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Title: Criticality Safety Evaluations Part I

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Criticality Safety Evaluations

Part I

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Objectives

- Determine what a criticality safety evaluation is.
- Define the components to a criticality safety evaluation.
- Define what is needed and how to create a criticality safety evaluation.

Criticality Safety Evaluations

- **Purpose**
  - Evaluate fissionable material operations in terms of criticality safety

- **Goal**
  - Document the completion of the ANSI/ANS 8.1 (*Nuclear Criticality Safety In Operations with Fissionable Material Outside Reactors*) requirement for Process Analysis (Section 4.1.2):

"Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the <u>entire process will be subcritical under both normal and credible abnormal conditions</u>. Normal and credible abnormal conditions shall be determined with input from operations or other knowledgeable individuals."

Credible

- **DOE-STD-3007-2007 defines credible as:**
  - "*the attribute of being believable on the basis of commonly acceptable engineering judgment. Due to the general lack of statistically reliable data, assigning numerical probabilities to events is not usually justifiable and when used should be backed up with references.*"

- **Is this credible?**
  - Has it happened before?
  - Is it reasonable to occur?
  - Justify why an event is credible or not credible

Double Contingency Principle

- **ANSI/ANS-8.1 Section 4.2.2:**
  – *"Process designs should incorporate sufficient factors of safety to require at least <u>two unlikely, independent, and concurrent</u> changes in process conditions before a criticality accident is possible."*
  – DOE-STD-3007-2007 defines unlikely as *"the attribute of being <u>improbable on the basis of commonly acceptable engineering judgment</u>. An unlikely event is an event that is not expected to occur more than once in the lifetime of a facility."*
  – Concurrent is two or more changes in process conditions occurring at the same time, or at least the opportunity is present.

- **No single credible upset will result in a criticality accident.**

Criticality Safety Evaluation Purpose

- **Develops the technical basis and rationale supporting the safety of an operation by identifying and establishing**
  - Natural process constraints
  - Engineered controls
  - Administrative controls
  - Conduct of operations
  - Conduct of training
  - Configuration management

Criticality Safety Evaluation Prerequisites

- **Institutional management**
  - Provides NCS engineers to assist operations
    - Establish a training and qualification program for the NCS engineers
  - Establishes policies, procedures, roles, responsibilities, and authorities for conducting evaluations
    - Institutions may differ but
      - The requirements (ANSI-ANS-8 standards, DOE orders and standards, etc.) are the same
      - The general approach used to develop the evaluation is very similar

Criticality Safety Evaluation Prerequisites (cont.)

- **Preferred approach**
  - Establish an evaluation team
    - Two Criticality Safety Engineers/Analysts
      - Author of the evaluation
      - Independent peer reviewer
    - Operations Responsible Supervisor
    - Operators
      - Knows more about the reality of operations
      - Involvement leads to better controls and better implementation
    - Additional Experts as needed
      - System engineers, seismic engineers, fire engineers, chemists, metallurgists, etc.
  - Team works through evaluation steps (next slide)

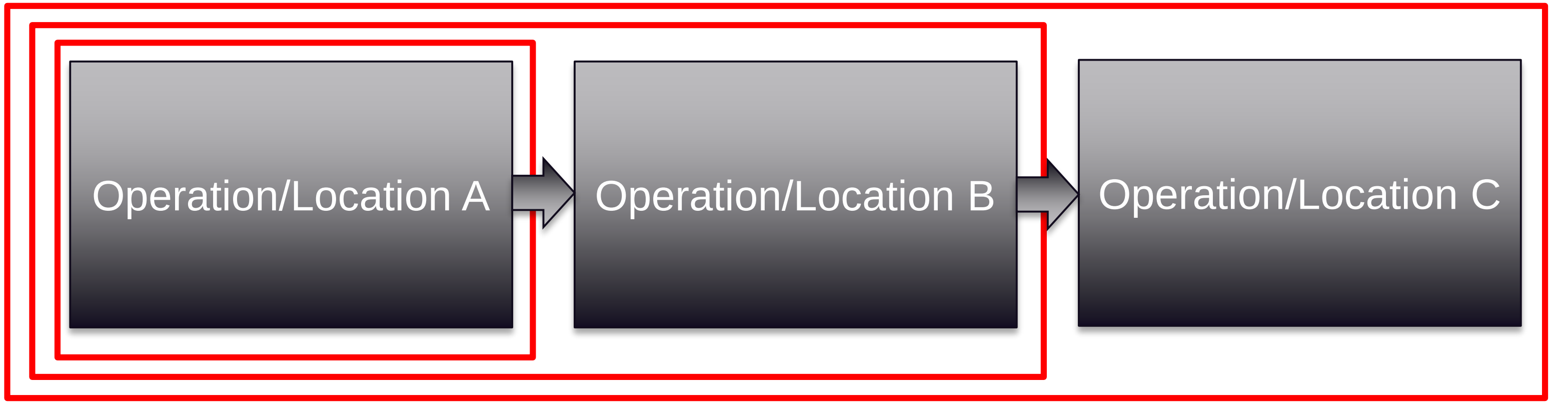
Steps of a Criticality Safety Evaluation

