

Criticality Safety Basics, A Study Guide

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Criticality Safety Basics, A Study Guide

LMITCO Criticality Safety Organization

September 1999

**Idaho National Engineering and Environmental Laboratory
Applied Engineering and Development Department
Lockheed Martin Idaho Technologies Company
Idaho Falls, Idaho 83415**

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Abstract

Nuclear power is a valuable and efficient energy alternative in our energy-intensive society. But elements that can generate nuclear power have properties that require these elements be handled with caution. If improperly handled, a criticality accident could result, which could severely harm workers and damage equipment.

This document is a self-study and classroom guide, for criticality safety of activities with fissile materials outside nuclear reactors. INEEL areas involved with such activities include laboratories, processing and conditioning areas, analysis and testing areas, and storage areas. Most material of concern in these areas is in the form of nuclear fuel assemblies, elements, or pieces. However, INEEL personnel are also concerned about criticality safety of material in many other forms (for example, samples, sources, and waste).

This guide provides a *basic* overview of criticality safety and criticality accident prevention methods divided into three parts: theory, application, and history. Except for topic emphasis, theory and history information is general while application information is INEEL-specific. General INEEL operating limits are discussed but, except examples, area- and operation-specific limits are taught elsewhere, often as formal on-the-job training.

Information presented here should be useful to all INEEL personnel who must know criticality safety *basics* to perform their assignments safely or to design critically safe equipment or operations.

However, this guide's primary target audience is fissile material handler candidates. These individuals must understand much of the information presented here. However, many lessons include clearly identified additional information that candidates may review at their own option. Also, where many examples are provided, candidates need review only two or three examples selected for applicability to the candidate's assignments.

This guide is revised as needed to reflect program changes, user requests, and better information. The most recent revision's substantive changes are summarized here and marked by a sidebar. Non-substantive changes are neither marked nor summarized. Revision 0 established the basic text, integrating various facility-specific programs. Revision 1 corrected paraphrased DOE-ID and NRC requirements, clarified data for fissile solutions and metals, and supplemented definitions.

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Acronyms, Initialisms, and Symbols

| | |
|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ATR | Advanced Test Reactor at TRA, acronym refers to reactor itself and to reactor's facility |
| ATRC | ATR Critical Facility at TRA, acronym refers to reactor itself and to reactor's facility |
| CAS | criticality alarm system, also called criticality accident alarm system (CAAS) elsewhere |
| CCA | criticality control area, formerly FMCA (Fissile Material Control Area) in some INEEL areas |
| CDS | criticality detection system |
| CI | criticality index; part of the more widely known TI. |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| FHU | fuel handling unit |
| FMH | Fissile Material Handler, also called Fissionable Material Handler elsewhere |
| FSA | FAST Fuel Storage Area |
| ICPP | Idaho Chemical Processing Plant, now known as INTEC |
| INEEL | Idaho National Engineering and Environmental Laboratory, ¹ formerly INEL (Idaho National Engineering Laboratory), formerly NRTS (National Reactor Testing Station) |
| INTEC | Idaho Nuclear Technology and Engineering Center, formerly ICPP |
| k_{eff} | effective neutron multiplication factor, also written as k , k_{eff} , $k_{\text{-eff}}$, and $k_{\text{-effective}}$ |
| LMITCO | Lockheed Martin Idaho Technologies Company, Inc. Idaho Falls, ID; primary INEEL contractor at time this revision was prepared (late FY99). BBWI (Bechtel BWXT Idaho, Ltd.) will assume the contract October 1, 1999. |
| MCP | management control procedure |
| NMIS | Nuclear Material Inspection and Storage |
| NRC | U.S. Nuclear Regulatory Commission |
| PRD | program requirements document |
| RWMC | Radioactive Waste Management Complex |
| TAN | Test Area North |
| TI | transport index, the criticality part of TI is often now called CI |
| TRA | Test Reactor Area |

¹ For this guide's purposes, the INEEL is limited to portions administered under DOE's current primary Management and Operator Contractor for the INEEL. This limitation typically excludes the Naval Reactor Facility and Argonne-West facility, which are technically part of the INEEL.

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Part 1 Theory

Part 1 addresses the theory behind criticality safety in three lessons. Information is general and basic. It applies to any criticality safety program.

However, information depth and emphasis is tailored for INEEL purposes. This tailoring should assist students and instructors in using their time more efficiently.

Fissile Material Handler candidates should understand concepts presented here but they need not review items presented as additional information.

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Lesson 1 The Atom and Its Particles

Introduction

Understanding criticality safety fundamental principles begins with the elemental building block of matter, the atom. A basic knowledge of the atom, its parts, how these parts bind together, and behavior of one of these parts lays the foundation for understanding the fission process. Lesson 1 provides this background information.

Review questions are provided at the end of this chapter to test your comprehension.

Objectives

Describe basic atomic structure.

Define atomic number, mass number, and isotope.

Explain how *binding force* keeps an atomic nucleus stable.

Describe two major ways in which a neutron can interact with an atomic nucleus.

Describe neutron scatter and its effect on a free neutron.

Identify two possible results from a neutron absorption event.

Topic 1.1 Atomic Structure

1.1.1 Molecules and Atoms

Matter is composed of molecules, which are composed of atoms. For example, water is made of water molecules. A water molecule is made of two atoms of the element hydrogen (H) and one atom of the element oxygen (O). A water molecule is commonly represented as H_2O .

An **atom** is the smallest component of a chemical element having all chemical properties of that element. Everything in the observable universe is composed of atoms. They are so small that one hundred million of them lined up, end on end, would be no larger than the tip of your little finger.

As small as it is, an atom is not the smallest particle of matter. Every atom can be divided into smaller components consisting of a core and an outer area, indicated in Figure 1. The core is called the *nucleus*. Orbiting *electrons* make-up the outer area.

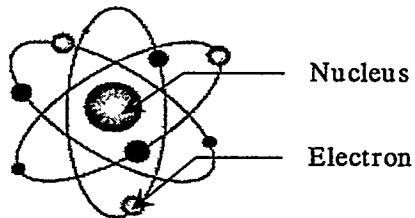


Figure 1 The Atom

1.1.2 Nucleus: Protons and Neutrons

An atom's nucleus primarily contains two types of particles: *protons* and *neutrons*. They are very similar in size and mass but differ in electrical charge. Protons are positively charged particles, while neutrons are electrically neutral. Overall, the nucleus has a net positive charge. Protons and neutrons are held together in the nucleus by a force called *binding energy*.

1.1.3 **Electrons**

Very small particles called *electrons* orbit the nucleus. Each electron carries a negative electrical charge equal to but opposite the electrical charge of a proton. An electron's orbiting motion provides energy that helps keep it separate from the nucleus. However, attraction between the nucleus' positive charge and the electrons' negative charge helps hold an atom together.

1.1.4 **Atomic Number**

The chemical identity of an element is determined by its atomic number. **The atomic number is the number of protons in an atomic nucleus.** Each element has its own unique atomic number. For example, all hydrogen atoms have one proton; all uranium atoms have 92 protons.

1.1.5 **Isotopes**

There can be several atoms of the same element with different numbers of neutrons in their nuclei. Using hydrogen as an example, two naturally occurring hydrogen atoms have one proton each in their nuclei, but one has no neutrons and the other has one neutron. As another example, all atoms with 92 protons are uranium. Different uranium atoms, however, can have 141, 142, 143, or 146 neutrons (^{233}U , ^{234}U , ^{235}U , and ^{238}U).

Atoms of the same element that differ only in numbers of neutrons are called isotopes of the element. **An isotope is one of a group of two or more atoms having the same number of protons but a different number of neutrons.**

Additional Information

Isotope is now often used instead of *nuclide*, but these terms originally were not synonymous (see definitions).

