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Reimagining Nuclear Engineering

To heal the divide over nuclear energy, the field needs to move from advocacy to understanding.

Since the first power reactors—Shippingport in the United States, Calder Hall in the United Kingdom, and Obninsk in the Soviet Union—were connected to electricity grids in the 1950s, nuclear energy has, in several countries, become a stable, reliable, low-carbon, baseload or "firm" source of electricity. Nuclear reactors today—for the most part of the light water vintage built in the 1960s and 1970s—supply just over 10% of global electricity consumption, even making up a substantial portion of all electricity generated in some countries, such as France, Belgium, Hungary, South Korea, and Sweden.

Over this same period of scale-up of the nuclear industry, a defining feature of nuclear technology has been the polarizing and enduring controversy surrounding it. In sharp contrast to many early optimistic projections and aspirations, nuclear energy has proven anything but too cheap to meter. With rare exceptions, nuclear plants—especially in the West—are seldom constructed on time and on budget. The rhetoric and logic of nuclear safety expressed in the language of quantitative measures of risk have done little to quell society's concerns about nuclear energy technologies. Skepticism about nuclear energy as a safe and reliable source of energy experienced a resurgence in the aftermath of the Fukushima Daiichi accident a decade ago, dampening the nuclear renaissance that nuclear engineers had expected at the start of the new millennium.

Nuclear reactors remain a technology whose risks and benefits, potential and real, are inequitably distributed in society, temporally and geographically. The fuel that powers reactors comes from mines that have poisoned Indigenous communities and Global South nations for decades. The connection between a nation's nuclear energy capability and its possession of nuclear weapons, though once direct and now more attenuated, nevertheless persists. And finally there are the environmental footprints of the nuclear era: its wastes. Though often described by nuclear engineers as a technically solved problem, the disposition of nuclear waste remains unresolved in most countries (Finland and Sweden are exceptions), its fate an ongoing open question, particularly in the United States. However this question may eventually be answered, nuclear waste will perhaps be the most enduring vestige of the Anthropocene.

Within this complex legacy, public trust in nuclear technologies and the institutions that govern them has been a scarce commodity. Independent of the particular shade of one's politics, the vast majority of us, when engaging with questions surrounding nuclear energy, label ourselves and others as either "pro-nuclear" or "anti-nuclear." The values that lie behind different stances on this complex technology—however nuanced—too often remain unexamined and are instead characterized as crude binaries. This for-or-against dichotomy has served to engender mistrust, deepen fears, pit different environmentalist agendas against each other, and contribute to unproductive conversations about how, whether, and what to do with nuclear energy. Tropes past and present on both sides have contributed to the entrenchment of this polarization. From catastrophizing the effects of radiation with cartoons of three-eyed fish, to casual dismissal of the severity of the six nuclear reactor meltdowns humankind has witnessed so far, anti- and pro-nuclear narratives are relentlessly mobilized by those on one side of the divide to demonize those on the other.

Against the backdrop of a nascent but rapidly developing industrial sector and an intensely and increasingly polarized discourse, the discipline of nuclear engineering emerged and grew—at first in the government laboratories of a small number of nuclear nations, and then as offshoots of various university engineering departments—as a distinct field of research and practice.

We are two academics trained within this discipline who do not identify with either side of the anti-pro nuclear divide. Nor do we necessarily even share with each other the same vision of the future and fate of nuclear technologies. Yet we agree (as do many nuclear professionals today) that the past and present dilemmas of our field—technical, social, political, economic, and ethical—are profound, and cannot be solved by simply picking a side and working within it. We also agree that in order to engage with the discontents of our field in a meaningful, productive way, we nuclear engineers must, irrespective of the future of the field and its technologies, learn to engage with its contradictions much more attentively than we have in the past—even if these contradictions ultimately remain unresolvable.

Here we offer a call to the field of nuclear engineering to reexamine its intellectual and ethical foundations and commitments. We are attempting to imagine a path toward a nuclear engineering discipline that better prepares its intellectual progeny to sense and reason with the inevitable moral dissonances that the management—creation as well as dismantlement—of nuclear technologies poses for society. Our critique of nuclear engineering as well as our thinking about how our discipline can do better is grounded in our own professional and intellectual journeys as nuclear engineers.