1. Define the process normal conditions (team)
2. Define the credible abnormal conditions (team)
3. Analyze the normal and credible abnormal conditions (NCS engineer)
4. Develop an appropriate criticality safety control set (team)
5. Iterate as necessary on all four of these aspects until the process will remain subcritical when operated (team)
6. Document the evaluation (NCS engineer)
7. Review the evaluation (team)
8. Iterate as necessary (team)
9. Approve the evaluation (supervisor)
10. Implement the control set (team)

Process Description: Defining the Normal Conditions

Relevant Information

- **Define the Process boundaries**



- **Operating procedure**
  - Defines the normal condition boundaries and is the underlying basis for constraining the credible abnormal conditions
  - Not finalized before the evaluation is completed (NCS controls flow into the operating procedure)

Relevant Information

- **System and equipment specifications**
  – Engineered drawings
  – Manufacturing specifications
  – Define interfaces with other operations
- **Feed and output stream characterization**
  – Material forms, e.g., metal, oxide, residue, waste, solution
  – Amounts
- **Material flow, i.e., the actual process confined to relevant aspects**

Normal Conditions

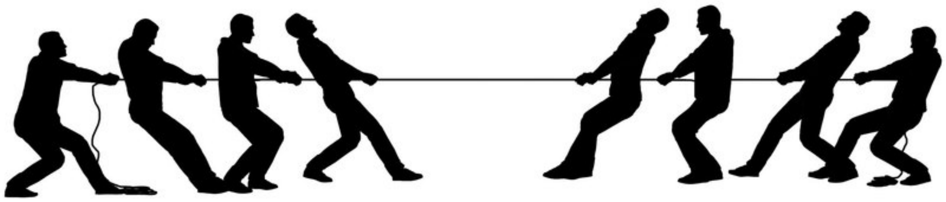
- **Conduct a physical walk down of the process**
  - If the process area/equipment does not physically exist, drawings may have to be substituted
- **Draft a process description**
  - Focusing on the critcality safety relevant aspects of the operation
- **Iterate and review the process description with the team**
- **Without ALL relevant information, it is impossible to evaluate a process properly**

Normal Conditions (cont.)

