SAND2013-7029P

NCSP
NUCLEAR CRITICALITY
SAFETY PROGRAM

Module 6
DOE Requirements and National Standards, and the National DOE Nuclear Criticality Safety Program

Presented by:
Jerry Hicks

DOE Requirements and National Standards, and the National DOE Nuclear Criticality Safety Program

- DOE Orders and Standards related to Criticality Safety from a Criticality Safety Professional Prospective
- Highlights of ANSI/ANS standards related to criticality safety evaluations
- Highlights of DOE STD-3007 related to the process analysis for criticality safety
- The relationship of various Authorization Basis (AB) documents to criticality safety

Learning Objectives

- Identify responsibility for safety
- Understand why national consensus standards are used
- Understand regulatory view of the relationship of safety to priorities
- Understand the core of safety management and criticality safety
- Understand the regulatory view of the most important work of a Process Evaluation for Criticality Safety (CSE or crit eval)

DOE O 420.1, Facility Safety

- Focuses on ANSI/ANS standards
  - In accordance with PL 104-113, Stated in 15 USC 272 (Page 505)
- Requires a documented criticality safety program
  - Approved by DOE
- Monitor for fissile material accumulation
- Criticality safety evaluations per DOE-STD-3007
  - Subject of most of this week.

Why we use the ANSI/ANS Standards

PL 104-113 requires the government to use industry consensus technical standards when they are applicable and available. The only out is if we show they are technically inadequate.

We are also obligated by this law to participate in the development of industry consensus when possible.

Several of the DOE criticality safety staff have participated for decades in the development of ANSI/ANS standards. A few more have participated for years.

The Senior DOE criticality safety staff thinks the ANS-8 standards are applicable and accurate.

DOE O 450.2, Integrated Safety Management

ANSI ANS 8.1, §4.1.1, Responsibilities.

Management shall clearly establish responsibility for nuclear criticality safety. Supervisors should be made as responsible for nuclear criticality safety as they are for production, development, research, or other functions. Each individual, regardless of position, shall be made aware that nuclear criticality safety in his work area is ultimately his responsibility. This may be accomplished through training and periodic retraining of all operating and support personnel. Nuclear criticality safety differs in no intrinsic way from industrial safety, and good managerial practices apply to both.

DOE O 450.2, Integrated Safety Management, cont.

Why would I start a discussion of DOE Order 450.2, Integrated Safety Management, with a quote from ANSI/ANS-8.1?

1. Integrated safety management and good conduct of operations is necessary to criticality safety.

2. This principle was first stated in the predecessor standard to ANSI/ANS-8.1 in 1969

3. DOE did not officially promulgate integrated safety management until prodded by the DNFSB in recommendation 95-2.

ISM Values Statement

The Department expects all organizations to embrace a strong safety culture where safe performance of work and involvement of workers in all aspects of work performance are ***core values*** that are deeply, strongly, and consistently held by managers and workers.

Safety is a value in the NCSP and the DOE. We will accomplish our mission while living our values.

ISM Guiding Principles

LINE MANAGEMENT RESPONSIBILITY FOR SAFETY.
Line management is directly responsible for the protection of the public, the workers, and the environment.
(Refer back to ANSI/ANS 8.1, §4.1.1, Responsibilities.)

CLEAR ROLES AND RESPONSIBILITIES.
Clear and unambiguous lines of authority and responsibility for ensuring safety shall be established and maintained at all organizational levels within the Department and its contractors.

COMPETENCE COMMENSURATE WITH RESPONSIBILITIES.
Personnel shall possess the experience, knowledge, skills, and abilities that are necessary to discharge their responsibilities.

ISM Guiding Principles, cont.

BALANCED PRIORITIES. *Resources shall be effectively allocated to address safety, programmatic, and operational considerations. Protecting the public, the workers, and the environment shall be a priority whenever activities are planned and performed.*

We are not here to create a work-free safety zone!

ISM Guiding Principles, cont.

IDENTIFICATION OF SAFETY STANDARDS AND REQUIREMENTS.

Before work is performed, the associated hazards shall be evaluated and an agreed-upon set of safety standards and requirements shall be established which, if properly implemented, will provide adequate assurance that the public, the workers, and the environment are protected from adverse consequences.

ISM Guiding Principles, cont.

HAZARD CONTROLS TAILORED TO WORK BEING PERFORMED.
Administrative and engineering controls to prevent and mitigate hazards shall be tailored to the work being performed and associated hazards.

OPERATIONS AUTHORIZATION. *The conditions and requirements to be satisfied for operations to be initiated and conducted shall be clearly established and agreed upon.*

ISM Core Functions

- Define the Scope of Work
- Analyze the Hazards
- Develop and Implement Hazard Controls
- Perform Work within Controls
- Provide Feedback and Continuous Improvement

This is a near equivalent to what is required of the process evaluation for criticality safety by ANSI/ANS 8.1 and 8.19.

A good criticality safety evaluation program will show the rest of the site how ISM should be implemented.

ISM Supplemental Safety Culture Elements

- **INDIVIDUAL ATTITUDE AND RESPONSIBILITY FOR SAFETY.**
  - *Individual responsibility for safe mission performance.*
  - *Questioning attitude*
  - *Mindful of work conditions*
  - *Assist each other in preventing unsafe acts or behaviors.*

- **OPERATIONAL EXCELLENCE.**
  - *Sustained, high levels of operational performance*
  - *High-reliability is achieved through a focus on operations*
  - *Find Murphy first*

- **OVERSIGHT FOR PERFORMANCE ASSURANCE.**
  - *Competent, robust, independent*
  - *Verify whether standards and requirements are being met.*
  - *Directed, independent reviews for fresh insights*

- **ORGANIZATIONAL LEARNING FOR PERFORMANCE IMPROVEMENT.**
  - Don't waste your mistakes!
- **Goal is "better than excellent", not just meet the requirements.**

ISM Supplemental Safety Culture Elements

- **INDIVIDUAL ATTITUDE AND RESPONSIBILITY FOR SAFETY.** *Every individual accepts responsibility for safe mission performance. Individuals demonstrate a questioning attitude by challenging assumptions, investigating anomalies, and considering potential adverse consequences of planned actions. All employees are mindful of work conditions that may impact safety, and assist each other in preventing unsafe acts or behaviors.*

- **OPERATIONAL EXCELLENCE.** *Organizations achieve sustained, high levels of operational performance, encompassing all DOE and contractor activities to meet mission, safety, productivity, quality, environmental, and other objectives. High-reliability is achieved through a focus on operations, conservative decision-making, open communications, deference to expertise, and systematic approaches to eliminate or mitigate error-likely situations.*

- **OVERSIGHT FOR PERFORMANCE ASSURANCE.** *Competent, robust, periodic, and independent oversight is an essential source of feedback that verifies expectations are being met and identifies opportunities for improvement. Performance assurance activities verify whether standards and requirements are being met. Performance assurance through conscious, directed, independent reviews at all levels brings fresh insights and observations to be considered for safety and performance improvement.*

- **ORGANIZATIONAL LEARNING FOR PERFORMANCE IMPROVEMENT.** *The organization demonstrates excellence in performance monitoring, problem analysis, solution planning, and solution implementation. The organization encourages openness and trust, and cultivates a continuous learning environment.*

Verification and Validation (V&V) ANSI/ANS 8.1 & 8.24

- ANSI/ANS-8.24*, Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*, and ANSI/ANS 8.1 require:
- Verification of Code System (8.24, §4, 8.1, §4.3.4)
  - Verify and document that the calculations are performed as intended
    - Usually by comparison of output to a suite of test problems provided by the code developers
  - Configuration control
  - The user is expected to know what a 'code system' includes

    For example: *code version* *data libraries* *machine (make and model)* *operating system* *compiler(s)*

Verification and Validation (V&V)

ANSI/ANS-8.24, *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations* requires:

- Validation documentation (§ 8)
  - Describing the method with sufficient detail to allow independent technical review
  - Using relevant experimental data (§ 8.1.2)
  - Stating the areas of applicability (§ 8.1.4)
  - Establishing a bias and bias uncertainty (§ 8.1.3)
  - Justifying the margin of subcriticality and an upper subcritical limit (§ 8.1.5 & 8.1.6)
- These requirements may be in a **validation report**, or included in the NCSE.

There is no lower limit on the number of experiments required.

The standards do not identify a lower limit on the number of benchmarks, but validation does require enough benchmarks (problem-dependent) such that reliable determination of subcriticality can be demonstrated.

For example – code calculations used in evaluating the re-assembly of Godiva. Godiva was of course the benchmark.

3007-2007 The NCSE Standard, Overview

NCSE or CSE: The process evaluation for criticality safety

Introduction: Why is the evaluation being done. Short, and not technical.

Process Description: What is being analyzed. Include process assumptions which impact the evaluation.

Unique requirements: Use if there are requirements beyond the normal requirements for a CSE. Usually not necessary. (If unnecessary, don't include.)

Methodology and Validation: How are you going to determine what you analyze is subcritical?

3007-2007 Overview, Continued

The Process Analysis and Evaluation and Results sections are often combined.

Process Analysis: Analyze and document the normal and credible abnormal conditions.

Evaluation and Results: Determine that the normal and credible abnormal conditions are subcritical.

Credited Controls and Assumptions: Identify the Hardware, Administrative Controls, and Assumptions that assure the system is subcritical under normal and credible abnormal conditions.

3007-2007 Content Discussion

The sections are described in series, and will be read in series. However, they have to be written in parallel.

Introduction Section:

- Why is the evaluation being done.
- Short Statement of what is being evaluated
- Relevant Background information if necessary
- Short, and not technical
    - A one or two paragraph summary of what the evaluation is about.
- From a regulator viewpoint – is this a priority to review, or are other evaluations higher priority?

Make it easy for your customers to read and understand where the safety envelope is.

The customers are Line Management, including operations managers & supervisors, and operators)

NOT the regulators, auditors, and review committees.

Regulators expect Operations to get work done. We *require* that it be done safely.

There is no law about delivery schedules; There is one about nuclear criticality safety.

3007-2007 Content Discussion, cont.

Description Section (Sometimes Called Process Description):

- Describe the system or process being analyzed
- Use drawings, sketches, and illustrations as needed
- Identify assumptions about the process
- Identify assumptions made to control the scope of the evaluation.
- Identify upstream and downstream interfaces that may impact criticality safety.
- Walkdowns and discussions with operations are necessary.
    - It is a good idea to get operations review of your early draft of this section.
- Regulator viewpoint: A knowledgeable reviewer should be able to identify the normal and most of the abnormal conditions after reading this section.

Sometimes you have to make assumptions to keep the evaluation tractable.
Nature of process assumptions that are not well known at the facility should be documented here. For example, you don't have to assume that Pu Nitrate solutions get so thick they will hardly flow at 250-300 grams per liter; Your operations folks and fellow crit engineers at the Pu facility should know that. On the other hand, you might assume, based on history and data, an average and maximum moderator density in certain types of waste.

3007-2007 Content Discussion, cont.

Methodology Section

Regulator Viewpoint: Don't be more complex than necessary. (KISS Principle)

Keep it short and simple.

The real customer, as defined in the ANS-8 Standards, is the first line supervisor. Next are the operators, although many of them will not read the evaluation.

The more distant customers, more or less in order, are operations management, site management, your local regulator, Other DOE criticality staff.
This group is in the line oversight function, as have some responsibility for safety.

The auditors are not customers.

3007-2007 Content Discussion, cont.

Methodology Section, continued

How do you decide what is subcritical?

Consider and use a graded rational approach from the simplest justifiable information and technique to the more complex only as necessary.

- Comparison to experiment
- Comparison to national standards and recognized Handbooks
- Simple hand calculations
- More complex hand calculations
- Simple (e.g. 1-dimensional) codes
- Complex (e.g. Monte Carlo) codes

Regulator viewpoint: Are the methods used appropriate to the nature and complexity of the process system?
Is complex code the *over-used default* method?

3007-2007 Content Discussion, cont.

Process Analysis Section, Regulatory Viewpoint

This, not the calculations, is the most important part of the evaluation.

Why?

"The determination, required by 4.1.2, that a process will be subcritical under normal and credible abnormal conditions requires careful study. The few criticality accidents that have occurred in industrial operations have resulted from failure to anticipate conditions that might arise; none has resulted from a faulty calculation of K_{eff}." (ANSI/ANS 8.1, Appendix A, 1st paragraph)

3007-2007 Content Discussion, cont.

More regulatory viewpoint-

The hardest part of criticality safety engineering -

Omission of credible upsets has been identified during regulatory reviews more often than desirable.

If you consistently fail to identify credible upsets, your operations customer will have to explain to the next of kin why the criticality accident happened. *(Unless you are lucky enough for oversight to shut operations down first.)*

The staff and regulators didn't identify omission of credible upsets at Tokai - - -

25

3007-2007 Content Discussion, cont.

The thought work to meet the 4.1.2 requirement is the most important part of the evaluation process.

The documentation is so we, and you, will know what you thought in a few months or years.

What 4.1.2 requirement ??

4.1.2 Process Analysis. Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions.

3007-2007 Content Discussion, cont.

Process Analysis Section continued

Know the system and process

- Walk the spaces and observe the process
- Discuss the process with operators and line supervision
- Begin analysis
  - ***Walk, observe, and discuss some more***
    Trying to do a criticality safety evaluation with only one walkdown often leads to fundamental flaws.
- Continue Analysis

3007-2007 Content Discussion, cont.

Process Analysis Section continued

- Identify and document the normal and credible abnormal conditions.

- **Verify the credible abnormal conditions with operations.**
- Identify the credible abnormal scenarios.
- Group and bound the scenarios if feasible.
  The appearance of this in the document will depend on the methods used to identify abnormal conditions.
- Control 2 or more nuclear process parameters if feasible.

3007-2007 Content Discussion, cont.

Process Analysis Section continued

- Determine whether the normal conditions are subcritical
  - If not, help operations select alternative processes, or process conditions.
- Determine whether the credible abnormal conditions are subcritical.
  - If not, add engineered controls and administrative limits until the critical conditions are no longer credible.
- Help operations arrange the process so that the natural, credible course of events is the normal condition.
- **Make it easy to do the job right.**
  - Make it harder to do it wrong than right.

3007-2007 Content Discussion, cont.

Process Analysis Section continued

The last criticality accident (Tokai-Mura) was at least partially caused by equipment being so difficult to use properly that the workers developed alternative, unapproved methods, that ultimately led to the unintended excursion.

If possible, make it harder to do the job wrong (and unsafely) than right (and safely).

3007-2007 Content Discussion, cont.

Process Analysis Section continued

Finally, with the controls implemented, is the system ***subcritical under normal and credible abnormal conditions***?

Some of the controls will fail some of the time. If it is credible that enough simultaneous failures could occur to allow criticality, rework the process analysis.

Either a different set of controls or a different process is needed.

3007-2007 Content Discussion, cont.

Evaluation and Results Section

- This section heading is optional, but the content is not. The content of this section is often included in the process analysis section.
- Report the calculational results that show the system is subcritical.

Regulatory spin:

- ➢ It is reasonable for some calculations to show critical conditions. Do not delete calculations just because they show critical conditions.
- ➢ If you don't know what is critical, you may not know what conditions to prevent.

3007-2007 Content Discussion, cont.

Evaluation and Results Section, Continued

The calculations and results must be reported in enough detail that an independent reviewer could:

- Repeat the calculations,
- or do alternate calculations,

and

- Verify that the calculations accurately represent the conditions in the process description

and

- Verify that the results accurately represent the credible abnormal conditions.
  - The reviewer may (and usually will) choose to check the calculations rather than repeat them.

3007-2007 Content Discussion, cont.

Required Controls and Assumptions

List the controls required to assure subcriticality

- Engineered Features
  - Passive
  - Active
- Administrative Controls
- Assumptions
- Other programs – discuss as necessary.

  Examples may include Safeguards, NDA, Radiation Protection, Materials Control . . .

Regulatory spin – Controls should be user friendly and fault tolerant

As mentioned previously, We assume conduct of operations and integrated safety management.

3007-2007 Content Discussion, cont.

Conclusions Section

This is an optional section. Use good technical writing principles.

Conclusion sections frequently include statements about double contingency, and subcritical under normal and credible abnormal conditions

If there are special requirements, state how they are met.

3007-2007, Linkage to DSA and 3009

What is 3009? DOE-STD-3009 is the safe harbor in 10CFR830 for how to write a Documented Safety Analysis (DSA).

Key components:

Chapter 1 Site Characteristics

Chapter 2 Facility Description

Chapter 3 Hazard and Accident Analysis (Criticality must be included if credible) Credible is ***not*** numeric***!***

The same definition as used in ANS 8.1 applies for criticality accidents.

Chapter 4 Safety Structures Systems and Components

Chapter 5 Derivation of Technical Safety Requirements

3007-2007, Linkage to DSA and 3009

What is 3009? - Continued?

Chapter 6 Prevention of Inadvertent Criticality – Usually a short description of the criticality program, key criticality prevention features, and criticality alarm systems.

Some sites have used chapter 6 of a sitewide DSA as the approved criticality safety program. This is neither discouraged nor recommended.

Chapters 7-12, 14, & 15	Other Safety management Programs
Chapter 13	Human Factors
Chapter 16	Provisions for Decontamination & Decomissioning
Chapter 17	Management, Organization, & Industrial Safety Provisions

3007-2007, Linkage to DSA and 3009, cont.

The process evaluation for criticality safety is a more in-depth analysis than the 3009 Hazards analysis.

The site should develop a method for considering *all* criticality controls for elevation to TSRs or DSA design features, and determining which ***if any***, should be elevated.

3007-2007, Linkage to DSA and 3009, cont.

Items to consider:
Active and Passive Engineered features as DSA design features
Engineered Features whose failure would result in less than one robust barrier remaining
Administrative Controls whose failure would result less than one robust barrier remaining

There should be few, if any, criticality safety controls elevated to the DSA & TSRs

Refer to chapter IV of 3007 for more detailed guidance.

3007-2007, Linkage to DSA and 3009, Example 1

A storage vault has many positions, with limits such that contents of several positions in a heap would be critical.

A credible seismic event would not collapse the storage racks, but could cause the items to come out of their positions and fall in a heap.

An Engineered Feature is recommended to restrain the items in the rack, and a Specific Administrative Control to use (e.g. latch) the engineered feature may be recommended.

3007-2007, Linkage to DSA and 3009, Example 2

Waste liquid is collected in a geometrically favorable tank. The next step in the process is transfer to geometrically unfavorable tanks for waste treatment processing.

Potential Design Features:

- Active control with concentration measurement and interlock;
- Only one flow path from final control point (i.e. no possibility of transferring the wrong tank [it happened; due to other factors, it was low concentration])

Potential SAC

Sample from a geometrically favorable tank; if acceptable unlock and allow transfer to second geometrically favorable tank, then second sample; if acceptable unlock and allow transfer to treatment.

3007-2007, Linkage to DSA and 3009, Example 3

An operation produces metal ingots that are about ¾ of the reflected critical mass. The credible over batch is two ingots. (not one ingot of double mass)

Mass, reflection, and interaction are controlled.

Any TSR Level controls?

No.

3007-2007, Linkage to DSA and 3009, cont.

Technical safety requirements (TSRs) means the limits, controls, and related actions that establish the specific parameters and requisite actions for the safe operation of a nuclear facility and include, as appropriate for the work and the hazards identified in the documented safety analysis for the facility: Safety limits, operating limits, surveillance requirements, administrative and management controls, use and application provisions, and design features, as well as a bases appendix. (10CFR830.3)

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 5
ANSI/ANS-8 Standards

Section 1: Overview

Presented by:
Shean P. Monahan

Objectives

- The student will be able to
  - Identify the purpose of the ANSI/ANS-8 national standards
  - Describe the relationship between ANSI/ANS-8.1 and ANSI/ANS-8.19
  - Identify those roles that are responsible for compliance to key requirements and recommendations of the standards
  - Describe the fundamental safety margin requirement for handling fissionable material outside of reactors
  - Describe the relationship between the fundamental safety requirement and the technical practices of ANSI/ANS-8.1

Standards Organizations

- American National Standards Institute (ANSI)
  - United States accrediting authority
    - License or certify organizations as being able to develop American National Standards (ANS)
    - Website
      - http://www.ansi.org/
- Standards are comprised of consensus industry best practices
  - Consensus process involves voting on the part of stakeholders
    - product and/or service organizations
    - users
    - other interested parties
  - Very different than the process used to develop government standards

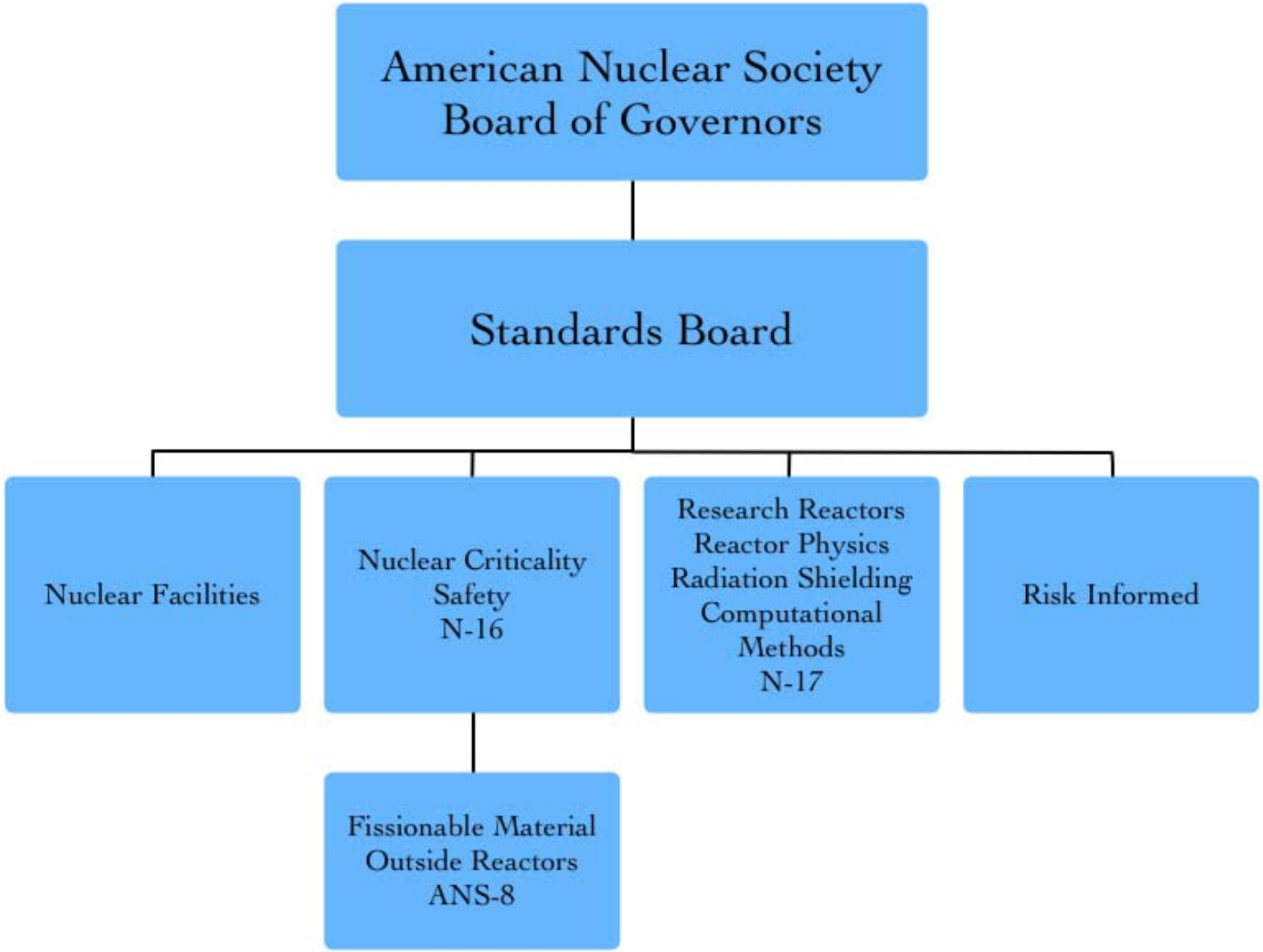
History

ANSI Mission

To enhance both the global competitiveness of U.S. business and the U.S. quality of life by promoting and facilitating voluntary consensus standards and conformity assessment systems, and safeguarding their integrity.

