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CRITICALITY SAFETY EVALUATION PROJECT DEVELOPMENT FOR UNIVERSITY OF CALIFORNIA BERKELEY NUCLEAR CRITICALITY SAFETY PIPELINE COURSE

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ABSTRACT

The Nuclear Criticality Safety Division at Lawrence Livermore National Laboratory (LLNL) has taken a unique approach to developing criticality safety evaluation topics in support of the University of California Berkeley criticality safety pipeline course. The evaluation topics are designed to go beyond the typical evaluation examples used for many training courses including vault storage and variations on storage arrays. These types of evaluations provide in-depth analysis into the fundamentals of criticality safety and are complex but may be far off from what a new criticality safety engineer may actually be evaluating. To provide more practical examples of criticality safety evaluation topics that are better fit for the knowledge level of a criticality safety engineer in-training, variations of current and future operations and research operations performed at LLNL are used as evaluation topics. Additionally, an emphasis on research is included in all evaluation topics as it allows students to take advantage of the concepts learned in class to apply them for process improvement, engineering equipment that is favorable for criticality safety, and negotiation tactics to work with operations personnel. The process used by LLNL to develop project topics for the pipeline course is provided in this paper. The intent is to provide an alternative technique for training students and potentially younger staff members in criticality safety on developing criticality safety evaluations.

KEYWORDS

Criticality Safety, Pipeline Course, Training, Evaluation

1. INTRODUCTION

Across the Department of Energy (DOE) complex of laboratories, there is a movement by Nuclear Criticality Safety Divisions to partner with universities to establish pipeline programs to offer courses on nuclear criticality safety. As universities tend to focus heavily on nuclear power and advanced nuclear reactor design, many students straight out of college do not have the knowledge or experience in criticality safety. The Nuclear Criticality Safety Division at Lawrence Livermore National Laboratory (LLNL) have partnered with the Nuclear Criticality Safety Division at Los Alamos National Laboratory (LANL) and Prof. Massimiliano Fratoni of the University of California Berkeley to offer a course at the University of California Berkeley [1]. As part of the class the students participate in hands-on experiments with fissile material and prepare a criticality safety evaluation as a semester long project.

The intent of this class is to teach students the fundamentals of criticality safety and provide them with real world experience in preparing a criticality safety evaluation. LLNL prepares new example operations each semester for students to choose from to prepare the evaluation. The goal for LLNL is to provide evaluation topics that go beyond the normal evaluation examples used in most trainings such as vault storage evaluations and variations on storage arrays such as waste drums and solution tanks. These are complex evaluations that provide broad experience with preparing evaluations; however, these types of evaluations are rarely needed at laboratories with existing fissile material programs. Additionally, these are not the type of evaluations that would be performed by a criticality safety engineer straight out of school with little experience in the field of criticality safety. LLNL focuses on evaluation topics based on variations of current and future production and research operations performed at LLNL to provide more realistic experience for an individual at that knowledge level. This paper will discuss the process LLNL uses for preparing example operation project topics to provide an alternative technique for training students and younger staff members in criticality safety.

2. COURSE PROJECT STRUCTURE

The structure of the pipeline course is to provide students with the knowledge and resources to perform criticality safety work at national laboratories through hands-on experiments, opportunities to learn Monte Carlo radiation transport codes, and lectures from actual criticality safety engineers from LLNL and LANL. The students are then required to take what they learn in the course and parallelly prepare a criticality safety evaluation over the entire semester to demonstrate competency. LLNL and LANL each provide two to four project options each semester for the students to pick from to perform their criticality safety evaluations. Students are allowed to choose their intended topics instead of being assigned a topic to allow them to pick an operation that they are interested in learning more about. Students then work in groups of three to four to complete the evaluation. Depending on whether LLNL or LANL provided the project topic determines which criticality safety engineers will be the mentors for a particular project. LLNL and LANL not only act as mentors for the students in the process of writing the criticality safety evaluation, but they also act as operations personnel by fielding questions and defining the process inputs needed to perform the operation.