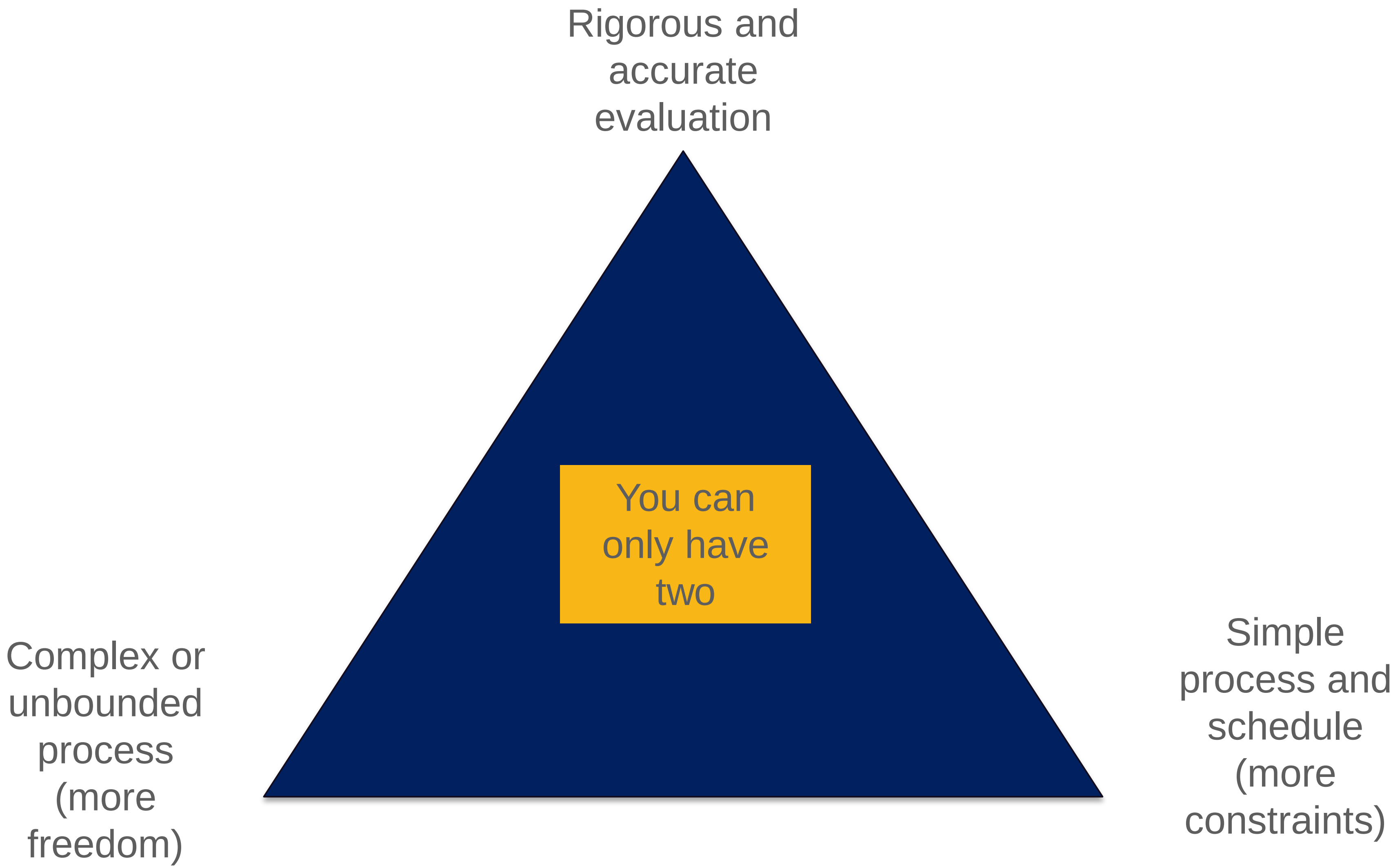
- **Consider if a criticality accident was not a possibility how would that change the process**
  - Would you use larger dimension vessels?
  - Would more material be desirable?
- **Keep an open mind and look for natural process constraints**
  - Perhaps the chemistry of the process dictates batch operations
  - Commonly used vessels happen to be geometrically favorable (extraction columns and pencil tanks, for example)

Normal Conditions (cont.)

- **The complexity of an evaluation is inversely proportional to the level of process constraints**
  - Constraints on the process translate directly into constraints on the relevant parameters and ranges of the parameters
  - There is a natural tension here between operations and criticality safety
  - Operations wants freedom to operate, NCS wantes constraints



Normal Conditions (cont.)



Normal Conditions (cont.)

- **What operations want?**
  - More freedom in operations
  - An evaluation as soon as possible

- **What NCS engineers want?**
  - A well defined, constrained process
  - Rigorous and accurate evaluation

- **What is required?**
  - Rigorous and accurate evaluation

- **This means:**
  - Complex process + rigor = Longer time to produce evaluation
  - Complex process + scheduling = Inaccurate evaluation (not enough detail)
  - Rigor + simplicity = Faster evaluation but more constraints

Normal Conditions (cont.)

