MODULE 4.0: NUCLEAR CRITICALITY SAFETY CONTROLS

Purpose

Welcome to Module 4.0 of the Nuclear Criticality Safety Directed Self-Study Course! This is the fourth of five modules in this directed self-study course. The purpose of this module is to assist you in identifying nuclear criticality safety controls and limits, and in evaluating the appropriateness of selected applications in the work environment.

This directed self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. There are seven sections in this module plus supplemental reading material. The module has self-check questions and activities to help you assess your understanding of the concepts presented in the module.

Before You Begin

It is recommended that you have access to the following material:

- Trainee Guide

Complete the following prerequisite:

- Module 3.0 Nuclear Theory

How to Complete this Module

1. Review the learning objectives.
2. Read each section within the module in sequential order.
3. Complete the self-check questions and activities within this module.
4. Check off the tracking form as you complete the self-check questions and/or activities within the module.
5. Contact your administrator as prompted for a progress review meeting.
6. Contact your administrator as prompted for any additional materials and/or specific assignments.
7. Complete all assignments related to this module.
8. Ensure that you and your administrator have dated and initialed your progress on the tracking form.
9. Go to the next assigned module.

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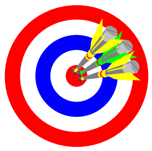


4.1 Upon completion of this module, you will be able to identify nuclear criticality safety controls and limits and recognize examples of workplace applications.

4.1.1 Define nuclear criticality safety.

4.1.2 Describe nuclear criticality safety control factors.

4.1.3 Identify examples of control factors.

4.1.4 Identify administrative and engineered controls.

4.1.5 Identify the hierarchy of control factors.

4.1.6 Distinguish between primary and secondary controls.

4.1.7 Define the double-contingency principle.

4.1.8 Define the role of contingencies in establishing nuclear criticality safety limits.

4.1.9 Identify conservatism as it relates to nuclear criticality safety.

4.1.10 Distinguish between neutron and gamma criticality alarms.

4.1.11 Given a scenario, determine compliance with NRC Regulatory Guide 3.71 and ANSI/ANS 8.3.

Learning Objective

When you finish this section, you will be able to:

4.1.1 Define nuclear criticality safety.

NUCLEAR CRITICALITY SAFETY

Introduction

Nuclear criticality safety has been defined as the protection against the consequences of an inadvertent nuclear chain reaction, preferably by the prevention of the reaction. Nuclear criticality safety for uranium facilities involves both preventive measures to maintain process conditions and mitigative measures to reduce the overall risk of nuclear criticality.

How Is Nuclear Criticality Safety Achieved?

Nuclear criticality safety is achieved by controlling one or more factors of the system within subcritical limits.

How Is This Control Generally Exercised?

Control may be exercised:

- Administratively through procedures (e.g., by requiring that a mass not exceed a posted limit)
- By physical restraints (e.g., by confining a solution to a cylindrical vessel with diameter no greater than the subcritical limit)
- Through the use of instrumentation (e.g., by keeping a fissile concentration below a specific limit by devices that measure concentration and prevent its buildup through reflux in a chemical system)
- By chemical means (e.g., by prevention of conditions that allow precipitation, thereby maintaining concentration characteristic of an aqueous solution)
- By relying on the natural course or credible course of events (e.g., by relying on the nature of a process to keep the density of uranium oxide less than a specified fraction of theoretical)

Nuclear Criticality

A nuclear criticality accident is an unintentional, uncontrolled nuclear

Accident

fission chain reaction. All operations with fissile materials should be performed to prevent the establishment of nuclear chain reactions and the sudden release of energy. When released, this energy would be in the form of heat and ionizing radiation. The ionizing radiation might be lethal to nearby personnel. Also, damage to equipment could possibly cause fission products generated by the incident to escape. Damaged equipment could result in the interruption of operation schedules and could lead to the release of sufficient material to provide a contamination problem or an environmental hazard.

The achievement of nuclear criticality safety depends on controlling either the mass of the fissile material or neutron behavior.

Self-Check Questions 4-1

Complete the questions. Answers are located in the answer key section of the Trainee Guide.

1. What is nuclear criticality safety?

2. Nuclear criticality safety control may be exercised by:

3. Nuclear criticality safety is dependent on controlling either:

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objectives

When you finish this section, you will be able to:

4.1.2 Describe nuclear criticality safety control factors.

4.1.3 Identify examples of control factors.

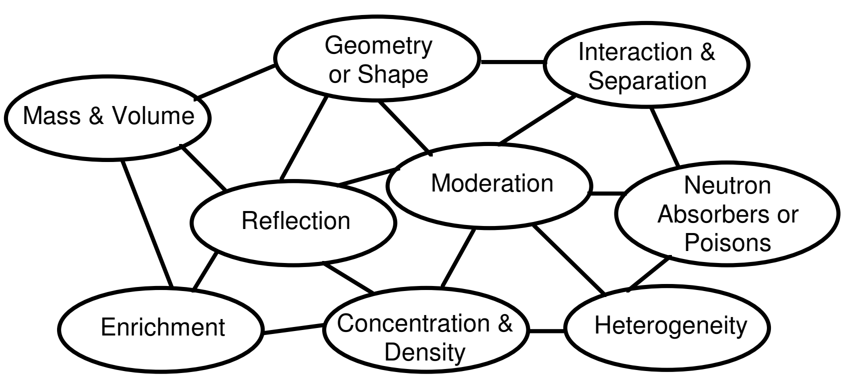
NUCLEAR CRITICALITY SAFETY CONTROL FACTORS

In order to maintain a system in a subcritical state, factors that can affect nuclear criticality must be controlled. These factors are:

- Mass
- Volume
- Enrichment
- Geometry and Shape
- Interaction and separation
- Moderation
- Reflection
- Concentration and density
- Neutron absorber or poisons
- Heterogeneity

These factors are interdependent. See Figure 4-1. Changes made to one of the factors may affect the parameters on the other factors. In this module, each factor is presented separately and it is assumed that everything else remains constant.

Figure 4-1. Nuclear Criticality Safety Control Factors



NOTE: The combined effects of several factors determine whether an array of nuclear material can become critical. Changes made to one of the factors may affect the parameters on the other factors.

MASS

Mass is the amount of fissionable material present. See Figure 4-2. The **critical mass** is the amount of a fissionable material that will support a fission chain reaction. The critical mass varies for different fissionable elements and different fissionable isotopes. Mass control is generally discussed with regard to solids. If the amount of material is kept small enough, neutrons will escape and the nuclear criticality is prevented.

Control Examples

Control examples may include:

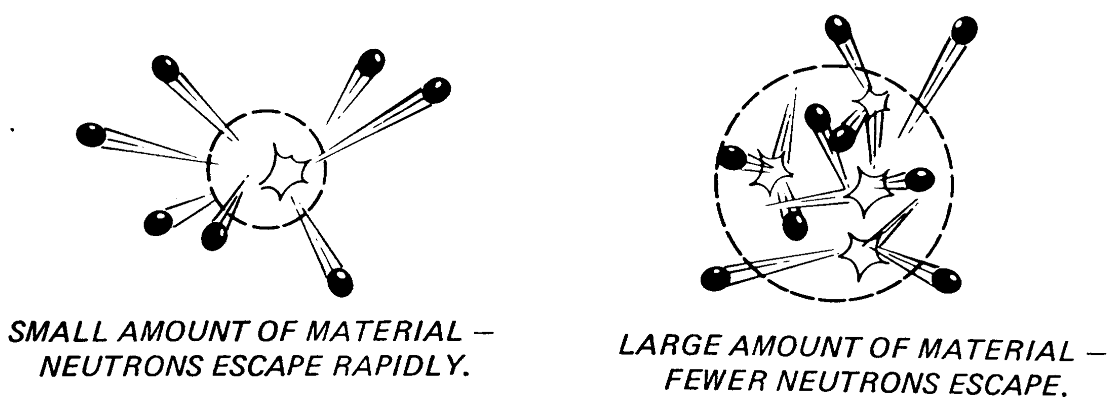
- Established limits on the amount of fissionable material allowed
- Volume favorable designs

Workplace Applications

Workplace applications for mass may include:

- Container identification
- Posted mass limits
- Holes in waste baskets
- Limited-size containers

Figure 4-2. Mass



VOLUME

Volume is generally used for control of solutions or powders. Limits are placed on the capacity of containers available for use in an area. Smaller containers allow neutrons to escape more easily. Containers should be geometrically favorable for specific fissionable material. See Figure 4-3.

Control Examples

Control examples may include:

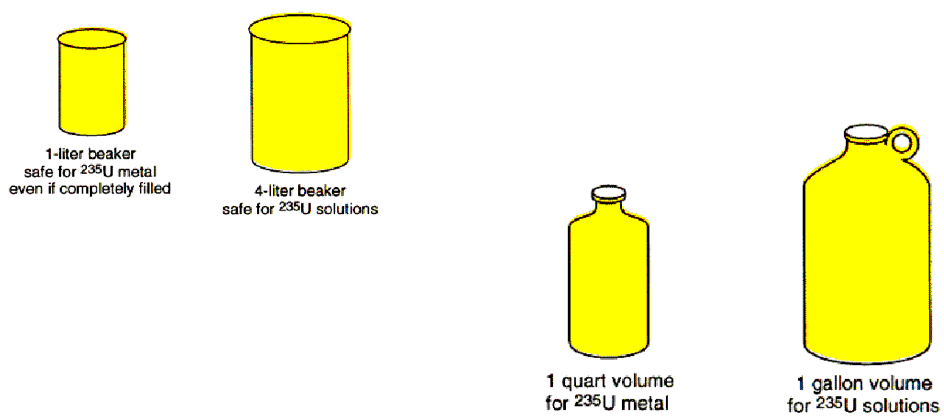
- Fixed geometry by construction
- Established limits on the amount of fissionable material allowed
- Geometrically favorable designs

Workplace Applications

Workplace applications for volume may include:

- Limited-volume process equipment
- Container identification
- Posted volume limits
- Limited-size containers
- Holes in waste baskets
- Overflow procedures

Figure 4-3. Volume



ENRICHMENT

Enrichment refers to the percentage of fissionable isotope. Enriched material has more than the normal or natural amount of the fissionable isotope. The higher the enrichment, the smaller the mass needed to sustain a chain reaction. When U-235 atoms become more plentiful in a given mass of uranium, the distance between them is smaller and they are more likely to be struck by a neutron and fission. When all other conditions are equal, the higher the enrichment, the smaller the mass required to cause a nuclear criticality. See Figure 4-4.

Control Examples

Control examples may include:

- Equipment, operation, or storage conditions must be designed for the highest enrichment that could possibly be used

OR

- Very stringent separation of areas/facilities handling different enrichments

Option 1: Treat all materials as if maximum enrichment.

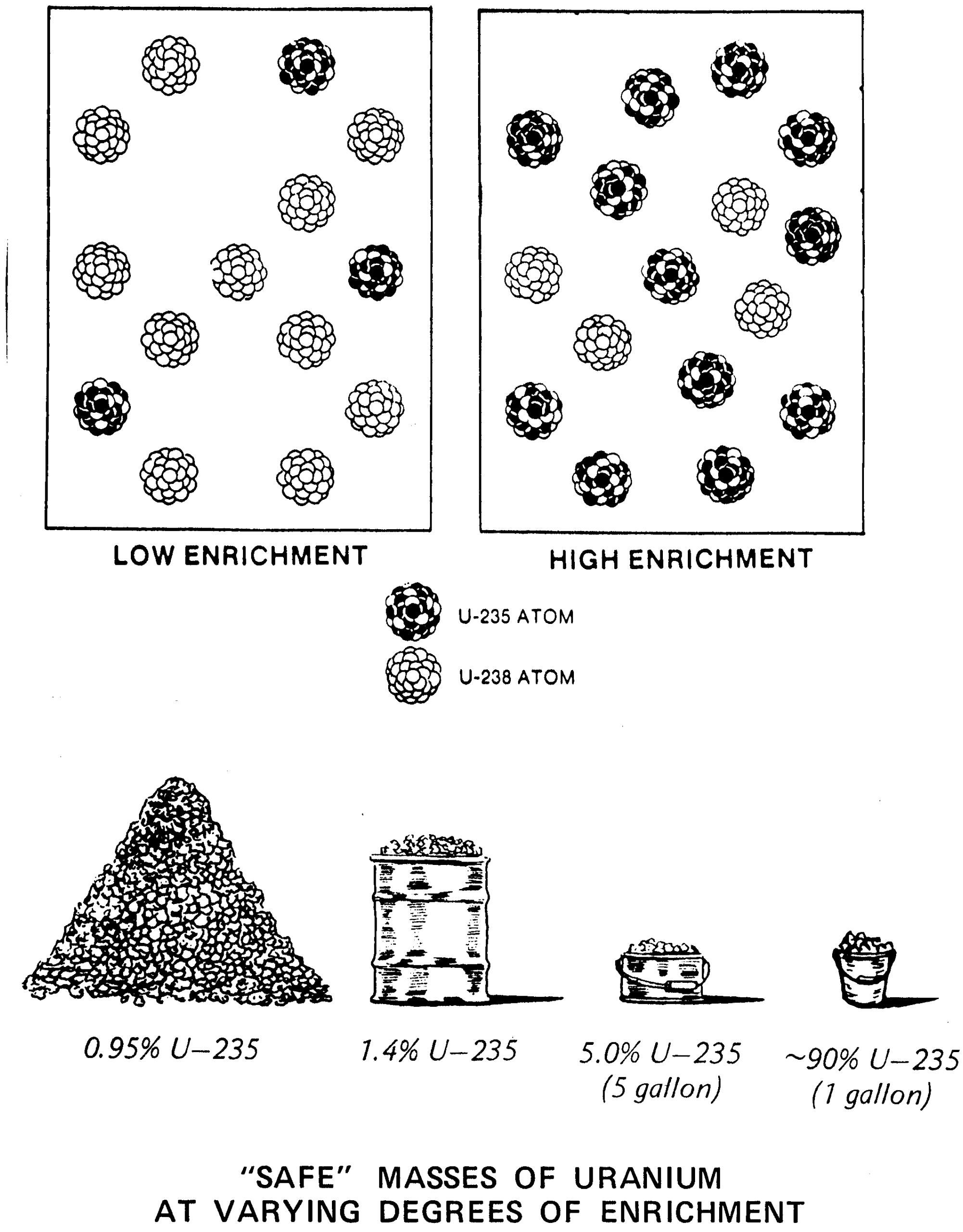
Option 2: Use higher limits for lower-enriched materials.

Workplace Applications

Workplace applications for enrichment may include:

- Color coding
- Computerized Special Nuclear Materials (SNM) inventory
- Container size
- Physical separation of areas
- Unique fittings
- Physically distinct containers
- Multiple sampling
- Accountability practices

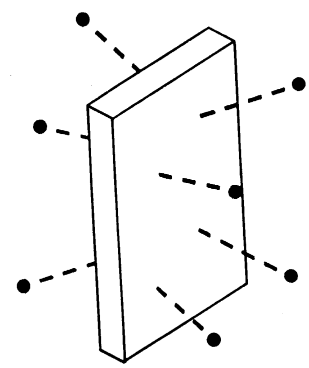
Figure 4-4. Enrichment



GEOMETRY OR SHAPE

Geometry refer to the size and shape of the material or container. For a given type of material, geometrically favorable designs are used to achieve a large ratio of surface area to volume so the neutrons have a greater chance of escaping. See Figure 4-5.

Figure 4-5. Geometry or Shape: Neutrons Leak Out and Do Not Cause Fissions



For a given amount of material, the sphere is the most reactive shape. The sphere has the smallest surface area for its volume; therefore, it is considered the least favorable shape. A neutron generated inside has a better chance of causing other fissions before it escapes into the environment. See Figure 4-6.

Control Examples

Control examples may include:

- Geometrically favorable dimensions that confine the materials to subcritical limits

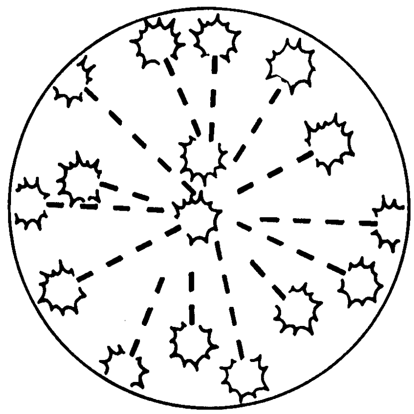
Workplace Applications

Workplace applications for geometry may include:

- Long, thin bottles; storage tanks; and extraction columns
- Planar array
- Specially designed equipment that maintains the desired spacing
- Slab tanks

- Slab trays (for fuel rods)

Figure 4-6. Geometry or Shape: Neutrons Causing Fissions



NOTE: "Favorable geometry" means favorable for safety. It does **NOT** mean favorable for sustaining a fission chain reaction.