Criticality Safety Standards

- Responsible Organizational Member
  - American Nuclear Society
    - http://www.new.ans.org/standards/
    - Patricia Schroeder
    - 555 North Kensington Avenue
    - La Grange Park, IL 60525
    - Phone: (708) 579-8269
    - Fax: (708) 352-6464
    - E-Mail: pschroeder@ans.org
    - Date of Accreditation: 3/14/1987


American Nuclear Society
Board of Governors
Standards Board
Nuclear Facilities
Nuclear Criticality
Safety
N-16
Research Reactors
Reactor Physics
Radiation Shielding
Computational
Methods
N-17
Risk Informed
Fissionable Material
Outside Reactors
ANS-8

Perspective

- All activity involves risk (in fact, existence involves risk)

- Absolute safety can only be achieved by absence of activity
  - Safety by itself has no intrinsic meaning
    - You can avoid food poisoning by not eating

- Safety and activity goals must be appropriately balanced
  - Should the airline industry cease to operate to avoid accidents?
  - Should you not eat in order to avoid food poisoning?
  - etc.

- Standards recognize this relationship

Organization

- Standards may be grouped into three general types (not official designations)
  - Administrative standards
  - Application standards
  - Emergency response standards

- Each standard has a functional domain
  - History and development process is such that boundaries are not always crisp
    - As the industry has grown more detailed standards have been developed for specific functional areas
    - Consistency between working groups has not been perfect
    - Future holds promise that the boundaries will be more clearly drawn

- No one standard is more important than another
  - If a standard applies, compliance is not optional

ANSI/ANS-8 Standards

Fissionable Material Outside of Reactors

Administrative		Application Specific			Emergency
8.1	8.20	8.5	8.12	8.17	**8.3**
8.10	8.24	8.6	8.14	8.21	8.23
8.19	8.26	8.7	8.15	8.27	

ANSI/ANS-8 Standards

Administrative	
8.1-1998; R2007	Nuclear Criticality Safety in Operations with Fissionable Material Outside of Reactors
8.10-1983; R2005	Criteria For Nuclear Criticality Safety Controls in Operations with Shielding and Confinement
8.19-2005	Administrative Practices For Nuclear Criticality Safety
8.20-1991; R2005	Nuclear Criticality Safety Training
8.24-2007	Validation of Neutron Transport Methods For Nuclear Criticality Safety Calculations
8.26-2007	Criticality Safety Engineer Training and Qualification Program

ANSI/ANS-8 Standards

	Application
8.5-1996; R2007	Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material
8.6-1983; R2010	Safety in Conducting Subcritical Neutron Multiplication Measurements In-Situ
8.7-1998; R2007	Nuclear Criticality Safety in the Storage of Fissile Materials
8.12-1987; R2011	Nuclear Criticality Control and Safety of Plutonium-Uranium Fuel Mixtures Outside of Reactors
8.14-2004	Use of Soluble Neutron Absorbers in Nuclear Facilities Outside Reactors

ANSI/ANS-8 Standards

Application	
8.15-1981; R2005	Nuclear Criticality Control of Special Actinide Elements
8.17-2004; R2009	Criticality Safety Criteria For the Handling, Storage, and Transportation of LWR Fuel Outside of Reactors
8.21-1995; R2011	Use of Fixed Neutron Absorbers in Nuclear Facilities Outside of Reactors
8.22-1997; R2006	Nuclear Criticality Safety Based on Limiting and Controlling Moderators

ANSI/ANS-8 Standards

Emergency Response	
8.3-1997; R2007	Criticality Accident Alarm System
8.23-2007	Nuclear Criticality Accident Emergency Planning and Response

Nuclear Criticality Safety

- **Nuclear Criticality Safety is**

  Personnel protection *from the* ***consequences*** *of a criticality accident, preferably by prevention of the accident*

- Encompasses all aspects of the operating environment
  - Procedures, training, engineering, maintenance, & configuration management, i.e., formality of operations
  - Assessments & reviews
  - Other precautions (e.g., shielding)

  in addition to physical protection (emergency response)

Purpose

- **PROTECTION of PERSONNEL (and PUBLIC)**
  - 8.1 Introduction
    - *Good safety practices must recognize economic consideration, but the protection of operating personnel and the public must be the dominant consideration*
  - 8.1 Section 4.1.1
    - *Distinction may be made between shielded and unshielded facilities, and the criteria may be less stringent when adequate shielding and confinement assure the protection of personnel*
  - 8.3 Section 4.1.1
    - *The purpose of an alarm system is to reduce risk to personnel*

Applicability

- Political consequences of accidents are not germane

- Technically, accidents without human consequences beyond those expected from normal work conditions, need not meet 8.1 or 8.10
  - However,
    - Claiming exemption must be supported by some technically based rationale or analysis
      - System dynamics must be considered
        - How does the system reach the critical state
      - Kinetics must be considered in determining consequences
        - What is the fission yield and the time frame?
        - Can the results affect people?

Standards Content

- Standards are comprised of industry best practices
  - Prescribe **what** programs shall and should do through requirements and recommendations
  - Do **not** prescribe **how** programs are to comply with the requirements and recommendations
    - Statements are purposely flexible
      - Individual institutions must decide on specific implementation

Standards Content *(Continued)*

- Arrived at through a consensus agreement process

- Structure has meaning
  - helps to define the relationship between statements
  - statements should not be read in isolation

- Words are very carefully chosen
  - convey a specific (unambiguous) meaning
  - ***say what they mean and mean what they say***
    - economy of words that is nothing short of impressive
    - paraphrasing statements is difficult and a bad practice
  - prudent default position
    - different words=different meanings
      - Credible versus possible
      - ANSI/ANS-8.3 Minimum accident of concern

Standards Content *(Continued)*

Section 5.6 Detection Criterion

Criticality alarm systems shall be designed to detect immediately the minimum accident of concern. For this purpose, in areas where material is handled or processed with only nominal shielding, the minimum accident may be assumed to deliver the equivalent of an absorbed dose in free air of…

- 1986 Version

  …20 rad at a distance of 2 m from the reacting material in 60 s.

- 1997-R2003 Version

  ...0.2 Gy/min (20 rad/min) at 2 meters from the reacting material.

Standards Content *(Continued)*

- The discussion that follows is intended to provide information on standards
  - History and relationship between standards
  - Structure of the standards
  - Roles and responsibilities defined by the standards
  - The DOE accepted meaning and methodology of implementation
    - Examples from various sites may be used to demonstrate particular implementation methodologies
    - Your site specific methodologies must be your implementation guide

Language of Standards

- Shall
  - Denotes a requirement
- Should
  - Denotes a recommendation
- May
  - Denotes permission, i.e., neither a requirement nor a recommendation

Conformance

- To conform with a standard

  All operations shall be performed in accordance with its requirements, but not necessarily with its recommendations

- However a rationale approach to safety demands

  That justification be provided for recommendations that are not implemented

- Understand that consensus standards are legally recognized
  - practices that a reasonable and prudent industry professional would exercise

Recommendations

- Three types of recommendations
  - Practices for which compliance is explicitly demonstrable but may not always be practical or beneficial to a particular site
  - Practices for which compliance is not explicitly demonstrable
  - Practices for which compliance is not always possible
- The type of recommendation should be clear from the context
- If in doubt as to the meaning or application of any requirements or recommendation, an official inquiry can be made

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 5
ANSI/ANS-8 Standards

Section 2: Administrative Standards

Presented by:
Shean P. Monahan

Unshielded Operations

- There are two administrative standards applicable to criticality safety programs for hands-on fissionable material operations:

ANSI/ANS-8.1

Nuclear Criticality Safety in Operations With Fissionable Material Outside of Reactors

ANSI/ANS-8.19

Administrative Practices For Nuclear Criticality Safety

Boundaries

- Both standards have programmatic administrative requirements
  - Some of the requirements are "*repeated*"
  - Unfortunately in some cases different language is used
    - Exact opposite of the goal of standards
    - Different committees and unclear demarcation of domain
  - Ideally requirements should only appear once in the entire series of standards
- Much of the duplication and conflicts is an artifact of the evolution and growth of the standards

ANSI/ANS-8.1 History

- First version appeared 1964
  - ASA-N6.1, *Safety Standard for Operations With Materials Outside of Reactors*
    - Originally the only standard
    - A profound effect on accident frequency
    - It contained only administrative (program) requirements and recommendations

- The modern version is a mix of administrative requirements and specific application information (single parameter subcritical limits)

Consensus

ASA-N6.1 Working Group Members	
Dixon Callihan (Chairman)	Oak Ridge National Lab
James Carothers	Lawrence Radiation Lab
H. K. Clark	Savannah River Plant
E. D. Clayton	Hanford Atomic
H. F. Henry	Gaseous Diffusion Plant
W. B. Lewis	National Reactor Testing
J. D. McLendon	Y-12 Plant
H. C. Paxton	Los Alamos Scientific Lab
C. L. Schuske	Rocky Flats Plant
Frank Woltz	Goodyear Atomic

ASA-N6.1

- Opening statement

  All operations with fissionable materials outside of nuclear reactors must be performed in a manner precluding the establishment of a nuclear chain reaction.

- The position of this statement within the standards signifies its importance
  - The entire reason for the existence of the standard
  - Eventually this became the safety margin requirement
    - i.e., 8.1, Section 4.1.2 Process Analysis

ASA-N6.1 Section 4, Nuclear Safety Controls

- **Procedures**…must be **supplemented** by appropriate **regulations** to ensure nuclear safety in the process. The **factors…**which, singly or in combination, **must be controlled** to effect safety include **mass…**the **dimension** and **volumetric** limitations imposed by equipment, the proximity of neutron **reflectors**, and the physical and chemical properties of the process materials, such as **isotopic** and chemical **concentrations**, **density**, neutron cross sections, and other nuclear properties.

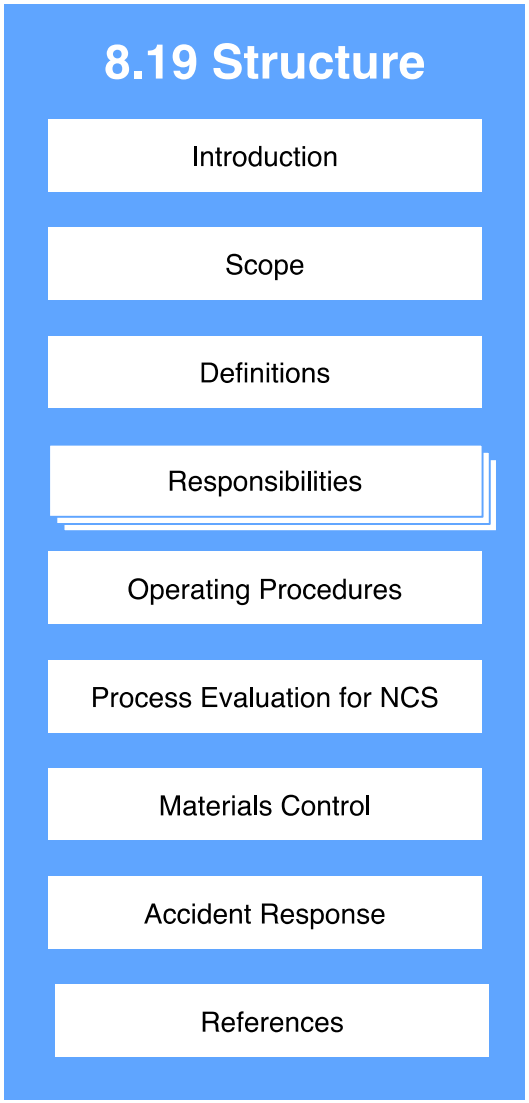
- Since not only the fissionable materials, but also their containers and immediate environment contribute to the conditions for criticality, all these **factors shall** be considered in specifying **nuclear safety limits**. **Maintenance of the specified limits at all times shall be the assigned responsibility of qualified operating personnel. Administrative procedures, with emphasis on safety, shall be established to clearly define this responsibility.**

ANSI/ANS-8.1

8.1 Structure

- Introduction
- Scope
- Definitions
- NCS Practices
- Single Parameter Limits
- Multiparameter Control
- References

ANSI/ANS-8.19


8.19 Structure
Introduction
Scope
Definitions
Responsibilities
Operating Procedures
Process Evaluation for NCS
Materials Control
Accident Response
References

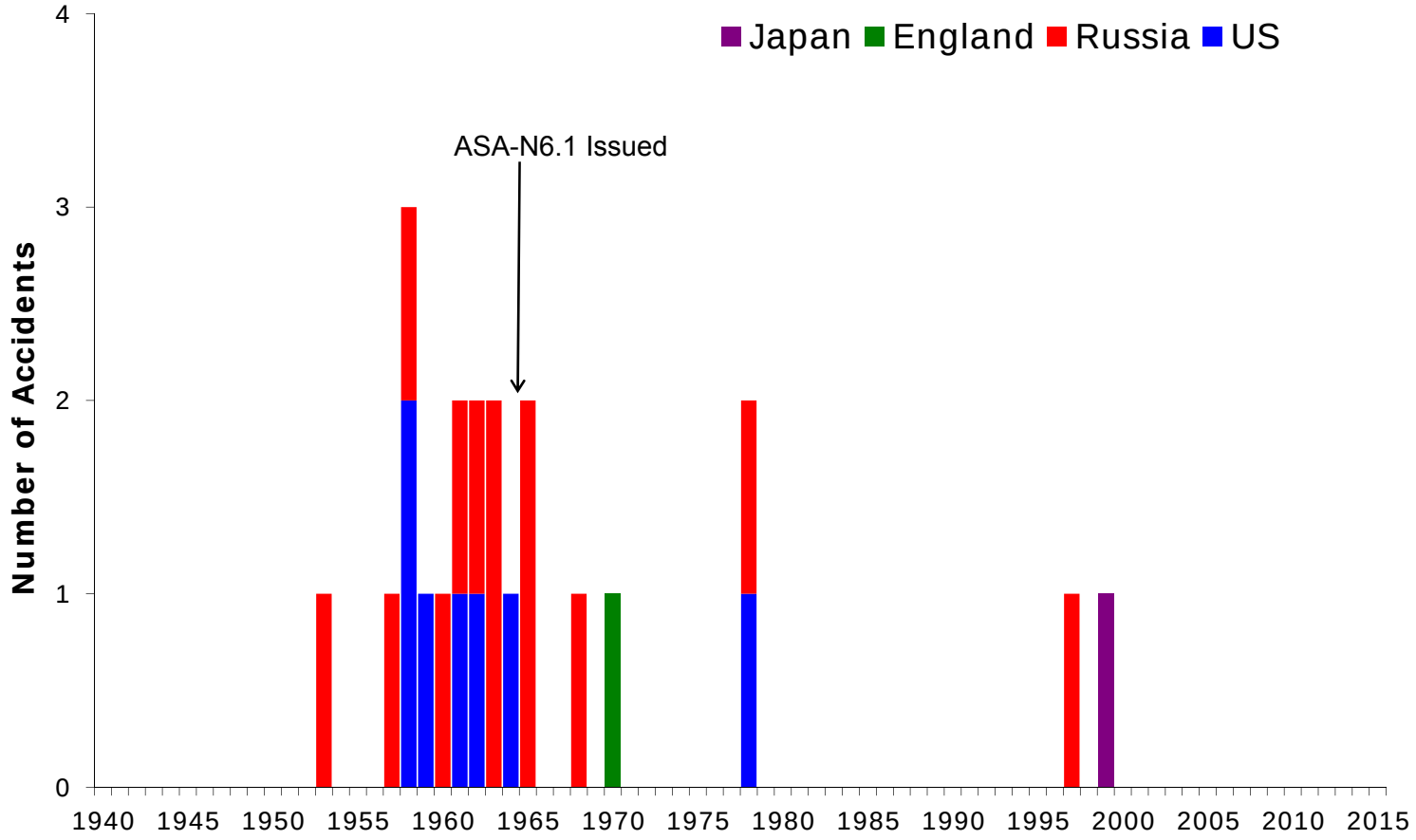
Equivalency of Structure

8.1		8.19
4.1.1 Responsibilities	Responsibilities	**4.0** Management Responsibilies **5.0** Supervisory Responsibilities **6.0** NCS Staff Responsibilities
4.1.2 Process Ananlysis **4.2** Technical Practices	Safety Margin	**8.0** Process Evaluation for NCS
4.1.3 Written Procedures **4.1.5** Operational Control **4.1.6** Operational Reviews	Conduct of Operations	**7.0** Operating Procedures
4.1.4 Materials Controls	Materials Control	**9.0** Materials Control
4.1.7 Emergency Procedures	Emergency Response	**10.0** Accident Response

Program Structure

- Responsibilities
- Implementation
  - Safety margin establishment (evaluations)
    - Technical practices
  - Procedures (NCS controls)
  - Reviews
  - Materials control
- Emergency Response

Process Criticality Accident History



NCS Program Responsibility

- The NCS program responsibilities as outlined in the ANSI/ANS-8 standards in large part is based on lessons learned from accidents
- Fundamentally (criticality) safety is an operating management responsibility
- Knowledge and acceptance of risk is essential

NCS Program Responsibility *(continued)*

- Examine the title of ANSI/ANS-8.1:

  *Nuclear Criticality Safety in **Operations** with **Fissionable** Material Outside of Reactors*

- It should be clear that the standard is directed at
  - those who actually handle fissionable material, i.e.,
    - Institutional or facility management and
    - Supervisors-those with direct responsibility over the fissionable material operation

- The responsibility for criticality safety at a facility is not the responsibility of the criticality safety advisors

Risk Acceptance

- Responsibility & authority belong with the risk
  - Any other structure is flawed
    - e.g., assigning responsibility to an external organization
  - Potential negative consequences include
    - Disaffecting those taking the risk
      - Controls are not established but imposed
    - Engendering an attitude of disbelief
    - Disconnecting the evaluation from reality
      - There is no motivation for efficient operation
- Separating responsibility and authority from the risk would be unthinkable in other disciplines
  - Radiological, industrial, electrical, fire
    - How would it look if the fire department was responsible for maintaining the combustible loading in a facility?

Risk Acceptances *(Continued)*

- Los Alamos National Laboratory
  - 1990 to 2003 responsibility had effectively shifted from operations to the NCS group
    - Guidance was replaced with permission
    - Understanding and acceptance by operations was cosmetic
    - Misalignment with the standards reached throughout LANL management
      - Rash of infractions in which management implied that the criticality safety group was responsible

Management

- Accept overall responsibility for safety
  - Continuing commitment **should** be evident
  - NCS differs in no intrinsic way from industrial safety and good managerial practices apply to both
    - e.g., Combustible loading may be determined by fire safety professionals but they don't monitor the combustibles

- Establish policy and make it known
  - Distinction may be made between unshielded and shielded facilities
  - Assign responsibilities and delegate commensurate implementation authority
    - **Should** be compatible with other safety disciplines

Management *(Continued)*

- Workers shall be aware that criticality safety is ultimately their responsibility
  - Supervisors
    - **Should** be made as responsible for (criticality) safety as for production, research, development, or other functions
  - Operators
    - Ensure risk and role awareness (Mayak 1953, Mayak 1957, Japan 1999)
  - Provide criticality safety **advisors** to supervision
  - Advisors **should** be, to the extent practicable, independent of operations

Management *(Continued)*

- Management shall
  - establish the criteria to be satisfied by nuclear criticality safety controls
    - definition, dependability, defensibility
    - distinction may be made between unshielded and shielded facilities
  - a method of monitoring the program
  - participate in periodically auditing the program
  - establish and maintain a configuration management system for identifying and controlling changes to
    - Facility conditions
    - Process conditions

Supervisors

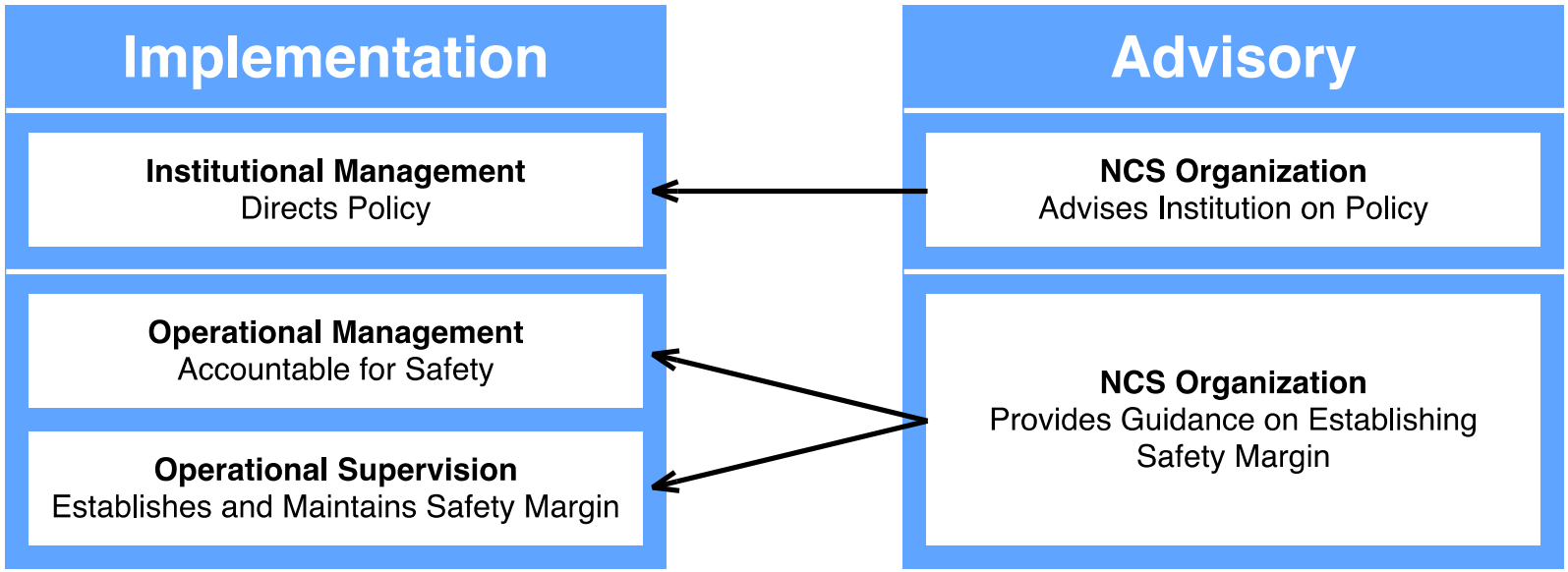
- Accept responsibility for safety of their operations
  - Knowledgeable of relevant criticality safety aspects
  - Require personnel to be trained to procedures and safety considerations
  - Develop and maintain written procedures
  - Verify, inspect, and maintain engineered features
  - Require compliance with good safety practices

NCS Advisors

- Provide technical guidance
  - Equipment & process design, procedures (controls)
- Maintain proficiency
- Collaborate with experts as necessary, e.g., seismic
  - likelihoods
  - engineering judgments (developing and and defending)
- Maintain familiarity with operations
- Assist in training operators (development and delivery)
- Conduct or participate in audits
- Review events for possible improvements

ANSI/ANS-8 Standards

General Responsibility Assignment



Implementation

- Evaluations
  - Safety margin establishment

- Infrastructure
  - Procedures (NCS controls)
  - Reviews
  - Materials control

Process Analysis or Evaluation

- ANSI/ANS-8.1, Section 4.1.2 and ANSI/ANS-8.19, Section 8.1 establish the Safety Margin Requirement*

*Before a new operation with fissionable material is begun, or before an existing operation is changed, it **shall** be determined that the entire process will be subcritical under normal and **credible abnormal conditions**.*

**Institutional policies need to emphasize this requirement*

Process Analysis *(Continued)*

"The PA requirement isn't everything, it is the only thing"

- It is purpose of criticality safety programs
  - Compliance constitutes an adequate criticality safety program
  - Non-compliance constitutes a fundamentally flawed program
    - even if every other requirement and recommendation is followed
  - The very first statement of ASA N6.1-1964:

    All operations with fissionable materials outside of reactors must be performed in a manner precluding the establishment of a nuclear chain reaction.

