Nuclear Criticality Safety Evaluations

Introduction

One of the more difficult tasks of a criticality safety engineer (CSE) is to develop the rationale for the establishment of controlled parameters and the proper documentation of the basis for subcritical limits derived for the controlled parameters. In addition, clear specifications of associated control and functionality requirements to safely operate a process or facility that contains fissile material must be clearly communicated to operating personnel.

Background

This white paper was identified by the ANS/NCSD Education Committee as important to meeting the overall mission statement of the NCSD, "To promote development of nuclear criticality safety expertise by providing opportunities that offer technical growth and recognition." An obvious area in which to promote development of nuclear criticality safety expertise is to define "best practices" on what constitutes proper documentation for a nuclear criticality safety evaluation, and the underlying logic used in the creation of this document.

General Discussion

The guidance provided in ANSI/ANS-8.19-1996, "Administrative Practices for Nuclear Criticality Safety," Section 8, states that, "Before the start of a new operation with fissile material, or before an existing operation is changed, it shall be determined and documented that the entire process will be subcritical under both normal and credible abnormal conditions." In addition, the evaluation of nuclear criticality safety "shall be documented with sufficient detail, clarity, and lack of ambiguity to allow independent judgment of results." To accomplish this, CSEs must be knowledgeable of operations that govern fissile processes and must be able to anticipate conditions that could develop to allow a criticality accident. In addition, the CSEs must have a firm grasp of the analytic tools and their limitations, license conditions, and standards and regulations. Finally, ANSI/ANS-8.19 requires that each documented evaluation of nuclear criticality safety shall be independently reviewed by personnel familiar with the physics of nuclear criticality and the facility operations, who were not directly involved in the preparation of the evaluation of nuclear criticality safety. The use of round-table panels has proved especially useful in these reviews.

Determination of Normal and Credible Abnormal Conditions

A key section of any criticality safety evaluation is the evaluation of normal and credible abnormal conditions that could lead to a criticality. Justification why the prescribed control(s) are adequate should be provided. The basic expectation for the evaluation in ANSI/ANS-8.1 is that operations with fissile material "will be subcritical under both normal and credible abnormal conditions." The assessment of these conditions should assure that the failure of a single barrier or control that results in a “change in process condition” will not result in a criticality accident. In addition, failure of each of identified control(s) should be unlikely and not involve a common mode failure.

The CSE must describe the suite of *credible* accident scenarios. There is normally a range of contingencies that needs to be considered and input from subject matter experts from multiple disciplines, including process specialists, operators, safety basis analysts, and other safety disciplines, is required for a comprehensive collection. For most criticality safety specialists, formal methods prove helpful (e.g., logic trees, event trees, fault trees, HAZOP, FMEA, What-If). The method used and rationale need to be documented so that the results and conclusions of this part of the evaluation can be reviewed by operations, process engineers, and other criticality safety specialists. The overall goal for each nuclear operation assessed is that the risk of a criticality accident is "highly unlikely.” Protection of operating personnel and the public must be the dominant consideration. Implicit in the guidance of the ANSI/ANS-8 series criticality safety standards is the concept of efficiency in addition to safety using a graded approach. In Section 1, ANSI/ANS-8.1 states that “…extensive operations can be performed safely and economically when proper precautions are exercised”, and the admonition that “good safety practices must recognize economic consideration…” stresses that the controls should be as cost effective as is reasonable.

Reviews

Technical reviews of criticality safety evaluations should be performed by personnel familiar with the physics of nuclear criticality and the operations, process or facility being evaluated.

Format and Content

Facility-specific administrative requirements ultimately dictate the format and content of an evaluation of nuclear criticality safety; however, the following elements are needed to meet the minimum acceptable requirements.

The evaluation of nuclear criticality safety documents the safety basis for the identification of controlled parameters for each process or operation, and the establishment of the implemented controls on those parameters to maintain the process or operations within applicable subcritical limits. The evaluation of nuclear criticality safety identifies and addresses the credible concerns (e.g., event sequences, contingent conditions) of importance to nuclear criticality safety for the defined system. The evaluation of criticality safety is prepared or updated for each new or significantly modified unit or process system at the facility, in accordance with established internal configuration management procedures by qualified criticality safety staff. It is further recommended that the limits and controls established in the evaluation be accepted by operations line management prior to initial implementation or revision thereof. This may be integral to the review and implementation process of the evaluation itself or via a separate nuclear safety requirements document.