Ions are included here only for a more complete description of atoms. In an uncharged (electrically neutral) atom, the number of protons (positively charged particles) is equal to the number of electrons (negatively charged particles). If an atom were to either lose or gain an electron, which sometimes happens, the atom would have an overall positive or negative charge. **An atom that is not electrically neutral is called an ion.**

1.1.6 **Mass Number**

Each isotope is identified numerically, but not by the number of protons. For example, uranium isotopes are identified by a mass number such as U-233 for ^{233}U and U-238 for ^{238}U . **Mass number is the total number of protons and neutrons in an atomic nucleus.**

Additional Information

Although technically incorrect, an atom's mass number is sometimes called its *atomic mass* or *atomic weight*. They are misidentified because mass number and atomic mass are nearly equal in value. The atomic mass of a neutron or proton is nearly one amu (atomic mass unit) and the cumulative mass of electrons is usually considered negligible.

Topic 1.2 Atomic Stability

1.2.1 Binding Energy

In light atoms, those with a low atomic number, the number of neutrons in the nucleus is approximately the same as the number of protons. In heavy atoms, those with high atomic numbers, the number of neutrons is greater than (up to about 1.6 times) the number of protons. For example, ^4He (helium) has 2 protons and 2 neutrons, and ^{238}U has 92 protons and 146 neutrons. In general, atoms with a higher atomic number also have a higher ratio of neutrons to protons. Why?

The ratio is greater because more neutrons are required to compensate for electric repulsive forces of protons on one another (like charges repel). Shared energy between neutrons and protons keeps repulsive forces from breaking the nucleus apart. **This force between neutrons and protons, which holds an atomic nucleus together, is called the atomic *binding force* or *binding energy*.**

1.2.2 Radioactive Decay

The heavier the element, the more likely proton repulsive forces will overcome binding energy holding the nucleus together. At atomic number 83 (bismuth), a point is reached where more neutrons can no longer maintain a stable nucleus.

However, a nucleus does not just fly apart because it is unstable. Atoms heavier than bismuth are naturally unstable, or *radioactive*. **Unstable nuclei stabilize their structure through *radioactive decay*, which allows an atom to rid itself of excess energy by releasing particulate and/or electromagnetic radiation.** Some atoms emit beta particles to attain stability, others emit alpha particles. Gamma rays are frequently given off with particulate alpha and beta emissions.

Additional Information

Radiological training discusses radiation and radioactive decay in more detail.

Elements heavier than bismuth are not only radioactive, they are also most prone to split (fission) and cause a chain reaction of fissions. This process is explained in the next lesson.

Topic 1.3 Neutron Interaction

1.3.1 General Background

An atomic particle can be free (not attached to a particular atom). Particles become free in a variety of ways but in this topic we are only concerned with the neutron. A free neutron exists because it was released (born) during a nuclear fission, a process that will be described in the next lesson.

A released neutron is free for only a short time. During that time it travels and interacts with one or more atomic nuclei. These interactions are important because criticality safety concerns can arise from them.

For our purposes, there are two major ways in which neutrons interact with atomic nuclei: *scattering* (with or without slowing the neutron) and *absorption* (with or without *fissioning* the nucleus).

The type of interaction a neutron undergoes depends largely on its energy. Neutrons are commonly divided into at least three energy groups, each of which defines a range of neutron velocities: *fast*, *intermediate*, and *thermal* (slow).

Additional Information

Most fission neutrons are born *fast*. They then go through a series of interactions, which might or might not end in another fission.

1.3.2 Neutron Scattering

Neutron scattering occurs when a neutron collides with a nucleus and bounces off. This interaction is called scattering because the neutron changes its travel direction (see Figure 2). The neutron also might slow down a little (lose energy) as a result of the collision.

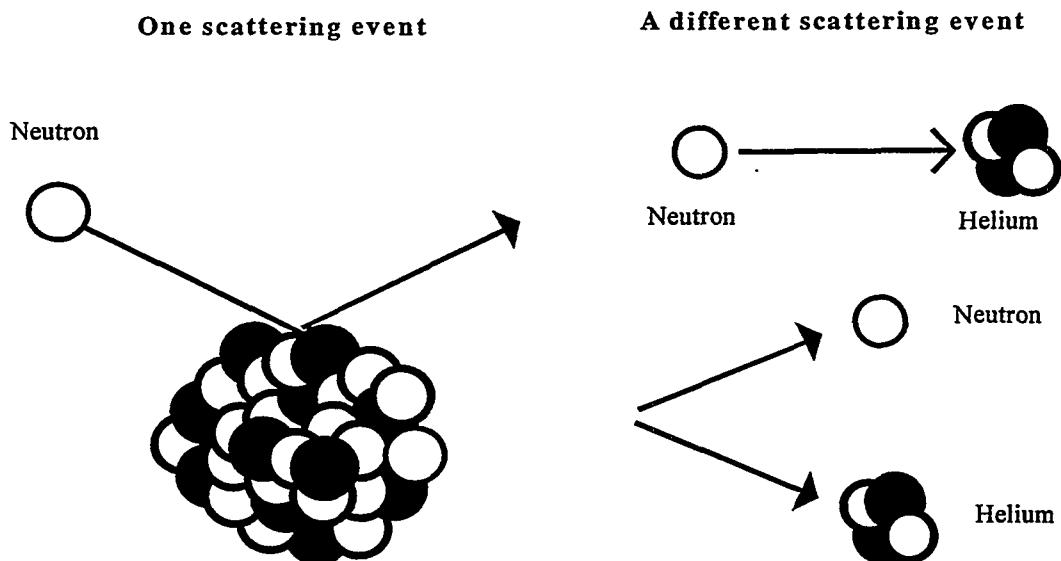


Figure 2 Neutron Scattering

Scattering is the most likely interaction a fast or intermediate neutron will experience. The extent to which a neutron loses energy depends on its energy before collision and the nature of the target (scattering) nucleus.

A fast neutron that collides with a heavy or intermediate nucleus usually rebounds, losing very little energy, in much the same way as a billiard ball bounces off a bowling ball.

If a neutron collides with a light nucleus, its energy loss is relatively large, similar to a billiard ball striking another billiard ball. With repeated collisions neutrons lose enough energy to put them at thermal (low) energies. At this point they are at the same energy level as gas molecules in the same environment. This is important because a thermal neutron is more likely to cause fission than a fast neutron.

Additional Information

Heavy nuclei are often identified as nuclei with an atomic number greater than 25. Neutrons colliding with such nuclei change direction losing little or no energy. This is called *inelastic scattering*. An inelastic scattering event is depicted on the left side of Figure 2. Inelastic scattering is one mechanism for reflecting neutrons (see Topic 3.3).

Light nuclei are usually identified as those with an atomic number less than 25. Neutrons colliding with light nuclei transfer some of their energy to the target nuclei. This is called *elastic scattering*. An elastic scattering event is depicted on the right side of Figure 2. The lighter the target nuclei, the more energy a neutron is likely to lose. Elastic scattering is a mechanism for moderating (Topic 3.3) and reflecting (Topic 3.4) neutrons.

1.3.3 **Neutron Absorption**

Fast, intermediate, or slow, a free neutron will soon be absorbed into a nucleus. **Neutron absorption occurs when a neutron collides with a nucleus and becomes part of that nucleus.** Also called neutron capture, this interaction is shown in Figure 3.

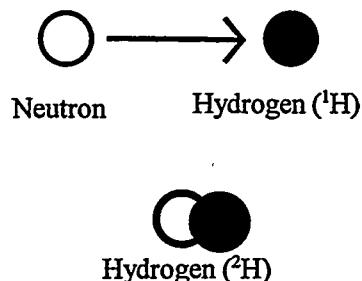


Figure 3 Neutron Absorption

An absorbed neutron can remain part of the nucleus or it can cause fission.

Additional Information

If an absorbed neutron remains part of the nucleus, the atom would give off its excess energy through radioactive decay. For example, a neutron could collide with a ^{235}U nucleus and be absorbed without causing fission. (Only 84% of thermal neutrons absorbed by ^{235}U atoms cause fissions). In this case, the nucleus would change to isotope ^{236}U and give off its excess energy as gamma radiation. Affects of neutron absorption without fission are discussed further in Topic 3.5.

Alternatively a neutron can be absorbed and cause the nucleus to fission. Fission is the process whereby a large unstable nucleus absorbs a neutron and splits into two fragments, releasing energy. Fission is described further in Lesson 2.