INTERACTION AND SEPARATION

Interaction occurs when neutrons from one location can reach and enter material at another location. Individual units are kept separated at distances determined by the Nuclear Criticality Safety (NCS) staff. When two or more subcritical units are brought closer to each other, they may become critical since each may gain extra neutrons. See Figure 4-7.

Control Examples

Control examples may include:

- Specially designed equipment that maintains the desired spacing

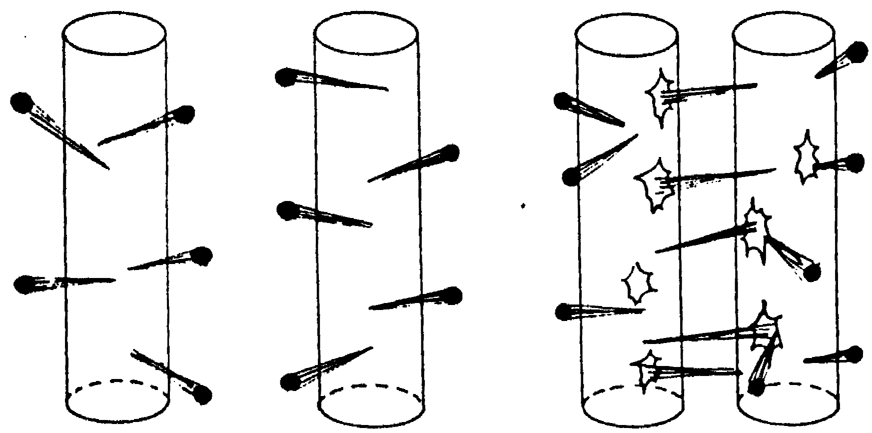
Workplace Applications

Workplace applications for interaction and separation may include:

- Storage racks that allow only specific numbers of containers with predetermined spacing
- Mechanisms that secure storage containers only at predetermined and properly spaced locations

- Stated separation criteria
- Birdcages
- Movement control procedures
- “Bumpers” to maintain spacing between carts and/or racks
- Limit to the number of carts

Figure 4-7. Interaction and Separation



When two containers are widely separated, few neutrons escaping from one will hit the other.

When two containers are placed close to each other, neutrons escaping from each will be more likely to hit the other.

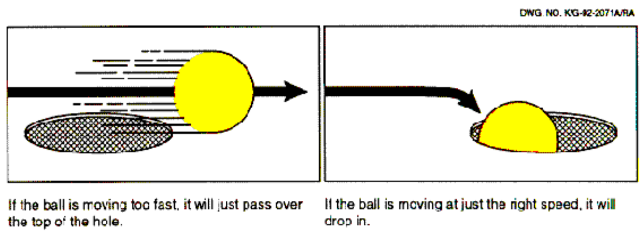
MODERATION

Moderation is the ability of a material to slow down a neutron. If a neutron hits a nucleus of equivalent mass, it can lose almost all of its speed. If it hits a heavier nucleus, it will not be slowed down as much.

It is much harder for a fast-moving neutron to cause a fission. The slowing down of neutrons increases the probability of causing a fission. The fissile atom can "catch" a slow neutron more easily than a fast neutron. It's similar to a golfer trying to sink a putt. See

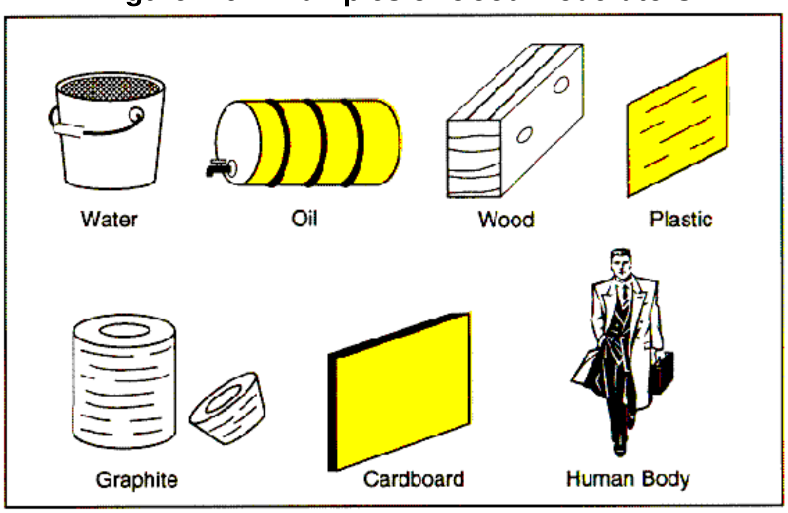
Figure 4-8.

Figure 4-8. Moderation



Items containing hydrogen and/or carbon are good moderators. Hydrogen nuclei are similar in mass to neutrons. Carbon, while not as low in mass as hydrogen, is also a very effective moderator because it absorbs neutrons poorly. See Figure 4-9.

Figure 4-9. Examples of Good Moderators



Control Examples

Control examples may include:

- Limiting or excluding moderating materials
- Controlling concentration

Workplace Applications

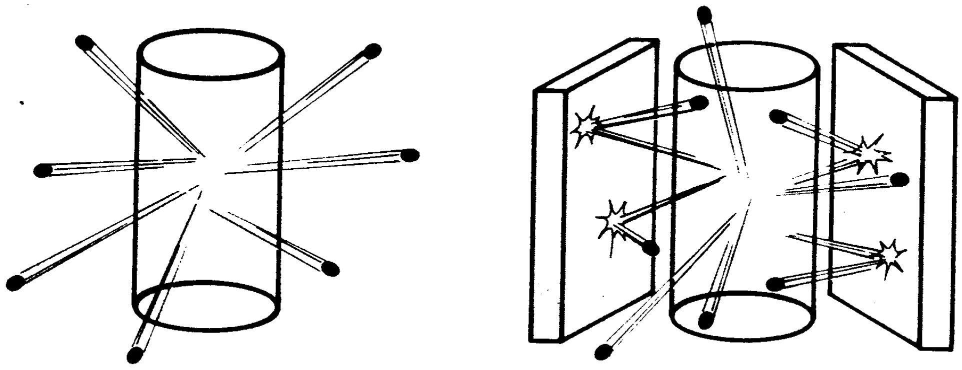
Workplace applications for moderation may include:

- Water-tight containers
- Sloped covers on storage racks
- Adequate drainage
- Fire fighting equipment that does not use water
- Doors shut upon initiation of sprinklers
- Moisture sampling
- Glove box logbooks
- Personnel access control
- Storage racks that allow only specific numbers of containers with predetermined spacing
- Control oil for gear boxes

REFLECTION

Reflection refers to the bouncing back of neutrons into the fissionable material, providing subsequent chances to produce a fission. See Figure 4-10. Escaping neutrons continue moving away in a straight line unless they hit something in their path. Under these conditions, less fissionable material is needed to become critical.

Figure 4-10. Reflection



Control Examples

Control examples may include:

- Maintaining spacing limits to control proximity of reflectors (for example, floors, walls, ceilings) to fissionable materials
- Using physical barriers

Workplace Applications

Workplace applications for reflection may include:

- Adequate drainage
- Fire fighting equipment that does not use water
- Mechanisms that secure storage containers only at predetermined and properly spaced locations with adequate separation from walls, floors, and ceilings
- Personnel access controls
- Composition controls (for example, use of poisoned reflector materials, such as cadmium sheets)
- Metal guards

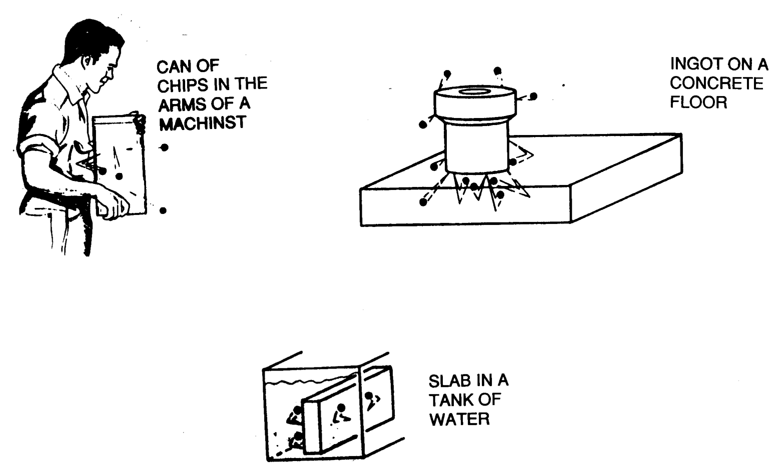
Figure 4-11 shows examples of good reflectors.

- Water
- Oil
- Plastic > 1 inch in thickness

- Graphite
- The human body

In addition, all construction materials, such as steel and concrete, will have some degree of reflective ability. For nuclear safety, it is better to have the system surrounded by air.

Figure 4-11. Examples of Reflection



CONCENTRATION AND DENSITY

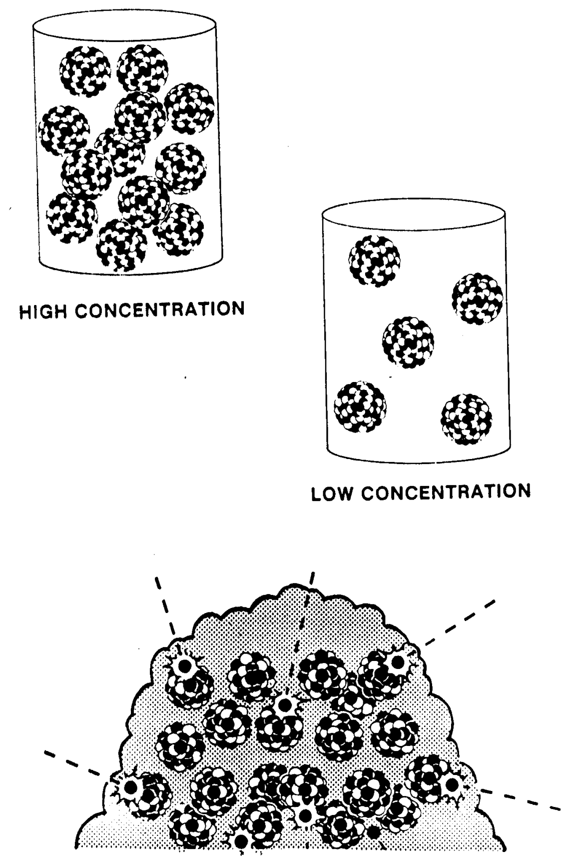
Concentration refers to the mass, or amount, of fissionable material in a volume of liquid. Density is similar to concentration, except it normally applies to dry metals or compounds.

As the concentration or density decreases, the atoms of fissionable material will spread further apart. Decreasing the concentration decreases the number of fissionable atoms per unit volume. Therefore, in low-concentration solutions or low-density materials, there is less chance of a neutron striking a fissionable nucleus and producing a fission. See Figure 4-12.

NOTE: This may not be true if the dilution is accomplished with a moderator.

High concentrations may be made safer by limiting the geometry or mass.

Figure 4-12. Concentration and Density



Control Examples

Control examples may include:

- Established and posted limits
- Procedures for sampling
- Instrumentation that measures concentration and prevents buildup

Workplace Applications

Workplace applications for concentration and density may include:

- Criticality controls signs indicating limits
- Color-coded containers

- Double-sampling: manual, on-line, automatic
- Prohibition of dry or soluble material
- Favorable geometry that is concentration-dependent
- Limits of solubility
- Precipitation protection
- Mixing (slurry vs solution)
- Instrumentation
- Process controls
- Configuration control

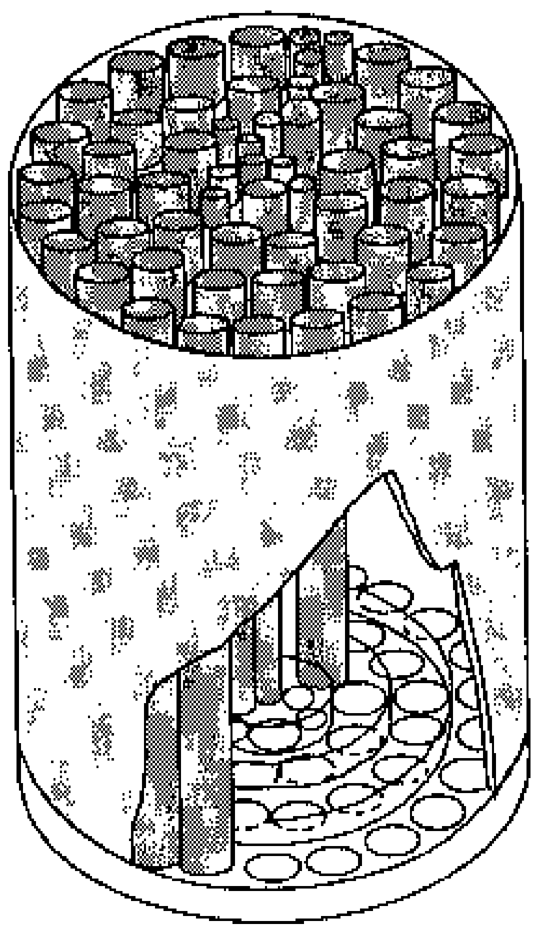
NEUTRON ABSORBERS OR POISONS

Neutron absorbers, also referred to as poisons, are materials that are effective at capturing thermal neutrons and not fissioning. Some commonly used neutron absorbers are cadmium, gadolinium, chlorine, and boron. Raschig rings, which contain boron, are examples of neutron absorbers.

By absorbing a neutron that might have struck a fissionable nucleus, the system is made safer. The use of absorbers or poisons as a control is discouraged by NCS staff because it requires that the absorbers/poisons be periodically monitored to ensure effectiveness and presence.

Poisons are generally used as a secondary control since the presence and effectiveness of the poison must be verified periodically. See Figure 4-13.

Figure 4-13. Neutron Absorbers or Poisons



Vessel poisoned by packing with CPVC pipe

Control Examples

Control examples may include:

- Chemical analysis
- Concentration control
- Procedures
- Scheduled monitoring for presence and effectiveness

Workplace Applications

Workplace applications for neutron absorbers or poisons may include:

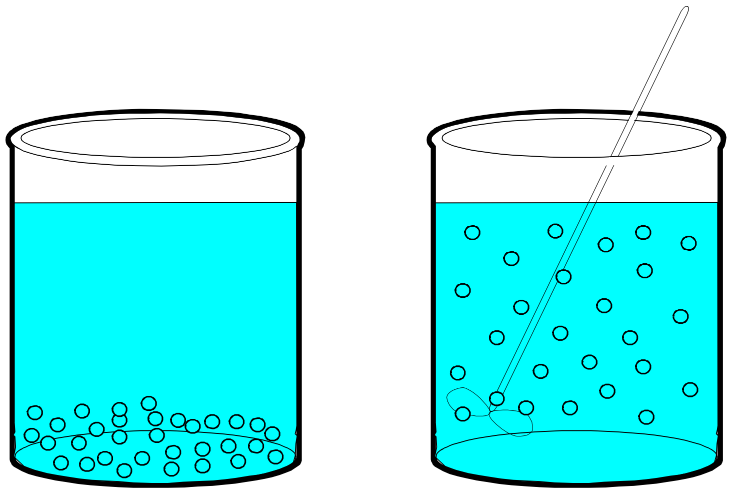
- Raschig rings made from borosilicate-glass
- Soluble poisons (boric acid, cadmium nitrate, gadolinium)
- Dry boric acid
- Boral plates

HETEROGENEITY

Heterogeneity refers to a mixture of solids and solutions with changing composition. See Figure 4-14.

Certain fuel fabrication steps, storage, and transportation may involve regular lattices of fuel elements in water; dissolving the spent fuel for reprocessing may involve either regular lattices or random arrangements of chopped elements. (Reference: *LA 3366 Criticality Control in Operations with Fissile Material*)

Figure 4-14. Heterogeneity



Control Examples

Control examples may include:

- Use of consistent minimum critical mass limit and dimensions

Workplace Applications

Workplace applications for heterogeneity may include:

- Mixing/sparging low enriched uranium (LEU) waste to maintain homogeneity
- Separate limits for solutions/powder/pellets

Self-Check Questions 4-2

Match each term in Column A with the correct definition in Column B. Answers are located in the answer key section of the Trainee Guide.

Column A
Terms

A. Mass

B. Enrichment

C. Geometry (shape/dimensions)

D. Neutron absorbers

E. Concentration

F. Moderation

G. Reflection

H. Interaction

I. Volume

J. Heterogeneity

Column B
Definitions

1. ___ Quantity of fissionable isotope per unit of volume.