- **Every process has a programmatic goal and natural process constraints**
  - Processes characterized as anything goes simply do not exist, always governed by procedures or plans
  - No one works with fissionable material on a whim
  - All parties need to understand that cost, both in terms of level of effort and money, must be weighed against the need and benefit

Common Mistakes in Normal Conditions

- **Inappropriate level of process detail**
  - Process description serves as the agreement on the process boundaries
  - Should be limited to the NCS relevant details
    - Guide for the process supervisor
  - Development is often iterative
    - Credible abnormal conditions may require process changes
    - New controls may need to be integrated into an operation

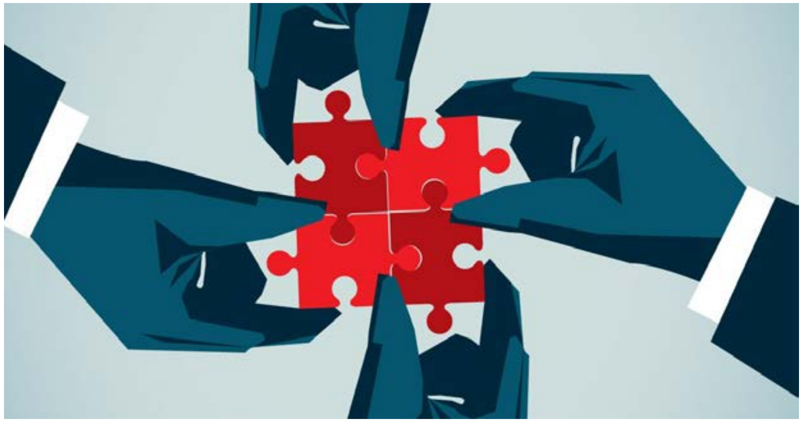
Common Mistakes (cont.)

- **Failure to account for environmental conditions**
  - The purpose of a walk down is both verification and identification of conditions
  - Items that seem irrelevant may be important
    - Adjacent operating conditions
    - Actual operating conditions
    - Walls or other neutron reflection
    - Sprinklers or other sources of moderation
  - Verify conditions bound the conditions in the facility. What happens nearby?

Common Mistakes (cont.)

- **Lack of engagement or inclusion of operations personnel**
  - Because of the technical complexity of criticality physics, operations might try to transfer all evaluation responsibility to criticality safety engineer
  - Criticality safety engineers may isolate themselves
    - Schedule pressure
    - Miscommunication/difficulty to get requested information
    - Process knowledge assumptions

- **<u>Good evaluations come out of effective cooperation between operations staff and criticality safety engineers</u>**



Process Description: Defining the Credible Abnormal Upset Conditions

Credible Abnormal Conditions

- **Credible does not mean possible!**
  - Impossible to create a list of *everything* that could happen
  - Focus on conditions that are believable
    - Is it reasonable to assume that more mass could be introduced into this location than allowed? How much? Why? Why not more?
    - Is it reasonable to assume water could enter this location? How much? Why? Why not?
- **There must be consensus agreement on the upsets and likelihoods**
  - If necessary there needs to be a conflict resolution process
  - The authority and responsibility is that of operations
  - Teams must be balanced in their risk perspective
- **Process supervisors and operators**
  - More familiar with the specific operating environment, equipment, and difficulties
  - Tend to think only in terms of normal conditions
    - Risk perspective is skewed towards upsets being less likely

Credible Abnormal Conditions (cont.)

- **Criticality Safety Engineers**
  - Broader experience with upsets that affect NCS parameters
    - Within the facility
    - At other facilities with commonality of operations
    - And in general
      - NCS engineers are reliability specialists both in terms of engineering and human factors
  - Broader experience in applying the institutional definitions of likelihoods
  - Risk perspective tends to skew towards upsets being more likely

- **For a team to be skewed too far towards either end is not desirable**

Credible Abnormal Conditions (cont.)

- **Engineering judgment may be used to determine if a change in process conditions is a credible abnormal condition**
  - Engineering judgment does not mean opinion
  - A fact based technical basis supporting the judgment is required
  - Disagreements concerning the credibility must be resolved
    - History
    - Engineering studies
    - Failure probabilities

Credible Abnormal Conditions (cont.)