There are four milestones throughout the semester tied to the progress of their evaluations that students must complete. At each milestone, the students present their work to the class with LLNL and LANL criticality safety engineers present. During this process they received feedback not only from teachers and mentors but from their fellow classmates. The first milestone is to complete the process description for an operation. This is the first key to understanding if the student acting as the criticality engineer understands the process well enough to evaluate it. The second milestone is to determine the normal and credible upset conditions for a particular operation. At this point students are only required to define what each condition entails. The third milestone is to present the analysis of the normal and credible upset conditions. The students are allowed the freedom to choose how they want to solve their criticality safety evaluation including radiation transport codes, industry accepted handbook data, and handbook data. The fourth milestone is to present the entire completed criticality safety evaluation really focusing on the criticality safety controls that have been developed.

3. PROJECT DEVELOPMENT

This paper only focuses on the project development process for LLNL as the process differs for LLNL and LANL. For LLNL, the main focus when developing a project scenario for the students is to provide options that are comparable to the work they would see as a young staff member in a criticality safety division. The evaluation topics are real life examples of operations currently performed, or future operations to be performed at LLNL. Many of the projects relate to operations performed in the plutonium facility at LLNL or at a plutonium or uranium production facility. However, there are many options related to research and development opportunities to highlight the vast array of work criticality safety engineers perform. The goal is to move beyond generic operation examples like storage vaults and storage arrays. These types of evaluations require extensive experience in criticality safety and provide little room for improvements on design or process.

LLNL evaluates operations that are currently performed at any site that LLNL has an established criticality safety program, which could be in Livermore or at the Nevada National Security Sites. Operations that need a criticality safety evaluation are assessed to determine complexity based on the operational needs for mass quantities and moderators/reflectors and classification levels. Almost all operations that LLNL performs are research based making the options desirable and interesting for students. The evaluations that are assigned to newer criticality safety engineers in the division are considered excellent candidates for this pipeline course. If at the time of project development there are no operations that fit the criteria, LLNL can make up a fictional operation. However, it would be in line with work performed by LLNL programs and would be based on research. The aspect of research is important to this process as it means that an operation is implementing process improvement to existing operations or a whole new operation is being developed. This gives students the greatest advantage of using all concepts they learn in class.

Once a project topic has been chosen, aspects of the operation are changed to include things like unsafe geometries, critical masses of fissile material, and introduction of superior moderators or reflectors. This is to make the evaluation process replicate real life and force students to utilize what they have learned in the class to overcome these complexities. Students are required to find new design features, different equipment choices, or reduce operational limits to make the system subcritical and present these options to operations personal for potential implementation. Although in real situations, the criticality safety engineer may not have the opportunity to make some of these drastic changes, this method helps students learn new ways to solve the same problem and gain confidence that there is more than one solution when working or negotiating with operations. This also helps broaden the students knowledge on available resources like national consensus standards, international standards, commercial equipment variations, favorable geometry equipment, and engineering principles to help them find alternative solutions or options.

As part of the project, the students are provided with the evaluation parameters. Due to the time constraints of the class, parts of the criticality safety evaluation need to be omitted from the project or provided to the students. For LLNL, two credible upset conditions, fire and earthquake, are omitted from the process due to needing to know more about the documented safety analysis for a facility, which is not part of this course. Additionally, if students want to perform calculations, an upper subcritical limit of $k_{eff}\pm2\sigma\leq0.97$ is provided. Although validation is taught during the class it is a high-level overview and not enough detail for students to perform an independent validation.

3.1. Project Description

The operation descriptions provided to the students by LLNL are written purposely to be vague and include insufficient detail about the overall operation. The descriptions may say how much fissile mass they want to use in an operation but may not identify a form or any configuration. It might state that shielding is needed for the operation but not specify what type, how much shielding is required, or here it will be placed in relation to the fissile material. Additionally, nothing about how the operation is performed or flow or operations is provided. This technique forces students to interact with their mentors and simulated operations personnel to get key information needed to perform their evaluation, and without it could hinder them from completing their project and the course. However, mentors and operations personnel will not provide any details that are not requested by the students. This means that students must work together to truly understand the process and identify the gaps in information. Students then need to prepare questions for mentors and operations personnel that entice them to provide the answers that they seek. The purpose of the mentors is to guide the students on how to complete this project successfully, but it is the responsibility of the students to reach out to mentors with questions or concerns, as the mentors will not reach out to the students. This whole process is intended to replicate the process criticality safety engineers endure when preparing a criticality safety evaluation. Additionally, it helps students gain experience in refining their questions to get a specific answer and highlights the number of individuals involved with preparing an evaluation.