Process Analysis *(Continued)*

- Directed at management & supervision of operations
- Originates from a rationale approach to safety
  - Don't perform an operation if a criticality accident can realistically happen
  - Recall that the ASA-N6.1 opening statement used the term *preclude*

Process Analysis *(Continued)*

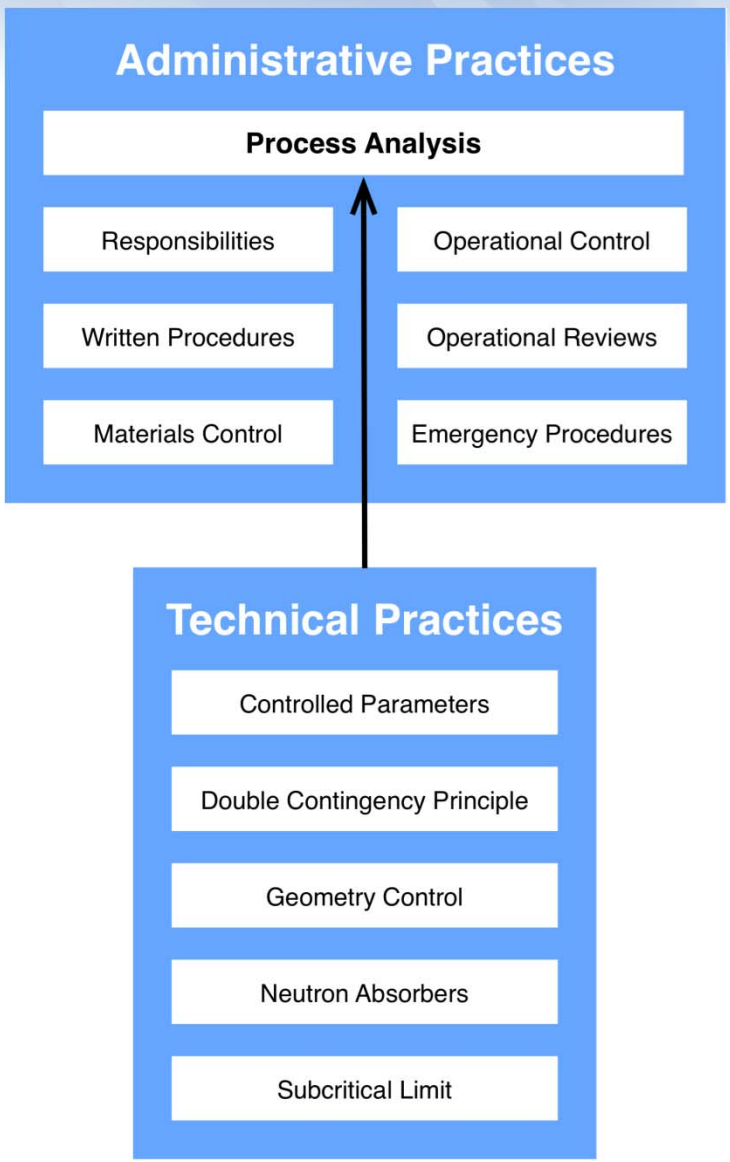
- Evaluations shall
  - Be led by or directly involve process supervision
  - Identify
    - Normal conditions (procedures)
    - Credible abnormal conditions
    - Controlled parameters and limits
  - Be fully documented
  - Independently reviewed

Process Analysis *(Continued)*

- ANSI/ANS scope of credible abnormal conditions
  - The original framers of the standard were concerned only with the processes themselves
    - Different time (cold war) with a different perspective
    - Acts of nature were simply considered out of bounds
      - Effects were largely unquantifiable at the time
  - Did not include (or exclude) external phenomena
    - Earthquakes
      - The one exception, ANSI/ANS-8.7, is evidence that this was not part of the original scope
    - Weather (tornados, hurricanes, etc.), plane crashes, meteorites, etc.

Technical Practices

- Establishing the safety margin is achieved by controlling one or more parameters of the system within subcritical limits
- Controls may be
  - Natural or credible course of events
  - Engineered feature requirements
    - Passive
    - Active
  - Administrative requirements
- There are five technical practices supporting the Process Analysis requirement
  - Controlled Parameters
  - Double Contingency Principle
  - Geometry Control
  - Neutron Absorbers
  - Subcritical Limit


Administrative Practices
Process Analysis
Responsibilities
Operational Control
Written Procedures
Operational Reviews
Materials Control
Emergency Procedures
Technical Practices
Controlled Parameters
Double Contingency Principle
Geometry Control
Neutron Absorbers
Subcritical Limit

Technical Practices *(Continued)*

- 4.2.1 Controlled Parameters
  - Specify the parameters under control and the limits
  - Understand how variations in these parameters influence the safety margin (k_{eff})
- 4.2.2 Double Contingency Principle
- 4.2.3 Geometry Control
  - Use dimensional control when practical
  - Prior to use verify validity and dimensions
  - Maintain
- 4.2.4 Neutron Absorbers
  - Maintain effectiveness
  - Extra ordinary care should be exercised for soluble poisons
- 4.2.5 Subcritical Limits
  - Derive from experiments when applicable data is available
  - May be derived from validated computations

Technical Practices *(Continued)*

- ANSI/ANS-8.1, 4.2.2 Double Contingency Principle
  - This recommendation statement appears in no other standard

*Process designs **should** incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent **changes in process conditions** before an accident is **possible**.*

Technical Practices *(Continued)*

- Double Contingency Principle
  - Perhaps the most abused and misunderstood statement in all of the standards
    - Nothing difficult about this recommendation
    - There is a persistent misconception that language does not correctly match the purpose and scope
    - In actuality it is the purpose and scope that is misunderstood
  - It too is based on a rationale approach to safety
  - Language of and directed to management and supervision

Technical Practices *(Continued)*

- The DCP is NOT a statement of safety margin
  - It is in the technical practices section for a reason
    - One of several
    - Its status is no different than any other technical practice
    - Subservient to the Process Analysis requirement
  - It is the industry accepted *best practice* for complying with the actual safety margin requirement whenever practical
    - Equivalent to the use of redundant systems of other safety disciplines
    - Origins lied in recognition that humans make mistakes
      - Back-up administrative requirements with physical constraints (geometry)
  - It is a recommendation precisely **because compliance may not always be possible or necessary**

Technical Practices *(Continued)*

- What does this statement mean?

- Contingency
  - An event which may but is not certain to occur
  - Something that may or may not go wrong
- Principle
  - A basic rule, law, or assumption

- The DCP is a best practices methodology, i.e., a rule
  - It is either applied or it is not during the performance of an evaluation

Technical Practices *(Continued)*

- By definition:
  - It is not possible to

    lose a contingency

    - or to

      lose double contingency

  - The standard does not identify or require a *double contingency analysis*

- Such terminology is inappropriate, incorrect, and confusing
  - It has largely arisen from the misinterpretation of the DCP as the safety margin requirement

Technical Practices *(Continued)*

- Examine the PA requirement and DCP recommendation together

*Before a new operation with fissionable material is begun, or before an existing operation is changed, it **shall** be determined that the entire process will be subcritical under normal and **credible abnormal conditions**.*

*Process designs **should** incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent **changes in process conditions** before an accident is **possible**.*

credible abnormal conditions

≠

changes in process conditions

Technical Practices (Continued)

- ***Credible abnormal conditions*** has a broader meaning
  - If one, two (or even more) concurrent changes in process conditions is a credible abnormal condition, the system must remain subcritical
  - If a single change in process conditions results in a critical system, compliance to the
    - DCP is not achievable nor is it required
    - PA requirement is necessary
      - i.e., this single change in process conditions must NOT be a credible abnormal condition
- The bottom line
  - There is NOT necessarily a one-to-one correspondence between changes in process conditions and credible abnormal conditions

Technical Practices *(Continued)*

- ***Changes in process conditions***
  - is purposeful language
    - common language of the personnel charged with compliance, i.e., management and supervision of the operations
  - has a broader meaning (and more conservative)
    - it does not mean parameters and certainly does not mean controls
    - a single change in process conditions may affect two or more parameters simultaneously
      - Water ingress into solution filtering gloveboxes; filter boat volume is limited to 7-liters
    - conversely, multiple parameters may have to be controlled to reduce the likelihood a single change in process conditions to an acceptable level

Technical Practices (Continued)

- There is a distinction between
  - control implementation methods
  - controls (limitations on parameters)
  - changes in process conditions
  - credible abnormal conditions

- Each is separate entity and should be mentally maintained as such, despite commonality

- Example
  - Several years ago LANL was contacted by a another site
  - In that program, changes in process conditions, was interpreted as a compromise to a control and labeled a “contingency”
  - Further they had expanded the definition of a control to include implementation methods

Technical Practices (Continued)

- So they had declared the loss of mass control within an unfavorable geometry tank to be “doubly contingent” via
  - Contingency 1: Supervisor A would verify and sign the log prior to mass transfer
  - Contingency 2: Supervisor B would cross verify and sign the log prior to transfer

- After one particular transfer of material it was discovered that both signatures were missing
  - At that point they were compelled to report a “loss of double contingency”, whatever that means

Technical Practices (Continued)

- How many items are wrong with this story?
  - The actual control was on a limitation on mass, this was not recognized
    - Controls are limitations on parameters
  - Single change in process conditions---DCP cannot be nor does it need to be applied
  - Implementation methods for the control and infrastructure must support some level of over-mass as
    - unlikely and anything beyond it as being incredible
    - there was never any mention of complying with the PA requirement
      - In fact there was no acknowledgment in their program of the requirement

Technical Practices *(Continued)*

Credible

≠

Possible

Technical Practices *(Continued)*

- The word ***possible*** was purposely chosen to be different from, and to convey a different meaning than the word ***credible***

- As it appears in the DCP the word ***possible*** is defined as being less likely, i.e., more rare than ***credible***

  - *…two, unlikely, independent, and concurrent changes in process conditions* actually occurs a criticality accident is **tolerable**[1]

    - i.e., an incredible abnormal condition has occurred

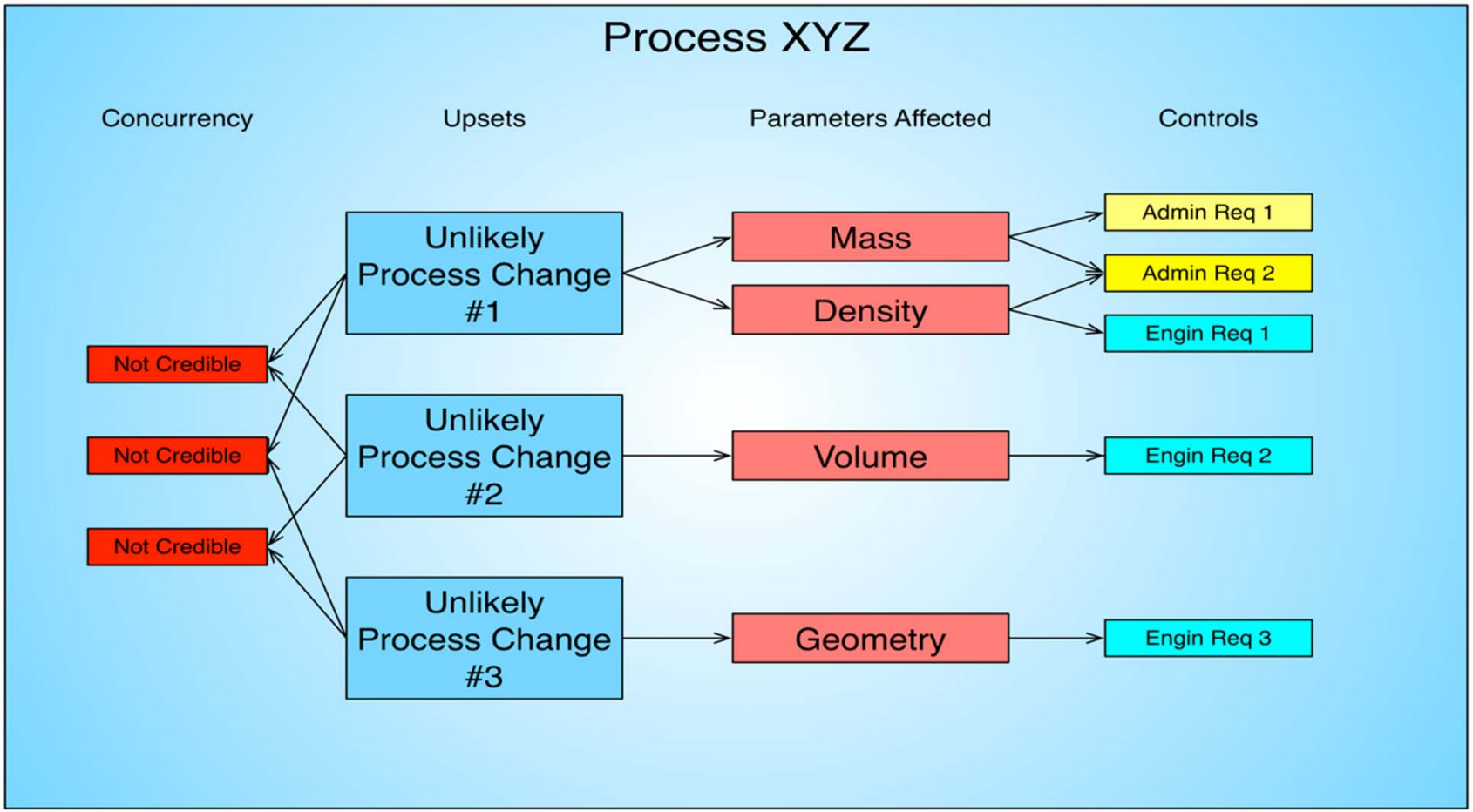
    - Incredible ≠ Impossible

Slide 69

1 Don't use the word "tolerable" – comment from Pilot 2 evaluators.
Douglas G. Bowen, 1/26/2012

Technical Practices *(Continued)*

- Incredible events occur
  - The airline industry has an impeccable safety record
    - The likelihood of any major aircraft crash is ~ 1 out of 2 million
    - Some accidents simply beat the odds
    - July 19th, 1989 UAL Flight 232; Sioux City, Iowa
      - All three independent hydraulic lines were severed
        - odds against simultaneous failure had previously been calculated as high as a billion to one
        - what is the proper response given this information???


Process XYZ
Concurrency
Upsets
Parameters Affected
Controls
Not Credible
Not Credible
Not Credible
Unlikely Process Change #1
Unlikely Process Change #2
Unlikely Process Change #3
Mass
Density
Volume
Geometry
Admin Req 1
Admin Req 2
Engin Req 1
Engin Req 2
Engin Req 3

Technical Practices *(Continued)*

- The goal is to
  - design processes with due consideration to natural process constraints
  - procedures,
  - and controls
  - such that process changes that can have significant impact on the criticality safety margin are
    - unlikely (or will not) occur
    - Independent (of other unlikely significant process changes)
    - Rare enough that (when coupled with sufficient recovery mechanisms) that the simultaneous occurrence will not happen

Technical Practices *(Continued)*

- Unlikely
  - a functional definition is built-in by the subservient relationship of the DCP recommendation to the PA requirement

- Credible
  - Believable, rational, plausible, ***reasonable***
    - Can this event/upset realistically happen?
    - **No numerical value is assigned to this definition**
    - ISO 1709 equivalent

      "Consider all reasonably foreseen abnormal conditions"
  - Words that it is not
    - Conceivable, imaginable, ***possible***, ***non-trivial***

- Institutions need to have specific program definitions

Procedures

- Written operating procedures exist to facilitate and document the safe and efficient conduct of operations

- Operations for which criticality safety is pertinent shall be governed by written procedures

- The procedures shall
  - include NCS controls and limits
    - integrated part of the normal conditions
  - be periodically reviewed by supervision
  - be reviewed by NCS advisors

Procedures

- The procedures should be
  - organized for convenient use by operators
  - conveniently available to operators
  - free of extraneous materials
  - such that no single, inadvertent departure can cause a criticality accident
    - Does this conflict with the PA requirement?
    - How is this reconciled with the Double Contingency Principle?

Procedures *(Continued)*

- This is not an exemption to the PA requirement or the DCP recommendation
  - Inadvertent departures from procedures must be part of the assessment of **changes in process conditions**
    - If an inadvertent departure from procedure
      - is a credible abnormal condition the system must remain subcritical
      - results in a critical system, it must not be a credible abnormal condition
        - Write procedures such that multiple departures would be required for this change in process conditions to occur
          - Don't rely on a single departure from procedures as having to be incredible (defense-in-depth)

Materials Control

- Movement of fissionable material must be controlled as specified in written procedures
- Materials shall be labeled
- Area postings shall be maintained specifying limits on parameters subject to procedural control
  - Conflict with Section 7.6 of ANSI/ANS-8.19
- Access to fissionable material handling areas shall be controlled
- Additional considerations should be given to equipment in an extended shutdown as fissionable material characteristics can change over time

Validation

- ANSI/ANS-8.1, Section 4.3, Validation of a Calculational Method
  - Offshoot of the Technical Practices section
    - 4.2.5 Subcritical Limits, in particular

- Applies to subcritical limits derived from calculations
  - Not limited to computer based methods or subsets
  - Applies to any computation

- Detailed elaboration within the standard

- Augmented by ANSI/ANS-8.24, *Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations*

- Implementation is site specific

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 3
Process Facility Criticality Accidents
Section 1: LA-13638

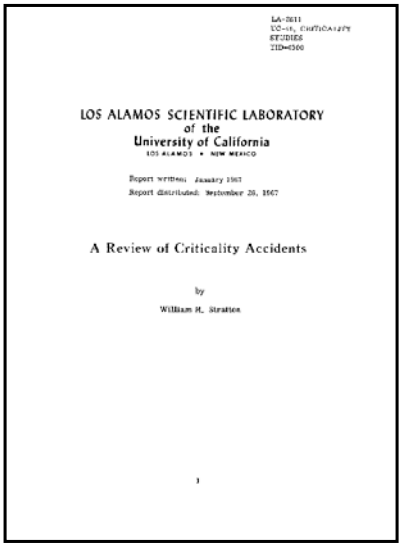
Presented by:
Shean P Monahan

NCSP

Objectives

- Introduce LA-13638 “A Review of Criticality Accidents” published in 2000
- Learn about the 1953 accident at Mayak in the USSR (first process criticality accident)
- Learn about the 1999 accident at Tokai-mura in Japan (last process accident)
- Understand the common characteristics of the process criticality accidents and lessons learned

2



LA-3811
UC-41, CRITICALITY
STUDIES
TID-4500

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Report written: January 1967
Report distributed: September 28, 1967

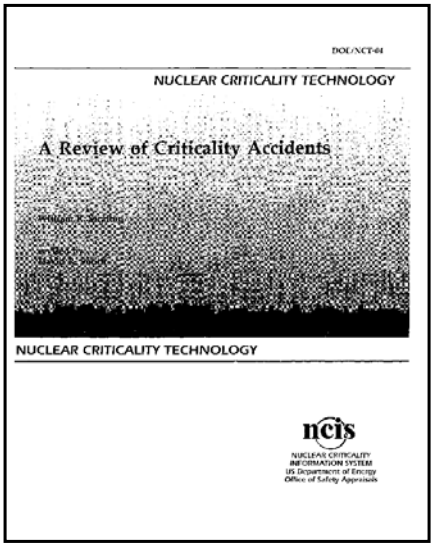
A Review of Criticality Accidents

by

William R. Stratton

3

4



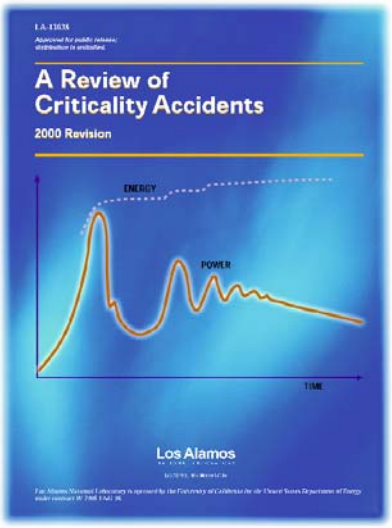
DOE/NCT-04

NUCLEAR CRITICALITY TECHNOLOGY

A Review of Criticality Accidents

NUCLEAR CRITICALITY TECHNOLOGY

ncis
NUCLEAR CRITICALITY
INFORMATION SYSTEM
US Department of Energy
Office of Safety Appraisals



5

LA-13638 Part I

- Chronological presentation of process criticality accidents
  - Overview
  - Summary description of each accident
    - References to more in depth documents when available
  - Physical and neutronic characteristics section
  - Observations and Lessons Learned

6

LA-13638 Part II

- Chronological presentation of reactor and experimental accidents
  - Overview
    - A. Fissile solution systems
    - B. Bare and reflected metal assemblies
  - May be discussed during the T&EP Second Week (SNL or CEF)

7

Nuclear Criticality Accident

The release of energy as the result of inadvertently producing a self-sustaining or divergent chain reaction

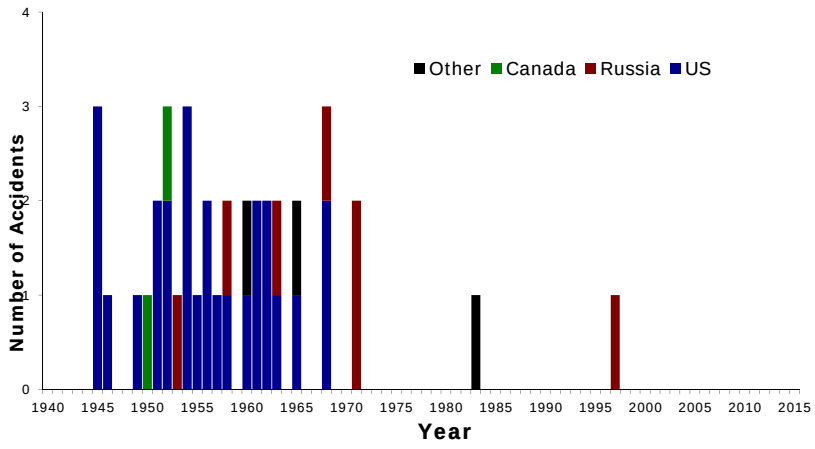
8

Critical Assemblies/Reactor Experiments

- >50,000 experiments
  - Designed to determine critical point
- 38 accidents
  - 12 deaths
  - 5 occurred in working reactors
    - Water Boiler, Godiva, Dragon, SL-1, NRX
  - 33 occurred in critical experiment facilities
- Defined as:
  - Severe damage to the system
  - Severe over exposures to humans
  - Physically unpredicted or equipment malfunction

