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Curriculum-embedded Epistemological Foundations in Nuclear Engineering

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Curriculum-embedded epistemological foundations in nuclear engineering

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1 Abstract

Dialogue on the topic of nuclear energy has a rich history including the transition from military to civilian applications, the legacy of the political entanglements of nuclear waste management, and the varied public perceptions of the risks of radiation. This complex historical context, juxtaposed with the present need for rapid deployment of low-carbon energy systems to combat energy crises in the coming decade, make nuclear energy an interesting case study as an historically entrenched field on the cusp of renewal. Situated at these crossroads, we present an analysis of how engineering has been previously defined by nuclear engineers and how the role and responsibilities of engineers and of the technologies they produce and promote have been taught and perpetuated. This work explores the *beliefs about knowledge and the role of the engineer* that are embedded in how students train in the field and practice of nuclear engineering. We present here an analysis of embedded value systems in core textbooks typically used in undergraduate and graduate nuclear engineering studies in the US, specifically looking at what is considered essential to being a nuclear engineer. Key themes discussed are engineering as problem solving, the relevance of multidisciplinarity, and the authoritative nature of knowledge. The analysis considers the context in which the textbooks were written and how the embedded worldview found in the textbook shapes the current landscape of nuclear engineering education, research, and practice. We analyze what nuclear engineering students are implicitly taught about their roles and responsibilities via presentation of technical course material. Overall, this case study investigates nuclear engineering for its curricula-embedded epistemological foundations and offers reflections on the relevance of beliefs about knowledge to engineering problem solving.

2 Introduction

The term “engineering”, linked in origin to both “ingenious” and “engine”, describes a profession linked to the virtues of originality and innovation as well as the artifacts and processes developed to enhance human flourishing. We take these elements (production of tools, original innovation, and the commitment to human welfare) to be foundational (though incomplete) due to their ubiquity and use this as a starting point for our analysis [1], [2]. These commonly referenced elements, being considered as definitive of engineering, along with the broader conceptualization of engineering, have expansive repercussions on the practice of engineering and on the technological tools and innovations which shape society. How the engineer understands their role and responsibilities impacts what they create and how they create. The epistemic assertions underlying the defining elements of engineering can be both informative of and limiting to the present-day understanding of engineering. How has the identity of an engineer become linked to certain epistemological beliefs? And what effects do these beliefs have on the artifacts and processes created by engineers? Here, we explore these questions within the context of nuclear engineering.

With the goal of rapid deployment of advanced nuclear energy to combat energy crises in the coming decade, there follows a need for a well-trained and abundant workforce. As the industry is developing and growing [3], now is an auspicious moment to re-envision what it means to be a nuclear engineer, so as to learn from historical failures and successes, disasters and political climates and think critically about the formation of engineers. This work explores how beliefs about knowledge and the role of the engineer shape the field and practice of nuclear engineering, from its birth out of 20th century physics and World War II to present-day applications. By looking at what nuclear engineers should know and how they should know it, this work investigates how narratives of what engineering is and should be are sustained through nuclear engineering textbooks by examining key texts for their underlying values systems.

3 Acknowledging Subjectivities

As trained nuclear engineers, we, the authors, believe that engineering practices (including the methodologies for solving problems and the development of technologies) can add value to the world if sensitivities towards power differentials—in terms of societal impact, funding mechanisms, institutional settings, and policy frameworks—are thoughtfully incorporated. We embrace the limitations of engineering practices and believe they require dialogue with other approaches to problem-solving, sense-making, and ways of knowing. We also recognize that, historically and still in the present day, engineering practices have caused and sustained harm to communities and the environment knowingly and unknowingly, intentionally and unintentionally, and by the practice themselves and through the values embedded in the technologies they produce [4]. In the case of this textbook analysis, we acknowledge that our individual ideas of what *should* constitute engineering affect our analysis of what engineering *is*. However, we believe that it is worthwhile and useful to examine the patterns we identify in engineering texts despite our individual and shared subjectivities. As Harding summarized Proctor: “It is an epistemological mistake to conflate the motivation of research by social values or interests with an inevitable weakening of its validity, reliability and predictive powers” [5], [6]. Broadly, we wish to open conversations on what room for further epistemological flexibility there is in the discipline of nuclear engineering [7]. Through this analysis, we hope to display what we nuclear engineers struggle with epistemically (as expressed in foundational texts) and engage in conversation with other disciplines to inform the potential future evolution of the epistemological boundaries of the nuclear engineering discipline.