2. ___ Neutrons from fissionable material in one location reach and enter fissionable material in another location.

3. ___ Slowing down of fast neutrons.

4. ___ The percentage of ^{235}U.

5. ___ Material effective at capturing thermal neutrons.

6. ___ Nonuniform mixture of uranium and moderating material.

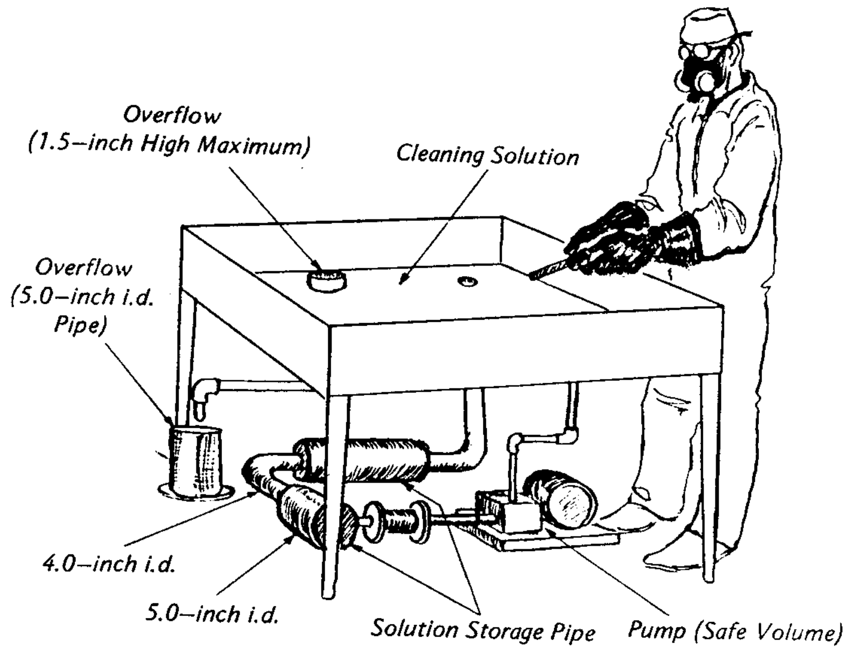
7. ___ Bouncing neutrons back into a container or reactor.

8. ___ Capacity of a container.

9. ___ Size and shape of the fissionable material.

10. ___ The amount of fissionable isotope in a system.

Directions: Illustrations in questions 11 through 14 show applications of control on certain factors. List at least three control factors on the lines next to each illustration.



11. __________________________ __________________________

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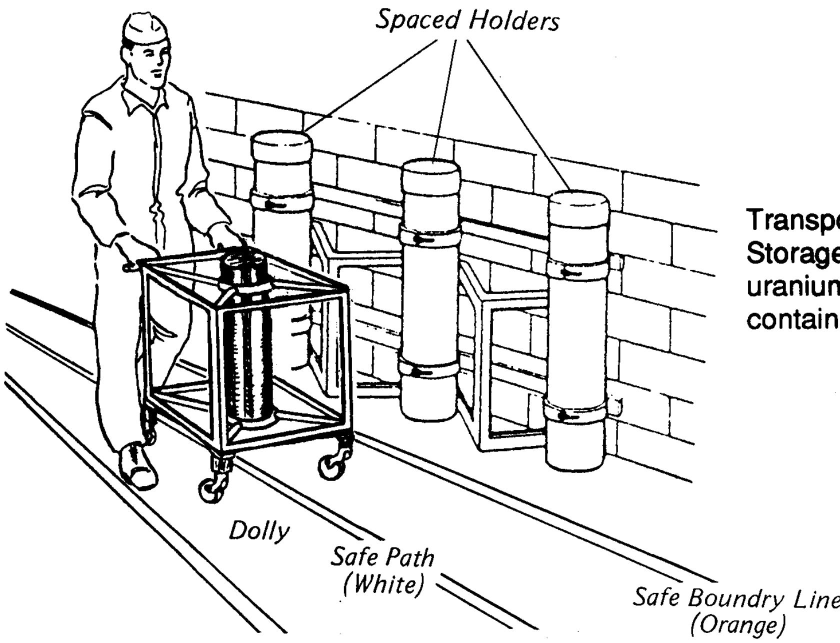

Transport Dolly and Storage Area for uranium-loaded containers.

12. ______________________ ______________________

______________________ ______________________

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13. ______________________________

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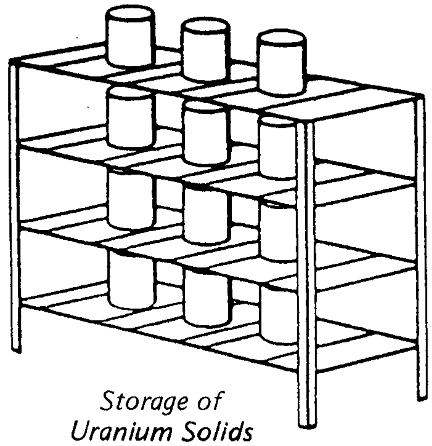

Storage of
Uranium Solids

14. ______________________________

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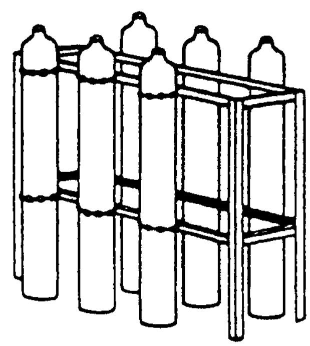


Uranium Solution
Bottle Storage

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

4.1.4 Identify administrative and engineered controls.

TYPES OF CONTROLS

Nuclear criticality safety can be achieved through the following means:

- Equipment design
- Use of process control instrumentation
- Compliance with operating procedures

Controls can be classified as either administrative or engineered.

Administrative Controls

Administrative controls are policies and procedures established by management to ensure that nuclear criticality safety controls are implemented effectively to maintain safe operating conditions (subcritical).

Examples:

- Established limits on the amount of fissionable material allowed
- Posted mass limits
- Zone markings
- Operating procedures
- Training programs
- Operations review
- Material identification labels
- Criticality safety analysis

Engineered Controls

Engineered controls are design and physical controls that effectively control neutron production via absorption, leakage, moderation, interaction, and geometry.

Whenever possible, the maintenance of control should depend on safety features incorporated in the equipment rather than on administrative controls.

Engineered controls can be either active or passive.

Definitions

Passive controls are features and devices used to provide positive control like favorable geometry.

Active controls are protective devices that generally implement administrative controls, but may be considered somewhat more reliable because automatic action replaces operator response.

Examples of active engineered controls are:

- Conductivity monitors
- Pressure indicators
- Temperature indicators

Passive controls are preferred. Examples of passive engineered controls are:

- Limited-volume process equipment
- Holes in waste baskets
- Raschig rings
- Overflow holes
- Birdcages
- Process columns
- Storage racks
- Slab tanks

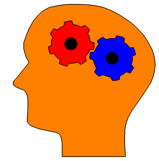
How NCS Control Factors Work

Table 4-1 lists the control factors previously discussed in this module, a brief explanation of how they work, and examples of each control factor.

Table 4-1. How Nuclear Criticality Safety Control Factors Work

Control	How It Works	Examples
Mass and Volume	Have a small enough number of fissionable atoms so the neutrons are more likely to escape or be captured.	• Administrative limits • Limited-size containers • Overflow holes
Enrichment	Have an enrichment that is so low that neutrons are more likely to be captured (absorbed) by ^{238}U or leak out than cause a fission with ^{235}U. As enrichment goes up, the amount of material needed to cause a nuclear criticality goes down.	• Limits on enrichment of uranium allowed to be handled in a building • Limited-size containers
Geometry or Shape	Have containers or equipment favorably shaped to allow the neutrons to leak out or escape.	• Geometrically favorable bottles • Geometrically favorable design for pipes and valves • Restricting or prohibiting the use of 55-gallon drums
Interaction and Separation	Ensure that subcritical materials are handled and stored in a way that does not allow neutrons from one unit to leak out and cause a fission in another unit.	• Properly designed storage racks • Birdcages • Properly designed storage tanks • Spacing procedures
Moderation	Remove material from the ^{235}U that is likely to slow down the neutrons. Neutrons will be more likely to escape or be absorbed before causing a fission.	• Limits based on optimum moderation • Engineered designs that prevent moderation
Reflection	Avoid items around the potentially critical materials that might reflect (bounce) neutrons back into the material.	• Limits based on optimum reflection (A safe mass is assumed to be surrounded by water.) • Equipment designed to minimize reflection
Concentration and Density	Keep the concentration of ^{235}U in a solution so low that the neutrons either escape or are captured.	• Sampling • Prohibiting the use of similar containers for different concentrations of material
Neutron Absorbers or Poisons	Add in a material that absorbs neutrons without fissioning.	• Raschig rings (borosilicate glass rings inside the storage vessel) • Cadmium sheets on the outside walls of a vessel
Heterogeneity	Ensure that heterogeneous mixtures of uranium and moderator cannot be critical.	• Choose minimum critical mass limit and dimension.

Activity 1 - Control by Practice/Equipment Design



Purpose: The purpose of this activity is to identify the control factor(s) affected by using the following practices or equipment designs.

Directions: Complete the control factor(s) column by indicating the control factor(s) for each practice/equipment design. Answers are located in the answer key section of the Trainee Guide.

PRACTICE/EQUIPMENT DESIGN	CONTROL FACTOR(S)
Example: Elevation of equipment	
1. Restricted use of plastic bags	
2. Slab overflow pans	
3. Double sampling and analysis	
4. Signs designating stacking limits	
5. Limited-size containers	

Self-Check Questions 4-3 ✓

Mark the following controls as "A" for administrative or "E" for engineered. Answers are located in the answer key section of the Trainee Guide.

______ 1. Overflow holes

______ 2. Raschig rings

______ 3. Training programs

______ 4. Operating procedures

______ 5. Birdcages

______ 6. Slab tanks

______ 7. Criticality Safety Analysis

______ 8. Posted signs

______ 9. Storage racks

______ 10. Materials identification labels

______ 11. Process columns

______ 12. Operations review

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objectives

When you finish this section, you will be able to:

4.1.5 Identify the hierarchy of control factors.

4.1.6 Distinguish between primary and secondary controls.

HIERARCHY OF NUCLEAR CRITICALITY SAFETY CONTROL FACTORS

ANSI/ANS Standard 8.1 provides guidance on selecting nuclear criticality safety control methods. A hierarchy of methods is suggested based on reliability and effectiveness of control. Alternative hierarchies have been recommended by other sources.

The Standard indicates those controls that should be considered as primary and those that are generally used as secondary controls.

NOTE: The hierarchy is arbitrary, with individual controls in one category having the potential to be favored over those controls in another category on a situation-by-situation basis.

Primary Controls

Primary controls are those that serve as the principal mechanism for the prevention of nuclear criticality accidents.

Secondary Controls

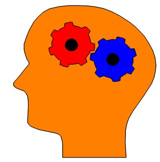
Secondary controls are generally administrative and equipment control mechanisms used to ensure the effectiveness of the primary controls.

Table 4-2 shows contributing factors in seven nuclear criticality accidents in U.S. processing plants.

Table 4-2. Factors in Seven Nuclear Criticality Accidents in U.S. Processing Plants

Contributing Factor	Number of Nuclear Criticality Accidents Involved
Critical configuration of liquids	7
Bulk transfer to unfavorable container	6
Valve problems	5
Unintended transfer	3
Ignorance of concentration in intended transfer	3

Activity 2 - Hierarchy of NCS Control Factors



Purpose: The purpose of this activity is to identify the hierarchy of NCS control factors.

Directions: Read the following statement and answer the questions. Answers are located in the answer key section of the Trainee Guide.

"...criticality safety is enhanced by arrangements of material and equipment that tend to make proper operation convenient and maloperation inconvenient." (Reference: *LA-3366 Criticality Control in Operations with Fissile Material*)

Questions:

1. How does this statement relate to the idea of a hierarchy of controls?

2. What are the possible consequences of using awkward or complex control methods in the workplace?

Self-Check Questions 4-4

Using the following control factors from ANSI/ANS-8.1, determine the hierarchy of controls from the justification listed. Answers are located in the answer key section of the Trainee Guide.

Administrative Practices	Soluble Neutron Absorber
Geometry	Solid Neutron Absorber

CONTROL	JUSTIFICATION
1.	• Relies on equipment design that has been proven reliable. • Is not easily changed. • Does require administrative controls to ensure that the wrong materials are kept out of the system.
2.	• Well-established control method. • Is relatively easy to maintain. • Requires monitoring to ensure effectiveness.
3.	• Convenient to use. • Generally used as a secondary control in a nonshielded facility. • Subject to precipitation when changes occur in a chemical processing environment.
4.	• Subject to high probability of human error. • Training and retraining must be provided to ensure that concepts and procedures are well understood by the employees to reduce error rate. • In order to be effective, cooperation must exist among management, supervisory staff, nuclear criticality safety staff, and employees.

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objectives

When you finish this section, you will be able to:

4.1.7 Define the double contingency principle.

4.1.8 Define the role of contingencies in establishing nuclear criticality safety limits.

DOUBLE-CONTINGENCY PRINCIPLE

The double contingency principle set forth in ANSI/ANS-8.1 states:

> "Process designs should, in general, incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a nuclear criticality accident is possible."

This approach would suggest that:

- With one contingency, nuclear criticality is not possible
- With a second contingency, nuclear criticality is not assured or likely, but not necessarily precluded

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Key Elements

The key elements are:

- The focus is on **changes** in process. Changes in process conditions may occur as changes in:

  - chemical process

  - physical configuration

  - material composition

- **Two** such changes are necessary before a nuclear criticality accident is possible.

- The changes must be:

  - **unlikely** (a change that is not expected to occur during the lifetime of the plant)

  - **independent** (a change that is not a result or condition of the first change)

- **concurrent** (a second change that occurs while the first change is still active)

Definitions

Contingency: A possible but unlikely change in a condition important to the nuclear criticality safety of a fissile material activity such that its nuclear criticality safety is decreased.

Double contingency principle: The philosophy requiring that process designs shall incorporate sufficient factors of safety so that at least two unlikely, independent, and concurrent changes in process conditions must occur before a nuclear criticality accident is possible.

Example

Figure 4-15 illustrates the double contingency principle when loading dry fissile material into a limited-volume container.

The following nuclear safety factors are controlled in the use of the container to store fissile material.

1. Mass - The container has a limited mass loading.

2. Moderation (dryness) - Any material placed in the container must be dry.

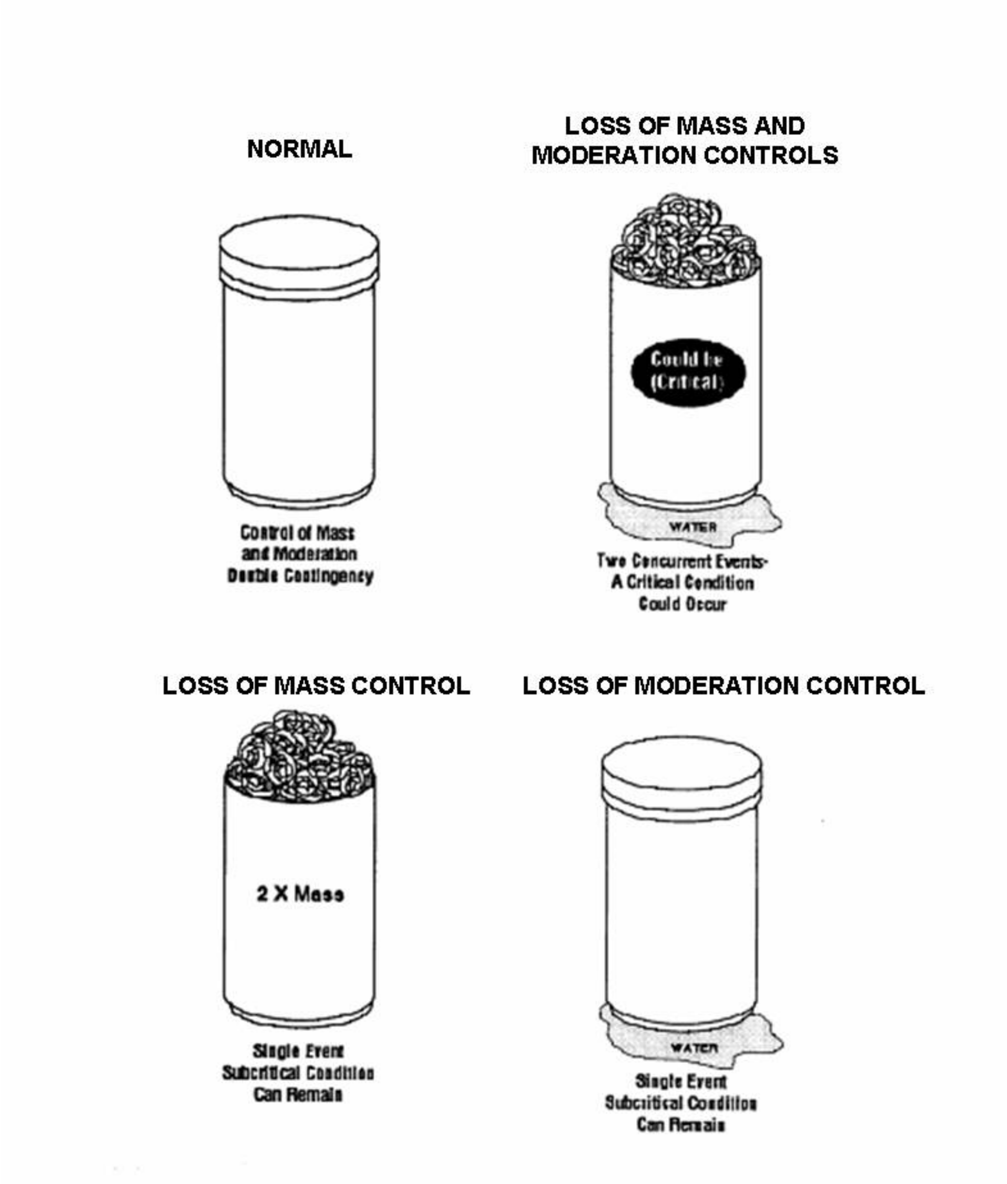
Loss of mass control: Loss of mass control in a limited volume container could occur should the material going into the container be improperly weighed or should the contents of the container be double-batched (twice the approved mass loaded into the container). A mass overload would be safe due to the moderation (dryness) control.