9

Experimental Facility Criticality Accidents



10

Process Facility Criticality Accidents

- Millions of operations since 1943
  - Designed with largest practical safety margins
- 22 accidents
  - 21 involving solution/slurry
    - 4 involving chemistry “gone bad”
  - 1 involving metal ingots
  - 0 involving powders
  - 0 in transportation
  - 0 in storage

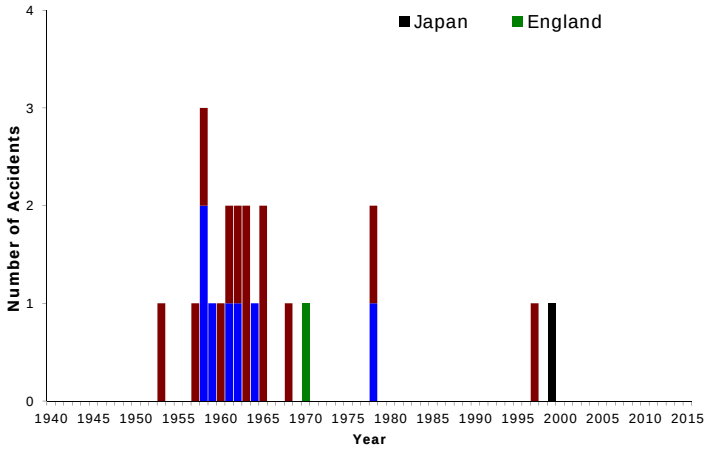
11

Process Facility Criticality Accidents

- By Country
  - 7 United States
    - 6 @ government facilities
    - 1 @ commercial facility, UNFR Plant
  - 1 United Kingdom
  - 1 Japan
  - 13 in the Former Soviet Union
- Frequency
  - 1957-1970; ~1 to 2 per year
  - 1970+; ~1 every 10 years

12

Process Facility Criticality Accidents



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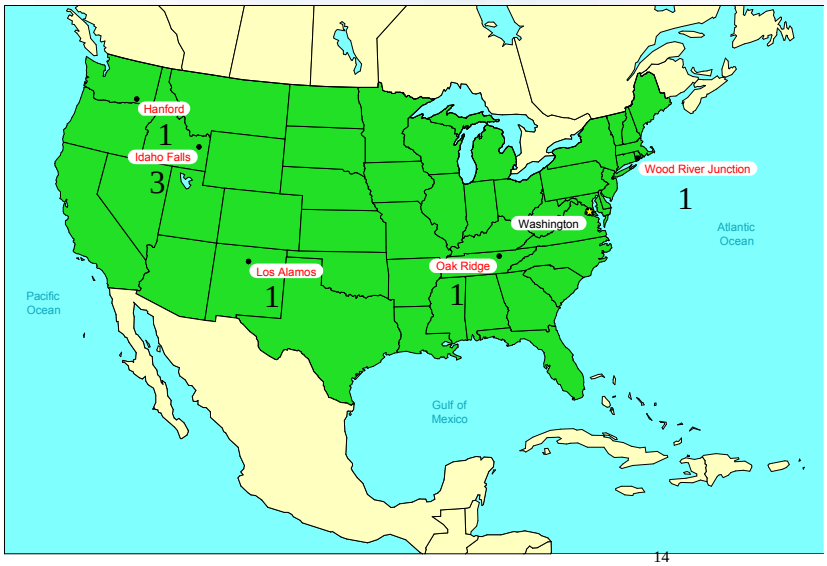

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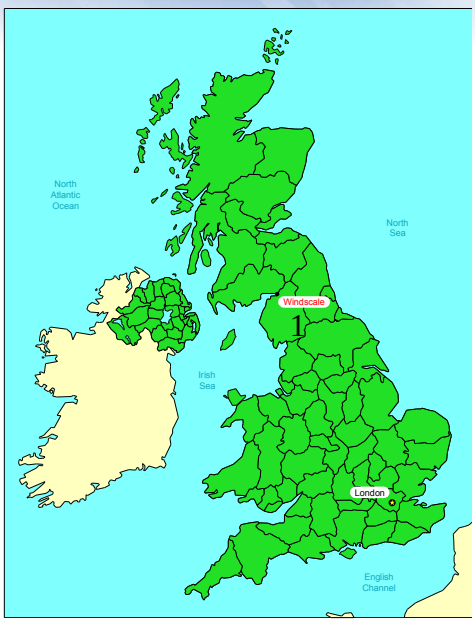
North
Atlantic
Ocean
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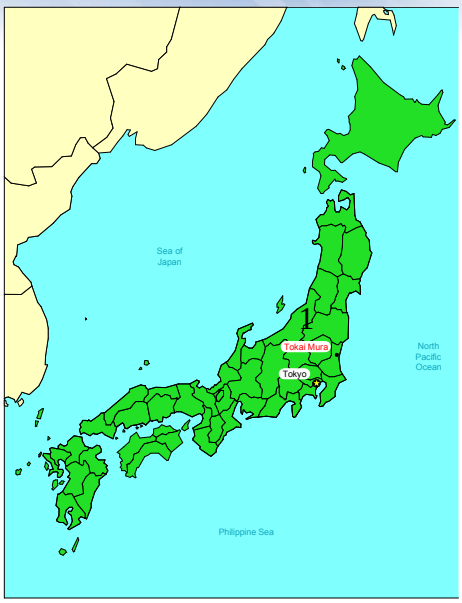
Windscale
1
Irish
Sea
London
English
Channel

15


Sea of
Japan
Tokai Mura
Tokyo
North
Pacific
Ocean
Philippine Sea

16

17

Process Facility Consequences

- 9 deaths
- 3 personnel required limb amputations
- Negligible environmental contamination
- No physical damage to equipment or facilities
- Measured public exposures
  - 1999 Japan accident only
  - Not health threatening

18

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 3
Process Facility Criticality Accidents
Section 2: The First Accident

Presented by:
Shean P Monahan

NCSP

Background Information

- Union of Soviet Socialist Republics
  - Mayak Production Association
  - Sunday, 15 March 1953
  - Facility was not equipped with an alarm system
- Pu extraction (fuel) and purification facility
  - Accident occurred in a $Pu(NO_3)_4$ solution interim staging area
  - Operations included sampling (purity, concentration), mixing, dilution, and volume measurement
- First process criticality accident in history
- Inevitable the day the facility was opened

20

Pu Nitrate Staging Vessels

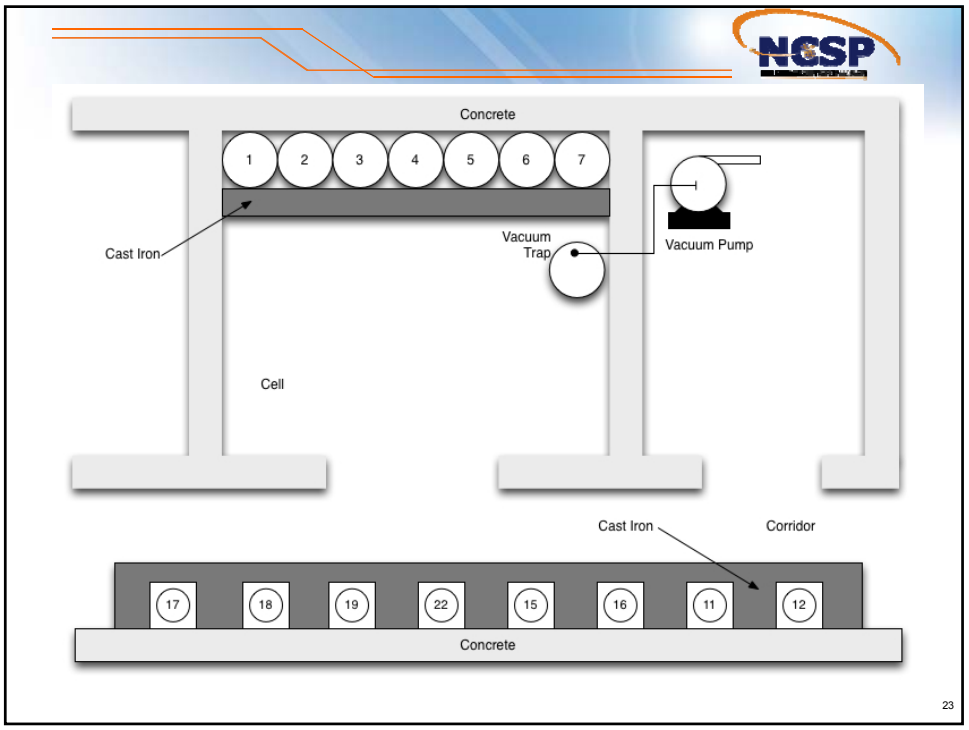
- 15 identical steel vessels
  - 40-cm (15.75-inches) in diameter
  - 32-cm (12.6-inches) high
  - H/D ratio = 0.8
  - Shielded by thick cast iron, ~2.2 mt/vessel
    - Cut-outs in the top cast iron shields allowed for access to the vessel connection ports

21

Physical Layout

- 7 vessels located in a concrete cell, 3 by 2 by 2.5 meters in size
  - original vessels installed in 1952
  - fixed piping for feeds, water, and nitric acid
- 8 vessels located in the adjacent corridor
  - installed when the first seven proved inadequate
  - no fixed piping or utility services
  - transfers between the cell and corridor vessels were done through hand-held hoses and a vacuum system

22



Criticality Safety

- Operations for each shift were handled through written instructions
  - shift orders
- Each vessel was limited to 500-grams of Pu
  - contents were recorded in an operational log
- Use of vessels 2, 4, and 6 was not allowed
  - cadmium sheets installed between vessels
- Review of sample analysis was required

24

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	672.0	44.8
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	672.0	44.8
2	10.0	58.0	5.8
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	672.0	44.8
2	10.0	58.0	5.8
3	15.5	567.0	36.6
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

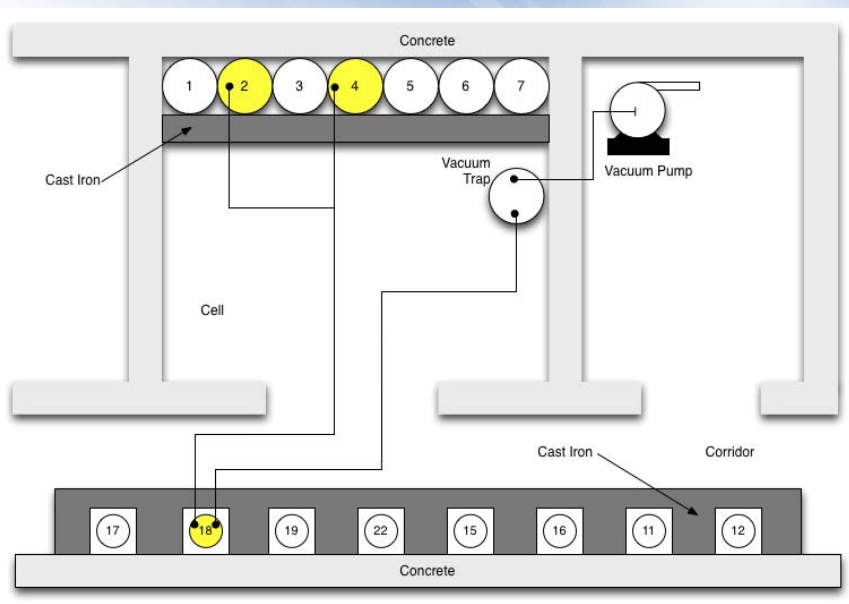
15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	**672.0**	44.8
2	**10.0**	**58.0**	**5.8**
3	15.5	**567.0**	36.6
4	**16.0**	**566.0**	**35.4**
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

Lead-Up Activities

- Shift orders included two incoming transfers to the concrete cell
- Operators needed to make room in the cell for incoming solution
  - Operators decided to transfer contents of vessels 2 and 4 to vessel 18
    - vessel 18 was listed as empty in the operating log
- Transfer would result in 624g Pu in 26 liters; 23.8g/l

30

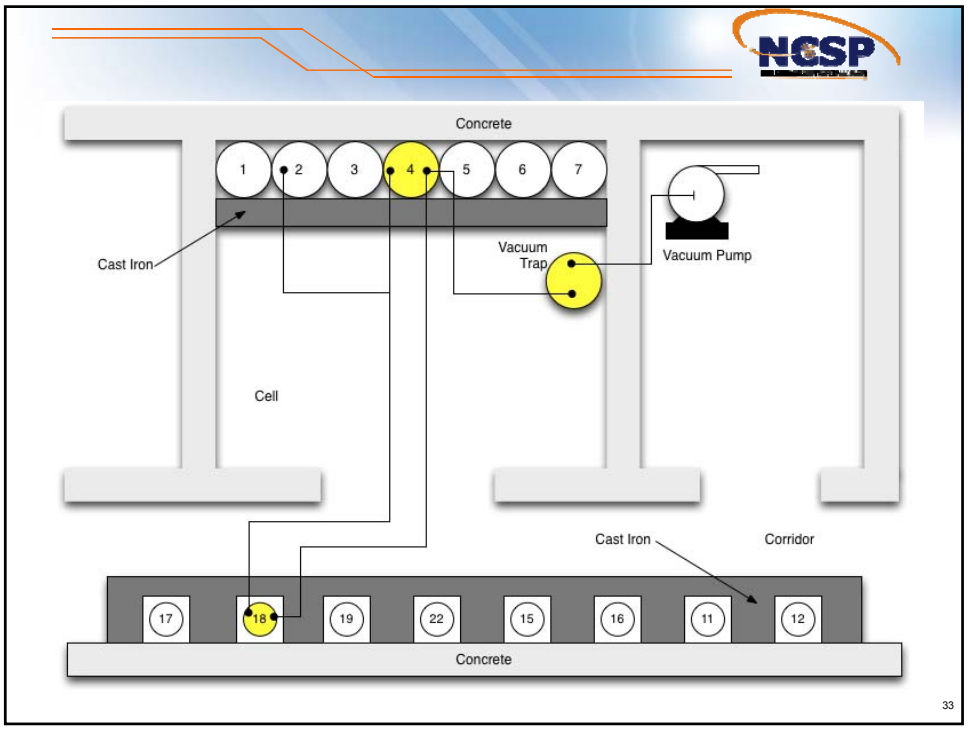


31

The Transfer

- One operator was stationed in the concrete cell at vessels 2 and 4 (cell)
- One operator was stationed in the corridor at vessel 18 (corridor)
- Hoses were held in place by hand
- Vacuum was applied to vessel 18 via 5-liter glass trap in the cell
  - Vessel contents 2 transferred
  - Vessel contents 4 transferred

32



The Accident

- After the transfer
  - Corridor operator (vessel 18)
    - disconnected the hose
    - observed an energetic gas release and foaming
    - noticed a significant rise in the temperature of the vessel
      - Estimated 60 °C above ambient (30 °C)
    - reconnected the hose
  - Cell operator (vessels 2 and 4)
    - observed a slug of solution entering the vacuum trap (5 liters)

34

The Aftermath

- The operators did not recognize an accident occurred, but
  - considered the situation unusual
  - agreed and completed a course of action
    - transferred the solution back into vessel 4
    - diluted it with water and nitric acid for cooling purposes
  - continued to work and finished the shift
    - received 15.5-liters containing 614 grams of Pu to vessel 5

35

The Aftermath

- Two days later:
  - One of the operators “abruptly” became ill
    - corridor operator (vessel 18)
    - Requested medical assistance
  - Symptoms were recognized as radiation sickness
  - Investigation initiated

36

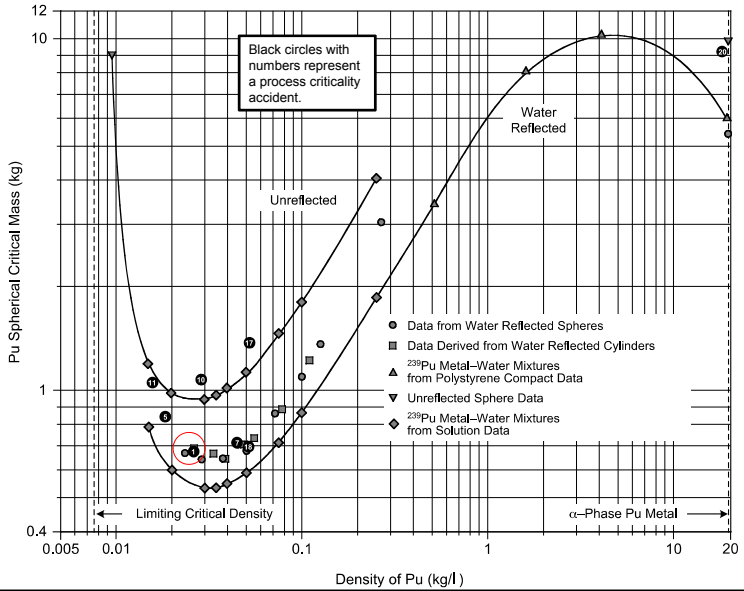
The Details

- Vessel 18 had not been empty on 15 March
  - Contained 5 liters of solution (218g Pu)
  - Unrecorded transfer from vessel 1 to 18 on some earlier shift
    - responsible person was never identified
  - Therefore after the transfer of the contents of vessels 2 and 4, vessel 18 contained

31 liters @ 27.2 g/l; 842 grams

37

^{239}Pu Critical Mass Curve (from LA-13638)



38

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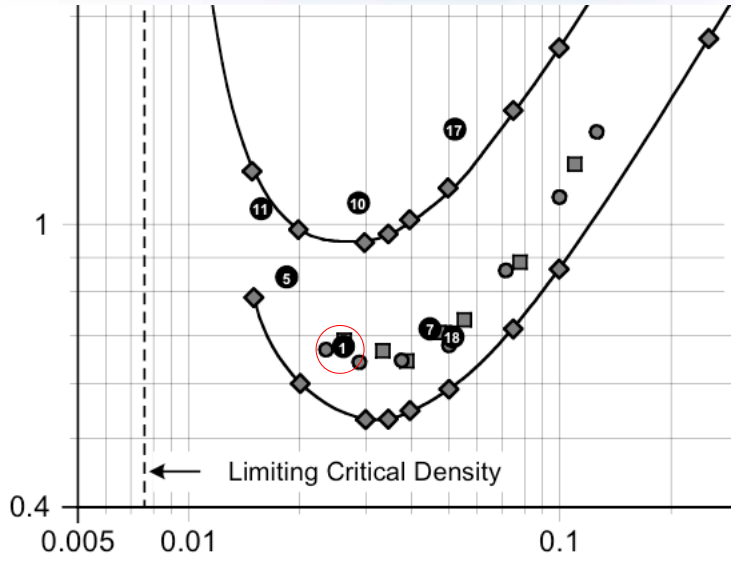

39

Causes

- Supervisors and operators
  - Had no knowledge or understanding of plutonium
  - Had no training or knowledge of criticality safety
- From their point of view the rules were nonsensical & interfered with production
- 1953
  - Stalin had just died (10 days earlier, 5 March 1953)
  - Production took precedence over safety

40

Consequences

- 2 x 10^{17} Fissions
  - based on a 60 °C temperature rise
  - more likely 2 to 4 x 10^{16} fissions
    - 10^{15} fissions/liter
- 100 rad dose to cell operator
  - No long-term effects
- 1000 rad dose to corridor operator
  - legs amputated; died 35 years later

41

Protection Against Loss of Mass Control

- 6-inch diameter vessels, ~7.5 feet (40 liters)
  - Eliminates criticality resulting from an over-mass of a single vessel
    - Control of geometry and spacing would have been engineered into the system
      - increased surface-to-surface spacing
        - ~27 cm versus ~2.5 cm
      - decreased solid angle
  - Eliminate administrative requirement prohibiting use of even numbered vessels
  - An accident would have required concurrent loss of control of mass, geometry (bulging) and/or spacing

1 Sievert = 100 rem (dose equivalent)
1 Gray = 100 rad (absorbed dose)

42

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NUCLEAR CRITICALITY SAFETY PROGRAM

Module 3
Process Facility Criticality Accidents
Section 3: The Last Accident

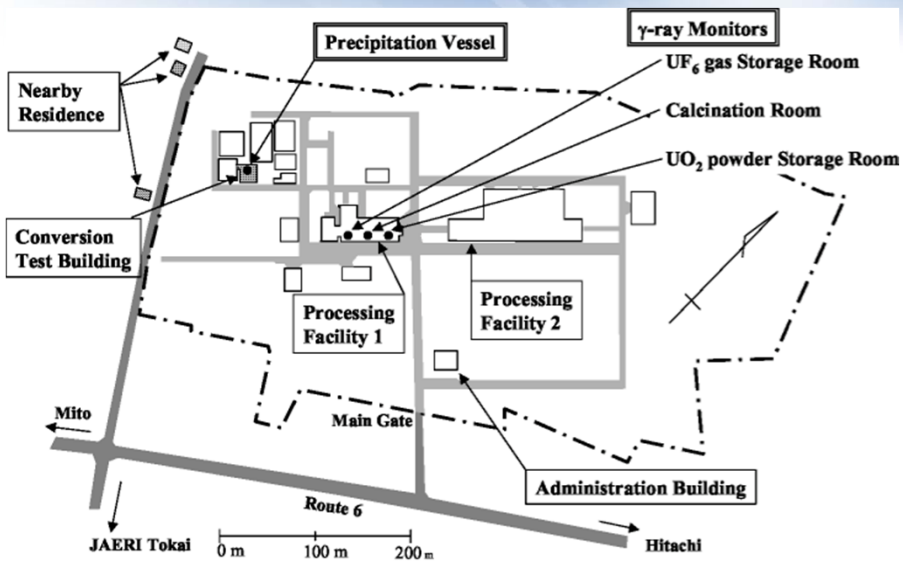
Presented by:
Shean P Monahan

Background Details

- Tokai-Mura, Ibaraki-ken Prefecture, Japan
  - JCO Fuel Fabrication Plant
  - 30 September 1999
  - Facility was not equipped with a criticality accident alarm system
  - Facility was equipped with a high radiation alarm

- JCO Fuel Fabrication Plant
  - 3 fissionable material handling facilities
    - 2 main buildings for UO_2 production from UF_6
      - processed up to U(5)
    - Fuel Conversion Test Building (FCTB)
      - processed up to U(20)
      - infrequently used

44



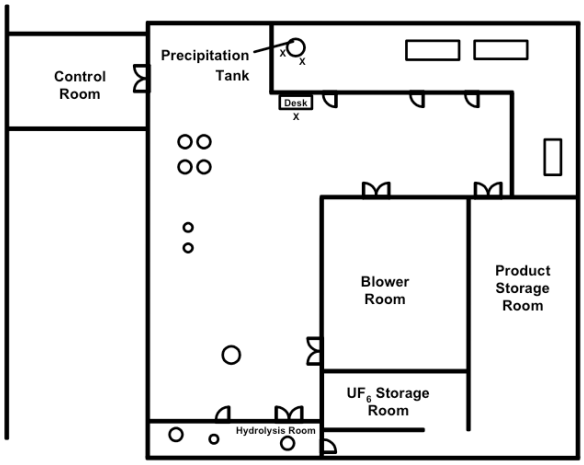
45

The Task

- JOYO reactor
  - 2 operators, and a supervisor were assigned to the FCTB
  - Orders were to produce a batch of uniform uranyl nitrate and to package it into 4 liter bottles
- Feed material was 16.8 kg of $U_3(18.8)O_8$ powder
  - Dissolved in nitric acid
  - The procedures for handling U(16) to U(20) limited the mass of any dissolution batch to 2.4 kg batches
  - Uniform uranyl nitrate, 45.4l @ 370 g/l
  - Package in 4 liters bottles (12 total)