- **Example: Supply line backflow**
  - A large volume acid tank was directly piped to an operation
  - Conceivably backflow could result in fissionable material in the tank
  - The supervisor intuitively felt that backflow to the degree necessary was not credible

- **Safety evaluations should not be based on intuition or imagination**
  - An engineering study was performed establishing that backflow was credible

- **Controls implemented to prevent backflow**

Tools for Identifying Upset Conditions

- **Hazard Evaluation Methodologies**
  - Hazard and Operability (HAZOP)
  - Checklist
  - **What-IF**
  - Failure Modes and Effects (FMEA)
  - Fault Tree
  - Event Tree
  - Probabilistic Risk Assessment (PRA)
  - Safety Review

Tools for Identifying Upset Conditions (cont.)

- **NCS engineers may use checklists and other aids to ensure discussions are complete**
  - Changes to shape or dimensions resulting from bulging, corrosion, or bursting of containers or vessels
  - An increase in fissionable material mass due to an operational error
  - A change in the amount of neutron reflection
- **Best to develop a list specific to the operation**
  - Can the tanks break?
  - Can the tanks leak?
  - Has it happened?
  - Is it a regular occurrence or rare?
- **Use the checklists as guides only**
  - Do not become blinded by or dependent on them

Tools for Identifying Upset Conditions (cont.)

- **Bring your operational perspective to the discussion**
  - Try to relay the real world practicalities of the operating environment
  - It is from this perspective that natural events and the credible course of events may be revealed
- **Don't be fooled by believing normal conditions will always prevail**
  - Operators will make errors, systems will fail
    - Do the steps of the process go against human nature?
    - Can the process be automated? Should it?

Tools for Identifying Upset Conditions (cont.)

- **In turn the Criticality Safety Engineer should bring safety perspective**
  - Determining likelihoods without concrete criteria is difficult
  - Tend to think in terms of abnormal conditions
  - Skew upsets toward more likely
- **Should be able to relate the abnormal conditions to REAL consequences**
  - Are you comfortable with the margin if there is inadvertently
    - One additional container?
    - Two?
    - Three?
    - A thousand?

What-IF Analysis

- **Not highly structured compared to HAZOP analysis or FMEA**
- **Questions begin with “What-If”**
- **May address any normal, abnormal, or accident conditions**
- **Simple:**
  – Can be performed more quickly than most other hazard evaluation techniques
  – Can possibly lead to endless list of permutations
- **Produces list of questions, associated outcomes, safeguards**

What-IF Analysis (cont.)

- **Need personnel from operations, criticality safety, and other disciplines who can provide insight into the process upsets**
- **Questions asked:**
  - What if the wrong material is introduced?
  - What if this valve leaks?
  - What if an earthquake occurs?
  - What if we introduce more mass?
- **Screen hazards to determine if they are credible and have an impact on criticality safety**
  - If it is not credible or has no impact on criticality safety, it is dismissed
  - It is it credible and has an impact, it is analyzed and must be determined to be subcritical
    - If it is not subcritical, additional controls are required to make the hazard not credible or less severe

What-IF Hazard Identification Table

- **Process: Receipt of Shipping Containers**

What-If	Causes	Consequences	Preventive Measures	Comments
What if certified shipping container is received damaged?	• Truck damage during transportation • Damaged container sent by shipper	• Structural damage • Damaged shipping container • Damage to fissile material in package	• Receipt inspection • Driver qualification • Shipper’s quality assurance program	
What if truck impacts building or dock?	• Driver error • Brake failure • Weather	• Structural damage • Damaged shipping container • Damage to fissile material in package • Personnel injury	• Robust shipping container • Driver qualification • Site speed limit	Truck backs up to dock to unload
What if load contains more containers than expected?	• Shipper error	• Maximum allowed Criticality Safety Index (CSI) for the shipment may be violated	• Shipper’s quality assurance program	

What-If Hazards Screening Results Table

What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
What if certified shipping container is received damaged?	• Truck damage during transportation • Damaged container sent by shipper	• Structural damage • Damaged shipping container • Damage to fissile material in package	Insufficient mass involved to support criticality	The 1 shipping container involved contains less than the minimum subcritical mass of fissile material	No
What if truck impacts building or dock?	• Driver error • Brake failure • Weather	• Structural damage • Damaged shipping container • Damage to fissile material in package • Personnel injury	Unmitigated scenario is not credible to result in criticality	Damage to certified shipping containers would be minimal due to backing speed	No
What if load contains more containers than expected?	• Shipper error	• Maximum allowed Criticality Safety Index (CSI) for the shipment may be violated	Infinite array of this shipping container is not subcritical		Yes