Loss of moderation control: Should liquid be somehow introduced into the limited-volume container during the loading operation or wet material placed into a container, nuclear criticality would not result due to the control of the mass parameter.

Since the occurrence of these events, singularly, is subcritical, double contingency is maintained.

After the loss of a single control, a single event can lead to a nuclear criticality.

Figure 4-15. Examples of Double Contingency



Interpretation Issues

Interpretation of the double contingency has been varied. The following issues have been identified:

- Although the standard includes the words "should, in general," in most cases (including NRC licenses) the principle is mandatory.

- For reactors, the design process generally focuses in systems being "single failure-proof."

- If there is **no positive prevention** of a process change (for example, prevention of flooding due to the presence of sprinklers), some facility procedures assume it occurs and then require double- contingency evaluation for subsequent process changes.

  If the assumed initial process change is highly unlikely, this approach could be viewed as "triple contingency."

Selection of Nuclear Criticality Control Methods

Nuclear criticality control methods are generally selected with attention to:

- **Reliability -** Probability of success when called upon

- **Range of Coverage -** Range of initiating events encompassed (for example, non-water fire fighting for multiple process areas)

- **Operational Support -** Requirements for testing, analysis, maintenance, and operator actions

Contingency requires assured support to take credit. All else being equal, system designs are favored if they have high reliability, a broad range of coverage, and minimal needs for operational support.

Evaluation Criteria for Compliance with Double Contingency

Control methods are evaluated for compliance with the double-contingency principle. The evaluation may take place during the design process or after the fact.

The three major criteria used in this evaluation are:

1. **Contingency Analysis** - Ensuring that at least two process changes are required before a nuclear criticality accident is possible.

2. **Failure Likelihood Analysis** - Considering a combination of failure probability (failure/demand) and demand frequency (demand/year).

3. **Independence Analysis** - Ensuring the absence of common-mode failure pathways.

In evaluating compliance with the double contingency principle, construction of detailed or informal logic trees can be useful.

One common example is a fault tree. A fault tree is, in general, a graphic model that shows the causal relationships between the undesirable top event (usually a specific system failure) and contributing subsystem failures at various levels down (lower tiers) to component failure and human errors. See Figure 4-16.

The tiers are connected by logic-gate symbols that represent their interrelationships. The logic-gate symbols connecting the tiers are:

- **AND** when **ALL** lower-tier events are required (A and B and C...)

- **OR** when **ANY** lower-tier event is sufficient (A or B or C...)

Facility Considerations for Control Methods

Facility considerations for control methods include the following:

- **Need for control** - Document design features important to nuclear criticality safety.

- **Manageability** - Ensure operation, maintenance, and other support levels are manageable.

- **Ergonomics (human factors)** - Reduce likelihood of human error.

- **Uniformity (throughout the facility)** - Reduce complexity, training, and human error.

- **Representative samples** - Minimize effort to take and effort/time to evaluate representative samples.

- **Inspection and cleanout of accumulations of fissile** - Need space, viewing windows, and access support, etc., to look at exhaust system, ducting, piping, equipment, etc.

- **Flushing** - Ensure compatibility with construction materials, line sizes and slopes, line structural support (for example, with respect to sag), valving, and entrance and exit points.
- **Installation** - Ensure adequate flexibility for initial installation

and subsequent modification.

Example of an Application

Table 4-3 shows an example of the application of the double contingency principle.

Figure 4-16. Fault Tree Example

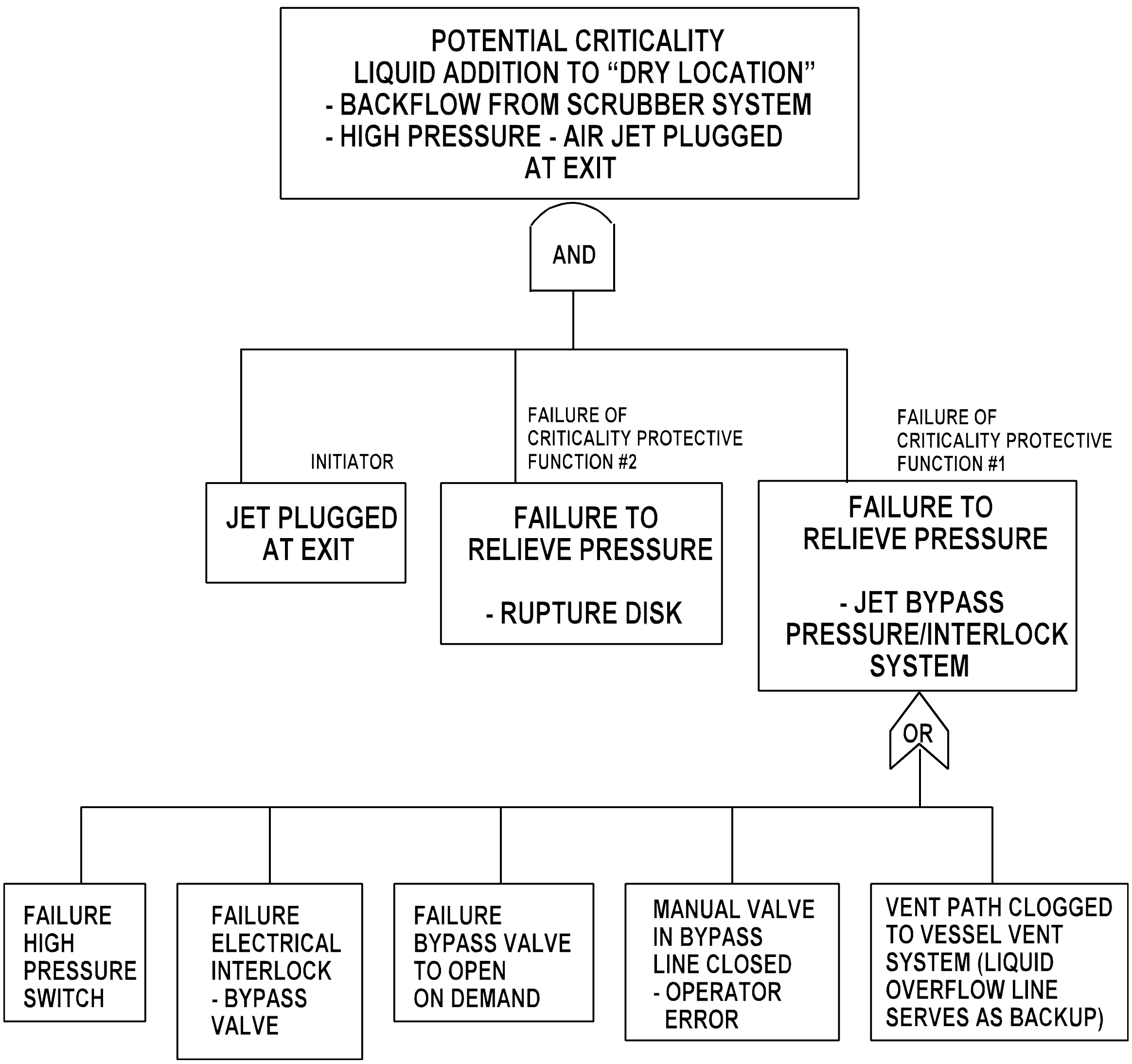
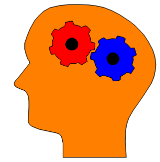


Table 4-3. Example of the Application of the Double Contingency Principle

ITEM	DESCRIPTION
Situation	Need to temporarily store liquid process waste.
Material	High-enriched uranium solution • of any chemical composition and concentration • mixed with any other materials (polyethylene, cloth, paper wipes, etc.)
Approach	Use 2.5-liter bottles (favorable volume for HEU solution). Space the bottles at least 15 inches edge-to-edge.
Subcritical Limits	Double contingency evaluation shows the following to be subcritical: • double batching (two bottles side-by-side) • water flooding the array • nominal reflection addition (e.g., nearby workers)
Extra Measure	Grid structure on the floor to maintain spacing.
Limitations	Will **NOT NECESSARILY** handle: • triple batching • double batching with flooding
Conservative Assumptions	Substantial conservatism exists in assuming: • 2.5 liters of solution in each bottle • optimum concentration of solution • optimum moderation

In this situation the "random factors of safety" inherent with the conservative assumptions would be very likely to prevent a critical configuration, even if the independent contingencies (multiple batching and flooding) occurred.



Activity 3 - Hierarchy of Control Parameters for Double Contingency Application

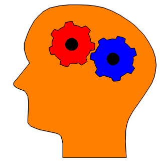
Purpose: The purpose of this activity is to identify the hierarchy of control factors.

Directions: A general hierarchy of nuclear criticality safety control parameters for double contingency applications is shown in the table below. Answers are located in the answer key section of the Trainee Guide.

1. Provide examples of methods for implementing each of the control parameters.
2. Compare this list to ANSI/ANS 8.1 hierarchy on page 4-33.
3. Discuss the appropriateness of placement for the two methods not addressed specifically by the Standard.

CONTROL PARAMETER	EXAMPLES	ANSI/ANS-8.1
1. Favorable Geometry		
2. Passive Engineered Controls		
3. Fixed Neutron Poison		
4. Soluble Neutron Poison		
5. Administrative Practices		

Activity 4 - Loss of Nuclear Criticality Control at a Fuel Fabrication Facility



Purpose: The purpose of this activity is to understand the importance of analyzing all credible accident scenarios as they relate to double contingency.

Directions: Read the case study. Answer the questions. Answers are located in the answer key section of the Trainee Guide.

Early in 1992, personnel at a uranium fuel fabrication facility notified the NRC of a loss of a criticality barrier. The licensee manufactures fuel for research reactors at this facility. One step in the process involves melting a zirconium-uranium metal mixture in an induction-heated mold inside a casting furnace. The mold is surrounded by insulation and a water-cooled jacket.

A mold heated to approximately 1900 degrees centigrade in the furnace developed a pinhole leak in the water-cooled jacket, allowing water to enter the insulation. The water flashed to steam, causing the mold to be ejected out of its holder and the molten metal mixture to be dispersed inside the furnace. Because of the limited quantity of uranium in the batch, there was no possibility of a criticality accident. However, dispersement of the metal mixture constituted a loss of geometry and, therefore, a criticality control violation. All material was contained inside the furnace.

As part of the investigation of this event, the NRC noted that the facility's safety analysis report (SAR) did not consider this accident scenario and had therefore not analyzed the potential consequences.

QUESTIONS:

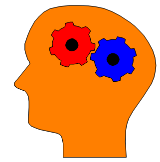
1. Which control factor was lost as a result of the disbursement of the metal mixture?

2. What other control factor was present in the system?

3. What is the lesson learned from this event?

4. As a regulator, what would you expect the licensee to do as a result of this event?

Activity 5 - Nuclear Criticality Safety Measurements Not Performed for Enriched Uranium Solution Storage Tanks



Purpose: The purpose of this activity is to understand the degradation of criticality safety measures that may potentially occur and remain undetected.

Directions: Read the case study. Complete the questions. Answers are located in the answer key section of the Trainee Guide.

Late in 1992, at a fuel fabrication facility, an audit found that required measurements of the volume of borosilicate glass Raschig rings in enriched uranium solution storage tanks were not performed as specified by the applicable standards (ANSI/ANS Standard 8.5). The audit also found this deficiency was identified in earlier audits, but facility personnel had not taken corrective actions.

Borosilicate glass Raschig rings are used as a fixed neutron poison in geometrically unfavorable storage tanks that store aqueous solutions of enriched uranium at concentrations ranging up to 400 grams of uranium per liter. Adherence to this ANSI standard is a requirement for the use of these tanks. In this case, the ANSI/ANS Standard 8.5 requires that the volume fraction of the rings be not less than 32% and the bed of rings not be collapsed in the tank.

QUESTIONS:

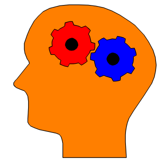
1. Which criticality safety control factor is being used in this process?

2. Why is it important that the Raschig rings NOT collapse in the tank?

3. What is the lesson learned from this event?

4. As a regulator, what would you expect the licensee to do as a result of this event?

Activity 6 - Potential Loss of Nuclear Criticality Controls



Purpose: The purpose of this activity is to understand the possible effect of potential loss of nuclear criticality controls.

Directions: Read each event. Complete the questions. Answers are located in the answer key section of the Trainee Guide.

EVENT 1:

In August of 1992, the NRC issued an event report concerning a potential loss of criticality control. During fuel fabrication, enriched uranium powder passed through a calciner into a geometrically favorable slab hopper where samples were taken to verify moisture content. After sampling, the uranium was sent to a large blender of unfavorable geometry. In this event, the wrong sample results were used to determine the acceptability for further processing. Operations personnel loaded uranium powder that had been sampled for moisture content, but improperly identified, into a large mixer of unfavorable geometry. After discovering the error, operators analyzed the material and determined that the moisture content was below the 10,000 parts per million (ppm) criticality control limit.

This event could have been significant if a batch had been sent to the mixer that exceeded the moisture content limit.

EVENT 2:

Operations personnel discovered moisture in low enriched uranium (LEU) powder in the off-gas portion of a newly installed large lot blender. The blender vessel geometry was an unfavorable configuration and could hold substantially more than a critical mass of LEU (approximately 18 kg). The single control parameter for the blender was moisture control. Facility personnel believed the uranium powder became oxidized and the heat generated by the normal processing drove out the moisture that subsequently collected in the off-gas portion of the system.

This condition was significant because water may collect in sufficient quantities and migrate back into the blender vessel, resulting in a potential criticality safety problem.

QUESTIONS:

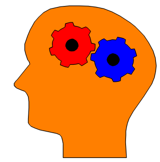
1. Which criticality safety control factor is being used in both of these processes?

2. In each event described, a blender vessel is used with an enriched uranium powder. What is the significance of the controls or lack of specific controls on the blender?

3. What are the lessons learned from these events?

4. As a regulator, what would you expect the licensee to do as a result of these events?

Activity 7 - General Electric, Nuclear Fuel and Components Manufacturing (NFCM)



Reference: NUREG-1450, *Potential Criticality Accident at the General Electric Nuclear Fuel and Component Manufacturing Facility*, May 29, 1991

Purpose: The purpose of this activity is to review an actual incident that occurred in a solvent-extraction system.

Directions: Read the case study. Answer the questions. Answers are located in the answer key section of the Trainee Guide.

BACKGROUND

On May 29, 1991, at the General Electric (GE) Company's Nuclear Fuel and Components Manufacturing (NFCM) facility approximately six miles north of Wilmington, North Carolina, an estimated 150 kilograms (320 pounds) of uranium were inadvertently transferred to an unfavorable geometry waste treatment tank. ("Unfavorable geometry" refers to a container or vessel that can hold enough uranium to produce a criticality.)

As part of the fuel manufacturing process, GE's NFCM (the licensee) has established a Uranium Recycle Unit to recover uranium from certain waste and scrap materials. In this process, scrap materials are dissolved in nitric acid, passed through a filter, and fed to a solvent-extraction (SX) system. The recovered uranium is then returned to the fuel manufacturing process.