4 Background

The term “nuclear engineer” was applied to the physicists and engineers who sought to deploy the power of modern physics in the 20th century. In addition to developing as a novel technical domain, nuclear engineering developed within a new organizational context [8]. Previously, physicists practiced their research within university science departments, but with the development of wartime research efforts, such as the Manhattan Project, top physicists and engineers found themselves employed by government and military-funded research initiatives. Post-WWII, these government research efforts continued via the establishment of national laboratories. The first national laboratory, Argonne National Laboratory, cites its establishment in 1946 as having the goal to perform “cooperative research in nucleonics”, another term used to describe the field of ‘nuclear engineering’ or ‘atomic energy’ [9]. This time period was marked by specific understandings of the role of technology [10]. During the war, there was a remarkable sense of urgency in technological development. In his memoir, Lieutenant General Leslie Groves Jr., director of the Manhattan Project, describes how technological development had to be driven forward even before scientific understanding. Without scientific confirmation of how the enrichment of uranium would take place, he ordered that the technological infrastructure be built, with the belief that if understanding came before action, it would be too late for the war effort [11]. In the years and decades following the war, disillusionment with the failed promises of technology started surfacing—a hallmark of postmodernism [12]. The birth of nuclear engineering, therefore, coincided with, developed out of, and contributed to shaping a time of transitions: from academic research to centralized war efforts, from the brand-new field of quantum mechanics to urgently demanded technologies, and from modernist views of boundless technological advances to the pessimism of postmodernism. Nuclear engineers—those who investigated the possible uses of nuclear physics and nuclear chemistry—were the leaders of a domain which was entangled with military applications both in essence and in practice. The atoms carried within themselves the energy to cause unfathomable damage, and even peaceful applications of nuclear energy were plagued by potential misuse since reactors used for production of electricity could be employed, with modifications, also for the production of weapons-grade fissile material [13], [14]. Moreover, civilian nuclear energy was developed in and continually situated within the legacy of weapons research, particularly at the national laboratories [15]. These contexts—the social, political, and technological—along with the intrinsic properties of the atom and its accumulating legacy shaped what we understand as the academic discipline of nuclear engineering today.

The engineer, imagined as an innovator and creator, is a key actor in technological advances. From its conception as a term in the late 19th century used to describe the practical arts, *technology* has been linked with *progress* [10]. With the engineer's emphasis on empiricism, rationalism, and the scientific method, this progress is quantitatively parameterized since evaluation of the enhancement of functional capacity, to the rational engineer, requires an agreed-upon metric. From this understanding, the role of the engineer is linked to the ability to parameterize characteristics and tune them as desired. This approach, which deconstructs complex physical systems in order to assess and optimize parts of a whole, is limited by the interactions of the parts and the possibility of integration into the whole. The whole is not always easily deconstructed, but, in the face of these limitations, engineers use their judgement to assess what is an acceptable model of the physical system within an acceptable error [16]. In this way, the design of engineered technologies are adapted to their intended application. Thus, in this process, values are embedded in the technologies themselves; Winner explains that the artifacts produced by engineers both reflect and affect the context in which they exist [4]. Haraway puts it even more explicitly: "Machines are maps of power, arrested moments of social relations that in turn threaten to govern the living" [17]. The values which underpin the engineer's objectives and the context in which the practice of engineering exists are relevant to the artifacts produced. Even more than being relevant, they are built into the very technologies in an inseparable manner. The fingerprints of the engineer—their contexts and values—are imprinted on the machines and technologies they produce. In this way, there are intrinsic and, therefore, inflexible values which are inherent to the nature of nuclear technologies. Winner suggests that the values in nuclear technologies are fundamentally authoritarian due to intrinsic properties of structure and organization which are associated with institutionalized patterns of power and authority [4]. It follows that nuclear technologies may be incompatible with other, perhaps more critical ways of knowing. As we analyze the underlying values of the field described in nuclear engineering textbooks, we are investigating how these inherent values, as well as the values of the individual authors, are expressed.

5 Textbook Analysis

To analyze what constitutes "nuclear engineering knowledge", textbooks from a variety of nuclear engineering topics have been surveyed for underlying belief systems and for what constitutes essential nuclear engineering knowledge [18], [19], [20], [21], [22], [23], [24], [25], [26]. Textbooks were chosen as an indicator of core nuclear engineering beliefs because of their role as references — they provide a deep and broad presentation of core content for both students and practitioners of the field. As references, textbooks often seek to be comprehensive and authoritative. This authority is often claimed on the basis that the text presents a factual and essential view of the topic. Notably, however, the knowledge presented in a text intrinsically shows the subjective choices of the author—for example, which topics should be considered as important, how topics should be organized, or even what knowledge is not deemed important enough for inclusion. The dilemma of objectivity of references is detailed in the context of scientific images and atlases in the late 19th century by Daston and Galison [27]. Like atlases, textbooks serve to “drill the eye of the beginner and refresh the eye of the old hand” while capturing essential and impartial knowledge of a topic [27]. Defining what is essential and approaching impartiality requires value judgements, however. We seek to make these underlying values and belief systems explicit by analyzing the role and responsibilities of engineers as written in nuclear engineering texts. Table 1 outlines the criteria analyzed in each of the texts.

Table 1. Criteria used in the textbook analysis.

Role of the Engineer “Who?” “What?”	Responsibilities of the Engineer “How?” “Why?”
- Goal of the text - Applications of nuclear engineering - Impacts of nuclear engineers/nuclear technologies	- Belief systems/attitudes - Assumptions, motivations - Risk conception and management - Public/engineer dynamics
Underlying belief systems	

Specifically, nuclear engineering textbooks were reviewed for how they define nuclear engineering and nuclear engineering knowledge both explicitly and implicitly, as outlined in Table 2. Explicit definitions include claims made about what constitutes an “engineering approach” or “engineering judgement”. Explicit descriptions of the role of the nuclear engineer include broad outlines of the fields and topics relevant to nuclear engineering as well as claims of what the engineer “must know”. When looking for implicit definitions, the texts were analyzed for underlying belief systems or assumptions. Indicators of this include phrasing of attitudes (e.g. what is “expected” of the nuclear engineer, or what nuclear power plant accidents have taught us), anthropomorphisms, and normative claims. Specifically, the analysis consisted of recording notes on the goal of the text, applications of nuclear engineering (indicative of what nuclear engineering “is”), the impacts of nuclear engineering and technologies, the responsibilities of a nuclear engineer, the language used that indicates underlying belief systems, and discussions of risk and public opinion. Narratives about risk and public opinion are specifically analyzed as topical categories because of the ways they obviate attitudes towards knowledge beliefs and priorities.