Aditi

I grew up in India in the 1990s, when concerns about energy access loomed large in the country, as they do even now. Largely cut off from global nuclear supply chains following India's nuclear test in 1974, the nation's nuclear scientists and engineers had, by the 1990s, reinvented and reverse-engineered the nuclear energy technologies that had been denied them. By the 1990s, nuclear energy technologies, then regarded as Indian, had come to be associated with national technological prowess, postcolonial autonomy, and modernity. Against this historical and cultural backdrop, nuclear reactors appeared in high school textbooks as a practically obvious and socially useful application of the principles of nuclear physics.

I arrived at the Massachusetts Institute of Technology to start my undergraduate studies in the fall of 2008, the same year that India and the United States had inked a nuclear deal granting India access to American nuclear energy technologies. Nuclear science and engineering appealed to me because it applied the physics that had captivated me as a high school student to the problem of energy access I deeply cared about. But I was also fascinated by the policy and social problems in which nuclear technologies were mired. What does it mean to design and manage these technologies equitably? Though having vast potential to support social progress, these technologies inevitably also produce serious harms. How should such harms, past and future, be repaired? Can these harms be sufficiently repaired to justify the continued existence of these technologies?

I searched for answers through coursework and in the world beyond my home department, through internships at the International Atomic Energy Agency headquartered in Vienna, at a French reactor design company (then Areva, now Framatome), and at a think tank in India (Center for the Study of Science, Technology and Policy). But the discussions at these places, while concerned with such familiar topics as nonproliferation, safety, waste, and public acceptance, were unable to accommodate what seemed to me the deeper underlying questions of purpose, of ethics and responsibility, and of the role of the engineer in society.

I started my doctoral studies in nuclear science and engineering in 2012 at a paradoxical time when enthusiasm about nuclear energy technology was growing because of its potential to meet future energy demands without contributing to global warming. Yet amid this enthusiasm, the March 2011 Fukushima Daiichi nuclear power plant accident had set off a crisis within the nuclear energy field, as it became immediately apparent that the risks of nuclear energy were far from well understood, let alone contained.

My education and professional experiences in the nuclear field so far had left me with an increasingly uncomfortable realization that something was missing in the ways that nuclear engineers were being trained. Fukushima brought this discomfort sharply into focus. The rigors of academic science and engineering did not prepare nuclear engineers to think and make decisions about the design, management, and governance of nuclear technologies in ways that could make sense of the complex amalgam of benefits and harms that were as much a part of the technology as the reactors themselves.

As an early-stage graduate student, I resolved to work at the intersection of engineering and the social sciences, to try to gain a better understanding of nuclear technologies in their social and political contexts. I would master the scientific and engineering fundamentals of the nuclear field, while also immersing myself in social scientific theory and methodology beyond my home department. One of my advisers—a sociologist—observed that not only would I have to learn to think like a nuclear engineer but also simultaneously learn how to observe and critique the nuclear engineers' ways of thinking. My first two years of graduate school—as I attempted to work inside as well as across each of these two vastly different ways of knowing—were both exhilarating and a time of constant intellectual crisis.

My doctoral research began with a hunch that the notion of risk was far more nuanced and complicated than the way it was conceived, formalized, and discussed in academic nuclear engineering. I was concerned that simplistic notions of risk were being perpetuated through nuclear policies, and through the teaching and practice of nuclear engineering.

I began to study (and continue to study) how designers of nuclear technologies make decisions in the early stages of design—decisions that go on to shape the safety, cost, and performance of the technology throughout its life. Other fields of engineering have a tradition of studying, critiquing, and improving design, but the pursuit of such self-knowledge—perhaps due in part to the wartime origins of reactor technologies, the relative youth, and, until recently, the insular nature of the discipline—has been largely intellectually alien in nuclear engineering. I am therefore a nuclear engineer in ways that the field at large does not yet understand are possible.