Review Questions

1. _____ and _____ are atomic particles that make up the atomic nucleus. protons, neutrons
2. _____ are atomic particles that orbit the nucleus. electrons
3. The _____ is the number of protons in an atom's nucleus, chemically identifying the specific element. atomic number
4. The number of protons and neutrons in an atom's nucleus is that atom's _____. mass number
5. Atoms of the same element with different numbers of neutrons, like ^{238}Pu and ^{239}Pu , are called _____. isotopes
6. An atomic nucleus is held together by a force exhibited between neutrons and protons called binding _____. force, energy
7. Heavy elements (atoms of elements with 83 or more protons) are unstable and _____. radioactive
8. A major type of interaction between a free neutron and a nucleus is neutron _____. (with or without slowing the neutron). scattering
9. As a result of a neutron scatter event, a neutron will _____. It can also lose energy (slow down). change direction
10. Another major type of interaction between a free neutron and nucleus is _____. (with or without fissioning the nucleus). absorption
11. As a result of a neutron absorption, a nucleus might keep the neutron (change to a different isotope) or it could _____. fission

Lesson 2 Nuclear Fission and k_{eff}

Introduction

To understand nuclear criticality, one must first understand some fission process basics. In this lesson you will learn fission fundamentals, how fission can result in nuclear criticality, and the definition of *critical condition*.

You will also learn about a neutron multiplication factor, k_{eff} , that describes neutron production for a specific set of conditions. This factor can *help* tell you whether fissile material in a given situation will be safe or possibly critical. However, the value of k_{eff} is only part of the information needed to determine if a system is safe or unsafe.

Review questions are provided at the end of this chapter to test your comprehension.

Objectives

Describe nuclear *fission* and *criticality*.

Describe radiation dose as a function of time, distance, and shielding.

Describe possible health effects from a criticality accident's radiation.

Define *fissile material* and identify three fissile materials of most concern at the INEEL.

Define subcritical, critical, and supercritical.

Topic 2.1 Introduction

An unstable atom changes to become more stable. It emits energy as alpha and beta particles and/or gamma rays. This change is called radioactive decay. But there is another way of altering an atom's structure, with help of a free neutron, to release much more energy. This process is called fission. The energy it produces, when harnessed in a reactor, is called nuclear energy.

Topic 2.2 Fission

Fission is the process whereby a large unstable nucleus, like ^{235}U , absorbs a neutron and splits into two fragments, releasing energy. Generally, two or three neutrons are released per fission event (an average 2.4 neutrons per ^{235}U fission), which might or might not go on to produce other fissions. Gamma rays are also released. Neutrons and gamma rays are an immediate radiological hazard to people near a criticality. Fission fragments are also highly radioactive, and will significantly increase radiation levels for the area.

Energy released by fission appears in several forms. Most occurs as *kinetic energy* (energy of motion) of fission fragments (which fly apart at great velocity). A substantial portion is *radioactive decay energy* of fission fragments. *Neutrons* and *gamma rays* also carry appreciable amounts of energy.

2.2.1 Liquid Drop Model

A useful analogy for understanding fission is the liquid-drop model of the nucleus. Just as surface-tension forces tend to maintain a liquid drop in a stable form, so do nuclear forces keep an atomic nucleus in a stable state. Considerable distorting force must be applied for a drop to be broken into two smaller drops. Similarly, considerable force must be applied (by a neutron) for a nucleus to undergo fission.

In nuclear fission, a neutron combines with a target nucleus (a uranium or plutonium atom) to form a compound nucleus. The compound nucleus has energy from the original nucleus and from the absorbed neutron. This nucleus is unstable, or excited.

Examine Figure 4. If distorting forces are strong enough, the drop acquires a dumbbell shape. At this stage, it is unlikely to return to its former shape, but will likely split into two droplets.

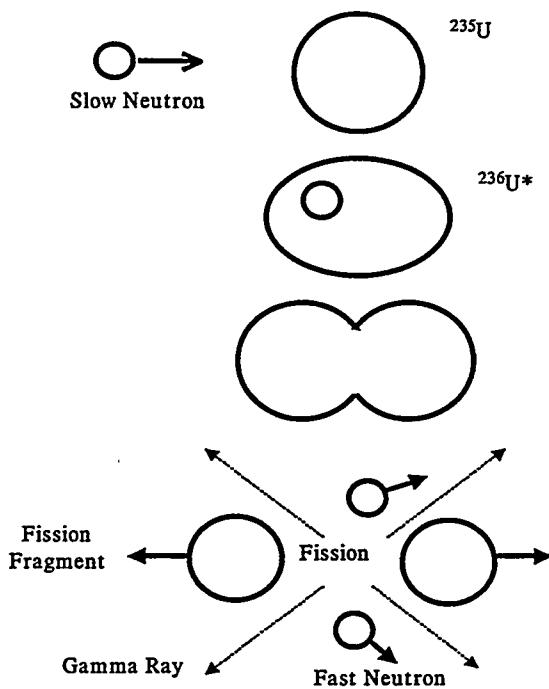
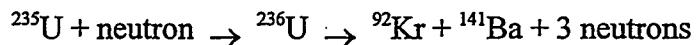
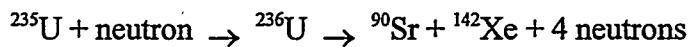


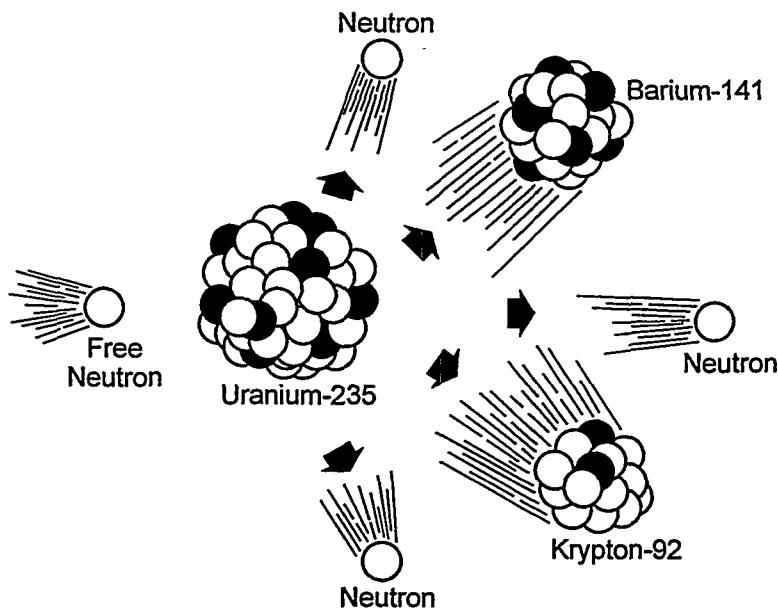
Figure 4 Liquid-drop Model of Fission

So it is with a fissile nucleus. If the nucleus absorbs enough energy to distort it, forming a dumbbell shape, it will in all likelihood split. Its binding forces are overcome. If the nucleus is not deformed enough by energy from the absorbed neutron, binding forces compel the nucleus to return to its original state. Excess energy is then removed by radioactive decay.

2.2.2 Fission Fragments

Fission fragments, or *fission products*, vary in size and composition. Over 40 different fragment pairs can be produced by ^{235}U fissions, two of which are shown in equations below. Figure 5 illustrates the fission described in the second equation below.





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Figure 5 $^{235}\text{U} + \text{neutron} \rightarrow ^{236}\text{U} \rightarrow ^{92}\text{Kr} + ^{141}\text{Ba} + 3 \text{ neutrons}$

Atomic masses of nearly all fission fragments fall into two broad groups: a light group, with mass numbers from 80 to 110, and a heavy group, with mass numbers from 125 to 155. In equations above, strontium and krypton are light fragments, while xenon and barium are heavy fragments.