46

FCTB



47

The Approved and Licensed Procedure

- Dissolution was to occur in a dissolver vessel
  - Batches were limited to of 2.4kg
- Once complete, each batch was to be transferred to a single geometrically favorable vessel
  - Uniformity of concentration was achieved by transferring to a single vessel
- Once all the batches had been completed
  - the solution would then be drained into four liter bottles through a valve located about 10-cm (~4-inches) above the floor
    - this did not allow for filling the bottles directly
    - solution would first have to be drained into a ladle, and then the ladle emptied into the bottles

48

Process Deviations

- Sometime earlier in the facility history management had approved dissolution in open top, 10-liter stainless steel buckets
  - JCO wide, not just in the FCTB
  - Process was more efficient by about 1-hour per batch

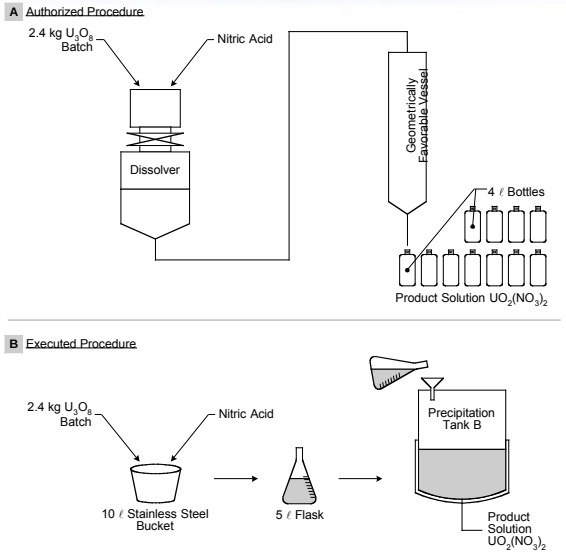
- The supervisor of this particular operation, noting that the precipitation vessel
  - had both a stirrer, to facilitate uniformity, and
  - better method of directly filling each bottle

  authorized its use

  * It is noted that the precipitation vessel also had a 1-inch thick water jacket for cooling purposes, although it was not germane the supervisors decision

49

The Authorized Process and Deviation



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51

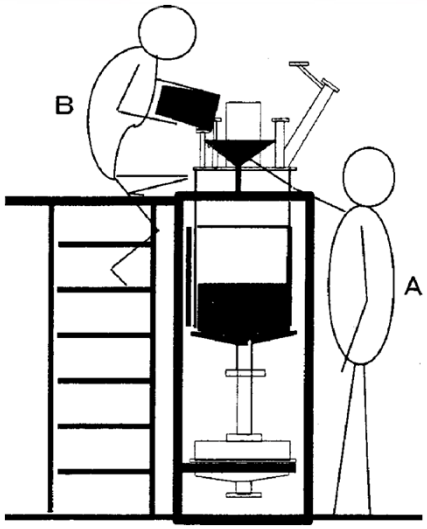
The Accident

- September 29th
  - Using the 10-liter stainless steel buckets, the three person team
    - **dutifully** dissolved 4 batches (2.4 kg), one at time, and
    - transferred the solution to the precipitation vessel

- September 30th –
  - 3 additional batches were dissolved and transferred
    - The accident occurred near the end of the pouring of the final batch ~10:35 a.m.
      - 183g U remain left in 5l flask
      - Beyond prompt critical burst
      - High radiation (γ) alarms sounded in **all** fissionable material handling buildings

52

Operator Positions



53

The Reaction

- The three operators evacuated FCTB
  - two began showing signs of radiation sickness immediately
- Two other fissionable material processing buildings evacuated
- Muster location moved due to high radiation levels
- JCO was unprepared for the accident
  - Expertise and detectors had to come from a nearby facility, JAERI
- The accident did not self-terminate
  - Likely that evaporated solution re-condensed
  - Otherwise evaporation may have led to termination
- 4.5 hours into the accident the Mayor recommended evacuation to the residents living within 350-meters of the site evacuate

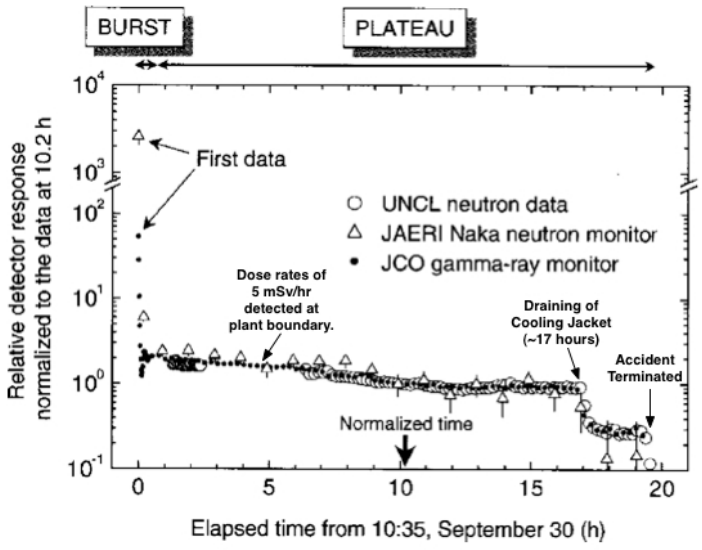
54

The Reaction

- 12 hours into the accident the prefecture officials recommended sheltering in place to residents within a 10-km radius due to airborne fission product activity
- About 14 hours into the accident through actions directed and authorized by the government
  - Several teams of operators attempted to drain the cooling jacket
  - Eventually (17 hours in) succeeded in opening the connecting water line outside of the facility
  - this did not terminate the reaction although the power level did decrease by about a factor of 4
- Finally terminated 20 hours in when the the remaining water was forced out by argon gas

55

Accident Power History



56

The Consequences

- 2.5 x 10^{18} fissions
  - 4-8 x 10^{16} first spike
- 3 operators exposed
  - (A) 1600-2000 rad – died after 82 days
  - (B) 600-1000 rad – died after 210 days
  - Supervisor 100 to 450 rad
- 235 members of the public exposed
  - 208 0.0 to 0.5 rem
  - 18 0.5 to 1.0 rem
  - 6 1.0 to 1.5 rem
  - 2 1.5 to 2.0 rem
  - 1 2.0 to 2.5 rem

1 Sievert = 100 rem (dose equivalent)
1 Gray = 100 rad (absorbed dose)

57

Contributing factors

- Weak understanding of criticality parameters on the part of the operators and supervisor
  - 45 liters was, of course, subcritical in intended vessel and bottles
- Company pressure to operate more efficiently
  - The use of the 10-liter buckets was a company approved deviation from the license
- Ridiculously difficult method of filling the 4-liter bottles
- Mind set of JCO **and** the regulatory authority
  - A criticality accident was incredible
    - Inadequate facility review, 10 years since their last review
    - Inadequate procedural review
    - Inadequate plans and equipment layout
    - Inadequate assessment of human factors

58

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Module 3
Process Facility Criticality Accidents
Section 4: Lessons Learned

Presented by:
Shean P Monahan

NCSP

Process Criticality Accident Lessons-Learned

- General considerations
  - No single failure accidents
  - No accidents attributed to hardware failure
  - No accidents attributed to faulty calculations
  - Human factors dominated all accidents
    - Communications
    - Understanding
    - Procedural violations

60

Process Accident Lessons

- Management (Program) Issues
  - Avoid unfavorable geometry equipment
  - Avoid cumbersome procedures
    - Make execution of the safe job easy
  - Important instructions must be in writing
  - Regularly observe operations
  - Evaluate operators understanding
    - Consequences of violating
      - Procedures
      - Limits

61

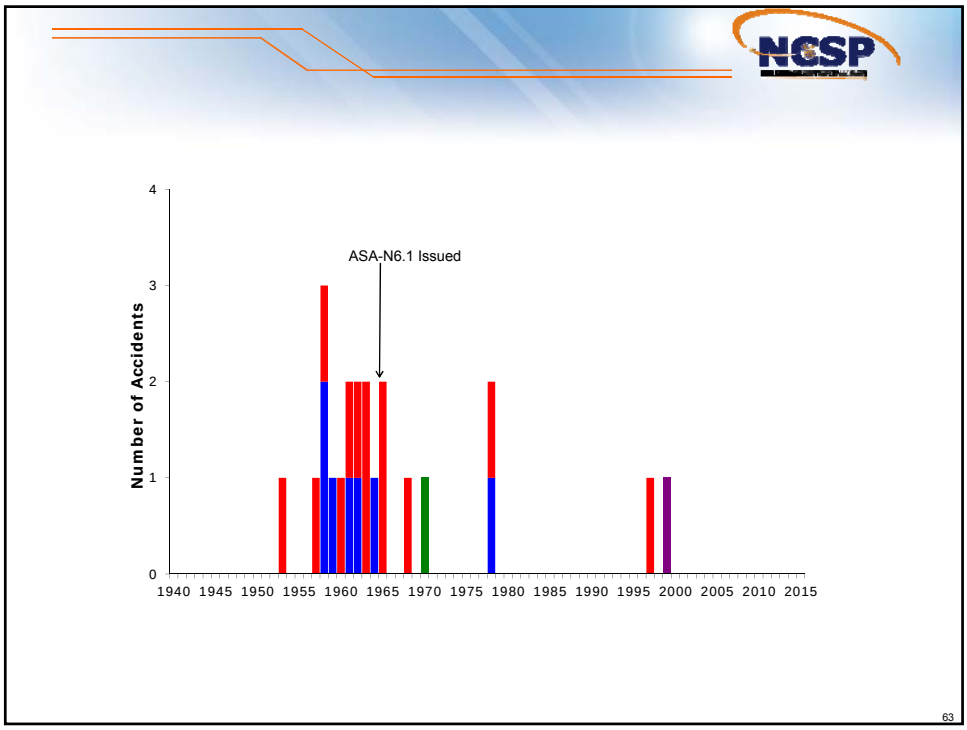
Process Accident Lessons

- Operator Issues
  - Understanding of and willingness to follow
    - Written procedures
    - Controls
    - Postings
    - Stop work policy

- Accidents occur when the lessons of the past are forgotten
- National standards are a way of programmatically incorporating the lessons from accidents
  - ASA N6.1-1964

    Safety Standard for Operations with Fissionable Materials Outside Reactors

62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Number of Accidents
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1
2
3
4
1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015
63

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NUCLEAR CRITICALITY SAFETY PROGRAM

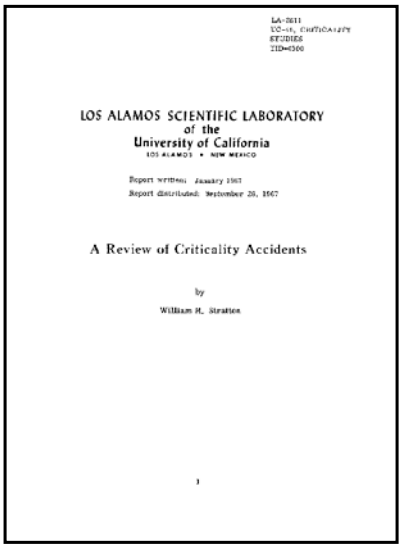
Module 11
Criticality Accidents
Section 1: LA-13638

Presented by:
Shean P Monahan

Objectives

- Introduce LA-13638 “A Review of Criticality Accidents” published in 2000
- Learn about the 1953 accident at Mayak in the USSR (first process criticality accident)
- Learn about the 1999 accident at Tokai-mura in Japan (last process accident)
- Understand the common characteristics of the process criticality accidents and lessons learned

2



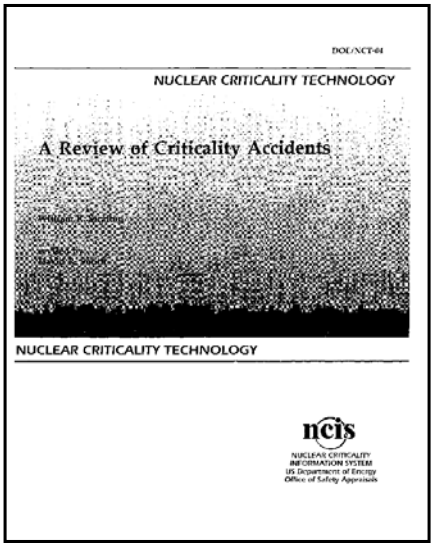
LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

A Review of Criticality Accidents

by

William R. Stratton

3



DOE/NCT-04

NUCLEAR CRITICALITY TECHNOLOGY

A Review of Criticality Accidents

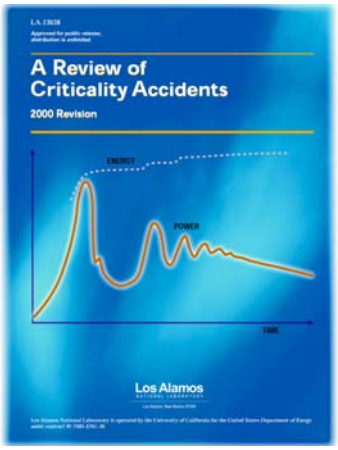
NUCLEAR CRITICALITY TECHNOLOGY

ncis
NUCLEAR CRITICALITY INFORMATION SYSTEM
US Department of Energy
Office of Safety Appraisals

Historical Criticality Accidents

- Basic reference: LA-13638
  - Reactors
  - Critical-measurement facilities
  - Processing plants

T. P. McLaughlin et al., "A Review of Criticality Accidents 2000 Revision," Los Alamos National Laboratory report **LA-13638** (May 2000).
http://ncsp.llnl.gov/basic_ref/la-13638.pdf



5

LA-13638 Part I

- Chronological presentation of process criticality accidents
  - Overview
  - Summary description of each accident
    - References to more in depth documents when available
  - Physical and neutronic characteristics section
  - Observations and Lessons Learned

6

LA-13638 Part II

- Chronological presentation of reactor and experimental accidents
  - Overview
    - A. Fissile solution systems
    - B. Bare and reflected metal assemblies
  - Will be discussed later in this presentation

7

Nuclear Criticality Accident

The release of energy as the result of inadvertently producing a self-sustaining or divergent chain reaction

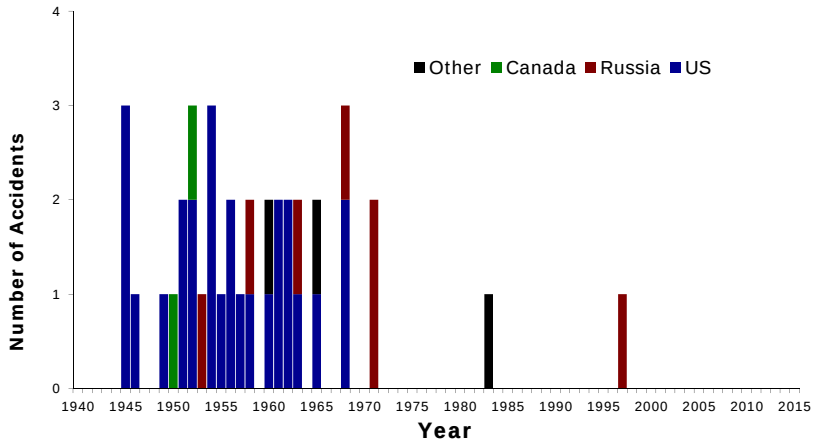
8

Critical Assemblies/Reactor Experiments

- >50,000 experiments
  - Designed to determine critical point
- 38 accidents
  - 12 deaths
  - 5 occurred in working reactors
    - Water Boiler, Godiva, Dragon, SL-1, NRX
  - 33 occurred in critical experiment facilities
- Defined as:
  - Severe damage to the system
  - Severe over exposures to humans
  - Physically unpredicted or equipment malfunction

9

Experimental Facility Criticality Accidents



10

Process Facility Criticality Accidents

- Millions of operations since 1943
  - Designed with largest practical safety margins
- 22 accidents
  - 21 involving solution/slurry
    - 4 involving chemistry “gone bad”
  - 1 involving metal ingots
  - 0 involving powders
  - 0 in transportation
  - 0 in storage

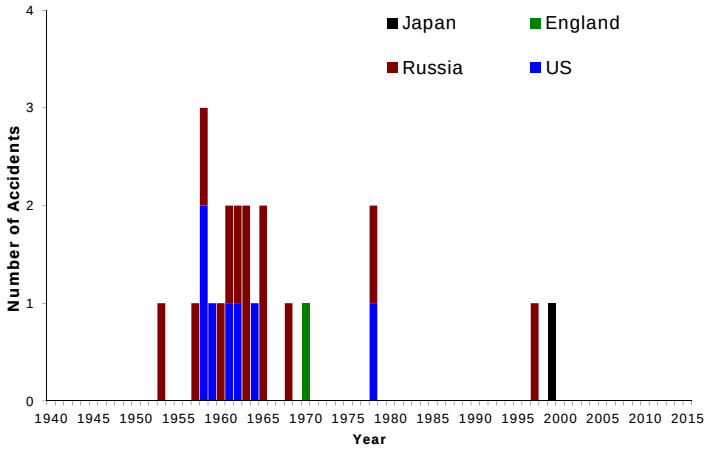
11

Process Facility Criticality Accidents

- By Country
  - 7 United States
    - 6 @ government facilities
    - 1 @ commercial facility, UNFR Plant
  - 1 United Kingdom
  - 1 Japan
  - 13 in the Former Soviet Union
- Frequency
  - 1957-1970; ~1 to 2 per year
  - 1970+; ~1 every 10 years

12

Process Facility Criticality Accidents



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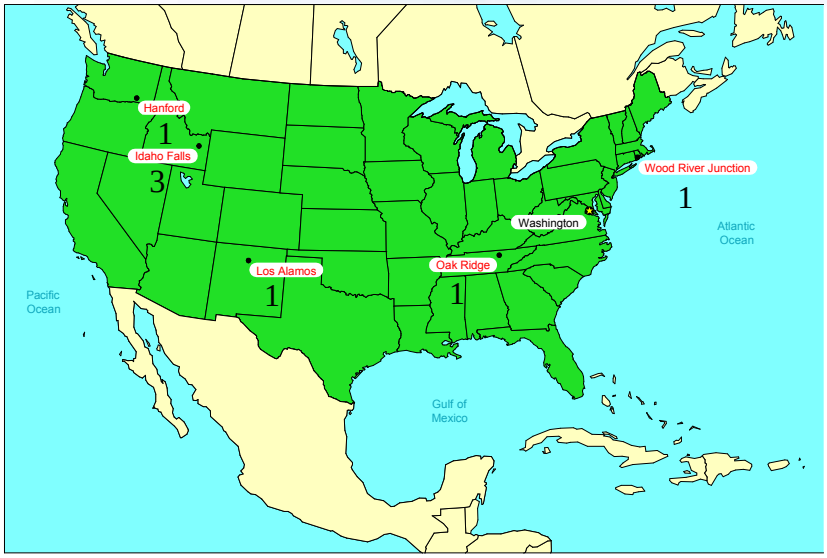

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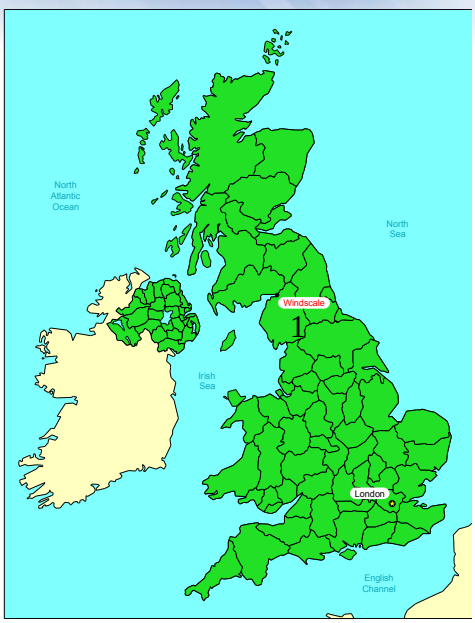
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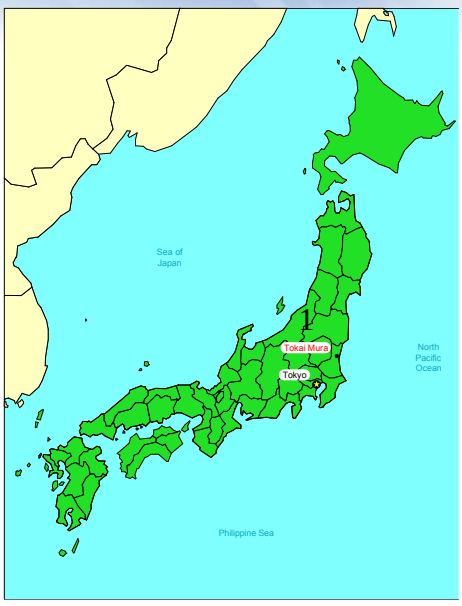
Sea of
Japan
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Tokai Mura
Tokyo
North
Pacific
Ocean
Philippine Sea

16

17

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18

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 11
Section 2: Process Facility Criticality Accidents
The First Accident

Presented by:
Shean P Monahan

NCSP

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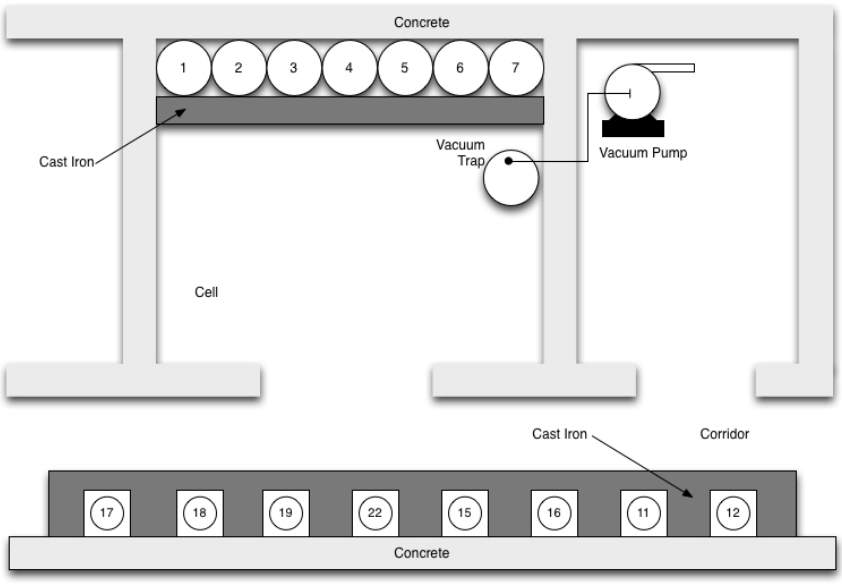

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  - contents were recorded in an operational log
- Use of vessels 2, 4, and 6 was not allowed
  - cadmium sheets installed between vessels
- Review of sample analysis was required

24

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

25

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	**672.0**	44.8
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

26

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	672.0	44.8
2	10.0	58.0	5.8
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	672.0	44.8
2	10.0	58.0	5.8
3	15.5	567.0	36.6
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