Denia

I was born and raised in the deeply anti-nuclear climate of Austria. The country's only commercial nuclear reactor project, Zwentendorf, was shut down by a national referendum in 1978, before it could be turned on. My early childhood memories include the vague disquiet of not being allowed to drink milk after the Chernobyl accident in April 1986. The radioactive plume making its way over Europe seeped into our home in the form of my mother's incessant—and luckily unfounded—worries about her pregnancy with my younger brother. In school, the apocalyptic fictional texts *Die Wolke* (*The Cloud*) and *Die letzten Kinder von Schewenborn* (*The Last Children of Schewenborn*) were assigned as required reading, impressing upon our young minds horrific images of what this mysterious, powerful technology could unleash. I remember my teenage years being punctuated with news images of students chaining themselves to train tracks to protest the shuttling of nuclear waste canisters between France and Germany. Perhaps surprisingly, even though I had profoundly internalized Austria's environmentalist sensibilities from a young age, I had not quite assimilated the dominant anti-nuclear narratives surrounding me. Instead, I suspect they may have piqued my curiosity about this mysterious, Promethean technology.

In the mid-2000s, while studying physics at university and as concerns about climate change were rising, I began to sense that electricity generation from nuclear energy might be an inevitable technological development path as the need for divestment from fossil fuels became more and more urgent. Powerful narratives about the promising future of nuclear energy convinced me that nuclear energy was an important part of the solution to climate change, and that there were "only" three technical challenges left to overcome: proliferation, cost, and waste. Public trust—except insofar as it was described as a problem of public acceptance of scientific expertise—was rarely mentioned as a significant issue that nuclear engineers should care about. At the time, it was not difficult to believe the widespread claims of nuclear energy advocates that the risks of nuclear accidents were now all but eliminated, and that our biggest safety and security worries lay in radioactive material transport and terrorist attacks. After all, Chernobyl was already decades in the past, and ubiquitous Western narratives of technological exceptionalism blamed that accident on the flawed reactor design and failures of Soviet bureaucracy.

I resolved to venture away from the abstract world of (astro) physics, and started a PhD program at the nuclear engineering department at the University of California, Berkeley, in 2005, during the heyday of the nuclear renaissance. The Energy Policy Act, a law promoting the construction of more nuclear power plants in the United States, had just been passed in Congress. Only a few months later, President George W. Bush announced the Global Nuclear Energy Partnership (now known as the International Framework for Nuclear Energy Cooperation), a program to promote the use of nuclear power internationally through a framework of "supplier" and "user" nations. With this as a backdrop, my environmentalist leanings led me to study the ever-growing radioactive waste problem. At the time, I treated it as a hurdle to overcome in order to enable the growth of nuclear energy in an environmentally responsible way.

Optimism about the bright future of nuclear energy technology seemed to be growing—until the 2011 Fukushima Daiichi nuclear power plant accident precipitated a reckoning among my nuclear engineering colleagues about our field's deep-seated assumptions, beliefs, and practices surrounding risk and safety. In the immediate aftermath of the accident, my fellow graduate students and I encountered among nuclear experts and authorities a slew of defensive stances: the accident was "beyond design basis" and so could not have been predicted; it was caused by a tsunami, and therefore was a natural and not a technological disaster; and "if only the generators had not been in the basement" the accident would have been circumvented entirely. At a UC Berkeley-University of Tokyo summer school co-organized by a small group of nuclear engineering academics and social scientists from both institutions several months after the accident, nuclear engineering students were given a rare opportunity to intentionally reflect as a group on the role and responsibility of our nuclear community in this disaster.

However, it was not until I left the intellectual silos of the nuclear engineering discipline that a diverse community of scholars and a range of scholarship that engaged with societal issues surrounding nuclear energy opened up to me, which allowed me to formally explore the contradictions and dissonances I had been encountering in my professional trajectory from a different academic angle. I started acquiring new vocabulary and intellectual lenses that allowed me to study aspects of nuclear technology in ways that productively challenged the presumed wisdom and underlying assumptions of the graduate training I had received. In this way, I set out on a different route to understanding the entanglement of nuclear energy with society, as I sought to envision a path for the future of the nuclear engineering discipline that engaged with, rather than neglected, its complex social and political legacies.

