Ethical Responsibility Formation of Students in a Nuclear Engineering Course Through Inquiry Learning

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This article presents an approach of embedding sociotechnical competency development in a traditional technical undergraduate course in an Engineering Physics program. An inquiry project was integrated into the course and served as the main evidence of the students' demonstrated ability to integrate social, ethical, and technical analyses. Surveys were administered to collect feedback and student perspectives on their learning outcomes and the impact of the course components. Results from 2017-2019 were analyzed to examine the possible mechanisms and principles by which particular course components contributed to enhancing ethical responsibility, and how ethical responsibility is conceptualized for the nuclear industry context.

Keywords: sociotechnical competencies, sustainability, engineering ethics, inquiry learning

INTRODUCTION

Engineering ethics – both in the nature of engineering practice and the impact of engineering work – intersects ethics of many dimensions including the philosophical, technical, business, professional, environmental, legal, and bioethics (Andrews, Shaw, & McPhee, 2018; Budinger & Budinger, 2006). The impact of engineering work, including energy systems, extends well beyond the immediate use of technology into the social institutions, distribution of resources, culture, health, and environment. The breadth of desired engineer competencies reveal the social, cultural, and political dimensions of an engineer's professional practice, despite the predominant perception of engineers as technical experts meeting business needs (Jamison & Heymann, 2012; Jørgensen, 2012; J. C. Lucena, 2003). Even as the need increases for collaboration across disciplines, no longer can the technology experts be 'disconnected from the civil society' (Lawrence, 2015).

The critical theory perspective and systems paradigm challenge us to examine what it means to 'teach engineering ethics.' We acknowledge and accept that it cannot be expected that individual engineers will carry the entire responsibility for ethical and equitable decision making in engineering. The organizational culture and structure, the contractual arrangements within the industry, engineering teams, and policy instruments can either enhance or constrain responsibility in engineering decisions. In working towards presenting a solution to a problem, or the implementation of a new technology, engineers will need to acknowledge competing interests and act as a mediator to negotiate for a practical solution. In some aspects, engineers will have to re-assert themselves as the stewards of public safety, and as co-decision makers, instead of being treated as commoditized instruments (Spink, 2008) of the business machinery.

Simultaneously, we pay attention to the engineers' privileged position – e.g. as experts and high-income earners, with greater proximity to large-scale project decisions – and its role in the unequal influence relations engineers have with other knowledge disciplines and/or community stakeholders. Engineers can be important mediators or gatekeepers for the input of diverse stakeholders on the technology development (e.g. machine learning bias). Therefore, our working vision for engineering ethics education is two-fold: (1) to empower students as moral agents who effectively negotiate for social and ethical responsibility in the technology industry; and (2) to motivate and equip students to actively include and respond to the perspectives, concerns, experiences of the stakeholders whom, otherwise, are made invisible in the decisions regarding engineering projects.

Identifying Student Needs in Our Local Context

In our experience of working with undergraduate students enrolled in energy systems courses since 2012, these are the challenges we observed particularly relevant to nuclear engineering students:

(1) The public as an entity, has and will continually present concerns about all nuclear projects. So far, many students have found themselves defensive to these concerns, which they recognize hinders the communication and dialogue of engineers with the public. This perceived divide between the public and nuclear engineers limits the students' openness to partnership with local stakeholders, which may lead to a loss of invaluable information and sustainable strategies fitting to local contexts.

(2) Some students also presented a narrow definition of what counts as their work in nuclear engineering. By treating engineering solely as technical and morally neutral, the ethical considerations are treated as outside the scope of an engineer's responsibility. Such definition also fails to acknowledge the social impact of, and implicit biases in, the engineering decisions.

(3) There is also limited heuristic and analytic tools to conduct the social and ethical analyses (Fisher, Konrad, Boenink, Schulze Greiving, & Walhout, 2016), to critique the dominant discourses that shape the taken-for-granted objectives that may reproduce social injustices (Baillie & Armstrong, 2013), and to construct a systems architecture of complex sociotechnical interdependencies (Ottens, 2010) that enable the prediction of long-term impact. Sustainability philosophies and life cycle analyses already challenge us to assess 'true costs' of technology.

(4) Finally, there is a low sense of agency among some students. When they perceive a disagreement between their personal morality and the expectations of their employer, they believe they must conform to the latter. Instead of partaking in the deliberations at an organizational or policy level as valued experts, the instrumental view of engineers as 'doers' reinforces the discouragement of critical thinking and action.

As a result, we developed the following learning outcomes to be achieved in the course taught by Nagasaki. The introductory course to nuclear engineering (Engineering Physics 3D03) provides important technical foundations for nuclear engineering, and has weekly lectures, weekly labs, assignments and a group project. The following learning objectives, therefore, do not replace but are in addition to the principles of nuclear engineering that are fundamental to the course:

- Be able to analyze and integrate social impact considerations for nuclear engineering: Students are provided lectures and assignments that integrate discussions on nuclear technology advancement directions, industry trends, international and federal governance, regional sustainable energy portfolio, local decision making processes related to energy system design and nuclear waste management.

- Investigate nuclear energy issues as sociotechnical systems problem (Costa, Diehl, & Snelders, 2019): Students are first exposed to the interdependencies between the economic, social, and environmental dimensions of sustainability (triple bottom line) during lectures. Some historical and geopolitical complexities are also explained.
- Critique the taken-for-granted design and industry practices against ethics and equity principles: Students are presented case examples where bias in the system modelling can be created from inherited metrics, inaccurate assumptions, and the way public discourse is constructed about technologies and policy decisions.