THE EVENT

On the evening of May 28, 1991, the Uranium Recycle Unit control room operator noted that the interface level between the organic and aqueous phases within the SX process could not be maintained.

Although the operators became aware of the interface level around 9:30 p.m., the problem actually started about an hour earlier but was apparently unnoticed by the operators.

The interface problem was caused by a malfunction of the SX Column A level control valve, LCV-300.

When efforts by the control room operator to correct the level control valve problem were unsuccessful, attempts were made to control the process by throttling a manual valve located upstream of LCV-300. Manual throttling continued until shift turnover at 11:00 p.m.

The relief control room operator requested that maintenance investigate the problem with the level control valve.

Until maintenance personnel arrived approximately two hours later, the floor operator continued to throttle the upstream valve manually.

After approximately an hour and a half of troubleshooting activities, maintenance personnel concluded that the valve could not be repaired because replacement parts were unavailable.

At the direction of the control room operator, maintenance personnel forced LCV-300 open by redirecting air pressure in the valve actuator.

Forcing the valve open caused the SX process to be ineffective and had the effect of creating an open pathway for high concentrations of uranium to be transferred directly to the aqueous waste quarantine tanks.

From the onset of the problem, feed material (i.e., crude uranyl nitrate) continued to be sent to the SX process. Aqueous waste from the SX process was fed to two favorable geometry quarantine tanks.

During a nine-hour period on May 28, 1991, the contents of approximately nine quarantine tanks were transferred to an unfavorable geometry waste accumulation tank located outside the fuel manufacturing building. Of these nine transfers, four were made without a measurement of their uranium concentration.

Transfers that were made after sampling and measurement, which showed concentrations of less than the 150 ppm transfer limit, were questionable because of sampling system problems. These problems were later confirmed by a calculational method (i.e., system mass balance), which showed that some of the analyzed tanks transferred had to contain uranium concentrations greater than 12,000 ppm.

At approximately 5:20 a.m. on May 29, 1991, a measured sample from the quarantine tank indicated a uranium concentration of 6,977 ppm compared to the transfer limit of 150 ppm. Based on this information, the control room operator transferred the contents to a safe-geometry rework tank and then shut down the SX process.

Unaware of the uranium concentration problems, a Waste Treatment Facility operator approximately 10 minutes later pumped the contents of the 20,000-gallon waste accumulation tank to a comparable treatment tank with unfavorable geometry at the Waste Treatment Facility located approximately one quarter mile from the fuel manufacturing building. Sample results for the material in the waste treatment tank at that facility revealed a uranium concentration of 2,333 ppm.

The licensee recognized the nuclear criticality potential of the problem but initially did not consider it to be an emergency condition.

As a result of these high concentrations, the licensee assigned a technical evaluation team to develop nuclear criticality mitigation and uranium recovery plans.

To minimize the nuclear criticality potential, operators continued air sparging (i.e., mixing) tank contents to prevent an accumulation of material in the bottom of the tank caused by precipitate settling.

The Uranium Recycle Unit

The Uranium Recycle Unit uses an SX process to recover the uranium. The aqueous waste stream from this process is fed into large tanks not critically favorable. The process is shown in Figures 4-17 and 4-18.

The criticality safety of this waste stream was designed to be assured by three independent control systems. These systems were process control, mass limit control, and density limit control.

Figure 4-17. Solvent-Extraction Process

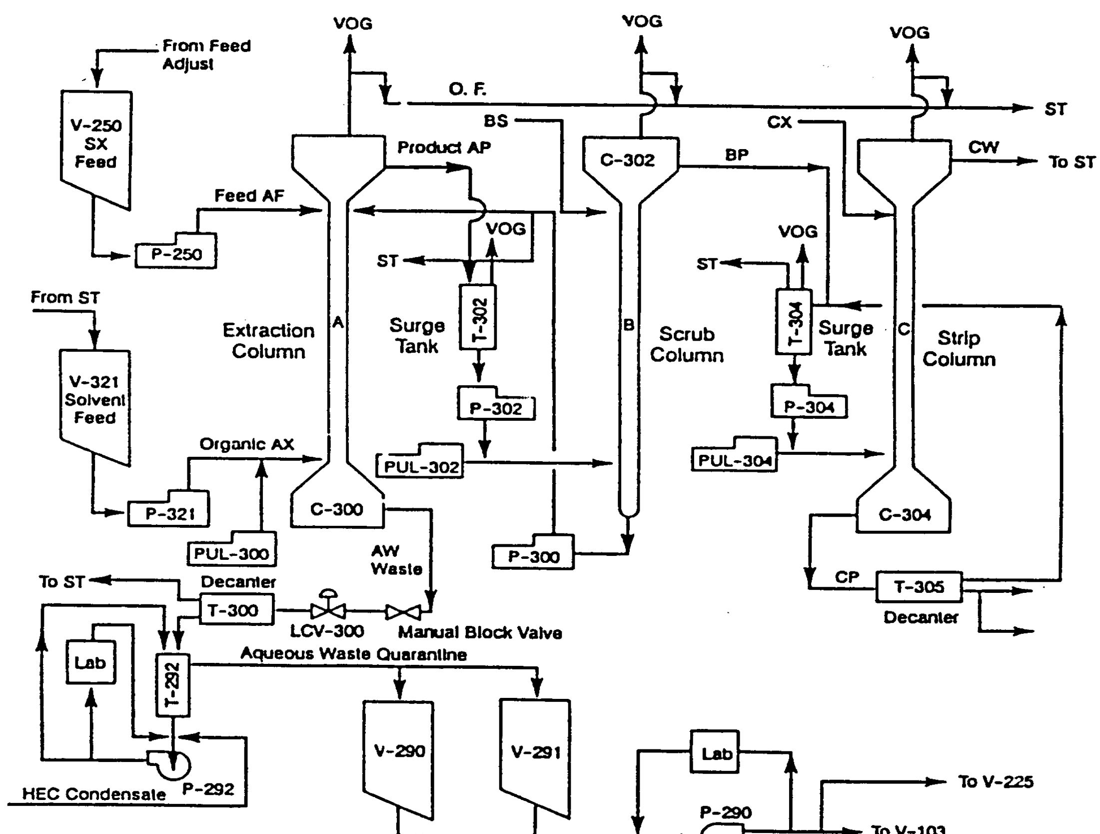
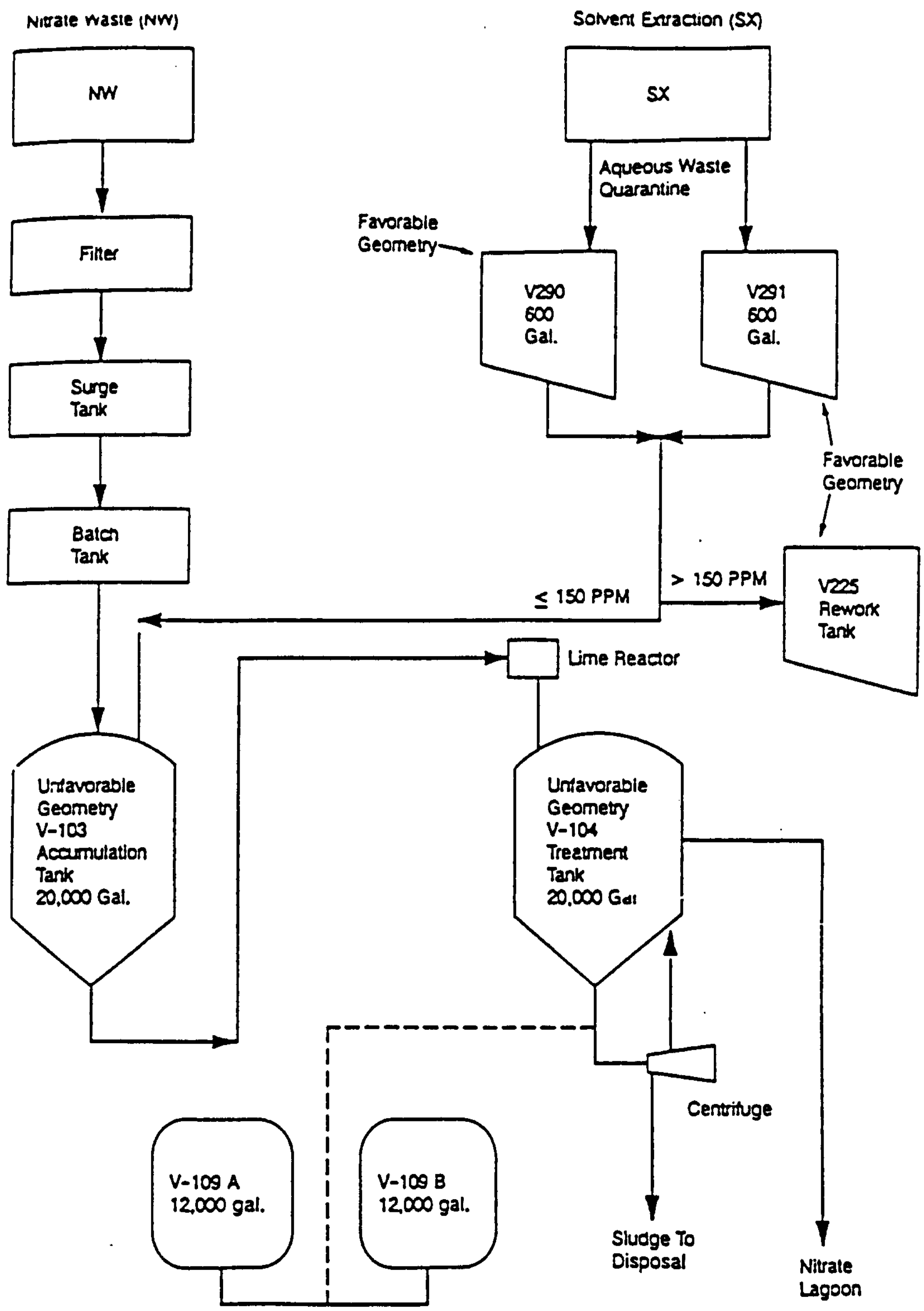


Figure 4-18. Nitrate Waste and Solvent-Extraction Process Waste Flow



Process Control

Process control would be implemented by a digital computer process control system that would automatically control the process parameters in such a way as to preclude unsafe quantities of uranium from leaving in the waste stream.

Mass Limit Control

Mass limit control would be implemented by (1) near real-time sampling and analysis by an automatic system of the waste stream in T-292 prior to discharge to the quarantine tanks and (2) analyzing the uranium content of quarantine tanks before release to tank V-103.

The mass limit of 12 kg of uranium was selected as a safe batch, considering uncertainties of the uranium heel in V-103.

The mass limit in a full 20,000-gallon tank resulted in the 150 ppm of uranium concentration administered to assure compliance.

Density Limit Control

Density limit control would be implemented by (1) providing recirculation to assure a homogeneous mixture of any solution and solids in tank V-103 and (2) a density probe and controller to close inlet valves if the appropriate set point is exceeded.

PROBLEMS

Process Control

When the facility was put in operation, the process control computer system was not developed as a safety barrier and operators routinely bypassed the automatic control features. The remaining barriers, however, should have been adequate.

Mass Limit Control

Two automated sampling systems originally were used to administer the mass limit. The first system was a continuous flow-sampling line from recirculation tank T-292 to the laboratory for periodic measurements.

The second system was by a recirculation sample line to the laboratory from quarantine tanks V-290 and V-291.

By 1987, the first circulating sampling system from T-292 was no longer used and was replaced with occasional manual sampling from a tap on T-292 or on the A column.

The manual sampling apparently occurred if the quarantine tank sample prevented a transfer to V-103 and the operators needed a second opinion.

As a result of deleting the T-292 automatic sampling system, the remaining sampling measurements had a much higher vulnerability to error because of the lack of redundancy.

The remaining sampling was required in the procedures but was inconsistently performed.

Density Limit Control

The first part of density control was provided by a requirement for constant circulation by pump of the contents of tank V-103. This requirement was added to reduce the criticality risk from the settling of suspended uranium solids into an unsafe density, on the assumption that a well-mixed uranium slurry would be safe. The tank is equipped with two primary pumps connected in parallel and with a backup pump, connected to emergency power, with a separate circulation loop.

The second part of density control was originally provided by a density monitor for tank V-103 with a set point alarm and automatic closure of a block and bleed valve. This density probe would presumably detect any unsafe precipitation of uranium or unsafe solutions that sank to the probe level. By 1987, this control had been deleted. The Criticality Safety Analysis of June 4, 1987, approving this change, concluded that the monitor was not necessary because the remaining controls met license requirements.

Of the three layers of designed controls, the first (process control) was installed but not subsequently considered to be a criticality safety contingency barrier. The second was significantly weakened by reliance on a single sampling system. The third control system was partially deleted.

Remaining Sampling Barrier

Because it was the only remaining barrier for some criticality scenarios, the sampling process system for the quarantine tanks increased in importance. It was essential that this process work well; however:

- The design of the circulation sampling system caused it to be vulnerable to not finding undissolved uranium particles, precipitated uranium particles, or uranium in the organic phase. The systems were also prone to plugging. Numerous such problems with nonrepresentative sampling systems had become evident through precursor events.

- The automatic feature of the circulating sampling system proved troublesome, and the laboratory technicians lost confidence in it. Manual sampling taken in the laboratory gradually replaced automatic sampling. In this mode, the sample results were verbally reported to the SX operators so they could enter the results in the computer system. The possibility of data transmission errors that would degrade the intended reliability of the overall control was always present.

- Another degradation of this control system was the capability and standard practice of bypassing the requirements of the computer control system. Compliance with the release limit and the requirement to sample before release to the quarantine tanks were defeated when operators ran the process in troubleshoot mode. (The operators were not intended to have access to this capability mode.) The record keeping of sampling and transfers from the quarantine tanks made it extraordinarily difficult to determine if operators complied with requirements.

Further, there was no evidence of management audits of the sampling process. If management does not consider audits important and if noncompliance was hard to uncover, it would be unreasonable to expect consistent application of the nuclear safety requirements for discharges from the quarantine tanks.

NRC Inspection Program

The NRC report on this event (NUREG-1450) concluded that the NRC inspection program had problems.

- The criticality safety inspection guidance and implementation did not focus on operations procedural compliance.
- The inspection program focused on administration of the Facility Change Request process and not the quality of the Nuclear Safety Analysis that supported approving the Facility Change Request.
- Inspections did not focus on ensuring that licensee management maintain appropriate oversight of licensed activities.

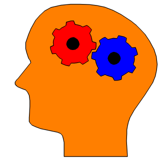
QUESTIONS:

1. Did the licensee initially recognize the potential nuclear criticality problem and consider it to be an emergency condition?

2. What was the last barrier against a nuclear criticality accident in an unfavorable geometry waste tank prior to release to the large volume tanks?

3. What was the evidence that showed that management audits of the sampling process occurred?

Activity 8 - Large Deposit of UO_2F_2 at the K-25 Site



Reference: Haire, Jonathan M., Karla R. Elam, and W. Curtis Jordan. "Nuclear Criticality Safety Analyses of a Uranium Deposit in the K-29 Building at the Oak Ridge K-25 Site, Oak Ridge, Tennessee," K/ER-310, July 1996

Purpose: The purpose of this activity is to review an actual incident that occurred in a uranium enrichment facility.

Directions: Read the case study. Complete the questions.

BACKGROUND

Two principal types of deposits of solid uranyl fluoride (UO_2F_2) are caused by leakage of moist air into gaseous diffusion plant equipment: a thin film that is spread over a large area and large, localized deposits. Hazard screening analysis identified equipment and facilities at the Oak Ridge K-25 Site that contained large and potentially unsafe deposits of enriched uranium. A probabilistic risk assessment was performed to estimate the likelihood of experiencing conditions that would favor nuclear criticality in LEU facilities.

An analysis evaluated the relative criticality accident risks from LEU and high-enriched uranium (HEU) deposits. This report observed that a key criticality control parameter employed for HEU deposits, that of positively excluding hydrogenous liquids (e.g.,water, oil), is not as effective for the deposits of LEU. It was also observed that some of the deposits of LEU would have a potentially critical mass if the degree of moderation were equal to that characteristically developed in uranyl fluoride exposed to air with ambient conditions of temperature and humidity (i.e.,H/U = 4). It was concluded that several of the large deposits of LEU pose a greater risk of criticality than deposits of HEU.