Table 2. Explicit and implicit definitions of nuclear engineering knowledge, with examples. Key phrases analyzed are shown in bold underline.

Explicit	Implicit
• Engineering approach or engineering judgement • What the engineer must know • Statements on the engineer’s identity	• Underlying beliefs and assumptions • Anthropomorphisms • Normative claims • Attitudes
Example: “Our objective can often be achieved by applying the accumulated	Example: “**Even if** the risks from low-level radiation were established quantitatively on a

engineering experience in a manner that empirically relates macroscopic quantities, for example, the pressure drop and flow rate through a tube, without obtaining the detailed distribution of the fluid velocity or density in the tube. This **engineering approach** can be used whenever the flow characteristics fall within the range of previously established empiric relations" [18] (pg 439).	firm scientific basis the setting of limits would **still represent a social judgment** in deciding how great a risk **to allow**" [25] (pg 449).
Example: "The overall **objective of radiation protection** is to balance the risks and benefits from activities that involve radiation" [25] (pg 449).	Example: "This presentation is designed to **clearly illustrate** how this recompression cycle must be designed and analyzed, a subtlety which **otherwise easily confounds the inexperienced analyst**" [18] (pg xxii).

The surveyed texts were all published between the years 1975 and 2022, shown in Figure 1. Multiple editions of the same text were not reviewed, but the forwards of second or third editions often mentioned updates such as changes in the unit systems presented, as well as more substantial updates of the technical content to include discussion of advanced reactor concepts.

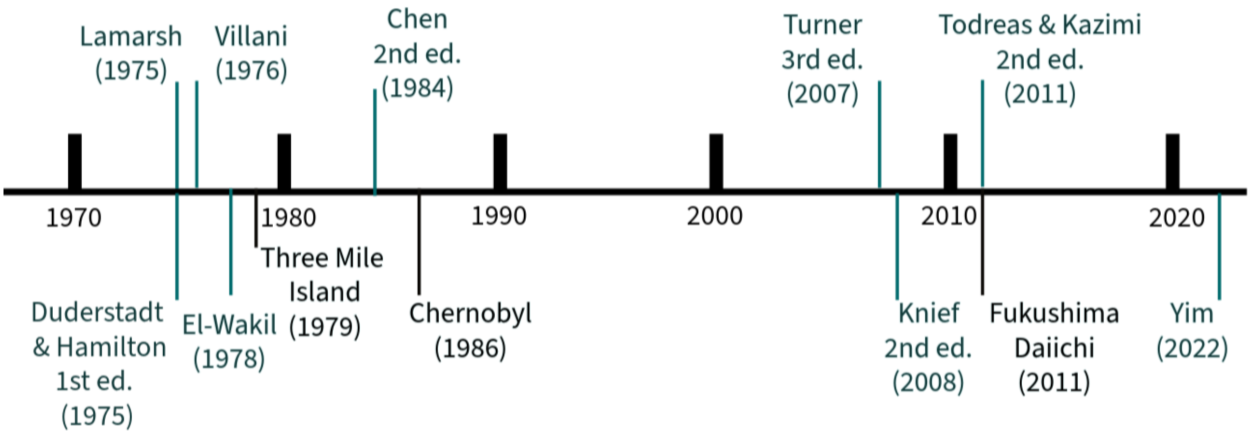

Figure 1. Timeline of the textbooks analyzed and historical events that are incorporated in some later editions of the textbooks as seminal case studies in nuclear engineering.

The aim was to survey textbooks from a variety of topics within nuclear engineering, from neutronics and thermal hydraulics to radiation biophysics and nuclear waste management policy. We note that several textbooks were unintentionally not included in this analysis and should be included in further studies. These include [28], [29], [30]. When faculty teach courses, textbooks are not always available, thus a compilation of course notes and journal articles is created. Such compilations are sometimes the basis of new books that are written, thus out of the necessity of teaching courses and evolving the curriculum. Although there exists no primary textbook or set of books that is exhaustive of nuclear engineering curricula, an analysis of some of the nuclear engineering textbooks that are available today offers a starting point for how knowledge is institutionally transferred throughout generations of engineering practitioners.

6 Themes

Key themes from observed beliefs about the identity of the nuclear engineer and of nuclear engineering knowledge include the authoritative nature of knowledge, the relevance of multidisciplinarity in complex problem solving, and the concept of the engineer as a problem-solver. These themes are detailed and discussed below.