Common Mistakes

- **Upset tunnel vision**
  - Criticality safety engineers tend to analyze bounding scenarios (not meant to be realistic)
  - Don’t let the extremes blind you to more likely upsets
    - Over-masses tend to be on the order of a couple hundred grams, although evaluations often analyze much higher values
    - Full water flooding of a glovebox is not credible but will a few inches be enough to cause an issue?
    - Most people call infinitely reflected not credible
    - Evaluation of dry material and fully flooded conditions, but fail to consider that intermediate moderation may be significantly closer to a criticality accident (optimum concentration)

Common Mistakes (cont.)

- **Considering changes in process conditions outside of the general framework of formality of operations, operating procedures (and/or natural course of events)**
- **Evaluations cannot and do not consider**
  - Absence of process goals
  - Untrained or unauthorized workers conducting operations
  - Abandonment of procedures
  - Willful negligence
  - Acts of terrorism or sabotage

Importance of Formality of Operations

- **Evaluations cannot account for severe faults in Formality of Operations**
  - Material Control and Accountability practices
  - Configuration Management
  - Conduct of Operations

- **16 of 22 process criticality accidents resulted wholly or at least partially from poor conduct of operations**
  - The solution in those cases was not more stringent controls but better conduct of operations

Credible Abnormal Conditions

- **Failure to correctly identify all of the credible abnormal conditions means the evaluation has failed**
- **There will be no way of knowing what the safety margin is for the operation**
- **This has occurred in the past**
  - 1971 criticality accident in England
  - Solvent ended up in a tank and the mechanism was never discovered
  - Inadvertent addition was “engineered” out of the system

Evaluation of the Process

Evaluation of the Process

- **Normal and credible abnormal conditions must be shown to remain subcritical**
- **There are a variety of analysis techniques available**
  - Experiments
    - Critical experiments
    - Subcritical experiments
  - Published subcritical limits
    - ANSI/ANS-8.1 and -8.15
    - Handbooks
    - Journals and transactions
    - Other NCSEs
  - Calculations
    - Codes (Verified and Validated)
    - Semi-empirical methods
    - Hand calculations

Importance of Experiments

- **Experiments are the preferred means for establishing subcritical limits**

- **ANSI/ANS-8.1, Subcritical Limit:**

“Where applicable data are available, subcritical limits shall be established on bases derived from experiments, with adequate allowance for uncertainties in the data. In the absence of directly applicable experimental measurements, the limits may be derived from calculations made by a method shown by comparison with experimental data to be in accordance with [ANS/ANS-8.1, Section] 4.3.”

Experimental Data Compilations

- **LA-10860-MS:** ***Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U***
- **ANL-5800:** ***Reactor Physics Constants***
- **LA-3067-MS:** ***Los Alamos Critical Mass Data***
- **NEA/NSC/DOC(95)03:** ***International Handbook of Evaluated Criticality Safety Benchmark Experiments***

- **>50,000 critical experiment sets conducted in the US alone.**

Industrial Nuclear Safety Guides

- **ARH-600:** ***Criticality Handbook***
- **TID-7016:** ***Nuclear Safety Guide***
- **DP-532:** ***Handbook of Nuclear Safety***

Simple Computations

- **There are a variety of simple computational techniques that can be performed by hand, calculators, or electronic spreadsheets**
  - LA-14244-M, Hand Calculation Methods for Criticality Safety- A Primer
    - One group and modified one group diffusion approximations
    - Buckling conversions
    - Core density conversion
    - Surface density method
    - Density analog method
    - Limiting surface density method
    - Solid angle method
  - This methodology has limitations which may not allow analysis of all upset conditions

Complex Computer Methods

- **Many, if not most, systems are complex enough that reference data, subcritical limits, and simple techniques are insufficient**
- **For those cases, it is necessary to use complex computer codes**
  - Deterministic methods; solve the transport equation by discretization of space, energy, angle
    - Solution is approximate
    - Geometrically limited, spheres, slabs, cubes
    - Excellent tools for parametric studies on the differences between systems, particularly minor differences
  - Probability based methods (Monte Carlo)
    - Builds a solution through mathematical simulation of neutron behavior
    - Extreme geometric flexibility
    - Can be time consuming both in model creation and execution