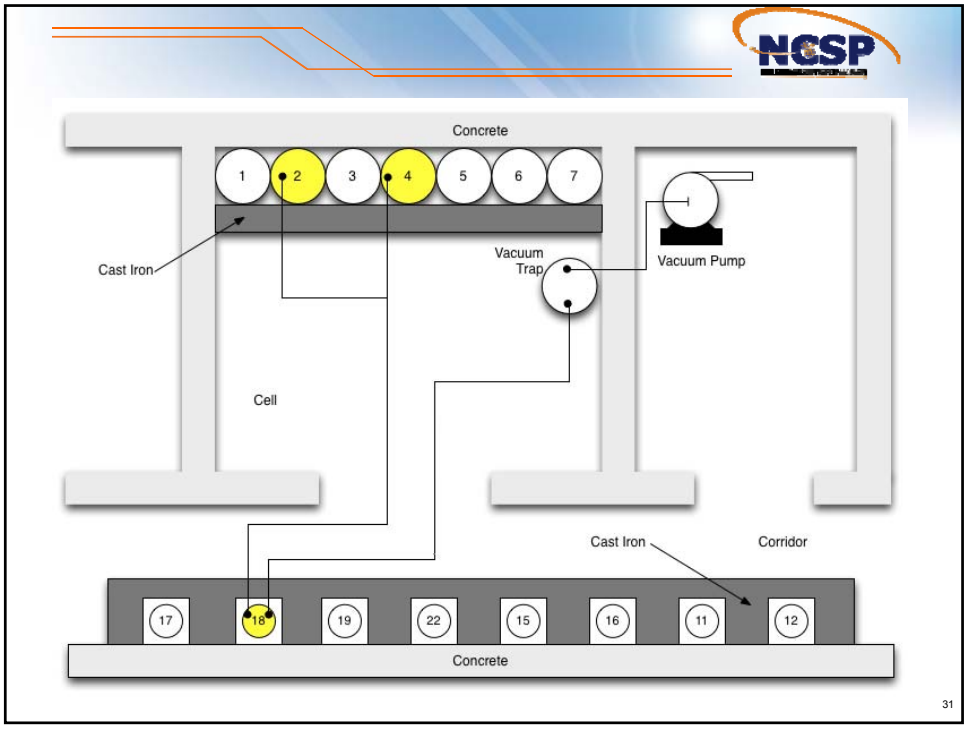
15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	**672.0**	44.8
2	**10.0**	**58.0**	**5.8**
3	15.5	**567.0**	36.6
4	**16.0**	**566.0**	**35.4**
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

Lead-Up Activities

- Shift orders included two incoming transfers to the concrete cell
- Operators needed to make room in the cell for incoming solution
  - Operators decided to transfer contents of vessels 2 and 4 to vessel 18
    - vessel 18 was listed as empty in the operating log
- Transfer would result in 624g Pu in 26 liters; 23.8g/l

30

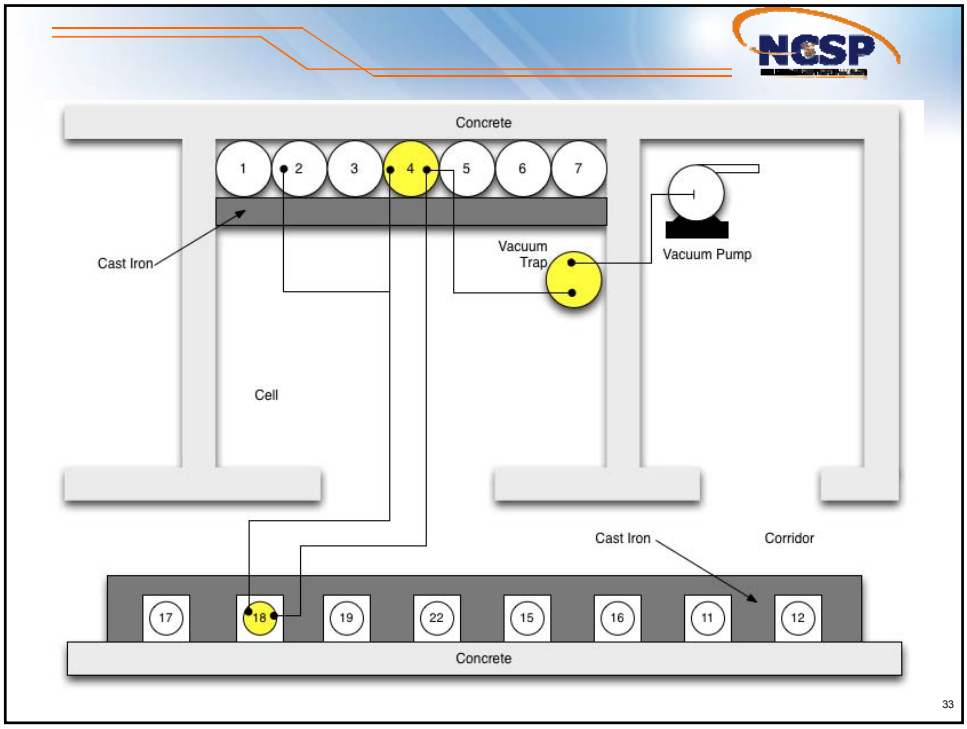


31

The Transfer

- One operator was stationed in the concrete cell at vessels 2 and 4 (cell)
- One operator was stationed in the corridor at vessel 18 (corridor)
- Hoses were held in place by hand
- Vacuum was applied to vessel 18 via 5-liter glass trap in the cell
  - Vessel contents 2 transferred
  - Vessel contents 4 transferred

32



The Accident

- After the transfer
  - Corridor operator (vessel 18)
    - disconnected the hose
    - observed an energetic gas release and foaming
    - noticed a significant rise in the temperature of the vessel
      - Estimated 60 °C above ambient (30 °C)
    - reconnected the hose
  - Cell operator (vessels 2 and 4)
    - observed a slug of solution entering the vacuum trap (5 liters)

34

The Aftermath

- The operators did not recognize an accident occurred, but
  - considered the situation unusual
  - agreed and completed a course of action
    - transferred the solution back into vessel 4
    - diluted it with water and nitric acid for cooling purposes
  - continued to work and finished the shift
    - received 15.5-liters containing 614 grams of Pu to vessel 5

35

The Aftermath

- Two days later:
  - One of the operators “abruptly” became ill
    - corridor operator (vessel 18)
    - Requested medical assistance
  - Symptoms were recognized as radiation sickness
  - Investigation initiated

36

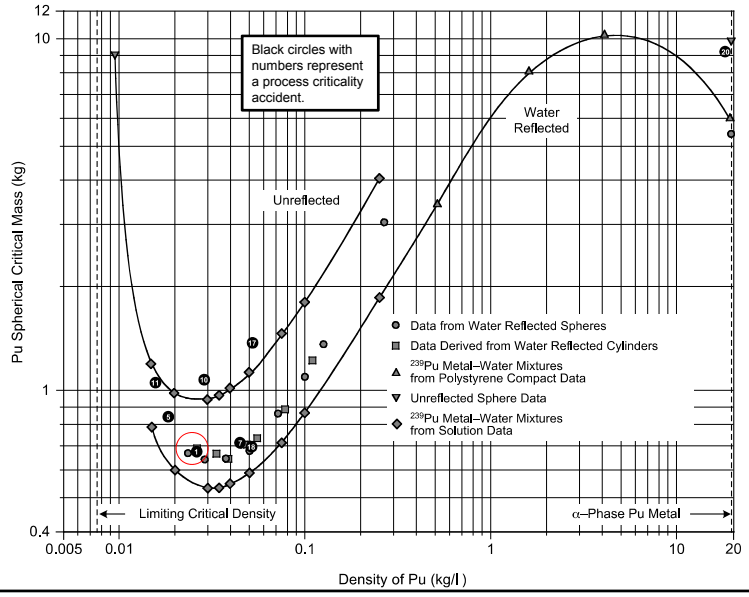
The Details

- Vessel 18 had not been empty on 15 March
  - Contained 5 liters of solution (218g Pu)
  - Unrecorded transfer from vessel 1 to 18 on some earlier shift
    - responsible person was never identified
  - Therefore after the transfer of the contents of vessels 2 and 4, vessel 18 contained

31 liters @ 27.2 g/l; 842 grams

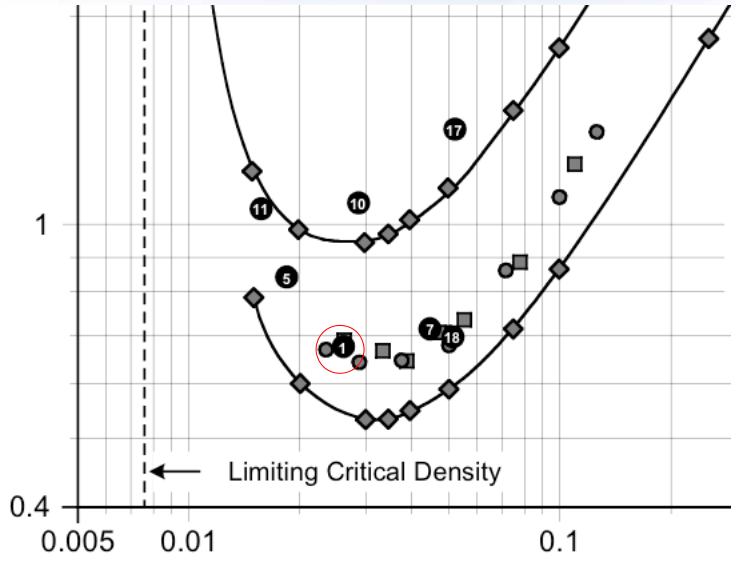
37

^{239}Pu Critical Mass Curve (from LA-13638)



38

^{239}Pu Critical Mass Curve (from LA-13638)



39

Causes

- Supervisors and operators
  - Had no knowledge or understanding of plutonium
  - Had no training or knowledge of criticality safety
- From their point of view the rules were nonsensical & interfered with production
- 1953
  - Stalin had just died (10 days earlier, 5 March 1953)
  - Production took precedence over safety

40

Consequences

- 2 x 10^{17} Fissions
  - based on a 60 °C temperature rise
  - more likely 2 to 4 x 10^{16} fissions
    - 10^{15} fissions/liter
- 100 rad dose to cell operator
  - No long-term effects
- 1000 rad dose to corridor operator
  - legs amputated; died 35 years later

41

Protection Against Loss of Mass Control

- 6-inch diameter vessels, ~7.5 feet (40 liters)
  - Eliminates criticality resulting from an over-mass of a single vessel
    - Control of geometry and spacing would have been engineered into the system
      - increased surface-to-surface spacing
        - ~27 cm versus ~2.5 cm
      - decreased solid angle
  - Eliminate administrative requirement prohibiting use of even numbered vessels
  - An accident would have required concurrent loss of control of mass, geometry (bulging) and/or spacing

1 Sievert = 100 rem (dose equivalent)
1 Gray = 100 rad (absorbed dose)

42

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 11
Section 3: Process Facility Criticality Accidents
The Last Accident

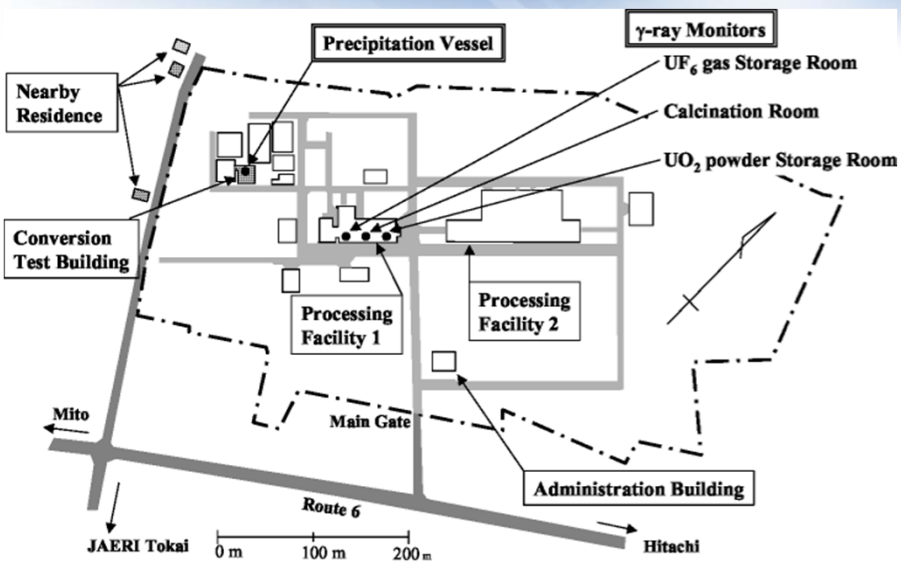
Presented by:
Shean P Monahan

Background Details

- Tokai-Mura, Ibaraki-ken Prefecture, Japan
  - JCO Fuel Fabrication Plant
  - 30 September 1999
  - Facility was not equipped with a criticality accident alarm system
  - Facility was equipped with a high radiation alarm

- JCO Fuel Fabrication Plant
  - 3 fissionable material handling facilities
    - 2 main buildings for UO_2 production from UF_6
      - processed up to U(5)
    - Fuel Conversion Test Building (FCTB)
      - processed up to U(20)
      - infrequently used

44



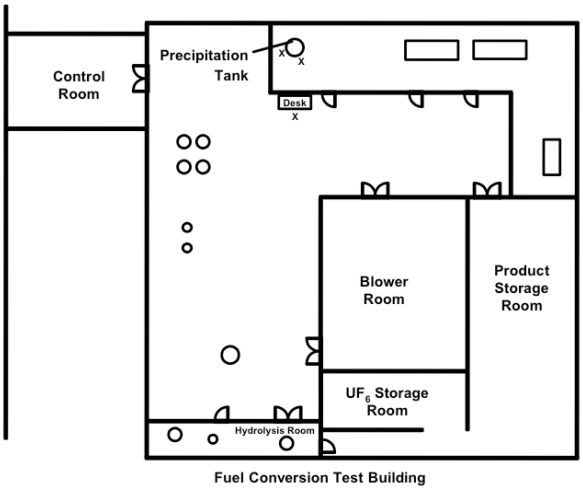
45

The Task

- JOYO reactor
  - 2 operators, and a supervisor were assigned to the FCTB
  - Orders were to produce a batch of uniform uranyl nitrate and to package it into 4 liter bottles
- Feed material was 16.8 kg of $U_3(18.8)O_8$ powder
  - Dissolved in nitric acid
  - The procedures for handling U(16) to U(20) limited the mass of any dissolution batch to 2.4 kg batches
  - Uniform uranyl nitrate, 45.4l @ 370 g/l
  - Package in 4 liters bottles (12 total)

46

FCTB



47

The Approved and Licensed Procedure

- Dissolution was to occur in a dissolver vessel
  - Batches were limited to of 2.4kg
- Once complete, each batch was to be transferred to a single geometrically favorable vessel
  - Uniformity of concentration was achieved by transferring to a single vessel
- Once all the batches had been completed
  - the solution would then be drained into four liter bottles through a valve located about 10-cm (~4-inches) above the floor
    - this did not allow for filling the bottles directly
    - solution would first have to be drained into a ladle, and then the ladle emptied into the bottles

48

Process Deviations

- Sometime earlier in the facility history management had approved dissolution in open top, 10-liter stainless steel buckets
  - JCO wide, not just in the FCTB
  - Process was more efficient by about 1-hour per batch

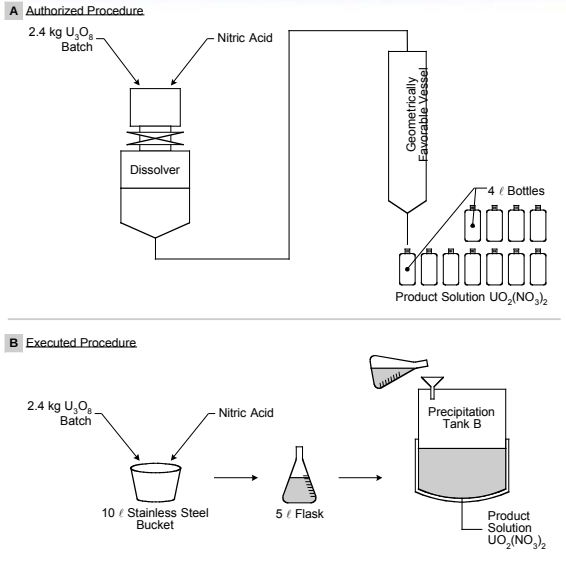
- The supervisor of this particular operation, noting that the precipitation vessel
  - had both a stirrer, to facilitate uniformity, and
  - better method of directly filling each bottle

  authorized its use

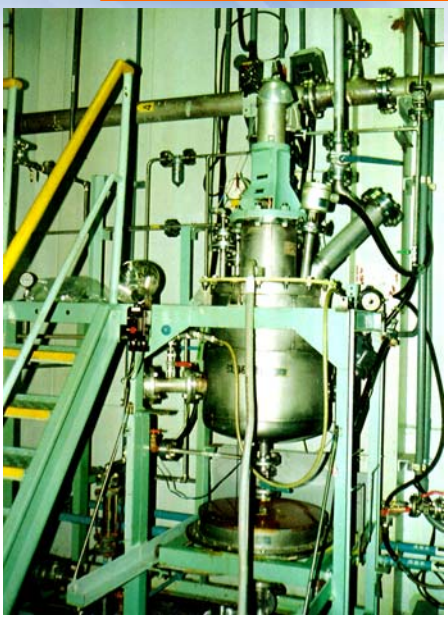
  * It is noted that the precipitation vessel also had a 1-inch thick water jacket for cooling purposes, although it was not germane the supervisors decision

49

The Authorized Process and Deviation



50



51

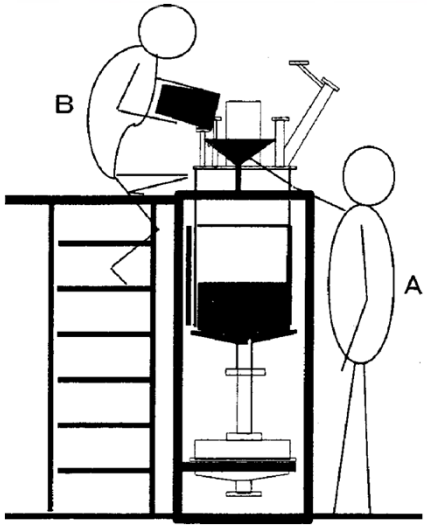
The Accident

- September 29th
  - Using the 10-liter stainless steel buckets, the three person team
    - **dutifully** dissolved 4 batches (2.4 kg), one at time, and
    - transferred the solution to the precipitation vessel

- September 30th –
  - 3 additional batches were dissolved and transferred
    - The accident occurred near the end of the pouring of the final batch ~10:35 a.m.
      - 183g U remain left in 5l flask
      - Beyond prompt critical burst
      - High radiation (γ) alarms sounded in **all** fissionable material handling buildings

52

Operator Positions



53

The Reaction

- The three operators evacuated FCTB
  - two began showing signs of radiation sickness immediately
- Two other fissionable material processing buildings evacuated
- Muster location moved due to high radiation levels
- JCO was unprepared for the accident
  - Expertise and detectors had to come from a nearby facility, JAERI
- The accident did not self-terminate
  - Likely that evaporated solution re-condensed
  - Otherwise evaporation may have led to termination
- 4.5 hours into the accident the Mayor recommended evacuation of the residents living within 350-meters of the site evacuate

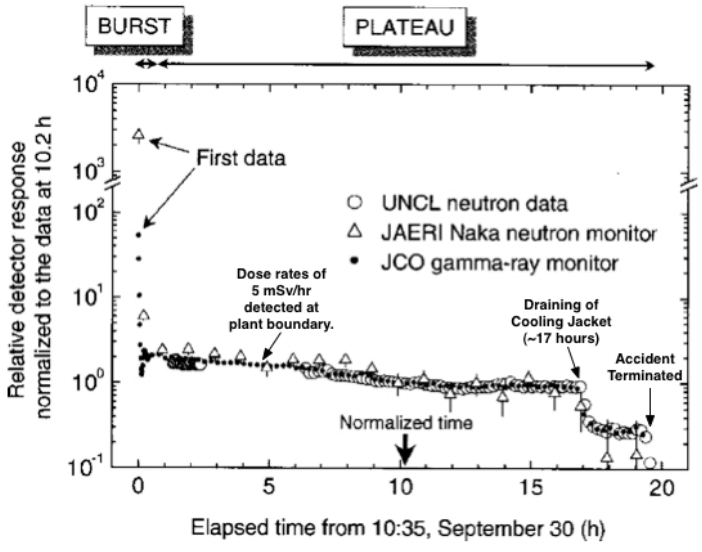
54

The Reaction

- 12 hours into the accident the prefecture officials recommended sheltering in place to residents within a 10-km radius due to airborne fission product activity
- About 14 hours into the accident through actions directed and authorized by the government
  - Several teams of operators attempted to drain the cooling jacket
  - Eventually (17 hours in) succeeded in opening the connecting water line outside of the facility
  - this did not terminate the reaction although the power level did decrease by about a factor of 4
- Finally terminated 20 hours in when the the remaining water was forced out by argon gas

55

Accident Power History



56

The Consequences

- 2.5×10^{18} fissions
  - $4\text{-}8 \times 10^{16}$ first spike
- 3 operators exposed
  - (A) 1600-2000 rad – died after 82 days
  - (B) 600-1000 rad – died after 210 days
  - Supervisor 100 to 450 rad
- 235 members of the public exposed
  - 208 0.0 to 0.5 rem
  - 18 0.5 to 1.0 rem
  - 6 1.0 to 1.5 rem
  - 2 1.5 to 2.0 rem
  - 1 2.0 to 2.5 rem

1 Sievert = 100 rem (dose equivalent)
1 Gray = 100 rad (absorbed dose)

57

Contributing factors

- Weak understanding of criticality parameters on the part of the operators and supervisor
  - 45 liters was, of course, subcritical in intended vessel and bottles
- Company pressure to operate more efficiently
  - The use of the 10-liter buckets was a company approved deviation from the license
- Ridiculously difficult method of filling the 4-liter bottles
- Mind set of JCO **and** the regulatory authority
  - A criticality accident was incredible
    - Inadequate facility review, 10 years since their last review
    - Inadequate procedural review
    - Inadequate plans and equipment layout
    - Inadequate assessment of human factors

58

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Module 11
Section 4: Process Facility Criticality Accidents Lessons Learned

Presented by:
Shean P Monahan

NCSP

Process Criticality Accident Lessons-Learned

- General considerations
  - No single failure accidents
  - No accidents attributed to hardware failure
  - No accidents attributed to faulty calculations
  - Human factors dominated all accidents
    - Communications
    - Understanding
    - Procedural violations

60

Process Accident Lessons

- Management (Program) Issues
  - Avoid unfavorable geometry equipment
  - Avoid cumbersome procedures
    - Make execution of the safe job easy
  - Important instructions must be in writing
  - Regularly observe operations
  - Evaluate operators understanding
    - Consequences of violating
      - Procedures
      - Limits