6.1 Authoritative nature of knowledge

The social role of textbooks as references shapes their content and the way their content is presented. Several of the texts surveyed expressed in their prefaces the desire to serve as both an instructive resource for students and a reference for practitioners in the field. This is noted in the second row of Table 3, which offers the example of a textbook published by the American Nuclear Society, a primary professional society of the discipline in North America. The intended purpose of this text is not just to instruct students, but to serve as an authority, implying that knowledge claims require qualification. In claiming this purpose, the text makes implicit claims about the nature of knowledge and responsibilities of engineers. That is, the stated authoritative and universal nature of knowledge implies that *a truth*, which can be found in a textbook, remains valid across time, space, and across decision makers. This universalism, however, fails to acknowledge the ability of the field to adapt, grow, or change fundamentally. More abstractly, through the understanding that the authority of the field lies in its *factual truth* rather than in the hands of decision-makers, a sense of the objectivity of the nuclear sciences is cultivated, shifting the responsibility away from individuals to the indisputable higher authority of facts.

Table 3. Some excerpts analyzed from the textbooks, our interpretation of the excerpt, and discussion on the implications of our reading of the text. These excerpts contribute to the theme of *the authoritative nature of knowledge*.

Text analyzed (emphasis added by the authors)	Authors' interpretation of the text's claims	Discussion of the authors' interpretation
"published as one of a continuing series in [ANS]'s program for providing the nuclear community and related fields **authoritative** information in monograph form" [19] (pg iii).	• Textbooks must serve as an authority. • Engineers base their practice in truth, and truth is dictated by vetted references which summarize the foundational science and engineering designs. • The information presented is uncontestable.	The practice of engineering is colored by the understanding of science/engineering practice as universal. The textbook seeks to provide information which is true across time, space, and culture. This could limit the growth of the field. (See Section 6.1 for further interpretation.)
"**everyone** has had the experience of a cigarette ash dropped innocuously on his hand" [24] (pg 7)	• This is an example to which every reader of the textbook can relate.	Although effective at explaining heat capacity, this statement confidently but falsely claims that this experience is universal. This might be considered an historical artifact, but statements like this (which persists in the 3rd edition published in 2016) can limit the present-day representation of the engineer to what it was in the 1980s.

"This presentation is designed to clearly illustrate how this recompression cycle must be designed and analyzed, **a subtlety which otherwise easily confounds the inexperienced analyst**" [17] (pg xxii)	• Textbooks help prevent pitfalls in learning. They should be used to help students learn the "correct" way to analyze. • Students and early-career engineers are easily confused by certain engineering topics.	This makes apparent the power difference between students and their instructors. Instructors (or textbook authors) in this mindset are authorities who have the right answers to help easily confused students. This, however, is only one way of viewing the dynamic between students and instructors. An alternative understanding might emphasize co-learning
"risk has been **unduly exaggerated** […] **In actual fact**, the risks from nuclear power are extremely low when compared with risks commonly accepted in other forms of human endeavor" [22] (pg 485)	• Risks are evaluated solely in a factual and rational manner. • Risks should be evaluated as relative and according to a standard that was constructed by engineering expertise. • Societal actors considered non-expert distort "true" risk when evaluating it. • The risks and safety of nuclear reactors are so well understood that this statement is universally true and should be taught to students of nuclear engineering.	See Section 6.1 for further interpretation. We note that this is only one text's view of risk.
"The remaining risk **must be acceptable** from the point of the people potentially affected by the presence of nuclear waste […] **Unfortunately**, the estimated risk does not determine whether the result is acceptable by the public. **The result does not dictate how people should feel about being safe**" [26] (pg 2)	• Feelings and emotions complicate risk management. • It is unfortunate that problems in risk management are not simply a matter of estimated risk; it is a problem or a bother that the public's opinion must be taken into account. • Some level of assumption of risk by the public is inevitable, and "acceptability" is the deciding factor for whether and how it is imposed.	We infer from this text that engineers prefer to solve problems in a way that focuses on estimation and quantification. The complications introduced by social factors and opinion are seen as undesirable, perhaps because of their subjectivity. No clarity on how what constitutes an "acceptable" risk and how it is determined—by or for affected people?—is offered. See further discussion of the related topic of rationality and quantification in Section 6.3.
"**It is evidently** not economically practical to reduce the emission of radioactivity from a nuclear power plant to zero, and **it is necessary**, therefore, to release to the environment, from time to time, small quantities of radionuclides" [22] (pg 563)	• It is *clearly true* that radioactive emissions cannot be zero for an economically attractive power plant. • Thus, since *economic practicality is a primary objective*, release of radionuclides is a *necessity*.	Rather than describing the contexts and conditions, this is prescriptive statement. It might have been said that release of radionuclides "is justifiable with stakeholder consent" under certain circumstances. The role of the engineer is asserted as an authoritative decision-maker who makes judgements based on what is evidently practical.

An explicit goal of several textbooks is to instruct the novice, and some texts reveal attitudes toward the novice and their competency. See, for example, Todreas and Kazimi's comments on students' mistakes in their text on thermal hydraulics, listed in the third row of Table 3. Some texts also seek to clear up misconceptions about nuclear technologies themselves. For example, Lamarsh addresses the conception of the risk of nuclear energy:

> "All engineering structures and devices inherently present some element of risk to their owners or operators and to the public at large. Nuclear reactors are no exception in this regard. At times, however, this risk has been unduly exaggerated, in some measure because of the innate fear of nuclear radiation on the part of the public, and also by the memory of the awesome effects of the nuclear weapons employed in WWII. In actual fact, the risks from nuclear power are extremely low when compared with risks commonly accepted in other forms of human endeavor. Indeed, to date, the safety record of the nuclear power industry has been excellent. […] However, nuclear power plants do discharge small amounts of radioactivity to their environs." [22] (pg 485).