One downside to creating evaluation topics based on altered real operations or future operations is that the students are not able to walkdown the operation to gain an understanding of the operation visually. This is a similar complaint to the storage array examples. This has made LLNL move more towards criticality safety evaluations based on operations outside of a nuclear facility. An example of this is LLNL's Inherently Safe Subcritical Assembly (ISSA) training center [2]. Two days during the semester, students travel to LLNL's ISSA training center to perform hands-on experimental training designed to illustrate criticality safety and reactor physics concepts. This allows students to actually see the base operation that they are evaluating and how criticality controls are implemented in a real operation. Students then have the responsibility for evaluating the altered operation that was provided. The requirements for students to enter a radiological facility are normally just general employee radiation training, which provides greater opportunity to allow the students to see real life operations. If a project is based in a nuclear facility, LLNL criticality safety engineers must mockup drawings or use pictures from the internet to help provide visual representations for the students. This tends to lead to many different interpretations of the operation.

3.2. Process Analysis

There are multiple ways to approach the process analysis section of a criticality safety evaluation to establish the basis for an operation to remain subcritical. When developing the evaluation topics, each project is solved by multiple criticality safety engineers at LLNL to ensure that the complexity is sufficient and to guarantee the evaluation can be solved using multiple different methods. This does not mean a full criticality safety evaluation is prepared but rather includes determining normal and credible upset conditions, the point of subcriticality, potential process changes or mass reductions, and potential criticality safety controls. The different methods include using Monte Carlo radiation transport codes, industry accepted handbook data, and hand calculations. It is important that students are afforded the flexibility to use any method or multiple methods to perform the criticality safety evaluation as they are taught all of these methods in the course. Another reason flexibility is required is that not all students have access to a radiation transport code. This could be due to licensing issues with the Radiation Safety Information Computation Center (RSICC) to obtain the code, export controls on the codes, or lack of training on the code. MCNP is taught as part of the course by Prof. Fratoni with help from LLNL and LANL, however, students still struggle with use of the code as they are learning it while writing the evaluation. Therefore, handbook data like ARH-600 or any other industry accepted handbook data is strongly encouraged to be used. If not for completing the evaluation, at least as a starting point in conjunction with the ANSI/ANS Standards. Many different handbooks and national consensus standards are provided to students during the course. As well as hand calculations are taught as part of the course, which can also be used as a starting point or to perform the analysis.

Experience with all methods is beneficial to the students, however, the development of the projects using a radiation transport code is significantly more beneficial. Radiation transport codes are consistently used to perform criticality safety evaluations at laboratories as well as part of every criticality safety training program, so obtaining this experience is invaluable to the students who want to go into the criticality safety field. Not only is the use of radiation transport codes beneficial to the students for learning purposes but is also beneficial to the criticality safety engineers at LLNL. Due to the issues listed above related to codes, LLNL criticality safety engineers provide training and help with other available codes that students may have access to like OpenMC or Serpent. As these are codes not generally used for criticality safety evaluations like COG, MCNP, or SCALE, it provides continuous training for the LLNL criticality safety engineers to understand additional codes.

3.3. Examples of Project Topics

LLNL works on developing and preparing new project topics for each class. The class is only offered during the fall semester, so topics are developed normally once a year. The number of project topics provided varies each semester depending on how large the class is, but ranges from two to four options. Past project topics may be re-used as one of the options for the semester but are normally updated to change some part of the operation. This may be done if a project topic is very popular among the students. This section provides various examples of projects that LLNL has developed for this pipeline course. Figure 1 shows an example of a project process description provided to students at the start of the semester.

NCS Projects

The descriptions of the following projects are for training purposes only. Additional information will be needed to evaluate these processes and develop proper controls. Do not consider fires or earthquakes. If calculations are used, the system can be considered subcritical when $k_{eff} + 2\sigma$ is less than 0.97.

Remember: There are multiple ways to approach each project and simplify the analysis. This is done by discussing control trade-offs with the customer, soliciting feedback, and developing a set of preliminary constraints and/or credited assumptions. For instance, if the customer agrees that the enrichment of uranium will be limited to 0.711%, then the NCSE engineer's job got a whole lot easier.