61

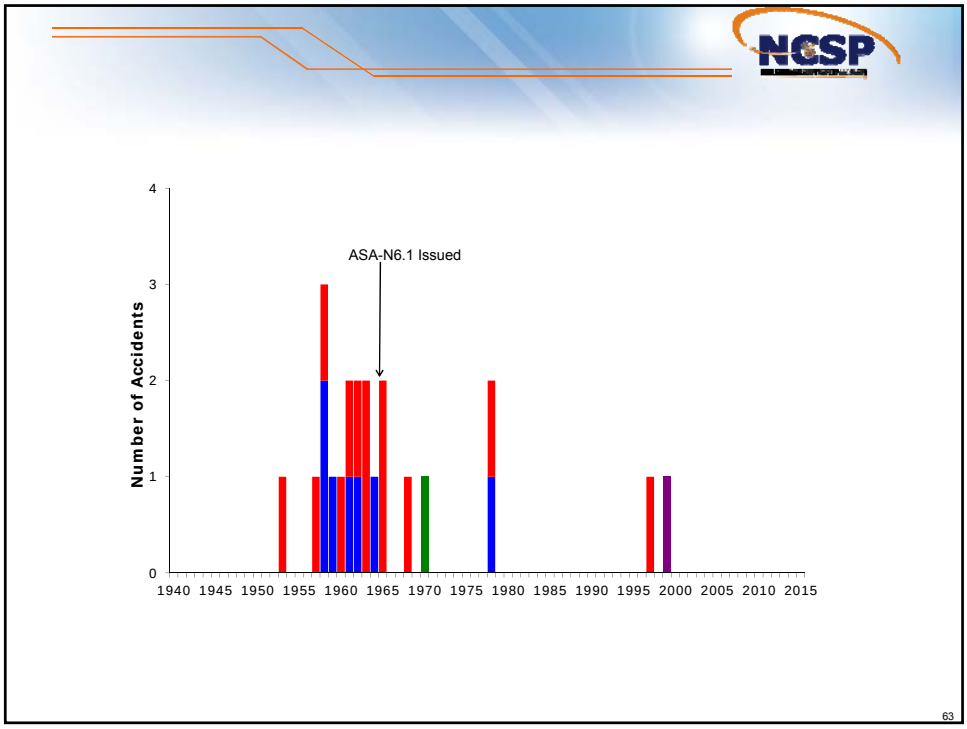
Process Accident Lessons

- Operator Issues
  - Understanding of and willingness to follow
    - Written procedures
    - Controls
    - Postings
    - Stop work policy

- Accidents occur when the lessons of the past are forgotten
- National standards are a way of programmatically incorporating the lessons from accidents
  - ASA N6.1-1964

    Safety Standard for Operations with Fissionable Materials Outside Reactors

62



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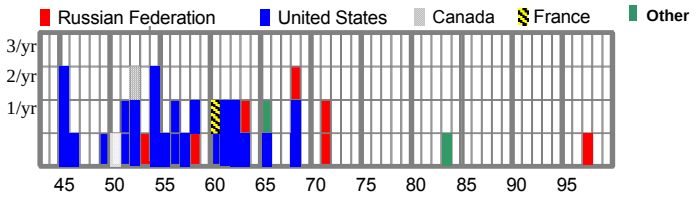
NUCLEAR CRITICALITY SAFETY PROGRAM

Module 11
Section 5: Criticality Accidents in Experiments and Reactors
LA-UR-12-20748

Presented by:
David Hayes

History of Experiments Criticality Accidents

History of Critical Assembly Accidents

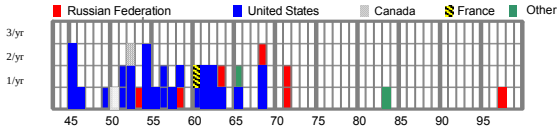


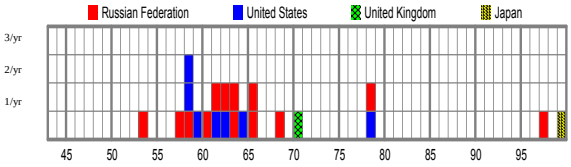
Year of Occurrence

65

History of Experiments Criticality Accidents

History of Critical Assembly Accidents





Year of Occurrence

66

Experimental and Reactor Systems Have Significant Similarities but Also Significant Differences from Process Operations

- **Similarities**
  - Both types of operations involve at least some hands-on materials manipulation and assembly
  - Both types of operations have the potential for handling materials with cross sections that are not well known
  - Hands-on steps must remain subcritical
  - Hands-on steps could be conducted under ANS 1 or ANS 8
- **Differences**
  - Experiments and reactors intend to attain the critical state (including even prompt critical in some cases)
  - Operational steps for experiments typically require a larger safety margin (the experiments are conducted to provide information to support processing)
  - Processing accidents have occurred almost entirely in solution systems, whereas experimental/reactor accidents occur uniformly across system types

67

Causes of Experimental Criticality Accidents

- **Primary for Hands-On Operations**
  - Human Error
- **Experimental Operations Criticality Accidents**
  - Human Error
  - Experiment Design Error
- **Design Error** is more obvious in critical assembly accidents, but it could be argued that this is also present in process accidents (this has not previously been asserted)

68

Interpretation of Lessons Learned

Questions to consider as we review past accidents:

•How do the "Lessons Learned" from past accidents affect the performance of the demonstrations being witnessed as part of this training at NCERC?

or

i.e., What would we do differently today to execute a similar operation or experiment?

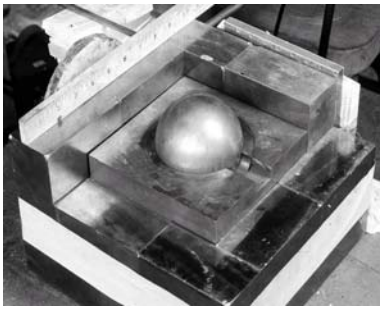
•Have the "Lessons Learned" been implemented from guidance from Standards (ANS 8, ANS 1, etc.), and/or have "Lessons Learned" been incorporated via conduct of operations (training, procedures, use of "good design" philosophies, etc.)?

69

Pu Sphere and WC Bricks

•**Location**: Los Alamos, New Mexico
Los Alamos Scientific Laboratory, Omega Site
•**Date**: August 21, 1945

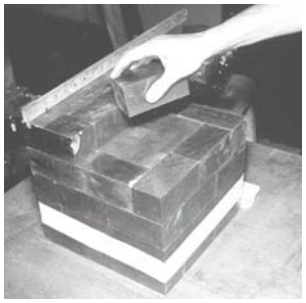
•**System/ Operation Description**: Lone experimenter performing a hand assembly of a nickel-clad (5-mil-thickness) delta-phase plutonium metal sphere reflected with tungsten carbide.



70

Pu Sphere and WC Bricks

•**Accident Initiator Description**: A lone experimenter was moving the final brick over the assembly for placement when he noticed from the nearby neutron counters that the addition of this brick would make the assembly supercritical. As he withdrew his hand, the brick slipped and fell onto the center of the assembly, adding sufficient reflection to make the assembly super-prompt critical.



71

Pu Sphere and WC Bricks

Consequence: Excursion with a yield of 1 x 10^{16} fissions.
One fatality (510 rem to experimenter, who died 28 days later).
One significant exposure (50 rem to Army guard stationed at building).

Lessons Learned:
- Use of criticality safety guidance for performing similar operations (ANS 8, ANS 1).
- Adherence to approach to critical (1/M) rules for hand assembly.
- Use of "two-person" rule for complex hazardous operations.
- Remote final assembly of near-critical configurations.

72

Pu Sphere and Beryllium Reflector

- **Location**: Los Alamos, New Mexico
  Los Alamos Scientific Laboratory, Pajarito Site
- **Date**: May 21, 1946

- **System/ Operation Description:** A demonstration was being performed involving the hand assembly of a nickel-clad (5-mil-thickness) delta-phase plutonium metal sphere surrounded by a spherical beryllium reflector.

73

Pu Sphere and Beryllium Reflector

- **Accident Initiator Description**: The top and final hemispherical beryllium shell was being slowly lowered into place; one edge was touching the lower beryllium hemisphere, while the edge 180º away was resting on the tip of a screwdriver. The person conducting the demonstration was holding the top shell with his left thumb placed in an opening at the polar point.

74

Pu Sphere and Beryllium Reflector

Consequence: Excursion with a yield of 3 x 10^{15} fissions.
One fatality (2100 rem to operator, who died 9 days later).
Seven significant exposures (360, 250, 160, 110, 65, 47, and 37 rem).

Lessons Learned:

- Use of criticality safety guidance for performing similar operations (ANS 8, ANS 1).
- Remote final assembly of near-critical configurations.

75

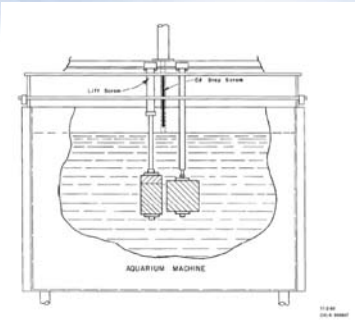
Two Large ^{235}U Metal Masses in Water

- **Location**: Los Alamos, New Mexico
  Los Alamos Scientific Laboratory, Pajarito Site
- **Date**: February 21, 1951

- **System/ Operation Description:** A water-reflected system was set up in 1949 to study the neutron multiplication of a single unit of fissile metal in water. The system had two scram processes. The first, with a quick response, was the process of raising the unit out of the water with a pneumatic cylinder; the second, with a slower response, was the process of draining the tank. Later, a traveling support was added so that critical separation distances between two units could be determined; a dropping cadmium screen provided an additional scram process.

76

Two Large ^{235}U Metal Masses in Water



•**Accident Initiator Description**:
The excursion was precipitated by an experiment that measured the critical separation distances of two enriched uranium masses (each 93.5 wt % ^{235}U) in water: one, a solid cylinder of 24.4 kg, and the other, a hollow cylinder of 38.5 kg. Sheet cadmium 10 mils thick was fastened to the inside surface of the solid cylinder and to the inside surface of the hollow cylinder. A paraffin slug filled the cavity in the hollow cylinder. At the completion of the critical separation experiment (at a multiplication of 65.5), the assembly was scrammed. The water started draining, the cadmium screen dropped, the solid cylinder (left-hand body in figure) was lifting, and an excursion was made evident by the jamming of neutron counters and the appearance on television of a vapor cloud above the water. Hydrodynamic forces generated by the scamming action moved the two fissile units closer together into a more reactive state.

77

Two Large ^{235}U Metal Masses in Water

Consequence: Excursion with a yield of 10^{17} fissions.
No radiation exposures to personnel, and no contamination found in the experimental area. Damage to the uranium fissile units consisted of a small amount of oxide flaking and blistering.

Lessons Learned:

•Best practice to design an experiment where control elements have monotonic worth curves.

78

Lessons Learned from Experimental Systems Criticality Accidents Monotonic Worth Curve for Control Elements

- **System Asymmetries Can Lead to Nonmonotonic Behavior**
  - Asymmetric geometry
  - Asymmetric composition
- **Aberdeen Pulse Radiation Facility (September 1968)**
  - Burst rod passed through a reactivity maximum before seating
  - On previous operations, the burst rod had reached its seated position
- **Can Occur in Critical Assemblies Where Component Insertion or Component Alignment Is Important**
  - Godiva-IV
  - Separation distance experiment, ZEUS
  - Honeycomb, Slotin
  - Solution fuel geometry change (splashing) from scram blade insertion, stirring, …

79

Jemima, Cylindrical, Unreflected ^{235}U Metal Assembly

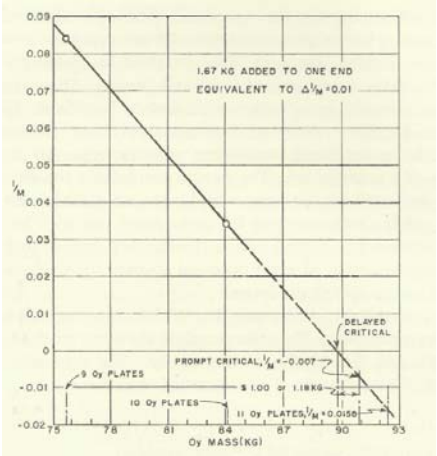
- **Location**: Los Alamos, New Mexico
  Los Alamos Scientific Laboratory, Pajarito Site
- **Date**: April 18, 1952

- **System/ Operation Description:**
A remote approach to a critical experiment was being performed on the Comet assembly using a set of the Jemima Plates (93 wt % ^{235}U metal, each 267 mm in diameter and 8 mm thick). Complete assembly of the two components had been made previously with six plates in the lower component, but with three and then four plates in the upper component. Adding the eleventh plate made the total assembly uranium mass 92.4 kg.

80

Jemima, Cylindrical, Unreflected ^{235}U Metal Assembly

•**Accident Initiator Description**: A plot of the reciprocal multiplication vs number of plates, or total uranium, shows clearly that the system should not have been assembled with 11 plates. Nevertheless, such an assembly was attempted following a computational error made independently by two people. Contrary to operating regulations, a graph of the data had not been plotted. The excursion was terminated by the automatic scram system.



81

Jemima, Cylindrical, Unreflected ^{235}U Metal Assembly

Consequence: Excursion with a yield of 1.5 x 10^{16} fissions. No radiation exposures to personnel, and no contamination found in the experimental area. No damage to the experimental materials or assembly.

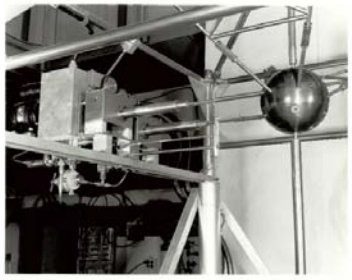
Lessons Learned:

•Practice proper Conduct of Operations.

•It is possible to perform controlled self-terminating excursions without damaging the assemblies, which stimulated the study of performing controlled prompt burst using Lady Godiva.

82

Godiva I (Lady Godiva)



Location:
Los Alamos, New Mexico
Los Alamos Scientific Laboratory
Pajarito Site

System Description

- An unreflected uranium (93.7 wt % ^{235}U) metal reactor fabricated in three principle sections that, when assembled, formed a sphere.

Applications included the

- one-dimensional spherical benchmark case for unreflected uranium metal critical mass determination;
- study of basic reactor physics, dynamics, and kinetic parameters for uranium metal systems;
- study of supercritical and controlled prompt critical nuclear excursions; and
- use as a fast neutron irradiation source.

83

Lady Godiva Accident #1

Date: February 3, 1954

Accident Initiator Description:
Maladjustment of control rod settings while preparing for burst operations.

Consequences: Excursion yield of 5.6 x 10^{16} fissions. No significant exposures to personnel or contamination of experimental area. Slight damage to support structure. No significant damage to fissile units; one uranium part needed some remachining.

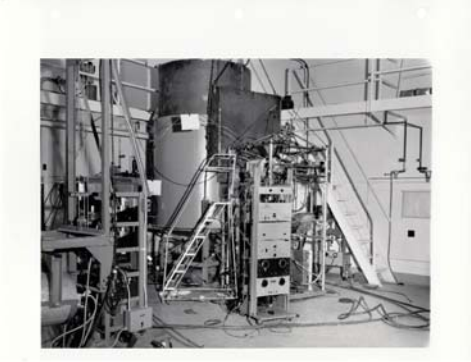
Lessons Learned:
•Execute proper Conduct of Operations.

84

Lady Godiva Accident #2

Date: February 12, 1957

Accident Initiator Description:
Added reflection from slumping of "add-on" experiment components while preparing for burst operations caused larger-than-expected excursion.



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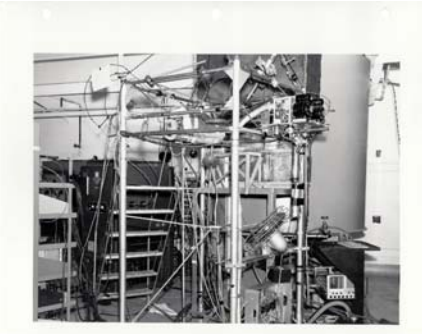
Lady Godiva Accident #2



Consequences: Excursion yield of 1.2×10^{17} fissions. Significant damage to structure and fissile components. Assembly was essentially destroyed for future use. No significant exposures to operations personnel. Some minor exposures were received by "clean-up" personnel.

Lessons Learned:
- Remote observation of experimental area.

86

Measures Taken to Reduce the Likelihood of Criticality Accidents

- **Criticality Safety Training**
- **Awareness of Criticality Limits**
- **Awareness of Evaluated Process Description**
  - **CSLA and interaction with CSO**
- **Operational Planning**
- **Written Procedures Derived from Standards**
- **Awareness of Previous Mistakes**

All of the above are components of a robust Conduct of Operations program.

87

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Module 12
Human Factors and Reliability Principles for Criticality Safety Evaluations

Presented by:
Susan Stevens-Adams, Ph.D.
Sandia National Laboratories
Albuquerque, New Mexico

Course Purpose

- Fulfill elements of Nuclear Criticality Safety Program (NCSP) mission and vision
  - Support safe, efficient fissionable material operations within DOE
  - Provide continually improving, adaptable, and transparent program
  - Communicate and collaborate globally
  - Respond to technical needs of criticality safety personnel
- Mission and vision identifies five-year goals in five technical program elements
  - Analytical methods
  - Information preservation and dissemination
  - Integral experiments
  - International criticality safety benchmark evaluation project
  - Nuclear data
  - Training and education

Course Purpose

- Training and education program element mission and vision
  - Offer hands-on training courses as needed by DOE
  - Identify and develop training needs and resources
  - Maintain technical capabilities of criticality safety professionals
  - Provide training and education for people new to criticality safety
  - Foster competency in art, science, and implementation of nuclear criticality safety
- Training and education five-year goals
  - International Handbook of Evaluated Criticality Safety Benchmark Experiments
  - Nuclear data
  - Analytical methods
  - Integral experiments
  - Other
    - Tutorial on human factors related to criticality safety

Course Objectives

- Understand basic human factors and reliability principles important for criticality safety evaluations
  - Identify critical human factors and reliability issues to look for, based on previous accidents
  - Understand importance of reliability for criticality safety evaluations
  - Create awareness of how humans relate to the effectiveness of administrative and engineering controls
  - Provide available resources for human factors support

What this course will NOT do:

- ***Provide exhaustive coverage of the field of human factors***
- ***Transform criticality safety engineers into human factors experts***

Course Modules

- 8.1: Introduction
- 8.2: Procedural Instructions
- 8.3: Human Machine Interface
- 8.4: Attention
- 8.5: Reliability
- 8.6: Summary and Application

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Module 12 – Part 1
Introduction

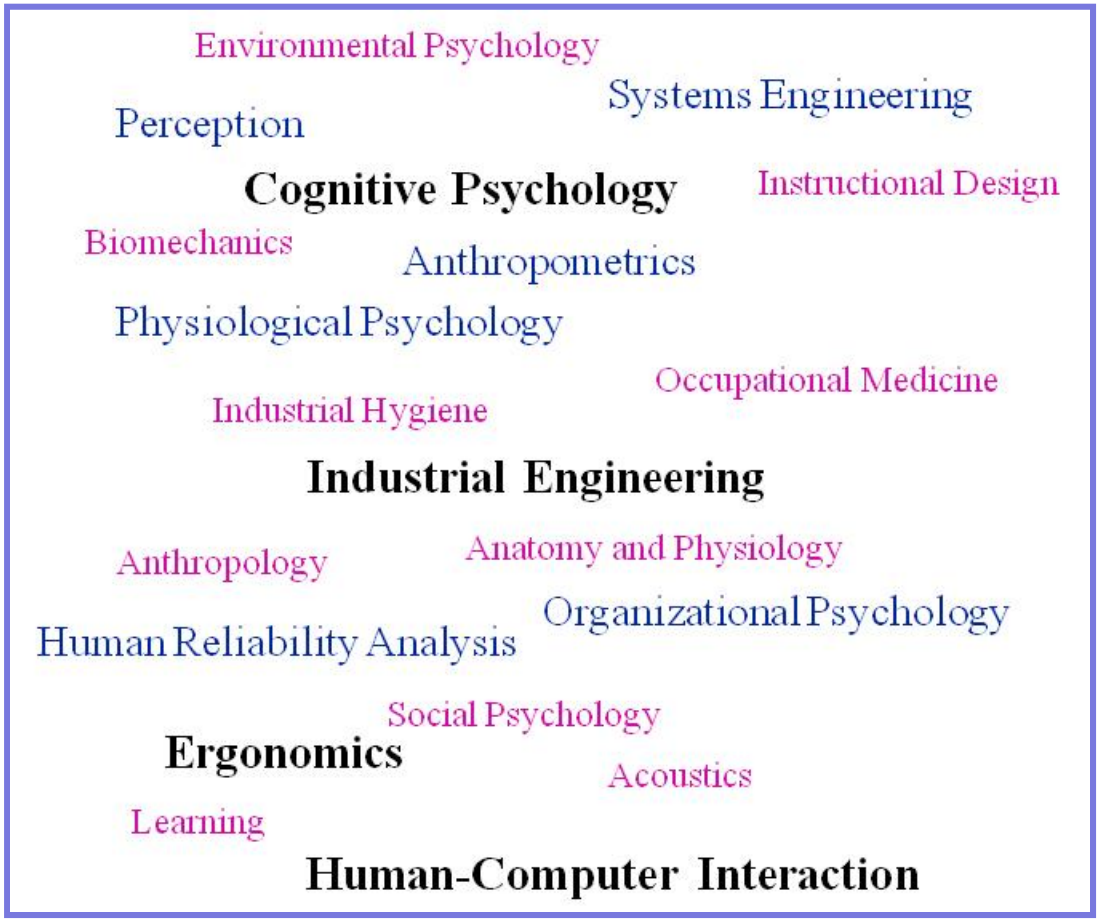
Presented by:
Susan Stevens-Adams, Ph.D.

Module 8.1: Introduction

- Human factors overview
- Reliability overview

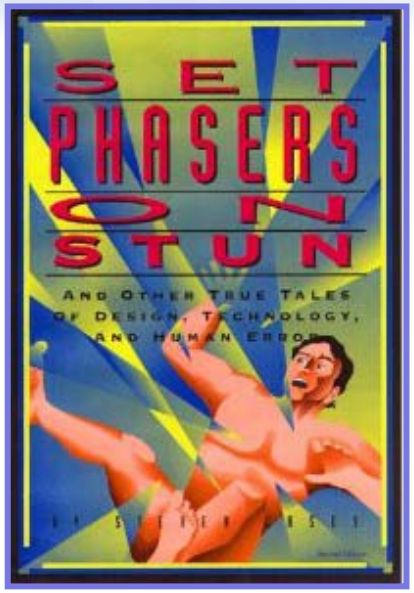
Definition of Human Factors

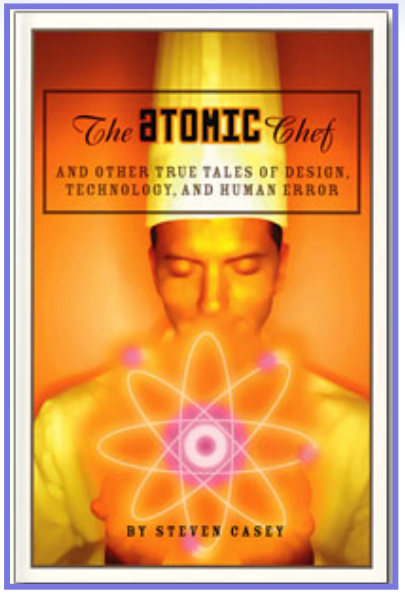
- Scientific discipline that applies knowledge about human abilities, characteristics, and limitations to design jobs, equipment, and environments
- A.K.A. ergonomics and human-centered design



Importance of Human Factors

- Reduced errors
- Usability
- Productivity
- Personnel satisfaction
- Safety





Structurally sound aircraft plummet to earth, ships run aground in calm seas, industrial machines run awry, and the instruments of medical science maim and kill unsuspecting patients, *all because of incompatibilities between the way things are designed and the way people perceive, think, and act.*

~Steven Casey, 1993

Human Factors Techniques

- Observation and task analysis
- Surveys and interviews
- Experimentation
- Assessment of workload and situational awareness
- Environmental measurements (illumination, noise, and temperature)
- Anthropometry (postures, forces, and load demands)
- Physiological measurements (heart rate, blood pressure)
- Analysis of records

Human Factors in the Complex

Organization	Contact	Phone
SNL/NM	Caren Wenner	505-284-5220
LANL	Walter Gilmore	505-667-2461
ORNL	Jack Schryver	865-574-4710
INL	Ronald Boring	208-526-0966
PNNL	Frank Greitzer	509-372-4251
BNL	John O'Hara	631-344-3638

BNL = Brookhaven National Laboratory; INL = Idaho National Laboratory; LANL = Los Alamos National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; SNL = Sandia National Laboratories

Human Factors for NCSP

- Fissile material operations represent a high-risk, high-consequence system
- Operations rely heavily on human involvement
  - Administrative controls require correct human action
  - Humans must read and interpret procedures
  - Humans execute the process
  - Humans bring a host of issues to work with them that can impact quality of work
- Review of 60 criticality accidents from 1953 to 1999 concluded that the *human element was not only present, but the dominant cause in all of the accidents* (LA-13638)

Ensuring that a criticality accident never happens again in a DOE facility is one key facet of the DOE mission...