Rise and decline

As the American nuclear industry scaled up rapidly through the 1960s and 1970s, and as companies such as Westinghouse and General Electric (at that time the corporate giants in the nuclear realm) captured domestic and international nuclear markets, nuclear engineering departments grew in both size (of students and faculty) and number across the country. Most nuclear engineering textbooks, written over this period and still widely used today, cemented the field's attachment to building nuclear reactors. These textbooks presented the future of the academic discipline of nuclear engineering not as being one that expanded the frontiers of knowledge, but as one in which nuclear reactors were built in increasingly large numbers around the world. It is not an exaggeration to say that these first-generation nuclear engineers imagined that their technological designs would save the world. As Lamarsh and Baratta's well-known and still widely used textbook puts it in its 2001 edition, "nuclear engineering is an endeavor that makes use of radiation and radioactive material for the benefit of mankind." The aspiration remains.

Nuclear engineers, both professional and academic, have thus, since the inception of the field, positioned themselves as advocates of the technologies they design. We have come to equate the future of our field with the fortunes of nuclear technologies. This stance of uncritical attachment, perhaps common to all fields of engineering, is especially problematic in our own, given that nuclear technologies have been so bitterly contested. The identity of nuclear engineering is thus expressed not just as a field of research and practice but as a form of political advocacy. The field is intellectually and morally compromised, its interests contrary to any obligation to understand and question its own assumptions, commitments, and biases.

The field of nuclear engineering must reexamine its pedagogical premises so that its professionals are trained to handle the field's technological, political, and environmental legacies in ways that resolve this conflict of interest. Such training demands more than the teaching of responsible engineering conduct and research practices that existing courses in engineering ethics typically offer. While important and necessary, those courses rarely bring critical theories and insights from intellectual and analytical traditions outside engineering to bear on the challenge of integrating principles of equity and justice into the education of engineers. We nuclear engineers must cultivate dual identities as both designers and critics of the technologies we build if we want to do our best work and serve and be trusted by society.

Just as the fortunes of academic nuclear engineering as a field tracked the rapid ascent and development of nuclear energy technologies, so, too, did they track nuclear energy's decline. By the late 1970s, lower-than-expected increases in electricity demand in some nations had led to the cancellation of tens of nuclear plant construction projects, a trend that continued in the aftermath of the 1979 Three Mile Island accident in the United States. The decade that followed saw the pursuit and then abandonment of the Clinch River Breeder reactor project, which was meant to prototype and demonstrate what was regarded, at the time, as the upcoming "advanced" nuclear reactor technology. A shrinking reactor market coupled with shrinking Department of Energy outlays for nuclear technology research and development inevitably led to a decline of nuclear engineering departments across the country. Some were shut down entirely and others absorbed into various fields of engineering. A handful, with reduced numbers of faculty and students, retained a distinct intellectual identity and have since continued to define the evolution of the field. The departments where we trained, at MIT and UC Berkeley, are in this group.

The past and present dilemmas of our field—technical, social, political, economic, and ethical—are profound, and cannot be solved by simply picking a side and working within it.

The field, for many decades, has been an inward-looking one, and its rise and decline have followed directly from this insularity. Because nuclear engineers have historically molded their discipline around the design, analysis, and development of existing or near-future technologies, they have created a path dependence on the nature of the problems and research questions with which they have been concerned. The pursuit of these research questions has led to an increasingly intellectually siloed and isolated field that has been able to sustain itself only by drawing on a limited set of funding sources, whose very availability is also contingent on the state of the nuclear sector. During the decades when nuclear energy was in retreat, the field was forced to shrink against its will, and its advocacy stance has typically been defensive and oriented toward solving the field's problems through technological fixes—an approach that has found considerable support today among some experts and advocates working to solve climate change. In the 1980s, following the Three Mile Island nuclear power plant accident, which, as nuclear engineers generally concurred, had been caused by "human error," reactor designers resolved increasingly to diminish the role of independent human decisions in nuclear systems by making them "walkaway" or "passively safe" and "idiotproof." These tendencies were amplified after the Fukushima Daiichi accident. Although such thinking has led to advances in reactor design and potential improvements in safety, it has far from addressed the central dilemmas of the field—dilemmas that are beyond the reach of technological fixes.

Safety in numbers?