If the audience for this particular discussion are students and novices new to the field, then it is notable to observe that this clarification was considered foundational enough (i.e. that it would endure in importance as the field evolves over the years) to be introduced in a text that is to be considered a reputable reference and foundational text. In this example, "actual fact" is placed in opposition to the "unduly exaggerated" fears of the public. Note that Lamarsh's comments on the safety record of nuclear power industry were written in 1975 before the nuclear accidents at Three Mile Island or Chernobyl. The idea of dichotomizing fact and fear has persisted, however. For example, an article from ANS's blog (not expressing the views of ANS) titled *Can we repeat facts about Fukushima often enough to overcome fears?* asserts that "unlike people who have been trained in nuclear sciences and engineering, facts do not matter as much to nuclear activists" who "relish in stimulating […] fear" [31]. This juxtaposition of fear and facts is rooted in the association of fears with irrationality. Within this mindset, *trained engineers* hold an authority which is grounded in objectivity of the truth. ANS's Principles of Professional Conduct lists this as a core principle: "We present all data and claims, with their bases, truthfully, and are honest and truthful in all aspects of our professional activities. We issue public statements and make presentations on professional matters in an objective and truthful manner" [32]. While we recognize these professional standards as noble and responsible in intent, the implied claim of these principles are that professional nuclear engineers speak in the language of facts, eschewing irrationality. This in turn reinforces the expert-lay divide by staking claims to who has the authority (or who does not) over determining what is "rational fact" and valued expertise (and what is not). If textbooks are to adhere to the principle of truthfulness, this requires recognition of the nuances of their objectivity and subjectivity.

The author or authority's voice and tone in the presentation of the text can also have an impact on the role of the nuclear engineer communicated in the text. Some texts emphasize the historical contexts and growth of the nuclear sciences, such as [25]. Others offer a more personal commentary on this development. For example, Lamarsh weighs in unequivocally on the use of nuclear weapons, referring to the "bombs which were presumably instrumental in the sudden termination of WWII" [22]. When referring to the language commonly used in the field to describe advanced reactors as "inherently safe", Knief comments that this is a claim that is "probably inappropriate" [23]. Also apparent are sensitivities to the effects of nuclear technologies, particularly nuclear weapons. Turner describes the existing data on human exposures to radiation. He states, "With its enormous scope and scientific value, the studies of the Japanese atomic bomb survivors have certain drawbacks", namely, the poor statistics due to the fact that "the exposed populations [were] lacking in healthy males of military age" [25] (pg 413). The lack of data on the populations fighting the war is framed as a shortcoming rather than a benefit for the lives spared. It is inherent and valid that the author's voice is present in their text, as shown in these examples. However, this subjective voice contradicts the claimed or assumed objectivity and underlying rationality of the textbook. That these textbooks and the subjective narratives contained within have nevertheless become authoritative, incontestable references in the field only further highlights the need for the critical inquiry of this paper.

Other obstacles to the authority of knowledge claimed by textbooks are expressed, for example, in the assaults on the credibility of experts and institutions discussed in the 2022 text on nuclear waste management by Yim [26]. Yim describes the history of efforts to dispose of nuclear waste in the United States and the US Department of Energy's subsequent loss of credibility by their inability to implement a solution. This case illustrates the complex nature of the social, political, and technical questions at play in nuclear technologies and demonstrates that the authority of knowledge of technical solutions is not sufficient for resolving the controversies surrounding nuclear technologies. In acknowledgement of this, Yim includes chapters on policy, regulations, and decision-making. By admitting and presenting the limits of technological expertise, perhaps the authority of knowledge is enhanced, in the sense that credibility is gained although the authority is less founded in the absolutism of knowledge.

In the nuclear engineering textbooks reviewed, we identify several key themes on the authoritative nature of knowledge. Namely, the textbooks often read as if they are books of universal facts which instruct both students and society by prescribing and defining factual knowledge. The textbooks are portrayed as objective and the authors are portrayed as primary and credible authorities, while simultaneously, the authors' personal perspectives are apparent in teach text. From our analysis, the textbooks analyzed offer a limited, specific, and subjective perspective on a scientific or engineering topic that reflect and reinforce what has been constructed to constitute valid nuclear engineering expertise. As such, the implicit as well as explicit values of the textbook authors are portrayed as authoritative knowledge, reinforcing the epistemic boundaries, logics, and underpinning values of the nuclear engineering discipline.