COURSE DESIGN: ENGINEERING PHYSICS 3D03 (EP 3D03)

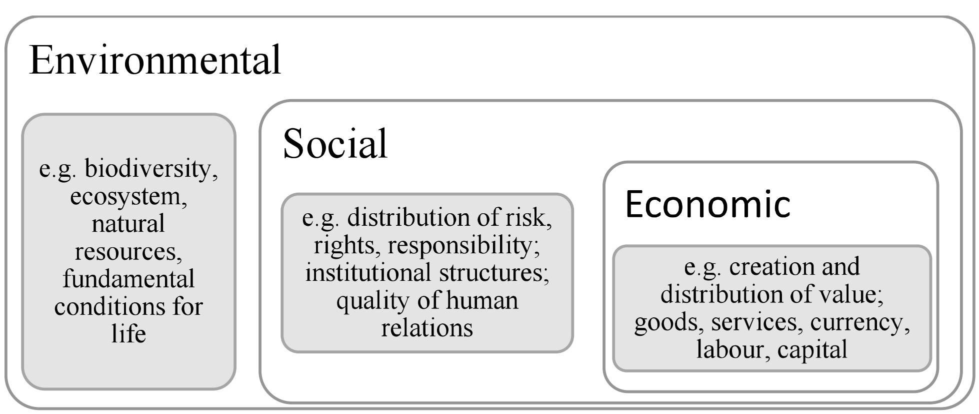
Sociotechnical Integration Frameworks in EP 3D03

We needed a framework that would help us articulate the ethical issues to be addressed by engineers, which, by its very externalization, would make action possible (and help explain why certain actions actually brought about change). Being able to see how the larger sociotechnical system operates is critical to analyzing why certain unethical, unsustainable, dehumanizing situations are maintained (Christensen & Erno-Kjolhede, 2012; Mazzurco & Daniel, 2020). Being able to see how we are embedded in the system is also crucial, towards identifying opportunities for change and re-imagining our influence on the system behaviour. Paulo Freire (1993) has profoundly articulated:

> Humans, however, because they are aware of themselves and thus of the world—because they are conscious beings—exist in a dialectical relationship between the determination of limits and their own freedom. As they separate themselves from the world, which they objectify, as they separate themselves from their own activity, as they locate the seat of their decisions in themselves and in their relations with the world and others, people *overcome the situations which limit them* […] Men and women respond to the challenge with actions […] directed at negating and overcoming, rather than passively accepting, the "given." (p. 99, emphasis added)

Given the emphasis on sustainability as the distinctive graduate attribute in the Faculty of Engineering at our institution (Racette & Nagasaki), we built on the triple bottom line (TBL) of sustainability (extending beyond a business) as the starting framework to present the systems view of engineering-society relations (**Fig. 1**). We clarify the common misconceptions (e.g. 'economic' being misinterpreted as 'economical'), and have the students explore the interactivity and the relationship between the three layers of TBL (e.g. economic disparity between communities leading to an unequal distribution of health burdens of a large-scale project; disruption of the local ecology affecting the economic activity).

FIGURE 1
EMBEDDED VIEW OF THE SUSTAINABILITY TRIPLE BOTTOM LINE



We also examine the embeddedness of engineering practice within an organizational environment, also embedded within specific regulatory and sociocultural environments. A brief overview of the history of nuclear energy in Canada plays an important role. Students quickly apply this longitudinal perspective to the assignments they work on, which are case studies from international contexts. The natural resource, political, military and private industry, and regulatory situations are discussed to explain why certain countries have adopted or are pursuing particular advancements in nuclear technologies. Technology development is no longer treated as a neutral, depoliticized process (Cech, 2013), and thus demand critical awareness and conscious deliberation from engineers.

Lastly, we introduce the concepts of technological mediation and equity. Technological mediation (Verbeek, 2011) explains how technology, inherently by its design, alters people's perception of reality and influences action. Equity, on the other hand, strengthens the understanding of the sociotechnical integration on multiple levels. For example, applied to the stakeholder analysis and TBL interaction, the topic of equity helps explain the relationship between socioeconomic inequalities and different vulnerabilities to risk. Extending the discussion of technological mediation, the equity lens helps foresee the unintended negative consequences of a technology design (and its social acceptance) in altering social relations and exacerbating disadvantages. Equity also introduces the students to the systemic, historically situated and socially constructed issues of privilege and oppression. Equity, in relation to diversity and inclusion, is perhaps one of the most misunderstood and inadequately explained notion in our experiences with engineering education. By practical application of the concept to engineering design, technology development, and workplace decision making, the lecture equips students with a much clearer framework to engage in these discourses.

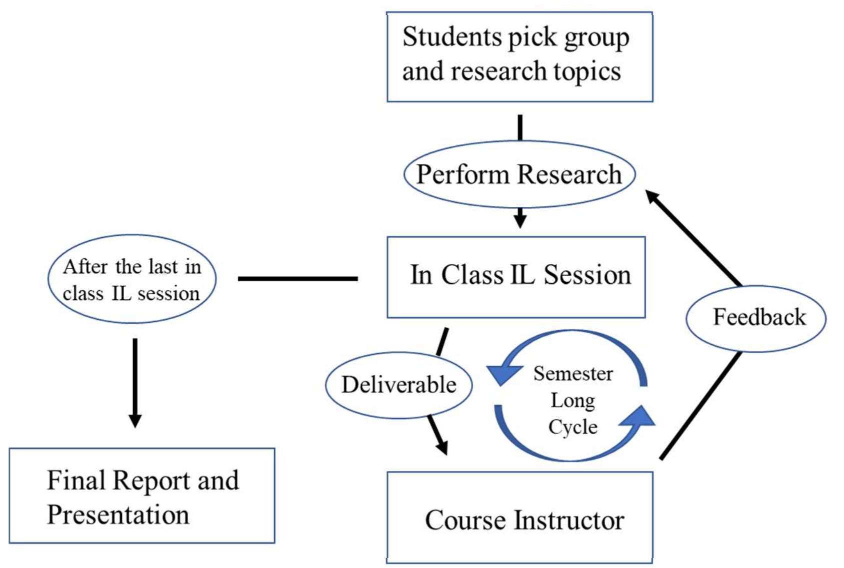
Inquiry Learning Design in EP 3D03

Building on our previous efforts to enhance the social scientific literacy of students enrolled in the energy systems courses (Ha, Nagasaki, & Riddoch, 2016), we integrated a guided inquiry learning (IL) approach to the group project in EP 3D03 from Winter 2017 onwards. Guided IL is a question-driven learning process (see (Christian, Hershock, & Melville, 2009) for distinction from structured IL). The students are performing research on a specific question to learn how to perceive, think about, and ultimately approach the question more like an expert would. The goal of inquiry includes complex knowledge construction, interpretation and action (problem solution). The learner takes an active role of knowledge creator, but not in isolation - nor does the self-directed nature of IL mean that the instructor stops providing instruction (Kirschner, Sweller, & Clark, 2006). In our setting, the instructional staff curates the introductory content and in-class activities to facilitate and aid the learners' inquiry process. The instructor guidance can include detailed examples of problem investigation process and outcomes. There is more general guidance in the beginning of the project, and more personalized feedback near the end of the term. The instructor provides constructive feedback on the learners' reasoning and process, helping students development judgment skills. The instructional staff's skillfulness (Carbonetto, 2019) and knowledge are important in posing thought-provoking questions which will require the students to further their own research to answer these new questions. Iteratively exchanging questions about a research project is expected to result in a more fulfilling inquiry process. The instructor serves as an enabler as well as partner in the knowledge construction process.