Verification and Validation

- **Verification and Validation of computer codes required by ANSI/ANS-8.24**
- **Verification Checks**
  – Code version, data libraries
  – machine (make and model), operating system, compiler(s)
- **Validation Report**
  – Describe the method sufficiently to allow independent duplication of the results
  – Using relevant experimental data
  – Stating the areas of applicability
  – Establishing a bias (and noting trends)
  – Justifying the margin of safety
  – Establishing a criterion of subcriticality

Establishing Limits and Control Selection

Control Selection

- **If the analysis shows**
  - Normal and credible abnormal conditions are subcritical
    - Controls on the parameters defined by the conditions must be identified and credited
    - Controls may eliminate or reduce the consequences of a process condition
  - Normal and/or credible abnormal conditions are not subcritical
    - The process must be redesigned and/or parameters must be further constrained over the original process

Control Selection

- **Criticality safety controls are limitations or restrictions on a parameter**
- **For any particular operation, there is usually only a subset of parameters that may be controlled**
  - Most common
    - Mass
    - Geometry
    - Moderation
    - Reflection
    - Volume
  - Less Common
    - Interaction, for individual operations
    - Density
    - Absorption
    - Enrichment, for individual operations

Control Selection (cont.)

- **In almost all operations, MASS must be limited**
  - Loss of mass control will eventually lead to a criticality accident
  - In some rare cases, mass does not need to be controlled if another parameter overrides the need
    - Density, e.g., <7 g/L (significant dilution) is subcritical regardless of mass
    - Volume, e.g., the amount of mass that fits into a container is limited by volume

Control Selection (cont.)

- **Institutional management must define the criteria a control must satisfy, but in general**
  – The controls selected must be
    - Verifiable
    - USEABLE
    - Independent of personnel charged with compliance, and
    - Resistant to failure and changes over time

Control Selection (cont.)

- **Preferred Order of controls**
  - Natural process constraints and credible course of events
    - Density limits, enrichment limits
  - Passive engineered controls
    - Static features not requiring external input of any type
      - E.g., racks, fixed volumes, geometry
  - Active engineered controls
    - Feature that may require electrical power, calibration, testing, and maintenance
      - E.g., concentration monitors
  - Administrative controls
- **Administrative requirements are always necessary**
  - Larger risk of drifting, such as unintended changes in the intent as time and personnel change

Control Selection (cont.)

- **Examples of poor controls**
  - Esoteric limits such as
    - Limits on k_{eff} (Do not operate above 0.95)
    - H/X ratios that are not verifiable
    - Poison concentrations that can fluctuate
- **Controls that are difficult to implement**
  - Criticality accident history has shown us that difficult to implement procedures/controls can be a contributing cause
    - Tokai Mura Accident

Control Selection (cont.)

- **The evaluation team must assess the control set for possible inclusion in the facility safety basis**
  - DOE-STD-3007-2007 establishes criteria for selecting controls for elevation to the safety basis
  - Your facility should have an established set of actual criteria to assess controls against

Evaluation Review

- **An evaluation review must be performed by an independent, second, qualified NCS engineer familiar with the operations and facility**
  - Review is of the process and evaluation, not just the documentation
  - It is recommended that:
    - A second criticality safety engineer be designated as an independent reviewer at the start of the process
    - Both the primary evaluator and reviewer should be involved with the entire process
      - Independence does not mean separate and isolated
      - Independence does mean:
        - » Not influenced or controlled by others in matters of technical judgment

Summary

- **Evaluation responsibilities of the supervisor/team**
  - Defining the process-team
    - Supervisor has the ultimate responsibility and authority
  - Determine the upsets and likelihoods-team
    - Supervisor has the ultimate responsibility and authority
  - Analysis-NCS Engineer
    - Responsibility to evaluate normal and credible abnormal conditions
  - Select appropriate controls-team effort
    - Supervisor has the ultimate responsibility and authority
  - Document the evaluation-team effort on content
    - NCS engineer is responsible for technical aspects
  - Independent review of the evaluation
    - Usually the responsibility of NCS engineers