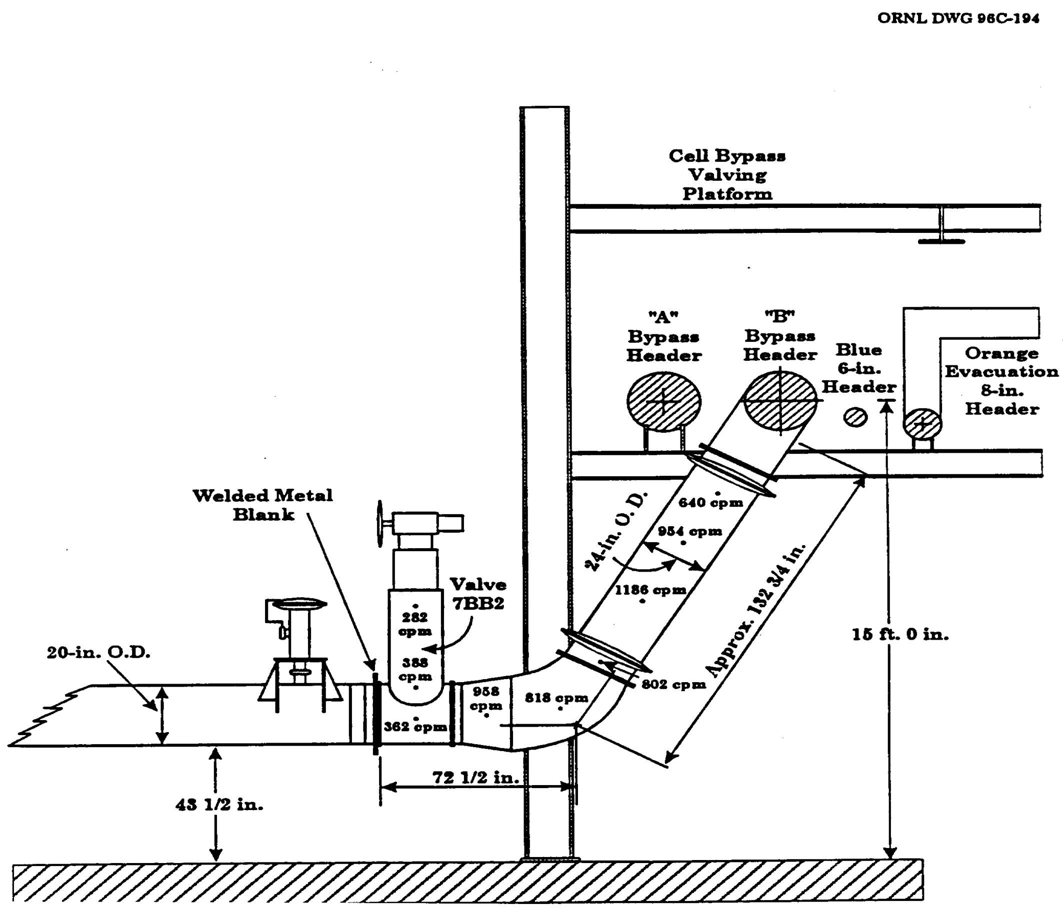
Calculations by the K-25 Nuclear Criticality Safety Department indicated that some of the LEU deposits, if they completely filled some of the pipes, potentially could become critical, even if they were not surrounded by effective neutron reflecting material. Several interim measures have been taken to lessen the likelihood of criticality. These include closing process equipment openings, isolating deposits by closing valves or installing welded partitions, monitoring with nondestructive assay (NDA) equipment, inspecting for roof leaks, and using administrative controls to limit building access.

DESCRIPTION OF DEPOSIT

The deposit is located in the B outlet valve and the 24-inch-diameter line leading to the B bypass line. The deposit extends from the top of a G17 valve, down the body of the valve, and through an approximately 5-foot horizontal run of pipe and then begins a 60˚ climb along a riser to the B bypass line. See Figure 4-19. UO_2F_2 is the assumed deposit chemical composition.

A 1995 NDA measurement estimated the mass of the deposit as 1,190 kg of uranium at an enrichment of 3.3 wt%, yielding 30 kg of ^{235}U. The previous estimate was 1,034 kg of uranium, 29 kg ^{235}U at an enrichment of 2.8 wt%. The 1995 measurement included the valve while the earlier measurement did not. The difference in fissile masses between these two measurements is attributed to a significant deposit in the G17 valve (10 kg ^{235}U) or to NDA measurement uncertainties. NDA staff indicate that the two sets of measurements are within their limit of accuracy and therefore agree. Uncertainties in measured mass and enrichment are estimated to be ± 50% and ± 20%, respectively. Based on gamma measurements, NDA staff believe that the deposit is uniformly distributed around the circumference of the 24-inch-diameter pipe and along the length of the pipe from the valve where the deposit starts to the connection to the B bypass line, where the deposit ends. These conclusions are based on holding a gamma detector to the surface of the pipe and observing no change in readings as it is moved around the circumference and along the pipe's length. Neutron measurements of the deposit have also been made by NDA staff. The count rates indicate a relatively uniform distribution of the deposit. Even though there is a small variation in count rate, the NDA staff believes that this can be attributed to end effects and that there is no major concentration of deposit. These data indicate that the deposit extends up the angled portion of the pipe and is not concentrated at the bottom or in the valve.

Figure 4-19. Schematic of Deposit Location Showing Nondestructive Assay Neutron Measurement Count Rates



If one were to assume a uniform distribution of uranium along the length of the pipe and 100 of the 1,190 kg of uranium in the valve, one would obtain a uranium loading of 63.8 kg of uranium per foot along the 205-inch length of pipe. Given a 50% uncertainty in NDA mass measurement, the maximum loading would be 95.7 kg uranium per foot.

The way in which the deposit was formed largely determines its chemical composition and hence its nuclear characteristics. Three possible ways have been identified for deposit formation:
(1) the result of cascade exothermic reactions (commonly called a fire) in 1981, (2) freeze-out of UF_6 in the cold leg, and (3) air in-leakage through the G17 valve, and expansion joint, or some other component.

It was first thought that this deposit resulted from the exothermic reactions that occurred in the K-29 building in 1981. A spectrum of metal fluorides was formed that was distributed near the fire location. The cascade line was opened to air, following the fire, as damaged equipment was removed; however, the location of these fires was several stages away from the location of the subject deposit and it is unlikely that the debris from these fires was transported across several stages of barrier without deposition to the location of present concern. The unit in which the exothermic reactions occurred (Unit 2) was placed on-line again following these incidents; however, the cell that was damaged was taken out of service permanently and some components were cut out and removed. This cell is where the deposit of concern is located.

The second possible scenario of deposit formation is UF_6 freeze-out. This cell did not operate again after the 1981 incident. Accordingly, the B-outlet line block valve was closed and the resulting “leg” to the B bypass line would be cold relative to the B bypass line itself. The UF_6 would condense on the cooler pipe leg surfaces if UF_6 pressures and temperatures were favorable for condensation; however, the entire K-29 building was heated during operation to keep UF_6 from freezing out, and so it is unlikely that conditions in the B outlet line would have been significantly different from the B bypass line. If the deposit were formed in this manner, it would be UF_6 and contain very little hydrogen. Also, since the assumption in the NDA measurements is that the deposit is UO_2F_2, if the deposit is UF_6 instead, the estimated mass of uranium in the deposit would be reduced by a little more than half when neutron measurement techniques are used.

Since there is some deposit in the G17 valve body neck, it is much more likely that the third deposit formation scenario is accurate. The bellows inside the valve body neck probably developed a leak, allowing moist air to enter the valve and the vacuum of the pipe body run. Moist air would be drawn through the valve and through the pipe riser section up towards the B bypass line. If this scenario is correct, one would expect a gradient in the deposit along the pipe length and the chemical form of the deposit should be UO_2F_2 with some degree of hydration. There would likely be more deposit nearer the valve than the B bypass line; however, the neutron count rate measurements show a larger count rate between the pipe expansion joint and the B bypass line. If the deposit formed after the 1981 fire, there would have been no flow of process gas past the failed valve, and therefore the moist air would have traveled farther along the B outlet line before coming into contact with UF_6 gas. In addition, a leak could have developed in the pipe expansion joint bellows, allowing moist air in-leakage and deposit formation up towards the B bypass line. Another possibility is that the deposit could have been caused by both these leaks.

It is generally believed that the deposit was formed by moist air leading in through the valve and/or the pipe expansion joint into the B outlet line. As such, the chemical form of the deposit is UO_2F_2. The NDA department staff believe that the deposit is annular and that it is relatively uniformly distributed along its 205-inch length. Since Unit 2 operated until the plant was shutdown in 1985 and since the system has not been breeched since then, the deposit should have a low hydrogen content.

Computer Model of Deposit

The SCALE-PC, version 4.1, computer code system was used to perform nuclear criticality safety calculations. This system of codes cannot reproduce the exact pipe system geometry. For example, the horizontal section of pipe reduces from 24-inch to a 20-inch diameter where it meets the valve body in a partial conical section. Also, there is a 60˚ elbow where the horizontal pipe bends to meet the bypass line. Certain simplifications were made in modeling the pipe with the computer programs. The pipe was modeled as being essentially infinite in length. This is a good approximation, because the overall length of the deposit in the pipe (205 inches) is many times its diameter (24 inches).

A sensitivity study was performed to evaluate factors that influence criticality and cause the deposit to remain subcritical. The four parameters studied were (1) enrichment, (2) neutron reflection, (3) deposit shape, and (4) hydrogen content (i.e.,H/U ratio). These parameters are compared to measured deposit enrichment and mass. The study of these parameters will help in planning the safe removal of the deposit into safe geometry containers.

Enrichment was varied in these calculations because there is uncertainty in the NDA measured enrichment. The latest nominal measured enrichment is 3.3%, but there is an ~20% uncertainty associated with this value. An earlier measurement gave a nominal enrichment of 2.8%. This section of the diffusion plant operated at a maximum enrichment of 3.59% during the last four years of its operation. Thus, calculations were made at 4% enrichment to include an upper uncertainty bound, and an enrichment of 3% was used as a lower bound.

Two levels of neutron reflection were calculated: 1 inch of water and 12 inches of water surrounding the pipe. Neutron reflection, or those neutrons that leave the pipe and are reflected back into the pipe to undergo reaction, is a measure of the influence of objects near the deposit pipe. Twelve inches of water is considered full water reflection. Full water reflection bounds all reflection conditions that are normal, including neutron reflection from adjacent equipment, structures, walls, floors, and any personnel in the immediate vicinity of the deposit. Twelve inches of water reflection is typically used in safety calculations as an upper limit condition. A 1-inch water neutron reflection condition was used as a practical, lower limit of neutron reflection. There is always some reflection of neutrons into a system from adjacent equipment, air, or the proximity of humans. This condition is considered nominal reflection.

A variety of deposit shapes was examined. The NDA Department staff believes that the deposit is annular, distributed around the inside surface of the pipe. This was concluded by moving a gamma detector around the circumference of the pipe. The gamma reading did not change appreciably, so it was concluded the deposit was annular. If the deposit had been along the bottom of the pipe, the NDA Department staff feels that there would have been a change in reading around the circumference. Also, according to NDA gamma measurements, it appears that the deposit is distributed roughly uniformly along the length of the pipe. Presently, there is no way to measure deposit annular thickness. Various thicknesses can be estimated, based on assumed deposit density, but deposit density is not known because the density depends on the deposit's chemical composition, including the hydrogen content. The calculations in this study considered annular deposits that were 2, 4, 6, and 8 inches thick. Also, various thicknesses of chord shapes were calculated. A chord is a horizontal line joining two parts of the circle of the 24-inch-diameter cylinder at heights of 4.5, 9, 13.5, and 19 inches so that the deposit filled the lower part of the pipe at these thickness. The cross-section processing section of the SCALE code does not allow for chord-shaped geometries; therefore, an "equivalent area" concept was used for these calculations. The cross-sectional area of the chord in the pipe was calculated, and an annular deposit radius giving the equivalent deposit cross-sectional area was determined. The KENO input section describes the chord geometry directly. The calculations also evaluated deposits that filled the pipe entirely.

The amount of hydrogen in the deposit controls the density and the amount of neutron moderation and has a large impact on critical conditions. The hydrogen content was changed by varying the input densities of the deposit materials. Calculations were performed for three orders of magnitude of H/U ratios, for an H/U of 0.8, 2, 4, 8, 16, 50, and 500. These H/U values correspond to a range of the theoretical densities of UO_2F_2 from 6.1 to 0.067 g/cm^3. Chord-shaped and full pipe deposits were calculated with H/U ratios of 50 and 500. Annular deposits were not formed at these high H/U ratios, since the deposit would be a flowable solution and would not likely be annular.

Results and Conclusions

The primary unknowns for these calculations are the deposit configuration (shape and distribution), and hydrogen content (density). Chord-shaped deposits are more reactive (become critical with less mass) than annular deposits. In other words, a chord-shaped deposit at a given value of kg U per foot has a higher k_{eff} than an annular deposit of the same pipe loading. This is because a chord-shaped deposit more closely approximates a sphere than does an annular deposit.

The conservative data predict that the deposit is subcritical if the H/U ratio is less than about 1.0; the deposit is critical if it fills the pipe at an H/U = 2; however, deposits exposed to air for a prolonged period of time could have an H/U ratio of approximately 4.0. The deposit is critical at an annular thickness above about 4 inches for an H/U of 4. At this annular thickness the deposit fills slightly more than 50% of the pipe volume. Also at H/U=4, a chord-shaped deposit that fills less than 50% of the pipe volume is critical.

The most realistic model of the as-is deposit assumes that objects that could reflect neutrons back into the deposit are not close by and also assumes an optimistic 235-U enrichment about midway between two NDA measurements. This indicates that even for these optimistic conditions, the deposit may become critical if the deposit fills or nearly fills the pipe and has an H/U approaching room conditions (i.e., H/U $\simeq$ 4). If the deposit is at an H/U of 4, an annular deposit 6 inches thick (fills about 75% of the pipe) or a chord-shaped deposit thicker than 13 inches (fills about 60% of the pipe) is calculated to be critical.

Recommendations

Near-term activities should focus on better characterization of the deposit. About all that is known at present is the approximate distribution of the total uranium and ^{235}U in the valve and piping. NDA staff should endeavor to establish the deposit's configuration and distribution. If possible, the hydrogen content of the deposit and its neutron multiplication factor, k_{eff}, should be nonintrusively measured. Techniques, such as associated particle imaging and gamma ray and x-ray imaging, might provide detailed deposit configuration information.

A practical near-term activity is to visually examine the deposit with a camera. Photographs showing the color of the deposit would give a qualitative indication of the deposit chemical composition, including the level of hydration. A bright yellow deposit would indicate that the deposit has a high degree of hydration with its composition likely to be UO_2F_2 - $2H_2O$ (i.e., the H/U is 4). An orange deposit would indicate that the deposit has less hydrogen content and might be U_2O_3 F_6 or alpha-phase UOF_4; a green deposit, nickel or copper fluorides, and perhaps UF_4; and a grey deposit, UF_4 powder.

If a camera can access the deposit, then it is conceivable that a grappling device can be placed with the camera and a sample taken of the deposit. Analytical chemistry measurements would then be made to determine the deposit's chemical composition, including its hydrogen content. It must be determined whether analytical chemistry laboratories have the capability of measuring the hydrogen content of uranium deposit material.

Photographs and analytical chemistry measurements of the deposit will enable detailed planning for safe deposit removal. The authors know of no way to place the deposit in an interim critically safe condition, short of deposit removal.

Since only NDA measurements are available now and no visual or chemical characteristics data are available of the deposit, one can only guess what steps a cleanup process would entail. Early, initial plans are to cut the pipe with torches (note that sawing causes vibration), lay the whole pipe section on the floor (to reduce the potential for gravity causing the deposit to collapse onto itself in the 60˚ riser section), cut the pipe into shorter sections (to reduce the fissile mass in any one section), separate the cut sections (to reduce interaction effects), remove the deposit from the cut pipe sections with shovels, and place the collected fissile material in geometrically safe containers for permanent storage.

QUESTIONS:

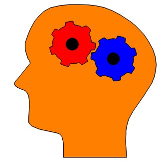
1. What two ways can deposits form in a gaseous UF_6 system and what physical form will the deposit take?

2. How is moderation being added to this deposit?

3. What controls can or have been put in place to control moderation?

4. What physical changes can occur in the plant that would affect the reactivity of the deposit?

Activity 9 - Thermosyphon Evaporator



Purpose: The purpose of this activity is to propose modifications that would allow a system to meet double contingency criteria.

Directions: Read the case study. Answer the questions. Answers are located in the answer key section of the Trainee Guide.

Note: This case study is not meant to be a complete nuclear criticality safety evaluation. It provides background information equivalent to what an NCS engineer might receive prior to an analysis from the process engineer.