When imagined and designed in the 1950s, commercial nuclear power reactors were, for that time, simultaneously one of the most complex peacetime technologies humankind had ever created, and also potentially the riskiest. Before nuclear reactors could be scaled up for practical use and built in significant numbers, the question of their safety or their riskiness had to be transformed into a knowable, more tractable problem. This is an endeavor that has taken many decades and that, in many ways, still continues.

An early study into the riskiness of nuclear reactor technologies was published in 1957 by the Atomic Energy Commission. Commonly known as the "Brookhaven Report, its findings were sobering. The authors had made a number of simplifying assumptions in their analysis, such as the absence of a reactor containment vessel, and the vaporization of the radioactive fuel into easily dispersible micron-sized particles. These assumptions yielded the staggering result of $7 billion (in 1957 dollars) for the potential cost of a nuclear accident—a number that simultaneously gave both government agencies and the private sector pause and led to a series of new questions. How accurate were these numbers? What was the true cost of a nuclear reactor accident? What was the likelihood of an accident occurring? And if truer estimates could be determined, what general guidelines, if any, could be used to make decisions about this risky but potentially beneficial technology? Although the authors of the analysis had calculated an exceedingly low probability of occurrence of nuclear accidents, the accuracy of that number remained as uncertain as the cost estimate.

To respond to such questions and uncertainties, nuclear engineers, while arguing for the safety of their reactor designs, relied on a definition of risk that was widely adopted in engineering disciplines: the product of a probability of a failure (in this case, of a nuclear accident) and the consequences of that failure (typically a cost estimate). The fact that the probability of an accident could never be empirically demonstrated did not deter the adoption of this formalized approach to risk. Indeed, for nuclear engineers, who wanted to demonstrate the viability of their technology, this definition of risk soon became not just a decisionmaking heuristic but also a pedagogical tool. As controversies around nuclear power expanded in the late 1960s and 1970s, nuclear engineers adopted the prescriptions offered by the emerging field of risk studies, which framed the public as irrational, emotional, neglectful of probability, and monolithic in its ignorance. The problem of risk thus became a problem of "public acceptance," which could be secured by educating the public about risk calculations.

Coupled with nuclear engineers' allegiance to the quantitative dimensions of risk, this vision of irrational laypeople has created an enduring expert-public divide. But risk is not a narrowly quantifiable concept. Even as a formal exercise in quantification, Fukushima showed, again, that neither probabilities nor consequences can be known in advance. In light of this imperfect knowledge, Fukushima also helps make clear that there can be many legitimate ways to think about risk. Even among scientists and engineers there has been significant disagreement about the risks of nuclear energy. One major challenge for nuclear engineering is to acknowledge that its way of framing the interpretation, assessment, and management of risks is incomplete and limited.

But this challenge comes with an opportunity: to invite other ways of sense-making about risk into solving a shared problem together. Any stance about how to think about and manage the irreducible uncertainties surrounding nuclear accidents is inherently the product of a subjective, value-laden exercise. Concerns about geographic and temporal scale, aesthetics, distribution of benefits, modes of ownership, governance and accountability, and alternative sources of energy, not to mention the unsolved legacy of nuclear waste, all bring entirely legitimate dimensions to discussions of what risk really is and how it should be conceived and managed. This complexity demands an approach to risk built on humility rather than overconfidence and reliance on methodological rigidity. It opens up the problem of risk to diversity of thought that makes a "solution" to a problem more robust and sustainable, a humble approach to problem-solving that includes all sorts of voices—lay and expert. Such an inclusive approach to thinking about nuclear risk is not only capable of identifying new, more satisfying routes to problem-solving; it is also part of the broader, ongoing, deliberative process by which humans make sense of their existence, and so is in and of itself an act of equity and justice.

How to breed a three-eyed fish

We nuclear engineers have a responsibility to understand that we are just as much part of society as we are servants of it, and that our decisions about research and design are limited by our discipline-bound understanding of the world. Probabilistic risk assessments have value and utility. But even beyond the deep uncertainties inherent in assigning discrete numbers to the behavior of complex systems, mathematical models or formal analysis cannot adequately capture environmental, social, cultural, aesthetic, and ethical factors of risk. We nuclear engineers need ways to engage with these dissonances and sit with the discomfort that arises from not being able to put messiness, complexity, contradiction, and paradox into a box and assign numbers to it.