For the IL project, the students work in groups of four, and can self-select topics relevant to nuclear engineering (e.g. *small modular reactors to replace diesel generators in off-grid Canadian communities; the state of Advanced Fuel CANDU Reactors; TBL impact analysis of molten salt reactors as an alternative to conventional reactors; International Thermonuclear Experimental Reactor and the future of fusion energy*). Upon selection of the research question the students then formulate who the stakeholders are in the system and how they may be impacted, how the environment will react to the nuclear system being investigated, and finally what do the economics of the system look like. By presenting the TBL as the foundation to the students in how they might pursue their research, the IL project gives an opportunity for students to explore current geopolitical issues and the role of the public in technology-related decisions. A successful IL process will see that the students are able to formulate ideas about their nuclear system, develop an understanding of how connected the TBL is, and provide tangible recommendations or commentary about the future of their system.

We dedicated four lectures as inquiry learning sessions (one of which is focused on the social and ethical analyses, as described in the above). The four lectures correspond to the newly defined four stages and deliverables of the IL project. The organization of the IL project into four stages reduces the cognitive load for the learners, and allow focused immersion into the tasks that require different modes of thinking (i.e. problem definition, data selection, methodology, interpretation of findings). Sociotechnical integration is performed mainly in the problem statement and interpretation sections. The four deliverables also allowed a greater frequency of instructor and peer feedback. The course director (Nagasaki) provided written feedback on each deliverable. We believe written communication is one of the most effective means to structure and clarify complex knowledge. Students had to articulate a concrete understanding of complex topics, highlighting gaps and misconceptions that could be targeted as well.

FIGURE 2
FLOWCHART OF THE IL PROJECT PROCESS



RESEARCH DESIGN

In order to evaluate the effectiveness of the inquiry learning strategy outlined above, we conducted Post-Course Surveys and in-depth interviews in 2017, 2018, and 2019. This paper focuses on the findings from our surveys. The survey was conducted online through a secure platform provided by the institution (Office of Research Ethics), completed outside the class time. The research assistant (Racette) made the announcements in class and on the learning management system, and was the only person with access to the raw data. There was a bonus mark of 1% for completion of each survey, and the research assistant (Racette) directly arranged with the course TAs to apply the bonus marks to the final grades. The anonymized survey data were shared with the research team only after the final grades were released.

In 2017 and 2018, an additional Pre-Course Survey was administered, focusing on the student motivations for enrolling in EP 3D03. The implementation of a Pre-Course Survey was not aimed at measuring changes on particular question responses (or performance) before and after the course, since our interest lies in exploring the *mechanisms* by which our teaching might be effective. The Pre-Course Survey responses can inform us with student needs and interests, which can inform our teaching strategies, but such purposes can be better served within the teaching setting (collecting student feedback quickly) than through a research study where confidentiality and conflict of interest were of concern. A select number of questions from the Pre-Course survey were transferred to the Post-Course survey administered in 2019.

Rating questions were provided descriptive scales, often followed by comment questions without a word limit. Open-ended questions had no word limit, but generally participants provided 2-4 sentences, or 25-70 words, per question. Completion of questions were all voluntary. All given responses were analyzed and included in the presentation of themes and counts. All qualitative responses were reviewed by all three researchers, to generate concepts and concept relations. The results were discussed in our regular meetings and based on their convergence, the analytic categories were developed.

TABLE 1
SURVEY PARTICIPANTS, 2017-2019

EP 3D03		**2017 Class enrolment: 21**	**2018 Class enrolment: 20**	**2019 Class enrolment: 27**
Pre-Course Survey (January)		14 responses (2 female: 12 male) Participant ID#: 701-714	8 responses (2 female: 6 male) Participant ID#: 801-808	N/A
Post-Course Survey (March)		10 responses Participant ID#: 701P-710P	12 responses Participant ID#: 801P-812P	7 responses (2 female: 5 male) Participant ID#: 901-907
Reasons for Enrolling in EP 3D03 (open-ended responses)	**Identified Themes**	Number of Responses (Pre-Course)		(Post-Course)
	Determined to Pursue a Career in Nuclear Sector	6 of 14	4 of 8	3 of 7
	Considering a Potential Career in Nuclear Sector	3 of 14	4 of 8	0 of 7
	Seeking Introductory Knowledge in Nuclear Engineering	6 of 14	3 of 8	5 of 7
	Seeking Detailed Knowledge in Nuclear Engineering Fundamentals	4 of 14	2 of 8	2 of 7
	Interest in Environmental Sustainability	3 of 14	1 of 8	2 of 7
	Interest in Health & Safety	1 of 14	1 of 8	1 of 7
	Interest in Societal Context, including Public Engagement and Social Justice	5 of 14	2 of 8	1 of 7

Because the surveys collect brief responses, the results were used to inform in-depth interview questions for further investigation. Nevertheless, survey responses provide important insights about their experience with the course, their self-recognized learning outcomes, and what is meaningful to them.

Because the class size is small, and the survey response rate ranged from 26-67%, we do not claim a complete representation nor generalizability from our findings. We do find useful the repeated patterns in student responses over the three years of data collection. We also find value in the diversity and uniqueness in student responses, which sensitize the researchers to the plural meanings of, e.g. engineer responsibilities, from student perspectives. The findings inform our understanding of the student interests, their learning experience, and the possible ways by which they construct their professional responsibilities.

Survey Participants

We were unable to collect consistent demographic information for all surveys, which will be corrected for future surveys. From 2017 to 2019, survey participants included students from engineering physics, medical physics, electrical engineering, mechanical engineering, and integrated science. Majority of the participants were in third or fourth year of their undergraduate programs. Many engineering students at this institution participate in co-op (paid internship) and combined programs (e.g. Engineering and Management), which extend their undergraduate experience to 5-6 years.