6.2 Relevance of multidisciplinarity in complex problem solving

Many of the texts emphasize how nuclear engineering is multidisciplinary. Following from its development from the varied fields of physics, chemical and mechanical engineering, and policy, among others, nuclear engineering includes a variety of topics despite being a relatively specialized field. By the same token, solving problems in nuclear engineering is complex and requires knowledge of technical details, economics, policy, etc. Many authors, in training students to become practitioners of the discipline, warn of the limitations of categorization and siloing of knowledge inherent in the *engineering approach* to problem solving. This approach is introduced as a guide for students which outline how to break down problems and systematically acknowledge uncertainties, their tolerances, and relevant assumptions [18], [21]. Some authors clarify that prescriptive approaches for solving problems are not always advisable given the multidisciplinarity of the problems at hand. The limitation of narrow approaches is explicit in texts focusing on the design of reactor cores and nuclear power plant theory. Todreas and Kazimi caveat: "We do not attempt to present a procedure for thermal design because nuclear, thermal, and structural aspects are intertwined in a complicated, interactive process" [18] (pg 29). Similarly, Duderstadt and Hamilton explain that "understanding of core physics is not sufficient. […] [The engineer] must learn how to interface his specialized knowledge of nuclear reactor theory with the myriad of other engineering demands made upon a nuclear power reactor and with a variety of other disciplines" [21] (pg 7). Although a deconstructive approach to problem solving is presented as a tool for engineers, the authors warn of its limitations. Analysis of the theme of the limitations of narrow approaches is summarized below in Table 4.

Table 4. Some excerpts analyzed from the textbooks, our interpretation of the excerpt, and discussion on the implications of our reading of the text. These excerpts contribute to the theme of *the relevance of multidisciplinarity*.

Text analyzed (emphasis added by the authors)	Authors' interpretation of the text	Discussion of the authors' interpretation
"We do not attempt to present a procedure for thermal design because nuclear, thermal, and structural aspects are **intertwined in a complicated, interactive process**" [18] (pg 183)	• Nuclear engineering is complex, so there is no *one* way to solve thermal design problems.	Here, the textbook authors make it clear that they cannot be prescriptive in their design. It is helpful that they are clear about the limitations of what the textbook can offer, while introducing students to key design concepts.
"nuclear analysis of the core […] must **interact strongly** with […] thermal hydraulics analysis, structural analysis, economic performance" [21] (pg 447)	• Certain analyses cannot be taken in isolation since they are highly interactive with other aspects of the reactor design, operation, safety, and economics.	Similar to the text in the row above, nuclear core analysis is deeply intertwined with other aspects of the reactor. The textbook authors make it clear that a singular problem cannot be solved without consideration of its relationship with other aspects of the reactor.
"Different approaches can be taken to site selection. These approaches include the technical approach, the public participation approach, the market approach, and the distributive justice approach […] What is needed is **an integrative approach that combines the strengths** of different approaches **while compensating the weaknesses** of the respective approaches" [26] (pg 485-486)	• Site selection (for nuclear waste disposal) can be done in ways that emphasize the most technically apt location, the most financially lucrative option, the most publicly supported option, or in a way which is most just to the communities affected. • Integration (possibly meaning optimization) is the way to manage the multiple and different approaches to the selection of the site for nuclear waste disposal.	Rather than saying the optimal solution should be obtained by balancing/optimizing the various approaches to site selection, the author recommends that the various approaches be integrated. This language avoids emphasis on quantitative methods (see Section 6.3) and shifts focus to a natural blending of techniques to highlight the strengths of multiple viewpoints.
"**Of course** one desires to minimize electrical generation costs **but** must also ensure that the safety of the reactor is not compromised" [21] (pg 459)	• Minimizing costs is the primary goal—and this should be obvious to the reader. • However, safety must also be maintained.	This is an example of the most frequently cited example of "multidisciplinary" analysis in the nuclear engineering texts reviewed: safety/design and economics. (See Section 6.2 for further analysis.)
"Design criteria are frequently **contradictory in nature**, and hence require **optimization**" [21] (pg 97)	• Maybe related to the quote above—minimizing costs and maximizing safety might be "contradictory in nature". • Optimization is *the* way to manage competing criteria.	Although the criteria are not specified, if safety and cost-effectiveness are the inherently contradictory criteria (related to the example in the 5th row, above), this framing of safety has implications on design and the practice of engineering. In this case, safety is framed as a costly burden, whereas it could be otherwise—an integrated and primary criterion. If criteria are contradictory *in nature*, then design is a fundamental competition of values. We note that the way of framing design in the text is just one

		method, although it is presented as *the* method of engineering design.
"The subject of nuclear reactor safety is **exceedingly complex**, enmeshed in a labyrinth of complex technical, regulatory, political, philosophical, and **even emotional issues**" [21] (pg 459)	- Surprisingly, even emotion is relevant to nuclear reactor safety.	The authors might be highlighting that emotional issues are often ignored, or they might be expressing that it could be surprising that emotional issues are relevant to engineering. It is valuable that this lesser-discussed aspect of engineering problem solving is named. It would be beneficial, we believe, to elaborate on how emotion cannot simply be erased from what might be considered a purely rational method of problem solving. (See Section 6.3 for further discussion of rationality.)

The interdisciplinarity of nuclear engineers frequently refers to the analysis of both cost and performance of nuclear systems [18]. In describing the "very important constraints" of nuclear fuel management, Duderstadt and Hamilton explain: "Of course one desires to minimize electrical generation costs but must also ensure that the safety of the reactor is not compromised" [21] (pg 459). In interpreting the structure of this statement, we see that the goal of minimizing costs is subtly ranked of higher importance than the goal of safety. When there exists a hierarchy of goals, the "engineering approach" classically is to weigh the contributing factors and perform a cost/benefit analysis. In the texts, oftentimes the bridging of technical and economic analyses are what simply constitutes "multidisciplinarity", however some texts point out other aspects such as aesthetic, socioeconomic, and environmental analyses [26]. Almost exclusively, however, the texts describe that the engineer manages multiple options via optimization of multiple analyses. See the final three rows of Table 4 for a summary of further evidence and discussion.