Additional Information

Fission-fragment nuclei are more stable than the original nucleus, but they are still relatively unstable and, thus, radioactive. They are unstable because they have too many neutrons for their atomic number and mass. They have roughly the same neutron-to-proton ratio as ^{235}U . But since they are lighter than uranium, they require a smaller neutron-to-proton ratio for stability. These fragments usually require about three beta decays to reach stability.

2.2.3 Heat

Fission-fragment atoms and fission neutrons move at high velocity as they carry off most fission energy. As they move, friction creates heat. Outside a reactor, a criticality accident will generate some heat, but the heat is generally not enough to damage equipment seriously. The material does not stay supercritical long enough to generate anything like the heat produced in a nuclear reactor.

Additional Information

In some criticality accidents resultant heat boiled liquid or melted solids, eventually reducing material to a subcritical condition. Such an accident typically releases enough heat to vaporize four gallons of

water. This is equivalent to heat from burning a quart of gasoline, *but the entire energy release takes place in only a fraction of a second*. If an accident occurs in an open or well-vented container, some material might be ejected. If the accident is in a closed or poorly vented container, pressure increases rapidly and the container *might* rupture. It is possible for an explosion to result from a criticality incident, but the explosion results from steam pressure (for example, the SL-1 reactor accident). It is *not* an "atomic bomb" explosion. No out-of-reactor criticality accident to date resulted in more explosive energy than that of a few firecrackers (see Lesson 6).

2.2.4 *Ionizing Radiation*

Fission and subsequent radioactive decay of fission fragments produce *four types of ionizing radiation: neutrons, alpha particles, beta particles, and gamma rays*. These radiations produce ions when interacting with matter. In the human body, ionizing radiation can cause skin or tissue damage. *Large quantities of penetrating radiation (neutron and gamma) are most likely to cause severe, possibly fatal, damage.*

A critical excursion produces billions of neutrons and many high-energy gamma rays. However, basic radiation safety principles apply: limit exposure time, increase distance from a radiation source, and shield people from a radiation source. As shown in Figure 6, a person standing very close to an unshielded criticality accident could receive a lethal radiation dose before he or she could move away. If a person is standing more than a few feet away, he or she can probably avoid lethal radiation doses, and severe damage, if he or she evacuates immediately. Although shielding will also reduce radiation exposure, it is often impractical to provide sufficient shielding against a criticality accident.

Therefore, evacuation can also be important when accidents are partially shielded.

Additional Information

If one is present when a critical excursion occurs, doses received from the first pulse are not avoided by immediate evacuation. This dose is usually not lethal if the amount of material involved is small, there is some shielding between the accident source and people, and/or people are at least a few feet away from the incident.

Our criticality accident history indicates that, if one does not receive a lethal dose from the initial burst of a criticality accident, evacuation can save one's life. Persons who evacuate immediately avoid further radiation dose from:

- any subsequent pulses, or from a quasi-steady-state criticality accident,
- radioactive decay of fission products, and
- radioactive decay of activated nuclides (such as atmospheric nitrogen that was activated by the accident's direct radiation and/or by fission product decay).

Studies indicate the third radiation source listed above is responsible for about half the possible radiation exposure from a criticality accident if people do not evacuate. This additional dose can be very damaging, or even lethal.

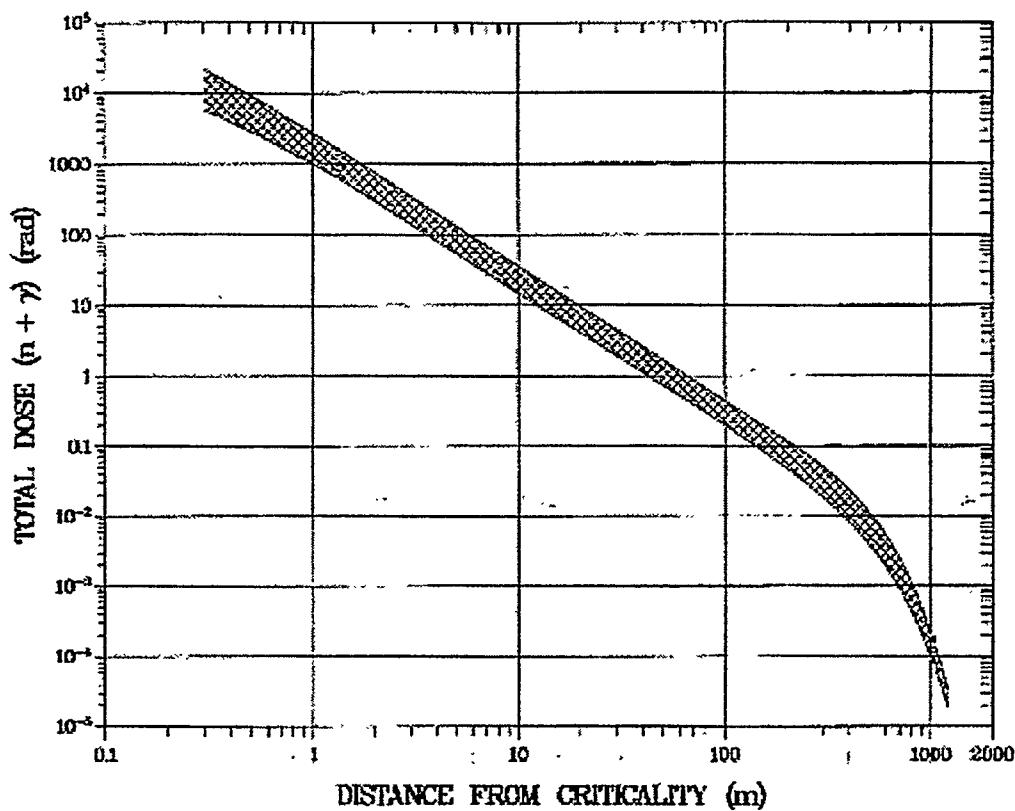


Figure 6 Criticality Accident Radiation Dose²

Topic 2.3 Fissile and Fissionable Materials

Materials that can fission are typically called fissile or fissionable material. These materials contain a significant quantity (mass, density, or concentration) of one or more isotopes that can fission. Such a material can be a mixture or compound containing elements with such isotopes, a relatively pure element with such isotopes, or the isotopes themselves.

Readers should note that, although technical and regulatory definitions for fission and fissionable differ, they have the *same* non-technical definition. That non-technical definition is used most often at the INEEL.

² 10^{17} fissions, assuming evacuation after 15 seconds (from LA-12808)

Additional Information

Technically, a *fissile* isotope is capable of fissioning at most neutron energies, but especially at *thermal* energies. Examples of fissile isotopes include ^{233}U , ^{235}U , and ^{239}Pu . INEEL has significant quantities of each of these isotopes, but ^{235}U (also often written as U-235) is the most abundant.

A fissionable isotope is now defined as any isotope capable of fissioning. *However*, there are other definitions. For example, *fissionable* once referred to isotopes, such as ^{238}U and ^{240}Pu , which require fast neutrons to fission; and DOE explicitly identifies specific isotopes (Appendix A) as fissionable.

The term *fissile* was coined recently to describe isotopes that require fast neutrons to fission. Fissile isotopes do not fission with thermal neutrons. Such isotopes include ^{238}U and ^{240}Pu . However, the term has not yet been widely accepted.

Fission with fast neutrons is *usually* not a criticality safety problem at the INEEL. However, fissile material is considered in criticality safety evaluations, both because it can fission and because it scatters neutrons.

Fertile isotopes can absorb neutrons and, through radioactive decay, become fissile isotopes. This process is called *breeding*. Important fertile isotopes are ^{232}Th that can be converted to ^{233}U , and ^{238}U that can be converted to ^{239}Pu . This conversion is important in breeder reactors. It is also important in U.S. commercial reactors because up to 40% of the fissions in near-end-of-life fuel assemblies occur in the bred-in ^{239}Pu .

Fertile material is a nuclear material sometimes included with or as part of fissile material, which is the only reason it is mentioned here. Breeding characteristics of fertile isotopes *usually* are not a criticality safety problem at the INEEL, although they are addressed when appropriate.