Participants in the study had minimal to partial knowledge in nuclear engineering. EP 3D03 counts as a core course for Engineering Physics students (all streams), and is a required core course for those pursuing the nuclear stream. EP 3D03 is also offered as an elective to other engineering, science and health science students. Information about the background motivation for enrolling in EP 3D03 are presented in Table 1. The participant number labels between the Pre-Course and Post-Course survey sin 2017 and 2018 do not correspond to each other (not paired).

RESULTS

Students' Prior Perceptions

In the Pre-Course Surveys of 2017 and 2018, one of the motivation-related questions asked: "Are you motivated to learn more about the societal aspects of the nuclear engineering/energy systems? Why or why not?" Students responded in an open-ended textbox. In 2017, 10 of 14 students began their answers with an affirmative ('Yes'), 3 students indicated negative (e.g. 'Not really'), and 1 student remained neutral. In 2018, 6 of 7 survey respondents indicated positive, while 1 responded 'No' (without explanation). Students' explanations are captured in Table 2, grouped by identified themes (e.g. need for awareness, action-orientation). Quotes were reduced for presentation.

Explanations for motivation to learn the societal aspects, in both the positive and negative responses, involved the students' perceived relevance of a topic to one's conceptualization of work (performed tasks and abilities) and/or role (in relation to other actors/stakeholders). In determining what is included in one's professional work and role, the survey responses suggest that the students' sense of personal and professional responsibility may be tied to: (a) the perceived impact of nuclear engineering (to what one should respond), and (b) the perceived autonomy in making the design decisions in technology development (whether one can respond). The former requires an effort to develop well-integrated understanding of the systems - of actors, issues, and causal relations - that help visualize and anticipate the impact of design decisions. The latter makes it important for engineering ethics education to build practical skills suited to specific engineering workplace environments.

Strong public opinions have always been part of the discourses around nuclear power, and it is not surprising that the public takes an important part of students' perceived world of nuclear engineering. We observe the tension between seeing the public as a threat to nuclear industry (i.e. defensiveness), and seeing the public as those passively impacted by the engineering work (i.e. service/advocacy). Both views may be able to agree on the benefits of nuclear engineering, but there would be different emphasis on the unequal distribution of benefits, of costs/risks, and of decision influences. There is also another spectrum of viewing public stakeholders, from 'uneducated,' to key informants, to partners in project success, to co-designers. We find 'role conceptualization' as an important part of making sense of one's ethical responsibility (**Appendix II**), which is discussed further below.

TABLE 2
STUDENT REASONS TO MOTIVATION IN LEARNING ABOUT THE SOCIETAL ASPECTS OF NUCLEAR ENGINEERING

Motivated?	2017	2018	Identified Themes
"Yes"	713: "… Engineers must always put their work into perspective… safety… and societal aspects of this cannot be ignored."	801: "… Nuclear engineering students **deserve to be at least aware** of what these societal aspects are." 805: "… we should **be knowledgeable** about the full impact of any work we partake in…"	Recognized Need for Greater Awareness
	701: "…it **should be part of my job** in designing… to take account the societal impact of a design" 703: "… engineers **have a huge hand** in societal development… learn from the past and **cater their work to the needs** of the future" 709: "… huge impacts … possible effects… should be explored **before introducing** new technologies." 710: "... I want to be sure … that [my work] ultimately will have a positive impact on society."	802: "… societal impact… Nuclear energy systems are **huge investments… planning and consideration [of stakeholder] needs**…" 804: "… it is everyone's **duty to ensure** the safety and well-being of our citizens."	Responsibility for Impact & Public Needs
	702: "… pivotal role that **public awareness and approval** will play…" 707: "… **better explain to others**… how beneficial nuclear energy can be." 712: "… I'm concerned with the general public's vilification of nuclear power…"	803: "… **public relations and acceptance** are key to the future development… how safe nuclear technology really is… the impact of clean energy… seems understated." 806: "… sustainability and the **public perception**…" 807: "… multiple considerations… Ultimately **the public will vote**…"	Public as Constraint to Inform & Manage

Motivated?	2017	2018	Identified Themes
"No"	704: "… I think it is important, I just feel like it is not relevant to me." 705: "… it is unnecessary to learn about the societal aspects of nuclear engineering, although it may be helpful to know." 706: "… it's an important aspect for other people to learn more about."	N/A	Irrelevance to Engineering Work

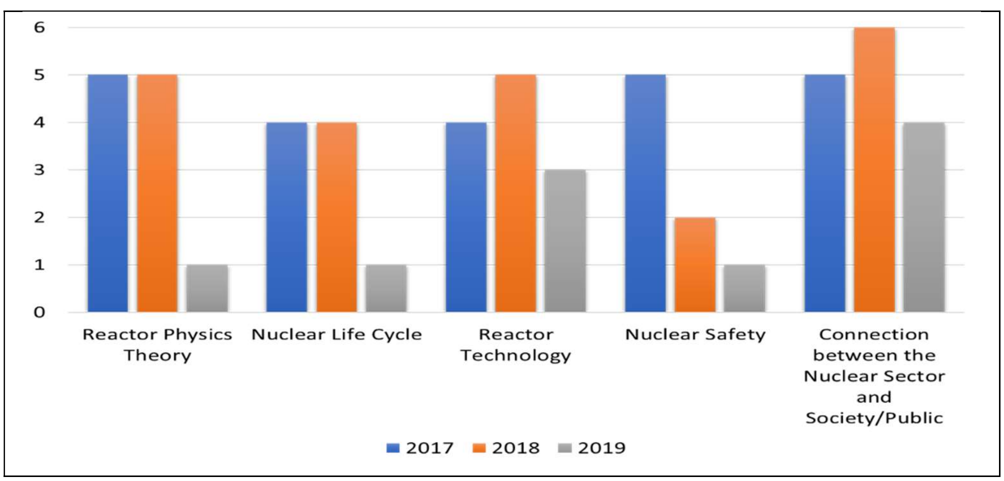
Feedback on the Course, Key Learning Outcomes and Effective Teaching Strategies

A Post-Course Survey was given to the students which asked them to identify what they felt were the three most important learning outcomes of EP 3D03. The question was asked in an open-ended format to allow the students to articulate in their own words what was personally meaningful to them. The resulting responses do not create an exhaustive list of all the learning outcomes that took place. Nevertheless, we aimed to see if the sociotechnical learning outcome category was memorably meaningful enough to be included in the selection of top three takeaways, along with the traditionally technical outcome categories of the course.