~Mission and Vision for FY09-18

Reliability Overview

- Probability that a system will perform its intended function satisfactorily.
- Equipment reliability
  - Hardware reliability
  - Software reliability
- Human reliability
  - Active failures
  - Latent conditions

Reliability in the Complex

Organization	Contact	Phone
SNL/NM	Stacey Hendrickson	505-284-2665
SNL/NM	Janet Sjulin	505-844-3902
LANL	Mike Hamada	505-667-1843
LLNL	Tom Bennett	925-422-5497
INL	John Forester	505-869-0238

INL = Idaho National Laboratory
LANL = Los Alamos National Laboratory
LLNL = Lawrence Livermore National Laboratory
SNL = Sandia National Laboratories

Reliability for NCSP

- Fissile material operations represent a high-risk, high-consequence system
- Reliability issues may have dire consequences
- Equipment must perform reliably
  - Vessels, valves, stirrers, dials, and switches
  - Generators, lighting, HVAC
  - Maintenance practices
- People must perform reliably
  - Adherence to administrative controls
  - Interpretation and use of procedures
  - Process execution
- Controls must be reliable

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Module 12 – Part 2
Procedural Instructions

Presented by:
Susan Stevens-Adams, Ph.D.

Module 8.2: Procedural Instructions

- Procedure is a tool that provides administrative control to help prevent hazards
- Effective procedures make the users' tasks as easy and straightforward as possible
  - Support different users and different users' tasks
  - Provide specific "how to" information
  - Provide only the content the user needs
  - Organize the content to match the users' tasks
  - Use layout, typography, and graphics that support user performance
  - Use clear and unambiguous language
  - Assure consistency and quality of human actions

Procedures

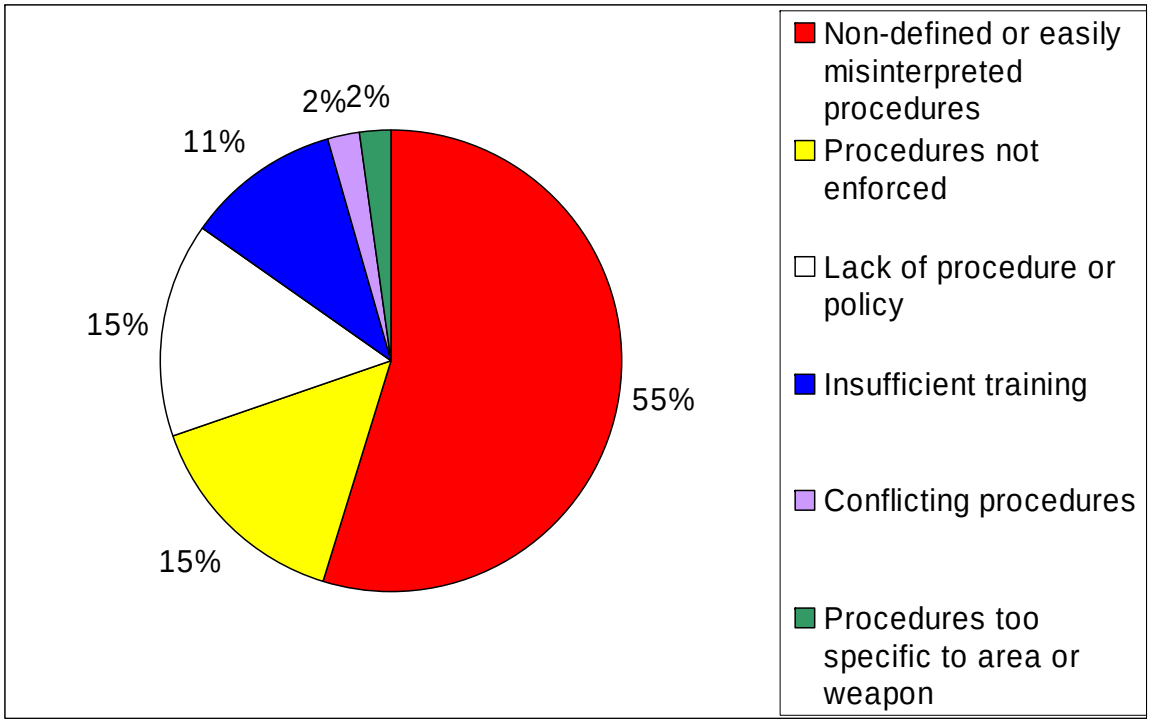
- ANSI/ANS-8.19, Section 7 discusses Operating Procedures
  - 7.1 The purpose of written operating procedures is to facilitate and to document the safe and efficient conduct of the operation. Procedures should be organized for convenient use by operators and be conveniently available. They should be free of extraneous material.
  - 7.2 Procedures shall include those controls and limits significant to the nuclear criticality safety of the operation. Procedures should be written such that no single, inadvertent departure from a procedure can cause a nuclear criticality accident.
  - 7.3 Supplementing and revising procedures as improvements become desirable shall be facilitated.

Common Issues in Procedures

- Ambiguous or vague steps
- Technically inaccurate information
- Mismatch between procedural steps and the order in which tasks need to be performed
- Critical information that is missing
- Lack of graphics for complex steps
- References to other procedures
- More than one instruction in a step
- Overuse of critical steps

Error Pathways from Procedures

- 526 of 1434 reported incidents (37%) at one DOE facility over a 13-year period from procedural issues
- Most issues involved vague procedures



From SAND2004-5416, *Human Error Mitigation Initiative (HEMI) Summary Report*

Procedures: Real-World Example

- Charlotte, NC, 8 Jan 03
- 19-passenger Beech 1900D turboprop crashed 37 seconds after take-off
  - Crew could not control elevator cables to pull plane out of a steep climb
  - Elevator control cables incorrectly adjusted during maintenance
  - Airplane rolled and struck U.S. Airways hangar
- Everyone on board perished

Procedures: Real-World Example

- Plane was in for regular maintenance two nights before crash
  - Occurs after every 100 hours of flight
  - Key parts inspected and fluids topped
- Problems with procedures in Maintenance Performance Manual led to faulty maintenance
  - Cable tensioning procedure was vague in parts
    - Some steps applied to complete re-rigging of the system
    - Unclear which steps were needed for cable tension adjustment
  - Many steps were for other aircraft and did not apply to 1900D
    - Step to “disconnect autopilot servo cables”
    - Beech 1900D aircraft did not have autopilot

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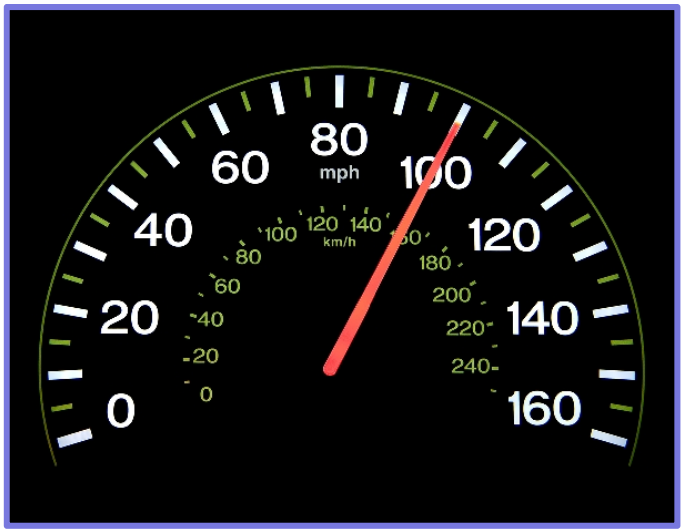
Module 12 – Part 3
Human-Machine Interface

Presented by:
Susan Stevens-Adams, Ph.D.

Module 8.3: Human-Machine Interface

- Human-machine interface consists of displays and controls to assist in accomplishing a given task
  - Displays allow machines to convey information to humans
  - Controls allow humans to provide inputs to machines



Failure to understand the needs and requirements of the users will preclude effective design and increase the likelihood of use error, device misuse, and adverse events.

~Wiklund and Wilcox, 2005

HMI: Real-World Example

A 33-year-old man undergoing treatment for a tumor in his shoulder died from a massive radiation overdose.

Therac-25 Cancer Radiation Therapy Machine

HMI: Real-World Example

- Tyler, Texas, East Texas Cancer Center, 21 Mar 86
- Therac-25 cancer radiation therapy machine
  - Delivered high-energy radiation with pinpoint accuracy
  - High-power X-ray mode of 25 million electron volts was selected by typing “x” on the keyboard
  - Low-power electron beam mode of 200 rads was selected by typing “e” on the keyboard
- Complicating factors
  - Therac-25 was operated from a control room separate from treatment room
  - Video camera and voice intercom were inoperative at the time

HMI: Real-World Example

- Technician accidentally pressed “x” instead of “e”
  - To correct the error, she quickly pressed “up” arrow key to select “edit” functions on display
  - Changed “x” to “e,” all within a span of 8 seconds
- Therac-25 developers did not think it possible to enter this sequence of commands in 8 seconds
  - Display was not designed to prevent this sequence
  - This sequence of commands had never been tested
- Sequence of commands tripped up computer
  - Machine remained in high-power X-ray mode
  - Display incorrectly showed low-power electron beam mode

HMI: Real-World Example

- Technician pressed “b” to turn beam on
  - Patient saw a blue flash of light and heard a frying sound
  - Patient experienced excruciating pain
- Computer displayed “Malfunction 54” a total of two times, so the technician repeated the process
  - Malfunction 54 code was not identified in user manual
  - Therac-25 display indicated patient received 1/10 prescribed dose
- Patient received three doses of 25 million electron volts
  - 375 times greater than prescribed dose
  - Patient died 4 months later
- Five other patients experienced similar overdoses
- Therac-25 recalled in 1987 for extensive design changes

Captain Kirk forgot to put the machine on stun. ~Ray Cox, 1986

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Module 12 – Part 4
Attention

Presented by:
Susan Stevens-Adams, Ph.D.

- http://www.youtube.com/watch?v=IGQmdoK_ZfY
- http://www.youtube.com/watch?v=FWSxSQsspiQ

Module 8.4: Attention

- Multiple studies similar to gorilla video
- ~50% of observers do not notice highly salient, ongoing, unexpected events
- Observers who do notice typically cannot accurately report details
- More observers notice unexpected events if the task is easy (number of passes) versus hard (separate counts of aerial and bounce passes)
- Observers may be more likely to notice if basic visual features are shared

There is no conscious perception without attention.
~Simons and Chabris, 1999

Selective Attention

- Concepts of selective attention and inattentional blindness apply to criticality safety evaluations
- What-if checklist is a common approach to identify potential criticality safety problems
  - What if something goes wrong?
  - Variations in parameters important to criticality safety
  - CSE may miss the gorilla in the process
- Subsequent development of controls may also be subject to inattentional blindness
  - CSE may attend heavily to one control to the exclusion of others
- Controls that take into account biases as well as limited attentional capacity are useful

Attention: Real-World Example

One bicyclist was killed and another was severely injured on a highway in France because of a tiny child's toy, no bigger than a stopwatch.

~April 1998

Attention: Real-World Example

- Tamagotchi handheld digital pet created in Japan
- Owner has to “raise” the Tamagotchi and attend to its needs
  - Feed and clean it
  - Play games to make the Tamagotchi happy
  - Punish or praise based on its actions
  - Provide medicine if it gets sick
  - Turn off the lights when it goes to bed
- Tamagotchi progresses from infancy to senescence, but will die if not properly cared for

Attention: Real-World Example

- Marseilles, France, April 1998
- 27-year old woman was driving a highway outside Marseilles
  - Rugged mountainous terrain
  - Numerous bicyclists
- Tamagotchi on driver's keychain began beeping
  - Driver had Tamagotchi only a few days and did not want to fail as a parent if it "died" prematurely
  - Correct buttons had to be pressed to silence Tamagotchi
- Driver was so focused on saving Tamagotchi that she failed to see bicyclists in the road

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Module 12 – Part 5
Reliability

Presented by:
Susan Stevens-Adams, Ph.D.

Module 8.5: Reliability

- Conditional **probability**, at a given **confidence level**, that equipment will **satisfactorily perform** its intended function, given **predefined circumstances**
  - Operating environment
  - Limitations such as operating time
  - Frequency and thoroughness of maintenance
  - Specified period of time
  - Failure data often have a large degree of uncertainty!
- Reliability and safety of a process can be impacted by two components of reliability
  - Equipment reliability (hardware and software)
  - Human reliability

Equipment Reliability

Equipment is not 100% reliable

Component	Failures Per Million Hours
Switch - Toggle	1
Switch - Pushbutton	10
Valve - Globe	2
Valve - Gate	30
Differential Pressure Sensor (flow meter)	200
Generator – Diesel Set	4000

From *Reliability, Maintainability, and Risk* by David J. Smith (2005)

Causes of Equipment Failures

Infant Mortality	Random Failures	Wearout Failures
Poor manufacturing	Conflict in designed strength and operational stress	Aging
Poor quality control	Insufficient designed-in safety factors	Wear
Poor workmanship	Higher than expected loads	Degradation in strength
Insufficient burn-in	Lower than expected strengths	Fatigue
Substandard materials	Human error in usage	Creep
Improper storage/transit	Misapplication	Corrosion
Contamination	Abuse	Mechanical, electrical, or chemical deterioration
Improper installation	Unexplained causes	Poor servicing
Improper startup	Mother nature	Short designed-in life

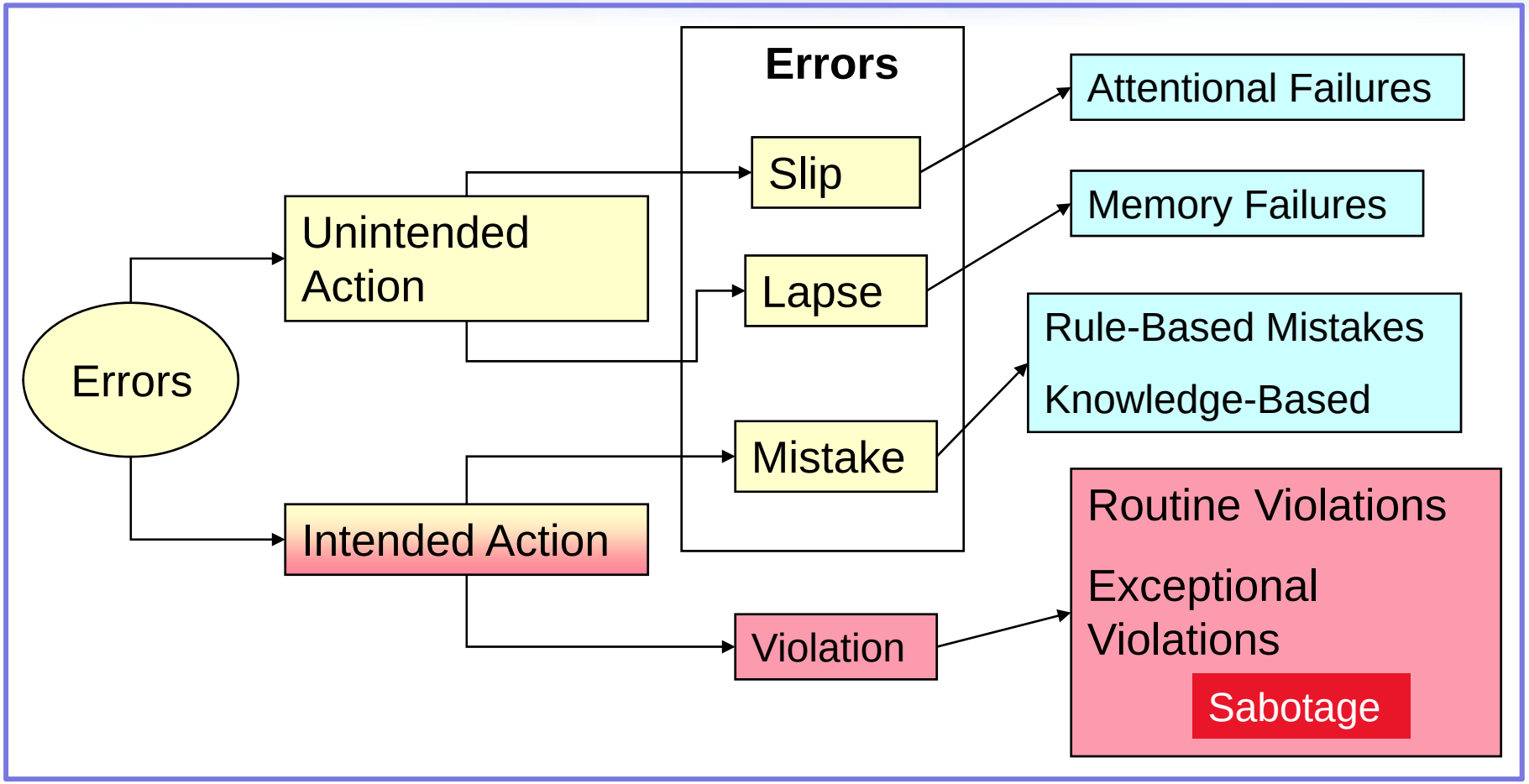
From *Reliability Engineering Handbook, Volume 1* by Dimitri Kececioglu (2002)

Human Reliability

Probability that an individual, team, or human organization will accomplish a mission under the given conditions, within acceptable limits, for a certain duration.

Traditional View	Human Factors View
Human error is inevitable and little can be done to prevent human error	Human is reliable in certain conditions, and performance is predictable
Explanation of failures: find people's inaccurate assessments, wrong decisions, and bad judgments (blame)	Explanation of failures: discover how people's assessments and actions made sense under the given circumstances
Causes: carelessness, poor attitudes, and inattention to detail	Causes: increases in system complexity and ambiguity in external systems
Cures: training and punishment	Cures: manage causes of error

Human Reliability



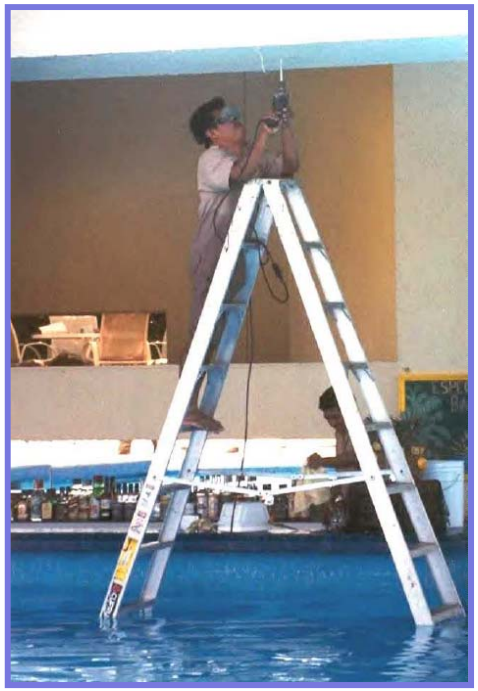
People cannot easily avoid actions they did not intend to perform in the first place.

Human Reliability

Error Type	Description
Slip	• Person does something, but not what they intended • Poor display-control compatibility or deviation from routine • Fixed by better displays/controls • Example: uranium recorded as 8 liters instead of 18 liters
Lapse	• Person forgets to do something they intended to do • Caused by failure of prospective memory • Fixed by checklists, procedures, explicit reminders • Example: forgetting to close a valve
Mistake	• Person does what they intended, but act is inappropriate • Caused by lack of knowledge • Fixed by training to improve knowledge or better displays • Example: turning right but did not see one-way street sign
Violation	• Person intentionally commits an inappropriate act • Caused by inadequate safety culture • Fixed by emphasis on safety culture or remedial training • Example: intentionally ignoring uranium mass limit

Human Reliability: Improvisation

- Improvisation occurs when well-meaning personnel attempt to complete tasks with minimal disruption and delay in the absence of sufficient guidance/materials
- Improvisation may be classified as mistakes or violations

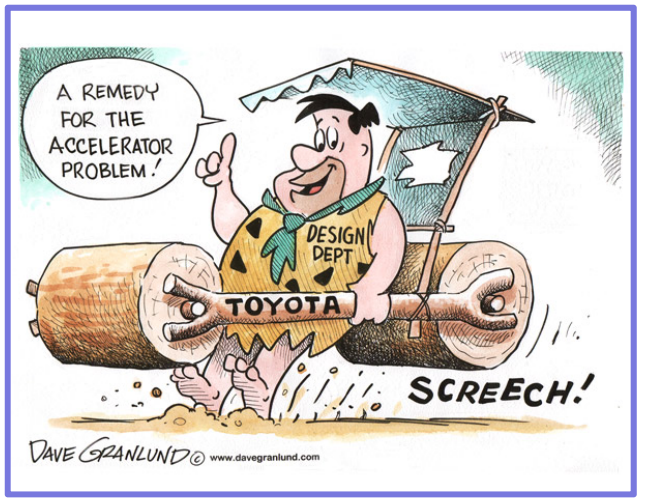


Reliability and Controls

- Controls are methods designed to eliminate or reduce hazards
- Engineering controls are more reliable than administrative controls
- Engineering controls eliminate hazard through system design – about 90%+ effectiveness
- Administrative controls use procedures or training to reduce hazards – about 50% effectiveness
  - Redundant administrative controls often necessary
  - Effort to ensure administrative controls work

Reliability: Real-World Example

- Toyota recalled 2.3 million U.S. vehicles, 21 Jan 10
- Mechanical sticking of gas pedal
  - Harder to depress or slower to return
  - Stuck in partially depressed position, leading to unintended acceleration
- 37 deaths attributed to pedal problem
- Lost revenue
  - Suspended sales of recalled models
  - Required vehicle repairs
- Multiple lawsuits and costly investigations



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Module 12 – Part 6
Summary and Application

Presented by:
Susan Stevens-Adams, Ph.D.

Module 8.6: Summary and Application

- Fissile material operations are high-risk and high-consequence operations that rely heavily on humans
- Human factors issues have played a major role in previous criticality accidents
  - Procedural Instructions
  - Human machine interface (usability)
  - Attention
  - Reliability (equipment and human)
- **Where do these issues apply to your operations?**

Understanding basic human factors/reliability principles and establishing controls to prevent common human factors issues helps ensure that a criticality accident will never happen again.