constitute this special issue are original research papers which, while selected from a workshop I organized at the OECD Nuclear Energy Agency, do not represent the views or official positions of that agency.

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