Because the question was open-ended, students were free to describe their top takeaways that fall under 1-3 of the learning outcome categories. Figure 3 presents the *number of students* who have highlighted each of the learning outcome categories, from 2017 to 2019. Since one student could describe up to three learning outcomes of the same category, the counts do not reflect the total number of mentions per category.

Combining all data from 2017 to 2019 (Fig. 3), the responses were categorized according to their alignment to the five key learning objectives of the course (Appendix I): Reactor Physics Theory (11 of 29 students), Nuclear Fuel Life Cycle (9 of 29), Reactor Technology (12 of 29), Nuclear Safety (8 of 29), and finally the Connection between the Nuclear Sector and Society/Public (15 of 29). The societal aspect of nuclear engineering was repeatedly noted as meaningful outcomes, even as the course continued to deliver very technical content in its labs, assignments and lectures.

FIGURE 3
SELF-IDENTIFIED TOP LEARNING OUTCOMES FROM EP 3D03



The numbers in the bars indicate the number of students from a given year that responded with similar course learning outcomes

In 2017 and 2018, in order to identify which aspects of the course effectively delivered on the sociotechnical integration, the students were then asked: “Which learning activities (e.g. assignment, particular lecture, group work) deepened your understanding of engineering-society relations (or socio-tech system)? How?”

Open-ended responses to the question referred to specific teaching strategies. Most recognition was given to the IL project (8 of 10 students in 2017, 8 of 12 in 2018). Assignments (3 of 10 in 2017) and guest lectures by Ha and others (5 of 10 in 2017, 6 of 12 in 2018) were also acknowledged as contributing factors. Example responses included:

> *The assignments, guest lectures, independent learning project, and independent learning project presentations helped deepen my understanding of these lectures. The assignments such as the one on the North Korea plant and learning projects help show a lot of the societal issues that go along with nuclear power more than the technical side of the course, which is also very important.* (707P)
>
> *I found the inquiry groups to be a very beneficial activity as the social, economical and environmental feasibility of nuclear energy was evaluated. I found this beneficial as it gave me an insight to the "real world" challenges faced with nuclear engineering.* (708P)
>
> *The group sessions with Minha deepened the understanding of engineering-society relations by examining the role of engineers in working with stakeholders of engineering projects. Specifically, a conversation had with Minha [Ha] regarding ‘expert privilege’ and how that influences interactions with the public was especially valuable. Given the importance of public involvement in nuclear engineering projects specifically, this conversation was very insightful.* (802P)

It was surprising that the students identified connection between multiple course components, besides the IL project, to contribute to sociotechnical learning. Students identified specific concepts, the triple bottom line framework, case topics, and analytic tasks involved in assignments, guest lectures, class discussions, and the IL project. The survey results indicated there exists a variation in the ways students meaningfully engaged with sociotechnical learning, and that the learners were actively making sense of the connection across course components (regardless of how the instructional staff labelled them).

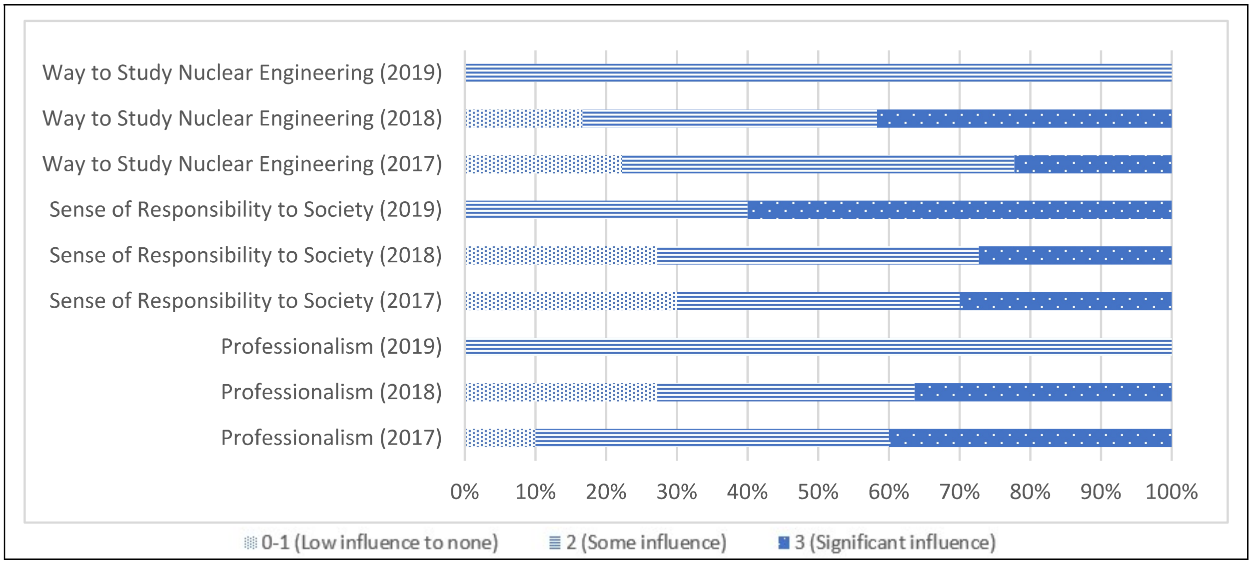
In 2019, the wording of the question changed, that did not directly ask the students to identify course components (“Has the course, Engineering Physics 3D03, influenced your confidence level in researching and integrating social considerations into engineering analyses? If so, please explain.”). Most responses did not mention specific course components, and the results could not be included.

Impact of the Inquiry Learning Project

In order to closely examine the impact of the IL project specifically, the students were asked to provide rating scores on the following statements:

> *Has the Inquiry Project resulted in any changes or effects on... (0 = no influence, 3 = significant influence)*
>
> *...the way you study nuclear engineering?*
> *...your sense of responsibility to society?*
> *...your sense of professional integrity and representation of the field?*

FIGURE 4
CHANGES RESULTING FROM IL PROJECT



Overall, there is an indication that the IL project can have moderate to significant influence on all three aspects above. This is important because we expect ethical responsibility to be made meaningful and practical only if it is included within the perceived boundary of one's professional identity and their task responsibilities. In order to explore whether such possible connections, participants were then asked to explain their rating responses, presented in the next section.