The scope and content of a particular evaluation of criticality safety should reflect the needs and characteristics of the system being analyzed and include the applicable elements as follows:

- **Scope** - This element defines the stated purpose of the evaluation and the properties (e.g., maximum enrichment and isotopes) of the fissile material being processed.
- **General Discussion** - This element presents an overview of the process being evaluated (new operation, proposed change or installation) and includes a process description, flow diagrams, normal operating conditions, system interfaces, and other aspects important to design considerations.
- **Criticality Safety Controls / Bounding Assumptions** – This element defines the controlled parameter(s) and summarizes the criticality safety controls on each identified parameter that are imposed as a result of the evaluation. This section also clearly presents a summary of the bounding assumptions used in the evaluation. Bounding assumptions include worst credible conditions (e.g., material composition, density, enrichment, internal/external moderation, structure) and boundary conditions. This section should also summarize interface considerations with other units, process subareas or areas.
- **Model Descriptions** – This element identifies and describes all models used in the evaluation, including those for both normal and credible upset conditions. The model file naming convention (if used) should be provided along with key input listings and corresponding geometry plots for both normal and credible upset conditions.
- **Calculation Results** - This element identifies and describes how the calculations were performed, what analytic methods or reference documents were used, and presents a tabular listing of the calculation results with associated uncertainty (e.g., $k_{eff} + 2\sigma$) as a function of the key parameters (e.g., wt. % H_2O). The assigned bias, bias uncertainty, and margin of subcriticality of the calculation should be clearly stated, made traceable to a documented validation report, and incorporated into both normal and credible upset limit comparisons, as applicable. This element may also directly reference hand calculations and/or published handbook results.
- **Safety During Upset Conditions** - This element presents a concise summary of the upset conditions considered credible for the defined operation or process system. This element includes a discussion as to how the established limits are adequate to maintain criticality safety for each credible process upset (e.g., accident sequence), and should clearly demonstrate how the double contingency principle is met, or if not, how multiple levels of controls are used to assure subcriticality. Basic steps to be documented in this section of the evaluation are:
    - ❑ Know the operation and system being evaluated. Facility and equipment drawings should be reviewed as well as process flow sheets or descriptions. Direct observation is strongly recommended for existing operations. Ancillary safety analysis for the facility may also provide insight on proper identification of credible nuclear criticality safety accident sequences (e.g., seismic design, sprinkler activation, loss of containment, etc.).

- Identify potential criticality accident scenarios. Input from operations personnel and process specialists is essential to proper identification of criticality accident sequences. The initiating event, enabling events, and failure mode(s) of each identified control or barrier for a given accident sequence should be assessed. Where practical, walkthroughs of the process are encouraged to identify potential accident scenarios.

- Control the risk. The risk of any credible criticality scenarios must be controlled. The preferred hierarchy of controls is 1) passive engineered controls, 2) active engineered controls, and 3) administrative controls. Each accident sequence shall identify required control(s) necessary to render it "highly unlikely". Identified controls should be documented, implemented, and maintained in accordance with site procedures.

- **Specifications and Requirements for Safety** - This element presents both the design specifications and the nuclear criticality safety requirements for correct operational implementation of the established controls. All assumptions subject to change by others should be clearly stated. These requirements are incorporated into operating, training, maintenance, and quality assurance procedure requirements. Operational concurrence by both process engineering and operations management is required to implement the requirements. Any new criticality safety analysis must integrate well with the existing safety analysis for the entire facility. Care must be taken for any impact on existing controls

- **Summary Compliance** - This element includes the pertinent summary statements, including a statement regarding license compliance if at issue.

- **Technical Review -** This element includes the statement, signature, and date that the evaluation of nuclear criticality safety was independently verified by another qualified criticality safety engineer, who was not directly involved in the preparation of the evaluation.

  As a final step for an existing process, the criticality safety engineer should walk down the facility and equipment to assure the evaluation reflects reality and should discuss the controls with the operations staff to assure practicality.

- **Appendices** - This element includes the summary of information ancillary to calculations (e.g., parametric sensitivity studies, references, key inputs, model geometry plots, equipment sketches, useful mixture nuclide identification/number densities, and related data) for each defined system.

Conclusion

"Before the start of a new operation with fissile material, or before an existing operation is changed, it shall be determined and documented that the entire process will be subcritical under both normal and credible abnormal conditions." This white paper presents guidance for acceptable format/content elements, which comprise a nuclear criticality safety evaluation, and provides "best practice" logic for documenting the controlled parameters and derivation of associated subcritical limits upon which nuclear criticality safety depends.