To serve as references, many texts attempt to be broad, incorporating scientific foundations, technology-focused details, comments on economic and safety analyses, and (sometimes) regulatory frameworks. No textbook or set of textbooks claims to be or effectively serves as a sufficient summary of nuclear engineering. The practical limitations to how much can be included in a text are usually acknowledged, but nevertheless which topics are given priority reflects the authors' values and priorities. In Lamarsh's *Introduction to Nuclear Engineering*, he explains that "in order to meet a publication deadline, the discussion of environmental effects had to be confined to those associated with radioactive effluents" [22] (pg viii). The original goal was to include a separate chapter on all environmental effects of nuclear power, but this was relegated to a section in the chapter on licensing and safety. Perhaps a practical reason for shortening the discussion on environmental effects is legitimate, but we note which topics are not essential *enough* to receive full treatment in the introductory text. This decision offers some insight into the priorities and pressures within the field; thorough discussion of environmental effects was lower priority than reactor physics, or at least environmental effects come after reactor physics and then receive less attention. This, however, is only one way of rationalizing the design of a reactor. It is feasible to frame the problem with environmental effects as a starting point, but the standard approach to nuclear engineering treats the environment as an addendum or final consideration.

We identify several elements of the key theme of the relevance of multidisciplinarity in the nuclear engineering textbooks analyzed. These patterns include comments that engineering is complex and involves the balancing of many demands. Most frequently, cost/benefit analysis or the combination of safety/design and economic analyses are cited. In the texts, optimization is the primary method for managing competing interests. From our interpretation, there is more to multidisciplinarity than economic and technical analyses; social and political aspects are also significant, and some texts make note of these. Even so, the multidisciplinarity acknowledged in these texts is limited in the sense that it generally fails to invite critical thought that may contest and expand the underpinning logics and assumptions of the nuclear engineering disciplines. Instead, the multiplicity of disciplines invited to engage with nuclear technology primarily encompass those that are instrumentally useful to reach an implicit normative goal of supporting societal progress through nuclear technology, with harmful impacts as discussed above an afterthought. We agree that no textbook can be fully comprehensive, and we believe that in generating a textbook, particular attention should be given to which topics are included and which are excluded. These decisions of what to highlight and dismiss sustain narratives of what is and should be essential to nuclear engineering.

6.3 Rationality and quantification in the pedagogy of problem solving in nuclear engineering

Complex problem solving, as it is taught in nuclear engineering texts, is often done by the deconstructive “engineering approach” as described in the previous section. Todreas and Kazimi are explicit in their definition of the engineering approach, which involves estimating via empirical correlations:

> “Our objective can often be achieved by applying the accumulated engineering experience in a manner that empirically relates macroscopic quantities, for example, the pressure drop and flow rate through a tube, without obtaining the detailed distribution of the fluid velocity or density in the tube. This engineering approach can be used whenever the flow characteristics fall within the range of previously established empiric relations” [18] (pg 439).

According to this definition, engineers accumulate experience to have a working understanding of a topic, and they then apply that knowledge in a limited way to solve technical problems. They do not always need to have a detailed understanding of the more fundamental science at play. Some authors emphasize the benefit of understanding the underlying science to better understand engineering applications. Lamarsh describes the value of a "firm understanding of atomic and nuclear physics, since these subjects underlie much of the profession" [22]. But in how the engineering approach is described, there is an emphasis on practicality. The textbooks imply that fundamentals are only useful in that they serve the application. Todreas and Kazimi summarize the “basic question” of engineering practice as “how to predict the practically needed (and measurable) macroscopic behavior on the basis of whatever microscopic behavior may exist—and to the degree of accuracy required for the application” [18] (pg 183). Here, the degree of accuracy required for the application is crucial. This requires a value judgement on what is considered appropriate or acceptable for a given system. This applies to the “engineering approach” more broadly, as well. The engineer must determine when and how much microscopic behavior is relevant to their application—or when the “engineering approach” applies to the problem at hand at all. In this way, the engineer must make subjective value judgements, and, if we interpret this in a manner consistent with the universalism and objectivity discussed in Section 6.1, the responsibility of the engineer is to do this in the most rational way possible, often by deconstructive and quantitative methods. In this singular approach to problem solving, there is some inflexibility. This approach does not necessarily provide solutions to questions like who has agency to make decisions on siting or in accident scenarios, for example, but these, too, are relevant to the operation of nuclear engineering technologies. Consistent with the dichotomization of fear and facts, rationality is elevated above other ways of knowing, such as emotion or imagination. This inflexibility, however, may be a barrier to more authentic exchange about issues in nuclear technologies such as safety and legacy.

Table 5. Some excerpts analyzed from the textbooks, our interpretation of the excerpt, and discussion on the implications of our reading of the text. These excerpts contribute to the theme of *rationality and quantification in the pedagogy of problem solving*.