Students' Responsibility Construction

Following the above rating question (Figure 4), participants were asked, "Please comment on the most significant change from the above." Overall, there was an indication of positive influence from EP 3D03 on the students' expressed confidence and commitment to ethical responsibilities. First, there was a strong indication that the students' perception of nuclear engineering work now integrated the TBL framework, assuming the corresponding analyses to be part of their engineering work. Associated comments included:

> *[…] as I now realize how necessary it is to give equal importance to the study of economic, societal and environmental impacts of this technology […]* (805P)

> *[…] I therefore have a responsibility to generate nuclear technologies while prioritizing the triple-bottom line.* (812P)

> *[…] but I am really glad that social issues were also covered because sustainability is important and there is more to be considered than just the best way to sustain a stable reaction. I am glad this perspective was brought up early and I will continue to consider it in future nuclear engineering projects.* (906)

Second, the students gave meaning to their sense of responsibility by their role construction in relation to the public. The descriptive outcomes of engineering on public welfare were embedded as the explanatory rationale for the self-selected direction or aim of their role in society. For example, 705P constructs a 'serving' role of engineers to the public, which has a different nuance from 'providing a paid service': "This [inquiry] project put into perspective just how much the public is affected by our decisions as engineers. We are meant to serve the public [...].” There is a sense of personally owned decision-making autonomy and influence that are important to note here.

In another example, 706P conceptualizes the nuclear engineers as the representatives or mediators of the industry-public relations: “[...] This course made me realize that the way nuclear workers behave directly impacts public trust of the nuclear industry.” The connection made between individual behaviour and broader societal relations suggests an awareness regarding the nature of societal relations itself (e.g. importance of trust and the historical/local context to current state), as well as an expanded scope of individual responsibility to contribute to such societal relations.

A different example shows how students can also conceptualize the public stakeholders in a way that alters the role and purpose of engineering. 806P comments “[...] It is the role of the engineer to phrase their solutions in a way where the public and analyze and be critical and see whether it is the best solution for them.” The public is no longer a passive recipient of ‘expert’ services, but rather autonomous and intelligent decision makers in their own right. The engineer then is making good choices available and facilitating learning about them. An example like this one can add practical details to, i.e. a servant leadership model of engineering. The evaluation of a ‘good engineer’ would inevitably include the effectiveness in enabling or empowering the community to make their best choice, through various communication, relationship building, and facilitation approaches.

There was attention paid to the differentiated roles within organizations that deliver engineering work. 802P comments: “Taking the course has heightened the importance of professional integrity and representation by highlighting the role of engineers and management in design choices [...].” Many roles and expertise are required for successful engineering work, and they inherently present the challenges of competing demands, expectations, interests, and influences. On both ends of the nuclear engineering-society relationship, enabling ethical responsibility may require replacing these broad terms with a concrete differentiation between stakeholders - and the plurality of roles each might play.

Given the positive indication of change in students’ ethical responsibility, we examined the qualitative responses more in depth, to analyze how nuclear engineers’ professional role and ethical responsibilities are constructed. Because meaningful comments were dispersed across multiple open-ended questions (including *students’ goals for future learning*, and their views on *where nuclear engineers fit into society*), we combined the open-ended responses for each participant before this analysis. Five key themes were identified (Appendix II): *problem definition, role identities, scope of nuclear engineers’ professional work, stakeholders to whom the engineer responds,* and *the expected qualities and abilities of a nuclear engineer.*

DISCUSSION

We first discuss the five themes of ethical responsibility from the survey data. This is followed by a discussion of the three key aspects of our teaching approach that were linked to the students’ self-identified meaningful learning with relevance to ethical responsibility development.

Ethical Responsibility of Engineers

A useful comparison can be made to van de Poel and Royakkers’ (2011) discussion of the responsibility of engineers in practice contexts. The authors define responsibility as:

> *... being held **accountable** for your **actions** and for the **effects** of your actions... Responsibility (both active and passive) is often linked to the **role** that you have in a particular situation... You often have to fulfill **a number of roles simultaneously** such as those of friend, parent, citizen, employee, engineer, expert, and colleague. In a role you have a **relationship** with others...* (p.9, emphasis added)

The most useful construct is the *role responsibility*, which the authors highlight as distinct from (though related to) *moral responsibility* (referencing moral obligations, norms and duties), and *professional responsibility* (we suggest considering the definition of professional ethics by Michael Davis, 2001). The unique roles engineers play in project situations, imply particular agency that can be exercised. Recognition of multiple, simultaneous roles expands the visible range of stakeholders to whom one responds (since roles have meaning only in relation to other roles and situations). This also expands the scope of recognized implications of one's actions. Choosing to include or exclude such implications as part of one's responsibility, in turn, defines the scope of what is considered legitimate work of the engineer. Thus, how one defines the role and work of engineers is not value-neutral, nor confined to individual morality alone, nor adequately addressed by generalized ethics theories aimed for universality. By conceptualizing the role(s) of engineers, learners and educators alike are inevitably engaged in shaping the directionality of engineers' actions and their impact.

We find it encouraging that the learners are able to expand their role conceptualization without having formed direct relationships with particular stakeholders. The construction of multiple roles makes it possible to imagine and willingly engage in forming such relationships. We expect that the formed relationships will play an important role in renewing and sustaining the role responsibilities of engineers.

A unique emphasis from our study on the ethical responsibility of engineers is on the understanding of the nature of ethical problems at hand. In EP 3D03, along with the TBL framework, a networked view of the stakeholder roles and relations offered a framework upon which to structure and organize the competing concerns, issues, and opportunities to cause change on the system-level outcome. The more concrete the micro- to macro-level connections in one's understanding of the issues, the easier it is to get 'unstuck' from feeling helpless in a situation to feeling confident to navigate different paths (Freire, 1993). It is not the complexity that discourages responsibility; it is a lack of structured clarity that disempowers action. Defining which aspects of the current system behaviour constitute ethical problems, then, determines what issues the learners will respond to, with what goals and standards of practice. The analytic endeavor shapes the directionality of engineers' actions and impact as well.

The students' desire to develop certain qualities and skillsets highlights the importance of building the learners' confidence in their *ability* to respond to the people, situations, and ethical challenges. Ability to perceive these three areas is already part of the responsibility formation, which can take place in lecture settings. Inquiry projects create an experiential evidence of students' ability to examine a new topic of choice, structure relevant information and analyses, and develop concrete recommendations at the design, interpersonal, organizational, and policy levels.