2. ISSA Heavy Water Experiment

The Nuclear Criticality Safety Division at Lawrence Livermore National Laboratory was recently awarded an NNSA grant to develop a subcritical heavy water benchmark for the Inherently Safe Subcritical Assembly (ISSA). Engineers would like to use as many fuel assemblies as possible, in a close-fitting configuration. The configuration will be placed inside a close-fitting, open-top acrylic box ($C_5O_2H_8$, density = 1.18 g/cc) with a wall thickness of 1 inch. A total of four He-3 neutron detectors will be placed at varying distances around the acrylic box during the experiment. The design of each He-3 detector can be approximated as a single polyethylene (CH_2, density = 0.96 g/cc) cylinder with a diameter of 4 inches and a length of 48 inches. Assume the acrylic box is centered in a cylinder of heavy water with at least 12 inches of water on all sides of the box.

An MCNP model of a single fuel assembly is provided.

Figure 1. Example Evaluation Project Topic Provided to Students

As seen in the process description, not much detail is provided about where the operation occurs, how many fuel assemblies exist, or the process for performing the experiment. Additionally, in this particular example a starting point of one fuel assembly modeled in MCNP is provided to the students. However, most projects do not include a computational model provided by LLNL. If students choose to use computational methods, the students must develop their own models to include in the criticality safety evaluation free of errors. Students can choose to prepare simplified models or detailed models depending on their process analysis needs. Figure 2 shows a detailed computational model created by students for the ISSA project described in Figure 1.

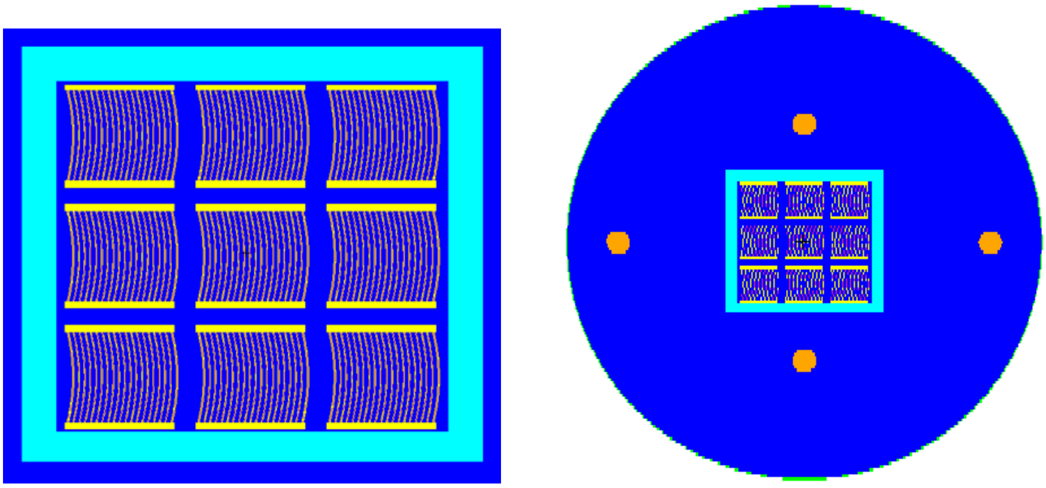

Figure 2. Computational Models of ISSA Constructed by Students

Some additional examples of past project topics include additive manufacturing of uranium metal, solidification of plutonium waste with an industrial mixer, ^{233}U experiments with composite shielding, carbon aerosol capture of uranium metal, highly enriched uranium machining, and a plutonium metal training assembly with depleted uranium reflectors. Figure 3 shows additional computational models prepared by students from some of the previous projects listed.