The INEEL has a large quantity of fertile material in the form of rods, modules, and pieces of Shippingport Light Water Breeder Reactor fuel and blanket.

Topic 2.4 Nuclear Criticality

Nuclear fission produces high-energy neutrons, usually two or three, which can go on to produce other fissions. If a released neutron causes another fission, and the process is repeated again and again, the effect is a self-sustained chain reaction. **This self-sustained chain reaction is called a *critical condition* or a *criticality*.**

Critical conditions are achieved intentionally in nuclear reactors, including critical assemblies and nuclear experiments. INEEL has had 52 nuclear reactors, but now, except for the Advanced Test Reactor (ATR) and its critical facility (ATRC), a critical condition should never occur at the INEEL.

2.4.1 Subcritical

A *subcritical* system is one in which each fission, on the average, causes less than one new fission. In other words, more neutrons escape or are captured by non-fissile atoms than are produced. Subcritical conditions might include one or more fission chain reaction(s). However, each chain is relatively short; it is not self-sustaining.

All systems at INEEL, except ATR and ATRC, must be kept subcritical.

2.4.2

Critical

A ***critical*** system is one in which an average of exactly one neutron from each fission causes another fission; other neutrons escape or are captured. Overall about the same number of neutrons are produced by fission as escape or are captured by non-fissile materials.

If a critical condition occurs when it is not intended to occur, the event is called a ***criticality accident*** or a ***criticality***. Both terms are used but ***criticality accident*** is preferred because ***criticality*** also refers to an intentionally critical condition.

Additional Information

In a nuclear reactor, the critical condition is a desirable and very delicate balance characterized by a steady power level. (For criticality safety purposes, reactors include critical experiments and critical assemblies.)

It is hypothetically possible to achieve a relatively stable critical condition inadvertently. This condition would not be continuously critical without some means of retaining material and limiting its temperature. Noncontinuous but relatively stable conditions would involve either a very slow increase in neutron production, or a slow oscillation about the critical condition. Such inadvertent critical conditions are not considered credible for INEEL operations.

2.4.3

Supercritical

A ***supercritical*** system is one in which each fission, on the average, causes more than one new fission. More neutrons are produced than escape or are captured by non-fissile atoms. The neutron population grows rapidly in a fraction of a second.

An uncontrolled supercritical excursion is also a ***criticality accident***. If a criticality accident is considered credible, the accident usually involves one or more supercritical excursions. This is the type of criticality accident that should concern INEEL FMHs.

Additional Information

Supercritical accidents occurred in nuclear reactors, with fissile ingots, and in systems for processing fissile solution, powder, or gas. Supercritical accidents are also considered credible with some fuel storage systems and with some waste materials although, to our knowledge, nobody has yet experienced such an accident. Let's not be the first!

A supercritical condition normally does not last long. Out-of-reactor it usually releases enough energy to displace or boil or melt material into a subcritical configuration within seconds. Following the excursion, however, material can sometimes return to a supercritical configuration. This return to critical could be caused by energy in the system, human action, or continuation of some automatic process.

Each supercritical excursion is called a spike or burst or pulse. It is characterized by high radiation levels (from gamma rays and neutrons) and heat.

Because a criticality accident can involve several spikes, do not enter a building or area in which a criticality has occurred. Emergency responders must consider the possibility of such spikes when developing a reentry plan, which must be approved before they enter the area. They must ensure the system is in a fairly safe condition before allowing others to enter.

Topic 2.5 Neutron Multiplication Factor (k_{eff})

Criticality safety engineers use a formula to *help* determine if a particular operation is critically safe. At its simplest, this formula compares the rate at which neutrons are produced (the average is 2.4 neutrons per ^{235}U fission) to the rate at which neutrons are lost (absorbed and escape). The result is a ratio that is either less than one, equal to one, or greater than one.

This ratio is the effective neutron multiplication factor, called k_{eff} or k-effective. If calculated correctly:

- a k_{eff} less than one indicates that more neutrons escape (or are lost) than are produced per fission event. In other words, a *subcritical* condition exists. subcritical: $k_{\text{eff}} < 1.0$
- a k_{eff} equal to one indicates the operation is just *critical*, the same number of neutrons is lost as is produced. critical: $k_{\text{eff}} = 1.0$
- a k_{eff} greater than one indicates the operation is *supercritical*, with more neutrons produced than lost. supercritical: $k_{\text{eff}} > 1.0$

Among other things, a system's calculated k_{eff} must not exceed 0.95 ($k_{\text{eff}} \leq 0.95$) for the system to be considered critically safe at the INEEL. This difference between critical and critically safe is a *minimum required* safety margin when limits are based on calculations. (This k_{eff} value is *not* the only criteria for deeming a system safe. Calculated k_{eff} sensitivity to small changes in the factors or parameters controlled (Lesson 3), analysis of what might go wrong, and several other items must be considered.)

Review Questions

- 1 A free neutron can be absorbed by a fissile atom, causing the nucleus to _____.
fission
- 2 When a fissile atom fissions, it releases energy that is eventually seen as _____ and _____.
heat, radiation
- 3 Neutrons are released from fission that can lead to a _____ of fissions.
chain reaction
- 4 When the number of neutrons produced is less than the number of neutrons lost, the system is _____. Gradually less than one new fission is produced from a fission.
subcritical
- 5 When every fission produces exactly one new fission, or the neutron production equals the neutron loss, a _____ condition exists and there is a sustained chain reaction of fissions.
critical
- 6 A _____ condition exists when neutron production is greater than neutron loss.
supercritical
- 7 At the INEEL a _____ accident is a fission chain reaction that is out of control.
critically
- 8 _____, or slow, neutrons are most likely to cause fission in fissile isotopes.
Thermal
- 9 Besides heat, radiation, and neutrons, the fission process creates _____.
Fission fragments
- 10 Fission fragments are highly radioactive. They emit _____ and _____.
gamma, beta

11 Two types of radiation that are particularly dangerous during a criticality accident are _____ rays and _____. gamma, neutrons

12 The effective neutron multiplication factor, k_{eff} , describes the ratio of neutron _____ to neutron loss. production

13 If k_{eff} is _____ 1.0, the system is subcritical. less than

14 If k_{eff} is _____ 1.0, the system is critical. equal to

15 If k_{eff} is _____ 1.0, the system is supercritical. greater than

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Lesson 3 Criticality Control Factors

Introduction

A critical condition is not an easy thing to create. Many factors or parameters work together to achieve a critical mass of fissile material. These factors can be grouped together in a variety of ways. Here, we divide physical factors important at the INEEL into eight categories to use the mnemonic *mermaids*:

| | |
|----------|---------------------------|
| M | Mass |
| E | Enrichment |
| R | Reflection |
| M | Moderation |
| A | Absorption |
| I | Interaction |
| D | Density and Concentration |
| S | Shape and Size |

All eight factors work together, but we will examine them individually. Controlling the value of a factor, alone or combined with other parameters, prevents criticality accidents.

Since ^{235}U is the most common fissile isotope at the INEEL, it will be used for most examples. Be aware, however, that each factor applies when discussing any fissile material (for example, ^{233}U or ^{239}Pu).

Review questions are provided at the chapter's end to test your comprehension.

Objectives

Identify criticality control factors represented by the mnemonic *MERMAIDS*.

Describe how a critical condition is affected by each criticality control factor.

Topic 3.1 Mass

Mass is the quantity of matter contained by a body, *regardless of its location on earth*. Mass is constant. It is not the same as weight because weight is affected by gravity. However, in most cases weight is a very good approximation of mass.

The mass of a material necessary to sustain a criticality is proportional to the total number of fissile atoms present, usually given in grams. *The fewer fissile atoms present, the less chance a free neutron will find and split another fissile atom.* All other things being equal, neutrons have a greater chance of escaping in a small mass than in a large mass.

A critical mass is the smallest mass of fissile material that will support a chain reaction *under specified conditions*. At INEEL, masses are kept as small as practicable, limiting the amount of fissile material allowed to accumulate at any one location.

Additional Information

Any activity involving, or any area containing, more than 15g ^{235}U must be evaluated and approved. Generic evaluations exist for activities and areas limited to fairly small quantities of fissile material.