Teaching Strategy 1: Triple Bottom Line as an Initial Framework for Sociotechnical Systems Thinking

The first key insight into the success of the IL process for students is shown through their repeated acknowledgement and referral to the three key dimensions of the TBL: economy, environment, and society. The TBL framework served as a useful template upon which the students could organize their analyses and findings. A conceptual framework to structure and integrate new information into a working knowledge, is an important part of the guidance provided to students conducting inquiry.

Instead of just listing the three dimensions of TBL, we had explicitly demonstrated the interactions and causal relations between the three dimensions. We hypothesize that explaining such mechanisms is important to provide an integrative framework that enables structured organization and addition of new content. Visualizing the interdependencies also makes visible the possibility (and necessity) to ask questions of impact and trade-offs: How any stakeholder's interest in one dimension of TBL will impact another; how a design choice will affect multiple stakeholders differently because of their different positioning or circumstances within the TBL. The framework that enables complex problem analysis and knowledge construction, would be the first starting place to make ethical responsibility practical.

Teaching Strategy 2: Integration

There are at least two levels of integration we identify from student experience. First, the content is integrated and reinforced in multiple teaching strategies throughout the course. Each learning activity reinforces the knowledge and skills gained in the course. As one student commented: "*I think it's important to remember that our actions don't exist in a void and this course maintained that consideration all the way* *through*" (807P). It is important to note that sociotechnical frameworks, concepts and analyses were incorporated into existing lectures, assignments, and the revamped IL project. An add-on approach to isolated modules can seem difficult in a content-heavy technical course, but the integration approach might be done to enhance (rather than compete with) the complementary alignment across teaching strategies for both the original and new learning outcomes.

Secondly, there is a clear integration of the technical and social/ethical analyses in the major deliverable - the IL report. One student in 2018 commented:

> *"[...] The independent learning group work throughout the term required us to research how our technology choice influenced society. We were able to identify many different stakeholders in the proposal to implement SMRs in Canada. Through research we were able to address any concerns these stakeholders would have with the project, and we were able to develop ways to mitigate these concerns. I am confident I will be able to translate this experience to future engineering analyses. The IL study showed how many 'roadblocks' there are to building new nuclear technology. It has changed my perspective on how capital projects are initiated and carried out."* (804P)

We reflect on the design IL project assessment, and what we observed in the student reports. The alignment between learning and assessment, we hypothesize, is crucial to reinforcing and rewarding student performance. Students earn grades in their analysis of the industry, regulatory, and sociopolitical context of nuclear technology development (e.g. advancing new types of reactor design) and implementation (e.g. shifting the energy portfolio) in particular regions. Students also earn grades by their assessment of the social impact of nuclear engineering decisions. The recommendations developed by students are based on the technical and social analyses they have conducted on their topic. Had the inquiry report focused solely on the technical or solely on the social aspects, we expect a different result on the students' confidence in integrating social and technical analyses in their study of nuclear engineering topics.

Teaching Strategy 3: Frequent and Personalized Instructor Feedback

A final takeaway from these results into the IL based approach is how effective and valuable the frequent and personalized feedback is for the students. An underlying role for the course instructor using an IL project is that there must be guidance given to the students throughout their research. As previously mentioned, the students will submit written deliverables to the instructor after each IL session. These deliverables will allow the instructor to prepare detailed feedback for the students. This will allow the instructor to present ideas and questions to the students about their findings that use the knowledge and experience the instructor has attained through their own career. This is an opportunity for the students to tailor their research plan using invaluable experience as a guide towards an effective research project that is also communicated effectively.

Some selected quotes are presented from the students in their answers to the following question: *"Why has the course Engineering Physics 3D03, influenced your confidence level in researching and integrating social considerations into engineering analyses?"*

> *"I have gained confidence by having researched the social considerations into engineering analyses but felt that I have much structure or guidance to how this research should be conducted. The feedback from Dr. Nagasaki was essential in helping <u>guide</u> the project but that was the only guidance I felt we had and not enough feedback to make sure I did this right."* (707P)

> *"I found that the inquiry project improved my confidence in researching <u>social considerations</u> in engineering analysis. Particularly, Dr. Nagasaki's comments were very well <u>thought out and practical</u>. They helped to steer the project to a <u>more profound conclusion</u>."* (706P)

"Yes, as the feedback we received after each session allowed us to view the holes in our own thinking, illuminating specific biases we might have had towards the subject that we ourselves could not see. In addition, this was again useful in broadening our scope to include considerations made by someone far more knowledgeable in the subject." (805P)

Not only is it important that the course instructor have knowledge and experience from their personal career that they can present in their feedback to the students to draw more thought-provoking conclusions to the research questions. The ability for the students to iteratively submit research deliverables and receive detailed feedback each time is a key component to why the IL process is successful in teaching the socio-tech connection and helping to develop a personal sense of responsibility in these students. By integrating the instructor's feedback into their work, the students can direct the focus of their research and what they will be learning through the IL process. The iterative nature of incorporating this feedback allows the instructor to provide a form of guidance for the students towards understanding the socio-technological interactions in their nuclear systems.

CONCLUSIONS

It is no small encouragement that an existing highly technical lecture/lab-based course can incorporate interdisciplinary content (sociotechnical learning) through an inquiry-based learning approach that required minimal change to the scheduling of instructional hours. The findings highlight that adult learners are apt to engage in new learning approaches if supported by the constructive alignment between the content, instructional staff (i.e. their values, message, insights, facilitation/inquiry skills), and the 'reward' structures within the course (i.e. grading scheme, feedback and input mechanisms, personalized learning). The researchers (who were involved in the instructional design) did not expect the spill-over effect of our efforts in inquiry learning design: Students recognized that the lectures (including guest speakers) and case study assignments also built knowledge foundation and skills utilized in the group inquiry project. Our investment into our own learning and teaching strategy development actually changed how we delivered (or modified) our previously existing content.

This study helped us identify important factors that supported our pedagogical design, which is specific to our local context. These include the interest and knowledgeability of the instructional staff in the sociotechnical content (e.g. sustainability, policy, design ethics), a useful framework that organizes the new content and guides analysis (e.g. triple bottom line system of systems), relevance of assignments to current events and the topics of student interest, alignment between various aspects of the course (e.g. lectures, assignments, inquiry project), and the explicit evaluation system that gives credit to the ethical and social analyses on a technological inquiry. It was also important to structure the inquiry project to have smaller deliverables to manage the workload and help students focus on distinct sets of skills, the role of instructor feedback cannot be understated.