BACKGROUND

Scrap recovery has a number of processes that produce contaminated and highly concentrated solutions. A new thermosyphon evaporator is to be installed to facilitate the processing of these solutions. Assume the evaporator design is proven safe for all degrees of interspersed moderation, all concentrations of solutions up to and including solid uranyl nitrate crystals (past operations have demonstrated that this is not an unlikely accident), all credible handling accidents, and interaction with other equipment in proximity to the evaporator. The only remaining portion of the criticality safety evaluation is to address the interface of the system to the hot liquid waste drain.

PROCESS DESCRIPTION

Very low contaminated and highly concentrated solution may be concentrated up to 375 g ^{235}U per liter using the thermosyphon evaporator. The thermosyphon evaporator is basically a shell-and-tube type steam heat exchanger that heats the liquid to boiling. Hot steam is piped through the shell of the heat exchanger. The liquid in the heat exchanger tubes boils. The bubbling liquid flows up and over to the phase separator column where the liquid drops to the bottom of the column and flows back to the bottom of the heat exchanger. The boiled liquid vapors, mostly water with some dilute nitric acid, flow out the top of the phase separator into a water condenser column. Cooling water cools the boiled liquid vapors back to a liquid. The cooling water is piped, again through a shell-and-tube arrangement, through the vapors and evaporator condensate in the condenser. The evaporator condensate, steam condensate, and used cooling water are discharged to the hot liquid waste drain. The process is summarized in the engineer's drawing attached as Figure 4-20.

Operations start by opening transfer valves V-1 or V-2 and turning on the transfer pump. Valves V-4, V-5, and V-6 are opened as necessary to fill the header tank and evaporator to the appropriate level, near the top of the glass column below the phase separator. The pump and valves are turned on and off and opened and closed as necessary to fill the system. Valves V-7 and V-8 are opened to provide approximately 5 to 20 psig of steam pressure (steam pressure above this value may cause excessive boiling). Valve V-11 is opened to provide cooling water to the condenser. The product is evaporated until it reaches approximately 375 g ^{235}U/ℓ or the foreman-specified concentration. The ^{235}U concentration is determined by taking a sample from valve V-10 and counting it on the well counter. When the evaporator reaches the desired concentration, valve V-12 is opened to transfer the solution to the evaporator product column.

If the solution is below 0.05 g $^{235}U/\ell$, it may be transferred using valve V-13 to the hot liquid waste system. After the product transfer, the appropriate valve is closed. Additional solution may be transferred to the evaporator for further operation or the evaporator may be shut down. To shut down the evaporator, the feed transfer pump and steam are turned off and the cooling water and remaining valves are closed after the evaporator cools.

A few other additional points to consider include:

- It only takes 820 grams of optimumly moderated ^{235}U surrounded by water to cause a criticality accident. (Approximately 1.4 kilograms of optimumly moderated ^{235}U will cause a criticality without **any** reflection.) The hot liquid waste line terminates to a series of large tanks.

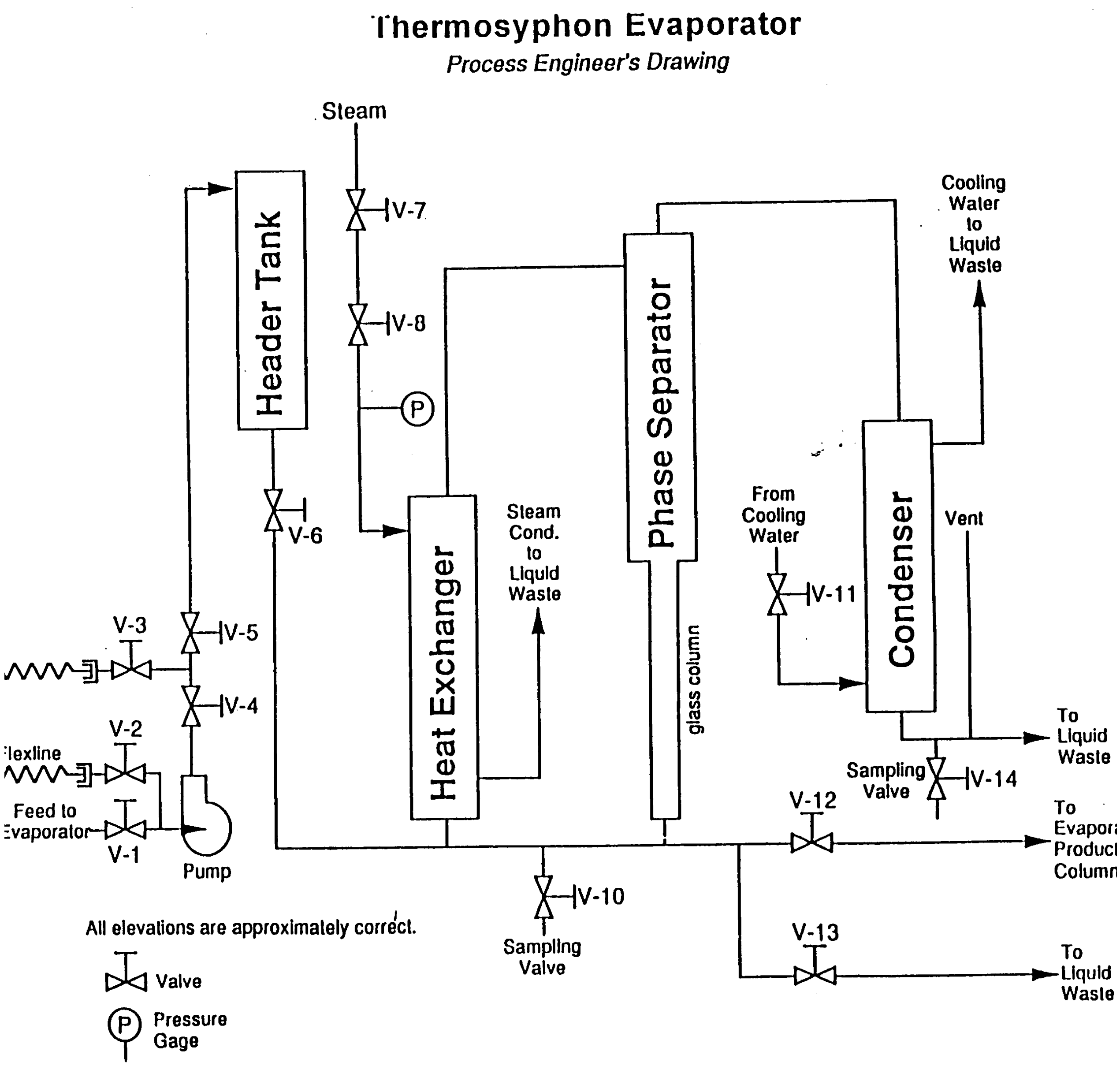
- The average operating capacity for the evaporator is approximately 20 liters of solution. The header tank has a 15-liter capacity. Considering maximum operating concentration of approximately 375 grams $^{235}U/\ell$, 7.5 and 5.6 kilograms of ^{235}U are contained in the evaporator and the header tank, respectively.

- Any solution discharged to the hot liquid waste system is restricted to 0.05 g $^{235}U/\ell$.

- Acids slowly deteriorate valves and piping, especially at elevated temperatures.

- Liquids are quite mobile. Given gravity potentials and pressure differentials, liquids can go almost anywhere. Steam in a liquid can make the liquid lighter and “lift” it in elevation similar to a percolating coffeepot. Steam condensing back to liquid leaves a void that causes a vacuum.

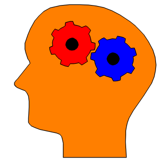
Figure 4-20. Thermosyphon Evaporator
Process Engineer's Drawing



QUESTION:

Using only the process description and the system drawing, propose modifications that would allow the system to meet double contingency criteria.

Activity 10 - Arc Melt Furnace



Purpose: The purpose of this activity is to identify potential accident scenarios and how the "accident" affects one or more of the control factors.

Directions: Read the case study. Complete the questions. Answers are located in the answer key section of the Trainee Guide.

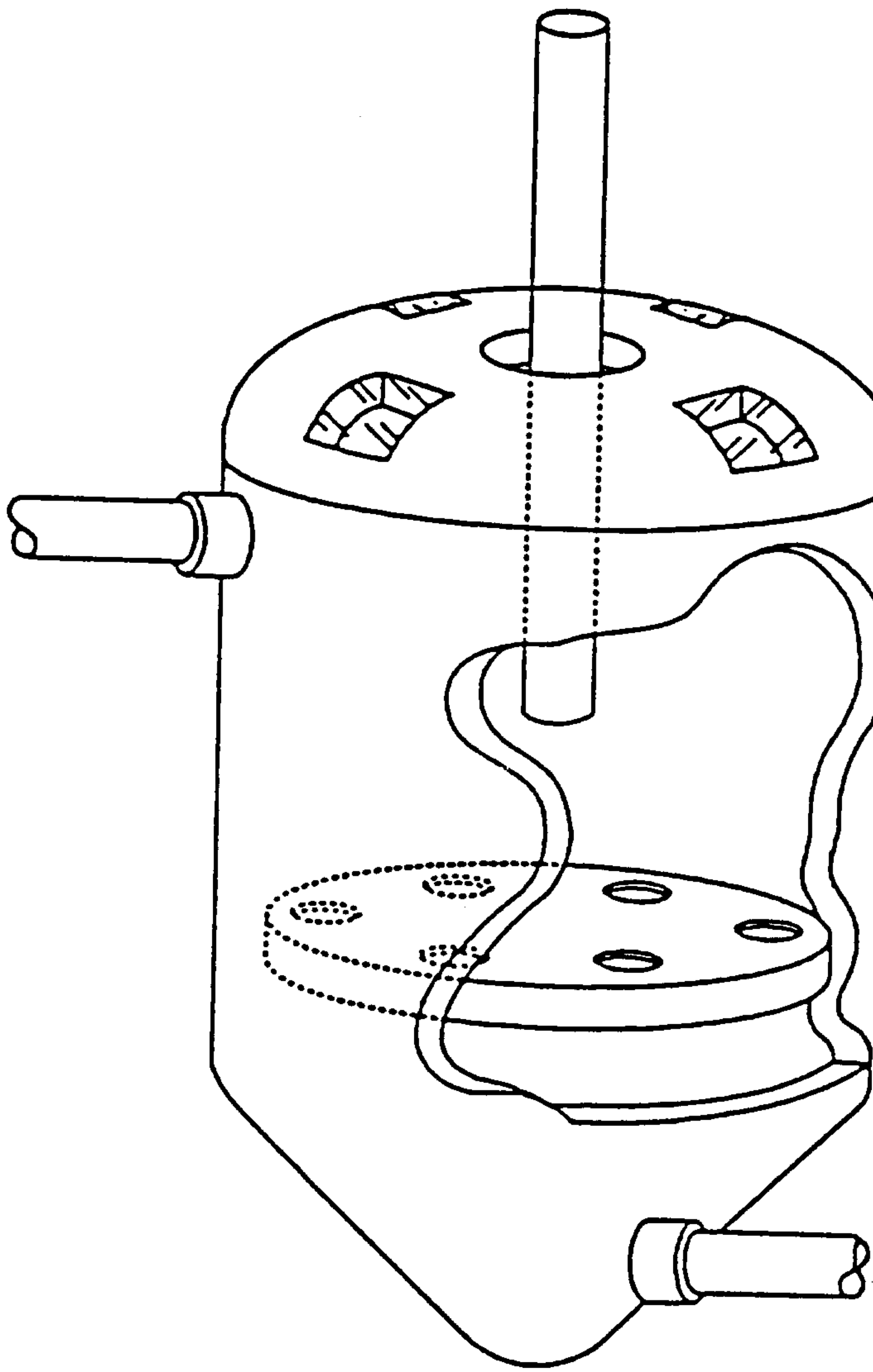
PROCESS DESCRIPTION

You are the nuclear criticality safety engineer assigned to evaluate a new process line your company is developing. The process takes 93% enriched uranium metal and mixes it with aluminum powder to form $UA1_x$ powder alloy. As part of the process, an arc melt furnace is used; you are currently evaluating this furnace. Precisely weighed quantities of uranium metal chunks and aluminum powder are placed into each of six cavities in a copper or graphite hearth inside the furnace. An electrode is positioned into the cavity and discharged, causing the uranium metal chunks and aluminum powder to melt and fuse together, forming a "button." The buttons are repeatedly removed, broken into pieces, and remelted in the furnace to homogenize the alloy. The furnace is also used to remelt "off-spec" $UA1_x$ powder from other process steps.

The process design engineer advises that desired throughput can be achieved by limiting each cavity to a maximum of 350 grams ^{235}U. He provides Figure 4-21 and the following data about the furnace:

- The furnace is a double-walled cylindrical vessel, approximately 16.5 inches inside diameter and 14 inches high.
- The cavities in the hearth are hemispherical, with approximate diameter of 4 3/8 inches. The cavities are positioned in a circular arrangement on a diameter of 9 1/4 inches.
- The furnace has a water cooling jacket surrounding the inner wall.

Figure 4-21. Arc Melt Furnace



QUESTIONS:

1. Identify potential accident scenarios and how the "accident" effects one or more of the control factors.

2. Propose modifications that would allow the system to meet double contingency.

Self-Check Questions 4-5

Complete the questions. Provide examples, where appropriate. Answers are located in the answer key section of the Trainee Guide.

1. What constitutes a change in process conditions?

2. Define "unlikely."

3. How can independence be judged?

4. When would changes be considered concurrent?

5. Does the double-contingency principle imply that the system should be critical following two changes (that is, two changes substantial enough to require protection)?

Directions: Explain how failure to meet the facilitation considerations could lead to "reduction" of a "higher-level control" (for example, favorable geometry down through soluble poison) to what effectively would become an administrative control.

6. Need for control

7. Manageability

8. Ergonomics
(human factors)

9. Uniformity

10. Representative samples

11. Inspection and clean-out

12. Flushing

13. Installation

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objective

When you finish this section, you will be able to:

4.1.9 Identify conservatism as it relates to nuclear criticality safety.

CONSERVATISM

General Considerations

General considerations for conservatism:

- Apply all assay uncertainties, manufacturing tolerances, and other anticipated variations, perhaps with a **slight** increase, so as to be conservative.
- Overall model should be verified to be conservative to ensure that actual configuration is subcritical.
- Overall model should not be excessively conservative.

What Are the Potential Pitfalls of Excessive Conservatism?

Potential pitfalls of excessive conservatism may include unnecessarily complex controls, which may lead to violations. These may result from forcing double contingency on configurations calculated to be critical that would actually be subcritical if more realistic (yet still conservative) assumptions were applied.

Another pitfall may include increased risks other than from nuclear criticality safety (for example, toxicity of non-water fire-fighting agents used to avoid optimum moderation conditions).

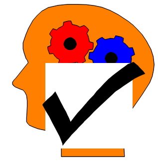
Examples of Conservative Applications

Table 4-4 shows examples of conservative applications in nuclear criticality safety analyses

Table 4-4. Examples of Conservative Applications in NCS Analyses

Control Factors	Examples of Conservative Applications in NCS Analyses
Mass and Volume	• Increase maximum expected mass and/or decrease minimum expected volume (see also Concentration and Density). • Assume a fuel pin lattice is completely occupied by fuel pins, even if some locations are empty (see also Interaction and Separation).
Enrichment	• Increase maximum expected enrichment.
Geometry or Shape	• Use shape that is somewhat more "spherical" (i.e., model ellipsoid or cylinder as a sphere of the same volume or cuboid as a cube of the same volume).
Interaction and Separation	• Decrease spacing of air-spaced units. • Modify spacing of units that are, or may be, moderated interstitially in a manner that increases reactivity. • Represent a large array of units as an infinite planar array (e.g., for fuel pins or fuel assemblies) or as a fully finite array (e.g., for containers stacked in x-, y-, and z-directions).
Moderation	• Assume flooding to optimum moderations (see also Heterogeneity).
Reflection	• Use more closely fitting reflection (e.g., by floors, walls, ceiling). • Assume "full-water" (30-cm) or concrete reflection for nominal conditions.
Concentration and Density	• Increase density of solids (see also Mass and Volume). • Assume optimum concentration (i.e., that with maximum reactivity) (see also Moderation).
Neutron Absorbers and Poisons	• Neglect presence of structural materials. • Neglect presence of absorbing elements in cladding material (e.g., iron in zirconium alloy for LWR fuel pins). • Assume lower neutron-poison content and/or worst-case poison distribution (e.g., soluble poison precipitates out or solid poison leaches or migrates).
Heterogeneity	• For LEU systems, assume optimum (maximum reactivity) configuration, based on both size of fissionable "pieces" and amount of interstitial moderator (see also Moderation, and Interaction and Separation). • For HEU systems, effect is generally not applicable.

Activity 11 - Conservatism in Nuclear Criticality Safety



Purpose: The purpose of this activity is to determine the conservative assumptions ("worst case") for each of the control factors in a given situation.