Table 1 Minimum Critical Mass Estimates (kg)

| infinite water reflection (from LA-12808) | ^{233}U | ^{235}U | ^{239}Pu |
|----------------------------------------------|------------------|------------------|-------------------|
| One aqueous solution sphere | 0.54 | 0.80 | 0.50 |
| One solid metal sphere | 7.6 | 11 | 5.2 |

In some ways, limits placed on concentration, density, or a number of fissile pieces are a type of mass control. However, such limits control more than fissile mass.

Many criticality accidents involve fissile masses that either exceed an established limit or accumulate in an uncontrolled manner and/or location (Lesson 6).

Topic 3.2 Enrichment

More than 99 percent of natural uranium is composed of more stable ^{238}U atoms, while less than 1 percent consists of ^{235}U atoms that fission readily. This low concentration of fissile atoms is not enough to sustain a chain reaction without other special materials (for example, heavy water). Therefore, fissile concentration is often artificially increased. This process is called *enrichment*.

Enrichment usually indicates the percent of atoms in a given mass of uranium that consist of the fissile ^{235}U isotope.

Up to a point, the greater the enrichment, the smaller the mass necessary to cause a criticality. This is because there are more fissile atoms available to capture neutrons and then fission, and fewer non-fissile atoms available to absorb neutrons.

Additional Information

Criticality controls can be based on enrichment, especially when only low enriched materials are available. However, at INEEL other controls are used to simplify procedures and provide flexibility. We assume 100% ^{235}U or most-reactive-time-of-life enrichment. Actual enrichments are usually much less. For example, ATR fuel is 93% enriched at beginning-of-life and 20-30% burned at end-of-life.

Most criticality accidents involve Pu or highly enriched U, but low enriched systems are not automatically critically safe. The ElectrostaI Fuel Fabrication Plant accident (Topic 6.14) involved low enriched uranium (6.5%) and a Siberian Chemical Combine accident (Topic 6.8) involved intermediate enriched uranium (22.6%).

Topic 3.3 Reflection

Reflection is neutron scattering in which neutrons are directed back into fissile material from which they escaped. Many neutrons normally escape if there is no reflector around the fissile material. *Reflectors tend to decrease the amount of fissile material required to achieve criticality, because returned neutrons are available to cause more fissions.*

All materials scatter neutrons and therefore can act as neutron reflectors. If a system is barely subcritical, adding anything close to the fissile material's surface could cause the system to become critical. For example, cadmium is typically used to absorb neutrons, to decrease k_{eff} , but when suddenly added to a fissile system, the initial effect is a k_{eff} increase.

The best reflectors do not absorb neutrons well; they mostly bounce neutrons back. Examples include water, steel, tungsten, wood, paraffin, paper, aluminum, and polyethylene. The human body, with its high content of water and carbon compounds, is all too often an excellent reflector.

Radiation shielding materials can be excellent neutron reflectors, when located very close to fissile material. Examples include lead, steel, concrete, water, and polyethylene. For this reason, shielding materials, such as lead bricks and lead blankets, are restricted in a criticality control area unless specifically evaluated. Such evaluations are necessary to determine fissile material limits compatible with radiation shielding. This is especially important because it is rarely practical to provide enough shielding (for example, six-foot-thick concrete) to protect

handlers completely from a criticality accident. However, it is usually very practical to protect handlers from most routine and abnormal radiological conditions.

Additional Information

Criticality safety limits are typically established assuming water reflection because water is a most efficient, commonly available, neutron reflector. Materials that reflect neutrons better than water are therefore called special reflectors at the INEEL. Very thick lead, concrete, and/or steel walls are examples of special reflectors.

Neutron reflection was a factor in two LASL accidents with a plutonium sphere (Topic 7.1, Topic 7.2) and in an Arzamas-16 uranium-sphere criticality accident (Topic 7.8). Neutron reflection with humans as reflectors was a factor in the January 2, 1958 accident at the Mayak Enterprise (Topic 7.4).

All good moderators are good reflectors, and will simultaneously slow down neutrons. Moderators are discussed in the next topic.

Topic 3.4 Moderation

Moderation is neutron scattering in which the neutron loses energy.³ Fission (fast) neutrons are slowed, but not absorbed, through collisions with small (light) atoms. This is important because neutron velocity (energy) significantly affects how a neutron interacts with a fissile nucleus.

Most effective neutron moderators are very light elements, including hydrogen (especially its isotope deuterium), beryllium, helium, carbon, and oxygen. They are effective because their nuclei are roughly the same size and mass as a neutron.

When colliding with these nuclei, neutrons slow down much like billiard balls hitting other billiard balls.

All materials containing hydrogen, and many materials containing carbon, can be good moderators. Such materials include water, polyethylene, paraffin, oil, and graphite.

However, a moderator *must* be mixed with fissile material to be effective. An array of fuel rods in water or graphite, and a fissile solution, are examples of such mixing. With the possible exception of hands, humans are *rarely* good moderators because they are not mixed with fissile material. Similarly, water that is not held in or near fissile material usually is not a good moderator.

³ This interaction is called *elastic scattering*. See subtopic 1.3.2 and Figure 2.

Additional Information

Before colliding with a fissile nucleus, a neutron might slow down too much, too little, or just enough to be easily absorbed. Optimum moderation is a condition of having just enough moderator to slow neutrons and maximize their chance of being absorbed in fissile nuclei. In some cases it is better to ensure optimum moderation is an acceptable condition. In other cases it is necessary to ensure optimum moderation does not occur.

Over-moderation is having significantly *more* than an optimum amount of a moderator.

If there is too much moderator, neutrons will probably be absorbed by nonfissile isotopes before they cause fission. For example, when there are enough hydrogen atoms per ^{235}U atom (approximately 500 to 1), more neutrons will be captured than are produced by fission. Over moderation can be assured by adding moderators, such as water or polyethylene, to a system. Such moderators must usually be controlled to ensure sufficient moderator separates or dilutes fissile material in all credible conditions. Such controls are usually called configuration, interaction, density, or concentration controls, rather than moderator controls (see Topic 3.6 and Topic 3.7)

Under-moderation is a condition of having too little moderator. In such cases, neutrons escape before they are slow enough to be readily absorbed in fissile nuclei.

Some criticality safety limits are based on keeping neutrons in an under-moderated condition. Such limits are often called moderator controls. These limits are usually implemented with administrative controls, supported by engineering controls.

Extra analysis is needed before establishing an upper moderator limit because *water is the most commonly used and effective fire suppressant*. Moderator limits almost always involve restricting fire-fighting methods. Fire fighting restrictions are never imposed lightly. In many operations fires are more likely to occur, and can be more destructive, than criticality accidents. If a fire fighting restriction is imposed, restrictions are posted to remind firefighters. Also, combustible materials are specifically limited to reduce fire risk.

Additional Information

Criticality safety limits are typically established assuming optimum water moderation because water is the most efficient, commonly available, neutron moderator. Materials that moderate neutrons better than water are therefore called special moderators at the INEEL. Very large quantities of beryllium and beryllium oxide are examples of special moderators.

Moderators played an important role in the Electrostal Fuel Fabrication Plant (Topic 6.14), Boris Kidrich Institute critical facility (Topic 7.5), VENUS critical facility (Topic 7.6), and RA-2 Reactor (Topic 7.7) criticality accidents.

Topic 3.5 Absorption (and neutron absorbers)

All materials absorb neutrons to some degree. But some materials are especially good at it.

Nuclear absorbers, sometimes called nuclear or neutron poisons, are materials that readily absorb neutrons, preventing them from colliding with other nuclei.

Nuclear poisons absorb neutrons without undergoing fission themselves.
Neutron absorbers tend to increase a system's critical mass.

Additional Information

Like ^{235}U , some nuclear poisons absorb low-energy neutrons much better than high-energy neutrons. Materials like *cadmium*, *boron*, and *gadolinium* are very effective as absorbers for low-energy neutrons. If enough of one of these materials is added to a fissile system and sufficient moderator (Topic 3.4) is present to slow down neutrons, a large proportion of the neutrons will be captured. In some cases, a moderator such as polyethylene is added to a system to ensure a neutron absorber will be effective under certain conditions. Such additions are not needed in other cases because, when there is enough moderation for fission to be a concern, there is also enough moderation for the neutron absorber to be effective.