And more: we need to understand and teach future generations of nuclear engineers that contestation and skepticism of expert authority are crucial elements of a functioning democracy and the integrity of any intellectual discipline. We need to stop separating the social from the technological, and imprint these insights into our education so that they can be embedded in policy and design of nuclear energy technologies.

Our vision for a new approach to the discipline of nuclear engineering is grounded in long-standing calls for a bridging between the sciences and the humanities. A humanist education grounded in history, culture, and politics is rarely required of students in science, technology, engineering, and mathematics—the STEM fields—at most universities. The limited epistemic scope of their education deprives scientists and engineers of tools, methods, vocabularies, and even sensibilities to engage with the fuller context of their raison d'être, and to examine their practice and technological attachments. We should be creating nuclear engineers who, in addition to being trained in the scientific and engineering rigors of the field, are intellectually flexible and disciplinarily multilingual, and so can situate their engineering knowledge in the much richer and complex social world that has to make sense of the technologies they design and create.

As just one example of self-awareness that can be built by reaching out to other disciplines, we can examine a norm of academic paper writing in our field (and STEM fields more generally): the ubiquitous use of the passive voice, which carries with it an implied connotation of neutrality and rationality, sanitized from all social context and impact. This "view from nowhere" is used to invoke objectivity and to smooth out inconsistencies in our knowledge and beliefs, thus manufacturing an uncontestable epistemic foundation for the discipline. Why, for example, do academic studies on uranium toxicity, full of radionuclide transport equations, solubility limits, and isotope concentrations in groundwater, rarely acknowledge the equity and justice dimensions of uranium mining impacts? This might sound strange to researchers so accustomed to strictly confining their studies to tightly controlled physical systems in order to guard against subjectivity or bias. However, omission of the social context in which nuclear technology is embedded implicitly renders claims of scientific neutrality deeply political. As we have already emphasized, the advocacy position characteristic of our field means that the high-impact technologies we create are shaped by our implicit politics. As nuclear engineers and responsible citizens, this is something we should be forthright about.

We nuclear engineers need to drastically improve our comfort with engaging with unmeasurable things. The question of how to do so is difficult to answer, but one place to start might be to train our students to write in a narrative form that situates our quantitative analysis in more complex, ambiguous social settings. Another might be to bring more awareness into our field about the ways that politicians, policymakers, activists, business leaders, and everyday people make real, and often momentous and wise, decisions in the face of conflicting facts and values and an uncertain future. The empathy borne of such understanding can in turn help create the mutual trust needed to collectively solve problems in a just and equitable way.

We are considered by many in our chosen field of nuclear science and engineering, and even consider ourselves, to be intellectual anomalies—three-eyed fish of a sort. It took the discipline nearly seven decades to produce the two (and a few more) of us. Yet we are part of a growing breed—a new kind of nuclear engineer, interested as much in reflecting on and resolving the moral and ethical challenges of nuclear technologies as in their design, creation, and propagation. Our existence was made possible by a tear in the epistemic fabric of the field, created by our mentors and advisers—themselves visionaries and disciplinary outliers—who saw, especially in the wake of the Fukushima disaster, potential in the questions we were asking. We hope that this opening to new ways of thinking and knowing comes to define the field as it intellectually reweaves itself to create nuclear engineers equipped with critical tools to engage with contexts and complexities of nuclear technologies past, present, and future.

Nuclear engineers will be needed far into the future for the stewardship of nuclear technologies that have already been created by our intellectual forebears, and which will outlive any single generation of us. But even if the ultimate aspiration of the field remains the solution of pressing real-world problems through the design and use of nuclear technologies—energy or otherwise—nuclear engineering must wean itself off of the strong, uncritical attachments it has formed to its technological creations, and teach nuclear engineers to simultaneously be creators and critics of their technologies. The reconfiguration of the intellectual identity of the field, if it does occur, is, in the short-term, likely to be tumultuous. In the long run, however, it is likely to lead to a more long-lived, intellectually robust field that can answer to its place in society with humility and grace—and to nuclear engineers who, through their intellectual and practical endeavors, are able to enter into a stronger, more trusting relationship with society.

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