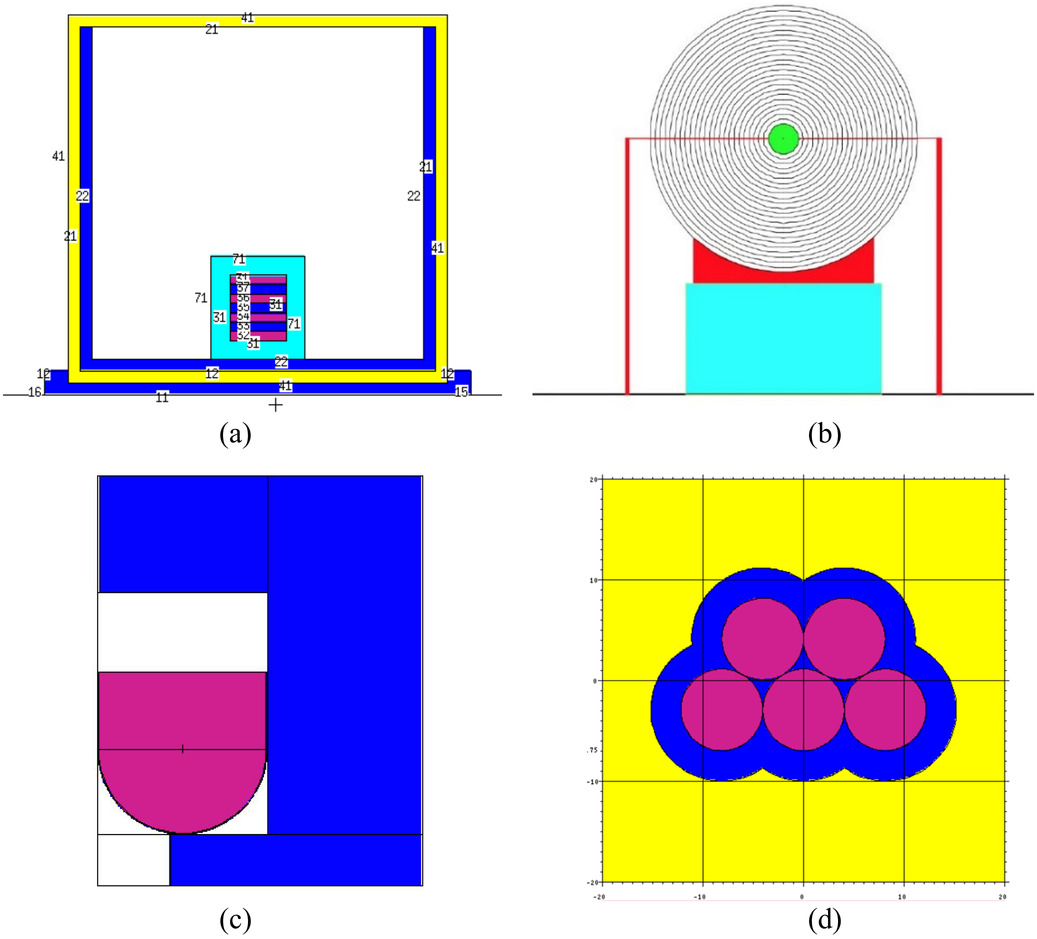

Figure 3. Criticality Safety Evaluation Computational Models. (a) ^{233}U metal blocks with composite shielding; (b) Plutonium training assembly with depleted uranium shells; (c) Industrial mixer for performing solidification; (d) Highly enriched uranium machining.

4. FUTURE CONSIDERATIONS FOR PROJECTS

The purpose of the pipeline course is to interest students in the field of criticality safety and provide them with as much valuable experience as possible. Therefore, some future considerations have been discussed for project development. Additional topics that include the students coming to LLNL to see an operation are highly desirable. With the use of our ISSA training facility, additional operations and experiments can be set up specifically for this class. Some operations include the use of Department of Transportation (DOT) containers to develop criticality safety evaluations for criticality safety indexes (CSIs). This would allow the students to become familiar with safety analysis reports for packaging (SARP) and get hands-on experience with the actual container. This one is also beneficial as the DOT containers could be transported to the University of California Berkeley. Although this falls into the category of a storage array, CSI calculations are required more frequently and do not have the same level of complexity as a vault storage array. Other topics include radiation test object experiments. This project could be set up so students could interact with the parts by using mock materials like plastics and metals (i.e., aluminum and stainless steel) to mimic the shapes to determine configurations of the radiation test object builds. The use of mock material also allows this type of operation to be transported to Berkeley. These are unique opportunities as normally when an operation is to be done with fissile material it cannot happen without the criticality safety evaluation. So, this allows more hands-on learning of the operation.

5. CONCLUSIONS

Developing projects for students that incorporate criticality safety fundamentals and is interesting is a difficult task. For the University of California criticality safety pipeline course LLNL has tried to find a creative solution to project topics. The topics provide students with real world experience by giving them actual operations to evaluate and encourage them to use their engineering backgrounds. The process of writing a criticality safety evaluation mirrors the difficult process of working with operations personnel and finding a balance in controls to meet subcriticality and usability. The end goal of project development is to stimulate students interest in criticality safety and also give them practical training to prepare them to be criticality safety engineers.

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