Criticality controls can be based on the quantity and sometimes the configuration of a neutron absorber. When neutron absorbers are used as a criticality control, special measures are often required to ensure sufficient neutron absorber, and moderator if applicable, are always present. For example, fixed neutron absorbers must be periodically checked if used in underwater fuel storage because they tend to corrode or leach quickly when exposed to water. As another example, a neutron absorber's presence must be verified before use if its equipment is disassembled for maintenance or repair.

Some materials are good neutron absorbers in metal form, such as boron or cadmium. Some are good neutron poisons in solution form, such as boric acid and gadolinium. Other neutron poisons are fission products, such as xenon, usually in a gaseous form trapped in the structure of an irradiated fuel assembly. However, fission products decay so they are rarely useful for ensuring criticality safety.

Topic 3.6 Interaction

Interaction is the exchange of neutrons between two or more fuel regions or masses of fissile material that are physically separated. Either or both masses could be subcritical alone.

Neutron interaction is usually controlled by separating units (specifically, controlling the distance between units).

Interaction can be dangerous because a fraction of neutrons leaking from one fissile mass might enter another fissile mass, supplying the additional neutrons required for criticality. Putting two or more fissile material masses close together has nearly the same effect as increasing the mass or size of either one by itself.

Additional Information

Interaction can make a system of favorable geometry (see Topic 3.8) containers unsafe. If interaction is not considered before grouping fissile material containers, a criticality could occur as containers are brought close together, even if each container alone is geometrically safe. Container shapes and sizes often make it too easy to place fissile material masses too close together.

In fuel storage, limiting the number and type of fuel units placed in each storage position usually controls interaction. Positions minimize interaction by ensuring that a minimum required spacing is maintained between each storage location and/or by using a neutron absorber between storage locations. The number of fuel units allowed out of storage at one time is also controlled to limit interaction.

Interaction control is a major basis for criticality safety and, in split-table critical assemblies, for some reactor controls.

Unplanned neutron interaction was involved in the LASL Honeycomb critical assembly (Topic 7.3), Siberian Chemical Compound plutonium ingot (Topic 6.19), and Novosibirsk (Topic 6.20) accidents.

Topic 3.7 Density and Concentration

Density and concentration are similar in that they are both often expressed as a mass per unit volume (for example, g/cm³ or g/mL or g/L or kg/m³). This is why they are often used interchangeably. For our purposes and for sake of our mnemonic, this use is adequate.

Density and concentration are normally defined as the mass of fissile isotope(s) per unit volume of material, for INEEL criticality safety purposes. For example, an unirradiated ATR fuel assembly has a ²³⁵U density of about 0.164g/cm³.

Up to a point, the denser or more concentrated a fissile material is, the less mass it takes to go critical.

Additional Information

Table 2 Minimum Critical Concentration Estimates (g/L)

| Infinite water reflection (from LA-12808) | ²³³ U | ²³⁵ U | ²³⁹ Pu |
|----------------------------------------------|------------------|------------------|-------------------|
| Aqueous solution | 11.3 | 12.1 | 7.17 |

Concentration refers to the mass of a particular material component per unit volume of material. In our case, it is the mass of fissile material or fissile isotope per volume unit of material, for example, 70g ²³⁵U/L or 10g ²³⁹Pu/cm³. Concentration and moderation (Topic 3.4) are directly related in fissile solutions.

As concentration increases from a very dilute (over-moderated) solution, the ratio of hydrogen atoms to fissile atoms decreases; fewer neutrons are absorbed by hydrogen, more are available to split fissile atoms. As concentration increases further, optimum moderation is eventually achieved; a criticality accident can occur with relatively little fissile material. Increasing concentration more removes more and more moderator; the solution begins to imitate a solid material (under-moderated). At this point, a relatively large amount of fissile material is required to achieve criticality. The optimum point at which a minimum amount of ²³⁵U is needed to achieve criticality is somewhere between 45 and 60g/L.

Density refers to how tightly atoms are packed together. Technically, density refers to the material as a whole rather than to a component, such as an isotope, in the material. Density is the ratio of an item's total mass to its total volume.

Starting with a very dense solid material, neutrons are more likely to be absorbed without causing fission, or scatter out of the material, than to cause fission. As density decreases, the chance a neutron will cause fission before it escapes increase until an optimum density is achieved. As density decreases more, neutrons pass through less material to reach the surface and escape is more likely.

Most out-of-reactor solution criticality accidents involved concentrated fissile material in a location that should not have had such material. See Lesson 6.

Topic 3.8 Shape and Size

3.8.1 General

Shape and size (geometry) can be controlled to permit safe handling of larger quantities of fissile material than would otherwise be permitted by mass control alone. Geometry control is the *preferred* criticality control method in most nuclear applications that could involve more than a minimum critical mass of fissile material.

3.8.2 Shape

Shape is *usually* the most identifiable factor in geometry control, because shape is readily visible and can be judged qualitatively, often without reference to scale.

Geometry control by shape is based on *neutron leakage*. A system cannot be made critical if it has a large enough *surface-to-volume ratio*. This is because a large proportion of neutrons will escape without colliding with fissile nuclei. Small-diameters and thin containers enhance neutron escape, as illustrated in Figure 7 for 5L (5000 cm³) of pure fissile material as a solution, slurry, or metal.

For a *constant* volume, a sphere is the most reactive geometry because it has the lowest surface-to-volume ratio. Relatively few neutrons leak from the system so k_{eff} is higher than it would be for a more favorable geometry. A short, fat cylinder and a cube are also like spheres, having relatively small surface-to-volume ratios.

A small-diameter cylinder is a much better geometry because, for constant volume, the cylinder's k_{eff} is lower than the sphere's.

A thin slab (a plane geometry) is one of the least reactive geometries because it maximizes the surface-to-volume ratio. *If* it would maintain its shape, a slab would be ideal. Unfortunately large volume, thin slabs tend to bow (begin to create interacting surfaces or, in tanks, develop local increases in slab thickness), because slabs are not as *structurally stable* as cylinders or spheres of the same volume.