Directions: Complete the following table. Answers are located in the answer key section of the Trainee Guide.

Situation: An operation involves combining two partially full containers of uranium oxide. The containers are approved to hold 10 kgs of 90% enriched dry oxide. Each container must be spaced a minimum of 12 inches from one another.

CONTROL FACTORS	CONSERVATIVE ASSUMPTIONS
Mass and Volume	
Enrichment	
Geometry or Shape	
Interaction and Separation	
Moderation	
Reflection	
Concentration and Density	
Neutron Absorbers or Poisons	
Heterogeneity	

Self-Check Questions 4-6

Match the **Example of Conservative Application** in Column A with a **Control Factor** in Column B. Answers are located in the answer key section of the Trainee Guide.

Column A Example of Conservative Application	Column B Control Factor
A. For HEU systems, effect is generally not applicable.	1.___ Moderation
B. Increase maximum expected enrichment.	2.___ Heterogeneity
C. Increase maximum expected mass and/or decrease minimum expected volume.	3.___ Mass and Volume
D. Assume flooding to optimum moderation.	4.___ Reflection
E. Assume full-water or concrete reflection for nominal conditions.	5.___ Interaction and Separation
F. Use shape that is somewhat more spherical.	6.___ Geometry or Shape
G. Decrease spacing of air-spaced units.	7.___ Neutron Absorbers
H. Neglect presence of structural materials.	8.___ Concentration and Density
I. Increase density of solids.	9.___ Enrichment

You have completed this section.
Please check off your progress on the tracking form.
Go to the next section.

Learning Objectives

When you finish this section, you will be able to:

4.1.10 Distinguish between neutron and gamma criticality alarms.

4.1.11 Given a scenario, determine compliance with NRC Regulatory Guide 3.71 and ANSI/ANS 8.3.

NUCLEAR CRITICALITY ACCIDENT ALARMS

Purpose

The purpose of nuclear criticality accident alarms and alarm systems is to alert personnel to promptly evacuate the area to reduce the risk of exposure to radiation. Generally, the nuclear criticality accident alarm system is meant to prevent large exposures to many people; however, they serve multiple purposes. By inducing evacuation, they mitigate exposure of persons in the area to residual radioactivity and to possible ongoing criticality pulses. Thus, they could be regarded as mitigation systems, like reactor emergency evacuations. In addition, they alert operators to the fact that, not only has a criticality occurred but also, in most cases, the existing situation has a high potential for another criticality. The criticality alarm thus permits prevention of further criticalities and exposure of persons by allowing prudent response of the operating staff. In this sense, criticality alarm systems are true safety systems.

Regulatory Guidance

NRC Regulatory Guide 3.71, "Nuclear Criticality Safety Standards for Fuels and Material Facilities," generally accepts the guidance and standards delineated in ANSI/ANS-8.3-1986, "Criticality Accident Alarm System," with a few limitations. These limitations are based on requirements specified in Section 70.24 of Title 10 CFR Part 70.

Section 70.24, "Criticality Accident Requirements," of Title 10 CFR Part 70, "Domestic Licensing of Special Nuclear Materials," specifies that licensees who are authorized to possess special nuclear material in excess of certain amounts are required to maintain a criticality accident alarm system.

ANSI/ANS-8.3-1986, "Criticality Accident Alarm System," not only addresses the need for alarm systems but also describes the characteristics of alarm signals, dependability, testing procedures, and emergency planning. The specifications for alarm signals include recommended sound pressure levels and activation mechanisms that do not depend on human action.

The standard also provides guidance on the criteria for system design including:

- Reliability
- Vulnerability
- Seismic tolerance
- Failure warning
- Response time
- Detection criterion
- Sensitivity
- Spacing

Table 4-5 provides a comparison of where the NRC Regulatory Guide 3.71 and ANSI/ANS Standard 8.3-1986 differ.

Table 4-5. Comparison of Regulatory Guide 3.71 and ANSI/ANS 8.3

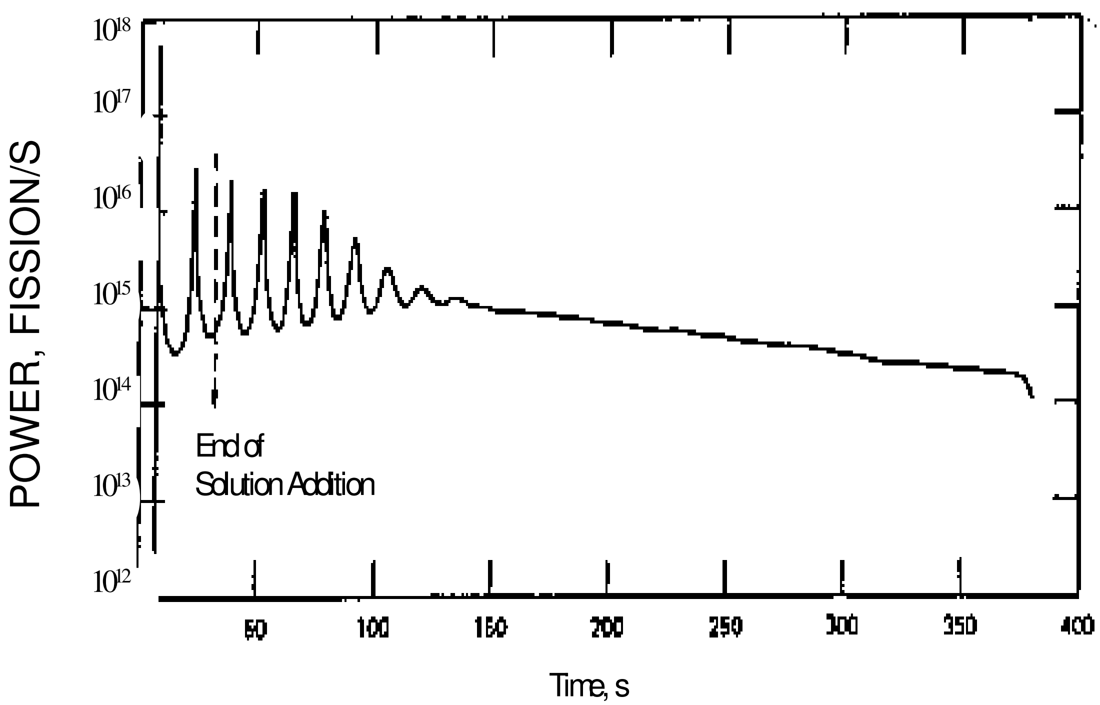
Item	NRC Regulatory Guide 3.71 (Based on Section 70.24 of Title 10 CFR Part 70)	ANSI/ANS-8.3 - 1986	Notes
Area coverage	"...in each area in which such licensed special nuclear materials is handled, used, or stored..."	"The need for criticality alarm systems shall be evaluated for all activities in which the inventory of fissionable materials in individual unrelated areas exceeds 700 g of ^{235}U, 520 g of ^{233}U, or 450 g of ^{239}Pu, or any combination of these three isotopes." (§4.2.1)	If such an evaluation determines that a criticality potential does not exist, the NRC Regulatory Guide suggests that the licensee request an exemption from §70.24.
Detector Coverage	Each area shall be covered by two detectors.	Coverage allowed by reliable single-detector channels. (§4.5.1)	§4.5.1 concerns providing consideration to the avoidance of false alarms and suggests that this may be accomplished by providing reliable single-detector channels or by requiring concurrent response of two or more detectors to initiate the alarm.

Background

A nuclear criticality accident occurs without advance warning. There are no discernible indications that the accident is about to happen. Therefore, nuclear criticality accident alarms are sometimes referred to as "after the fact alarms," because the alarm sounds after the criticality has occurred. If a criticality should occur, an immediate evacuation alarm signal will activate for nearby personnel. Generally, the alarm will sound at about half a second AFTER the criticality has occurred.

The initial pulse may be followed by successive pulses until the reaction is eventually terminated. Successive pulses can occur for several seconds to several days. Figure 4-22 illustrates initial and successive pulses, using data from the French CRAC 13 experiment.

Figure 4-22. Power Trace for the French CRAC 13



It also depicts the power trace for the French CRAC 13 experiment, showing initial and successive pulses followed by eventual quiescence. Solution was added through the completion of the second pulse.

Components

Criticality alarm systems are generally composed of neutron or gamma radiation detectors and annunciation (signal) equipment. In addition, administrative procedures are needed to ensure that the equipment is maintained and properly calibrated.

Detection Criterion

As stated in ANSI/ANS-8.3:

> "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 of concern may be assumed to deliver the equivalent of an absorbed dose in free air of 20 rad at a distance of 2 m from the reacting material within 60 s."** (Extracted from American National Standard ANSI/ANS-8.3-1986 with permission of the publisher, the American Nuclear Society.)

The minimum accident of concern assumption determines the alarm set point and the detector spacing in a work area.

Neutron vs Gamma Detectors

The selection of the detector will generally be determined by the fissile material being used and the type of radiation emitted in the event of a criticality accident.

Some facilities can accidentally produce gamma fluxes capable of setting off a criticality alarm without actually having a criticality. This situation would produce false alarms. These facilities would most likely use a neutron detector instead of a gamma detector.

The ^{6}Li used with other elements is an example of a neutron detector. Geiger-Mueller detectors and sodium iodide [NaI (Tl)] detectors are examples of detectors used to detect gamma radiation.

Criticality Accident Alarm System Logic

Criticality accident alarm system logic is a term used when describing the circuitry designed into the criticality accident alarm system to lessen the incidence of false alarms. It may also be referred to as coincidence control or decision-making logic.

It is recommended that there be a response from two out of three detector channels to initiate the alarm. In addition, the failure of any one detector channel would not compromise the functioning of the system. This makes the logic one of two for activation of the alarm signal.

It is highly recommended that battery backups be included in the system to ensure that power is maintained to the accident alarm systems during power failures.

Failure Warning

Criticality accident alarms and alarm systems generally have built-in signals that indicate a malfunction or loss of power. These signals may be visible, audible, or both. Some alarms have built-in battery backup systems with battery chargers.

Testing

The alarms and alarm systems are tested periodically to ensure that:

- The system is operating within the design specifications, especially following modification or repair, including maintenance of redundancy.
- The system responds to radiation as designed.
- The evacuation signal is audible above background noise. This signal must be discernible as an evacuation alarm.

Test results are recorded and maintained for each system.

How Does a Criticality Alarm System Work?

1. There are several monitors placed in locations that can be affected by a criticality accident.
2. If an accident should happen, the criticality accident generates radiation.
3. The alarm system will activate.
   a. The monitors will detect radiation (gamma and/or neutrons).
   b. The monitors are calibrated to specific set points.
4. The evacuation alarm signal sounds in all areas where dose COULD exceed 12 rad per ANSI 8.3.

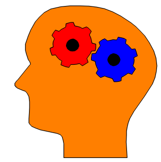
THIS IS AN AFTER-THE-FACT ALARM. THE ALARM SOUNDS AT ABOUT HALF A SECOND AFTER THE CRITICALITY HAS OCCURRED.

To meet the standards, the alarm must do two things:

1. Immediately detect an accident that would produce 20 rad/minute at 2 meters.
2. Initiate an audible alarm within 0.5 second of $\geq$75 dB but $\leq$ 115 dB and at least 10 dB above background noise.

There are many backup components built into the monitoring system. This is usually referred to as maintaining a high level of **redundancy**.

Activity 12 - Criticality Accident Alarms



Purpose: The purpose of this activity is to determine compliance or noncompliance status with ANSI/ANS-8.3 and NRC Regulatory Guide 3.71.

Directions: For each of the case studies provided, determine compliance status to the requirements in ANSI/ANS-8.3-1986 and NRC Regulatory Guide 3.71. Answers are located in the answer key section of the Trainee Guide.

Case 1: During a routine test of the criticality alarm system, a licensee discovered that several of the site's audible alarms (howlers) did not actuate. The licensee found that wiring to the alarms had been accidentally broken while other electrical cables were being pulled through the cable run that contained criticality alarm wiring. The licensee's system provided indication, prior to the next scheduled test, that some of the audible alarms had been disabled.

1. Does the situation described in Case 1 indicate compliance or noncompliance with the ANSI Standard and Regulatory Guide?

2. Specify the evidence you have to support your conclusion.

3. What lessons can be learned from this situation?

Case 2: Engineering drawings describing modifications at a licensed facility specified removal of "heat detectors (radiation)." The licensee's review of the modification package did not recognize that it included removal, rather than relocation, of criticality alarm system detectors.

When the specified detectors were removed, no alarm was generated at the system monitoring panel. Subsequent investigation disclosed that the alarm panel was wired in such a way that, although a "failure" light was activated at an intermediate panel (an unmanned location), a loss of power/loss of detector signal was not generated at the monitoring panel in a normally manned area.

4. Does the situation described in Case 2 indicate compliance or noncompliance with the ANSI Standard and Regulatory Guide?

5. Specify the evidence you have to support your conclusion.

6. What lessons can be learned from this situation?

Case 3: A licensee experienced an activation of the plant's criticality alarm system, but no criticality had actually occurred. Investigation found that the alarm had been generated when the uninterruptible power supply (UPS) circuit that powered the alarm system was turned off by means of a switch in the facility's main computer room.

The switch had been backfitted to the system to allow for cutoff of all power to the computer room in emergency situations and was not intended to affect power to the criticality alarm system. The modification review associated with the addition of the switch did not identify the fact that the planned location was between the UPS source and the primary criticality alarm system circuit.

7. Does the situation described in Case 3 indicate compliance or noncompliance with the ANSI Standard and Regulatory Guide?

8. What lessons can be learned from this situation?

Self-Check Questions 4-7

Answer the following questions. Answers are located in the answer key section of the Trainee Guide.

1. What is the purpose of a criticality accident alarm system?

2. "Each area shall be covered by two detectors" is a requirement of _______ coverage.

3. Geiger-Mueller detector is an example of a _______ detector.

4. What type of alarm system is a criticality accident alarm system?

Case 1: During an electrical storm, the criticality safety alarms at ONLY the waste treatment facility sounded because of a momentary power interruption. Personnel in the building did not evacuate but instead called Security, who in turn notified Radiation Control and Electrical Shop personnel. The electricians arrived at the building to silence the alarms. They had not received clearance from Radiation Control. They entered the waste treatment facility and silenced the alarms.

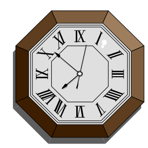
5. Does the situation described in Case 1 indicate compliance or noncompliance with the ANSI Standard and Regulatory Guide?

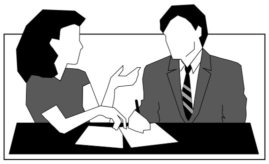
6. Specify the evidence you have to support your conclusion.

7. What can be inferred from the personnel response in this case?

8. What lessons can be learned from this situation?

It's time to schedule a progress meeting with your administrator. Review the progress meeting form on the next page. In Part III, As a Regulator, write your specific questions to discuss with the administrator.





Progress Review Meeting Form

Date Scheduled:________________________________**Location:**______________________

I. The following suggested items should be discussed with the administrator as to how they pertain to your current position:

- Fundamental concepts of nuclear criticality safety
- Identification of NCS control factors and their hierarchy
- Double contingency principle
- Conservatism
- Nuclear criticality accident alarms

II. Use the space below to take notes during your meeting.

III. As a Regulator:

- How do I verify the adequacy of the monitoring/alarm system design and performance requirements?
- How do I verify that NCS limits and control systems identified in the new or revised safety analyses are in place and are being followed?
- When I tour a facility to maintain familiarity with the entire process, how do I confirm that NCS practices observed seem satisfactory?
- Tell me how I verify by observation, discussion, and document review that NCS limits on controlled parameters and NCS control systems are contained in written operating procedures.
- What documentation related to nuclear criticality safety would you recommend I review prior to visiting or conducting an inspection at a specific fuel cycle facility?

Use the space below to write your specific questions.

IV. Further assignments? If yes, please note and complete. If no, initial completion of progress meeting on tracking form.

Suggested item:

- Review the Memorandum of Understanding between NRC and Occupational Safety and Health Administration (OSHA).

Ensure that you and your administrator have dated and initialed your progress on your tracking form for this module. Go to the module summary.

MODULE SUMMARY

In summary, this module addressed topics related to nuclear criticality safety controls. Some of the topics presented were:

- Definition of Nuclear Criticality Safety and Nuclear Criticality Accident
- Identification of Nuclear Criticality Safety Control Factors
- Types of Controls
- Hierarchy of Nuclear Criticality Safety Control Factors
- Double Contingency Principle
- Conservatism
- Nuclear Criticality Accident Alarms

Congratulations! You are ready to go to the next assigned module.