Text analyzed (emphasis added by the authors)	**Authors' interpretation of the text**	**Discussion of the authors' interpretation**
" Hence what we should really look for is a **'fudged-up'** boundary condition which, although it may have little physical relevance at the boundary, **does in fact yield the correct neutron flux** deep within the reactor where diffusion theory is valid" [21] (pg 153)	• The "engineering approach" to problem solving involves estimation and empirical methods.	While rationality is emphasized in engineering and the sciences, rational decision-making is especially relevant to engineering.
"**Even if** the risks from low-level radiation were established quantitatively on a firm scientific basis the setting of limits would **still** represent a social judgment in deciding how great a risk to allow." [24] (pg 449)	• A social judgment is necessary for risk assessment. • The engineer might want to avoid subjective social judgments by their "firm" quantitative methods. But this cannot be avoided.	See detailed discussion in Section 6.3.
"While intervenors have acted **irresponsibly** in many NRC license hearings, and in some cases caused extensive delays in the construction of much-needed electrical generating capacity, the adversary proceedings of the public hearing have generally proved to be a sound method for **determining the truth in debatable issues** and for **providing a meaningful input from the public concerned**." [22] (pg 493)	• Public hearings have been largely helpful in finding solutions or the "truth" and allowing for public input. • At the same time, public hearings have led to unnecessary and harmful delays.	We note that the textbook authors describe that public hearings have effectively led to "determining the truth"—meaning that engineers and the concerned public were able to come to a shared understanding of the "facts". Rather than reaching consensus, this language implies that those involved were able to come to the "right" answer. See Section 6.1 for a related discussion on the authoritative nature of knowledge.

Risk management is discussed in the texts as one of the key problems that must be solved by engineers, as seen in the third row of Table 5. Like the value judgements necessary for applying the engineering approach to problem solving, value judgements are needed to manage risk in engineering applications. Turner explains:

> "The overall objective of radiation protection is to balance the risks and benefits from activities that involve radiation. If the standards are too lax, the risks may be unacceptably large; if the standards are too stringent, the activities may be prohibitively expensive or impractical, to the overall detriment to society. The balancing of risks and

> benefits in radiation protection cannot be carried out in an exact manner. […] Even if the risks from low-level radiation were established quantitatively on a firm scientific basis the setting of limits would still represent a social judgment in deciding how great a risk to allow.” [25] (pg 449).

As described in the example of radiation protection, managing risk is done in a manner analogous to design optimization, using the engineering approach. However, Turner points out the limits of quantitative risk management by explaining "even if” the engineer can establish a “scientific basis” for managing risk, value judgements on what risk is socially acceptable are necessary. In the tone in which we are interpreting the text, the language of “even if” is revealing of attitudes distinguishing a firm, factual understanding (what Turner might call the right answer) from a more subjective social judgement (what Turner might call a barrier to that factual answer). At face value, this quote shows commitment to a utilitarian understanding of risk, that is, weighing costs and benefits. More broadly, the implicit framing of risk as a problem (which may or may not be true in the case of Turner) highlights the epistemological attitude that the inability to be “exact”, or perhaps purely quantitative, in solving a problem implies a weakening of the solution. In interpreting Turner, we read a sense of frustration with the inexactness of risk management—as if Turner is saying that it is annoying that one cannot get away from a social judgment, and since a social judgment is required, no exact answer can be construed. In this understanding, the engineer is profoundly committed to a singular method of problem solving. If the profession of engineering, as defined in nuclear engineering texts, is uncomfortable in managing inexactness or qualitative approaches to problem solving, this seems highly limiting to the effective development and implementation of technologies which are necessarily social in nature. In this case, perhaps we engineers can learn from other disciplines on what are equally valid and useful ways of understanding and problem-solving, other than the “engineering approach”.

Overall, rationality and quantification are predominant themes in the pedagogy of nuclear engineering, as revealed in the textbooks reviewed. Rationality and quantification are elements of the “engineering approach”, which is a value judgement rooted in these principles which is often taught as the way that engineers solve problems. Several of the textbooks analyzed carried an undertone of frustration towards problems which cannot be solved in a straightforward manner via the “engineering approach”, as it is defined in the texts. From our perspective, this points to the possibility that there are valid ways to solve or engage with problems beyond the engineering approach. We believe that engineers should learn from and collaborate with fellow problem-solvers who employ different methodologies or approaches, like social scientists or historians, who can offer critical and contextual frameworks that make visible the origins as well as impacts of the embedded values in and limitations of engineering disciplines.

7 Conclusion and Outlook

This work explores how beliefs about knowledge and the role of the engineer shape how students train in the field and practice of nuclear engineering via an analysis of nuclear engineering textbooks. We present an analysis of embedded value systems to examine what is considered essential to being a nuclear engineer. From the textbook analysis, we identify several key themes including the authoritative nature of knowledge, the relevance of (limited) multidisciplinarity, and the emphasis on rationality and quantification in pedagogy of engineering as problem solving. These themes, along with others, contribute to the historical narrative of what it means to be a nuclear engineer. In analyzing these themes, we identify a need for authors to acknowledge their subjectivities when portraying engineering information, that authors pay attention to what narratives are sustained by which topics are included and which are excluded from their texts, and that authors learn from and collaborate with researchers who solve problems via alternative and potentially critical methods to the "engineering approach". Looking forward, we hope to examine the possibility for the roles and responsibilities of the nuclear engineer to change and overcome the limitations (at best) and harms (at worst) of its discipline through the way that knowledge is curated, presented, and taught.

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9 Credit Author Statement

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