As is important in any qualitative study, the goal of investigation is not to simply prove that a strategy 'worked,' or claim that there are universal principles to apply in all settings. We find value in the process of a qualitative study itself, in that it brings the researcher/practitioners closer to the learner experiences with their nuanced voices and perspectives. We recognize that the students actively interpret and utilize the learning environment and resources, in ways that are meaningful for them. We do not assume our teaching strategies simply would work according to our logic, and depend on our learners as key knowledge holders who help us co-create the needed models of learning. Being able to respond to the identified needs and articulate (and maintain) the value of our work, are some of the important reasons why we engage in educational research, which runs parallel to our efforts to continue examining the specifics of our local context (school, discipline, industry, policy) that shape our engineering ethics teaching and learning.

This exploratory study allowed us to learn about ethical responsibility construction from students' perspective, which in turn challenged us to a deeper reflection on humane engineering education. We are challenged by the previous discussions on role conceptualization, relationship, and systems view of practice, to consider our own teaching and leadership philosophy, our view of learners as co-creators of knowledge, and our view of the classroom as part of a broader community of citizens.

Further qualitative study is needed in order to address questions regarding adult learners' ethical responsibility formation in engineering contexts. The following questions may be included, in order to examine, for example, how engineering ethics and responsibility are viewed in the sensitive, logical, formative, and social aspects (Ouweneel, 2014): In what ways are the learners responding to the new demands and potentials of our time? Which affiliations are important to them, and how do such relationships enhance or hinder ethical responsibility in practice? What role does pre-existing attitudes and personal histories play? How do learners make sense of and respond to multiple, competing narratives about engineers' ethical responsibilities? What experiences and affective responses motivate action?

ACKNOWLEDGEMENT

©2020 American Society for Engineering Education. ASEE Annual Conference Proceedings, June 2020, Virtual Conference. This current version includes revisions in the discussion of findings and the presentation of tables.

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APPENDIX 1
COURSE LEARNING OBJECTIVES, FROM ENGINEERING PHYSICS 3D03 SYLLABUS

A SUCCESSFUL STUDENT WILL BE ABLE TO DO THE FOLLOWING BY THE END OF COURSE:

Reactor Physics Theory
Conceptualize and explain the fundamental physical phenomena and processes relevant to nuclear reactors.

Nuclear Life Cycle
Describe and explain the fundamental physical and chemical processes relevant to nuclear fuel cycle and radioactive waste management. (Expected to apply this knowledge in 4th year)

Reactor Technology
Construct systems architecture of how nuclear power plants are designed and operated and how the safety of a nuclear power plant is secured.

Nuclear Safety
Understand the physics, chemistry, and biology of radiation, interaction of radiation with matter (including human body), and fundamentals of radiation detection. Apply these physics, chemistry, and biology principles to design radiation shielding (labs & assignment).

Connection between the Nuclear Sector and the Public/Society
Design and conduct an inquiry project, integrating ethical and social dimensions in the analyses of a nuclear engineering topic of choice (e.g. Ethical-Legal-Social Analysis).

APPENDIX 2
STUDENTS' PROFESSIONAL RESPONSIBILITY CONSTRUCTION – THEMES

	Problem Definition	Scope of Nuclear Engineer's Work	Role Identities	Responsibility to Whom	Expected Qualities and Abilities of a Nuclear Engineer
2017	Sociopolitical challenge (707P) TBL (708P) Social issues embedding tech (707P)	Ethics & integrity (702P, 704P, 705P, 706P) Analysis of the impact on people and society (701P, 705P, 706P, 707P, 708P, 709P), TBL (702P, 703P, 708P, 709P) Engineer-Society relations (705P, 706P, 709P)	Public servant (705P) Professional representative (706P)	Opposing sides of the debate (702P, 703P) The public, society, or community (701P, 705P, 706P, 709P, 710P) The future (706P) Workers (709P)	TBL or social consideration in engineering analysis (704P, 705P, 709P, 710P) Learning from history (701P) and different viewpoints (702P)
2018	Interwoven social issues (811P, 812P)	Technology advancement with triple bottom line priorities (812P)	Policymaker (812P)	Current and future society (803P, 804P,	Inquiry skills (811P) Long-term planning (807P)

	Challenge for sustainable future (812P) Complexity and scale (812P) Stakeholder relations – knowledgeability of the public (812P), respect for the public concerns (805P), effective public engagement and acceptance (802P, 806P) Importance of diversity within engineering environment (808P), the role of expert privilege in public engagement (802P) The role of the state (802P, 806P) Design choices with predisposed risks (802P) Roadblocks to building new nuclear technology (804P)	Safety in reactor and secondary systems design (803P, 807P) TBL/sustainability (805P, 807P, 808P) Equity analysis including diversity and bias (807P) Analysis of impact on people/society (808P, 809P) Mitigation stakeholder concerns (804P)	Outreach (812P) Social engineer (812P) Contributor to societal development (809P) Problem solver for grand challenges and stakeholder concerns (804P, 812P)	808P, 809P, 812P) Global community (807P) General stakeholders or public (802P, 804P, 805P, 808P) Regulators (802P)	Ethical and responsible decision making throughout life cycle (802P) Professional integrity (802P) Evidence-based confidence with healthy skepticism (803P) Holistic view of nuclear engineering beyond power production (806P)
2019	Gap in adequate public knowledge related to nuclear engineering and energy (905, 906) Need for interaction and mutual learning between key actors (904, 903)	Technical expertise (906) Safety (906) Enhancing public nuclear tech literacy (905, 906) Informing decision making (905, 906) Trust and relationship building (903, 904) Active engagement with society (903, 904, 905, 906)	Advisor (903) Guardian (903) Friend (904) Educator (905)	Public/society (903, 904) Local decision makers/leaders (905) Average person new to nuclear technology (906)	Political engagement (905) Effective communication/language (901, 904, 906) Strong technical knowledge and modelling skills (901, 903, 904, 906) Stakeholder analysis (902) Creativity (904) Leadership (904) Multidisciplinary knowledge including health and radiation physics (906) Professional operation skills (904)