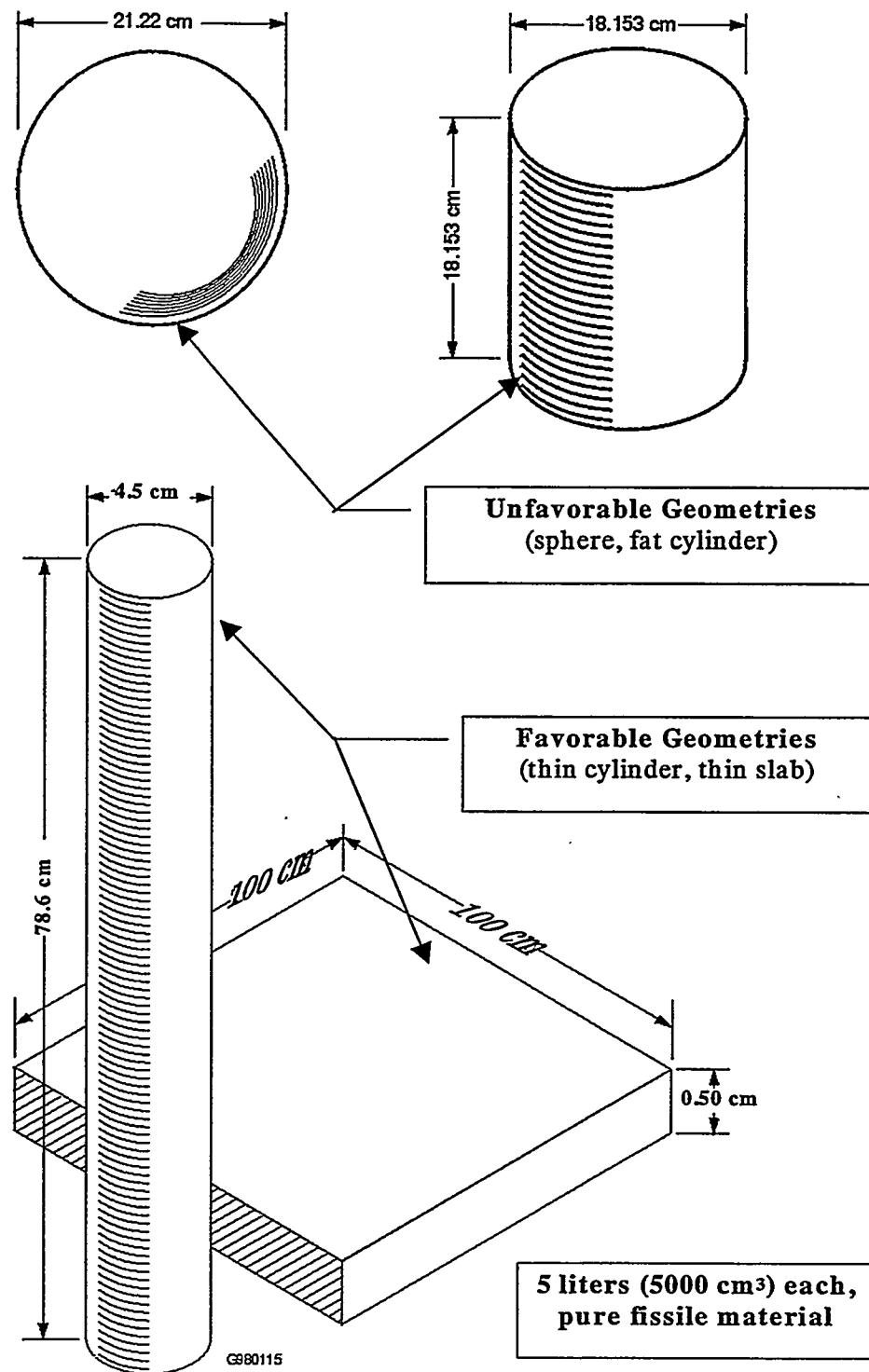


Figure 7 Favorable and Unfavorable Geometry Examples

Additional Information**Table 3 Minimum Critical Dimension Estimates (cm)**

| Infinite water reflection (from LA-12808) | 1 unit of 10kg/L water-X mix 233U | 235U | 239Pu | 233U | 1 metal unit 235U | 239Pu |
|----------------------------------------------|--------------------------------------|------|-------|------|----------------------|-------|
| Sphere diameter | 5.9 | 8.2 | 6.0 | 9.3 | 13 | 8.1 |
| Infinite-circular cylinder diameter | 6.8 | 10.0 | 7.0 | 5.1 | 8.0 | 4.6 |
| Infinite-slab thickness | 0.99 | 2.5 | 1.3 | 0.60 | 1.8 | 0.81 |

A *geometrically favorable* container is one that is safe by geometry because of its shape and dimensions considering its intended contents. A *geometrically unfavorable* container is one in which a critical mass could credibly be reached if controls based on other factors were not implemented.

Because of shape effects, one must be very careful about catching or collecting solution, sludge, or slurry in a bag, bucket, or similar container. One could inadvertently help cause a criticality by collecting fissile material from a geometrically favorable container or floor into a geometrically unfavorable container. Workers should know that fissile solution, sludge, or slurry might result from decontaminating equipment or from water leaking into a normally dry fissile container, as well as from processes intended to handle solutions. *Do not catch or drain fissile material in a temporary container unless Criticality Safety or Safety Analysis approved the container for this purpose.*

All solution criticality accidents involve geometries unfavorable for the fissile materials involved. In many cases subject vessels were not intended to contain any fissile material. In other cases, vessels were expected to contain dilute fissile material but the material became concentrated or some highly concentrated material was inadvertently transferred to the vessel.

Finally, geometry control sounds simple, but it is *only* as good as the controlled item's structural stability. Geometry controls *must* include whatever structural supports are needed to ensure important dimensions are maintained. This is why an annular design, which has a surface-to-volume ratio similar to a slab and a structural stability similar to a cylinder, is often preferred when sufficient space is available.

Bowed slab tanks were a factor in the Novosibirsk criticality accident (Topic 6.20). A small area of wall bent outwards over years of pressure from its contents, increasing slab thickness in that area. This is a *not* an uncommon problem with large slab tanks.

3.8.3 **Size (volume)**

In some cases the size or volume of a fissile system is small enough that the system cannot be made critical without increasing its size, regardless of its shape or its *credible* contents. In such systems, most free neutrons are so close to an external surface that they escape before effectively colliding with a fissile atom. In these cases, geometry control is very analogous to mass control.

In other cases the volume is not necessarily small, but it is physically limited to prevent over-batching intended contents. (For example, a storage position that physically prevents inserting too many fuel elements, assuming available fissile

material is limited to specific fuel elements.) This form of geometry control is very useful in most fuel storage facilities.

Additional Information

Table 4 Minimum Critical Volume Estimates (L)

| Infinite water reflection (from LA-12808) | X (fissile isotope) | | |
|----------------------------------------------|---------------------|------------------|-------------------|
| | ^{233}U | ^{235}U | ^{239}Pu |
| 10kg/L water-X mix sphere | 0.85 | 2.3 | 0.90 |
| metal sphere | 0.42 | 1.1 | 0.28 |

Volumes listed in Table 4 are very small, and do not account for effects of non-fissile, non-moderating materials. These volumes are often too small to be of much use as controls. However, minimum critical volumes that account for effects of credible materials (for example, some waste materials at RWMC) can be extremely large.

Systems that physically prevent overbatching are usually not called geometrically favorable although they exemplify one type of geometry control.

Lack of geometry control contributed to a criticality accident with plutonium ingots at the Siberian Chemical Compound (Topic 6.19).

Additional Information, Other Factors (Material Uniformity)

Material uniformity is included for completeness. However, INEEL issues associated with this factor can be described in terms of factors already included in the *mermaids* mnemonic. For example, *Density and Concentration* incorporate homogeneity issues for fluid fissile material, and *Moderation and Interaction* incorporate heterogeneity issues for solid fissile materials.

An homogeneous system is one in which there is no variation in material properties throughout the system (for example, a chocolate milk made from just the right amounts of milk, powdered chocolate, and stirring). Homogeneity is a measure of how little variation there is in a system.

In a heterogeneous system, material properties in at least one system location differ significantly from properties in another system location (for example, milk in which powdered chocolate is only partially mixed). Heterogeneity is a measure of how much variation there is in a system.

Material uniformity, or lack thereof, can involve mixed fissile isotopes (for example, MOX fuel), material phases (for example, a solid, slurry, solution, and vapor), or material types (for example, a concentrated solution and a dilute solution, or a naval fuel assembly and an ATR fuel assembly). Criticality safety based on assuming one material, rather than a mix, might be inadequate unless the basis material is significantly more reactive than other materials.

Homogeneity or heterogeneity affects criticality safety because, neutron behavior can be greatly affected by neutron location when material properties vary with location. Depending on materials and their configurations, a fully homogeneous system might or might not be more critically safe than a very heterogeneous system.

Criticality accidents involving problems with material phase include LASL (Topic 6.4), Siberian Chemical Combine Uranium (Topic 6.8), Windscale (Topic 6.17), and ICPP (Topic 6.18) accidents. The Wood River Junction criticality accident (Topic 6.13) is an example in which inadequate segregation and categorization of dissimilar fissile solutions was an important contributing factor.

Review Questions

1. _____ describes the amount of material in terms of its weight. mass

2. A _____ mass is the minimum amount of a particular fissile material, or critical isotope, necessary for a critical condition under specific conditions.

3. The _____ the fissile mass, the safer the system. smaller, less

4. _____ is the percentage of ^{235}U atoms in a mass of uranium. enrichment

5. Reflectors tend to _____ the amount of fissile material required to achieve criticality. decrease

6. Radiation shielding materials, such as thick lead, concrete and steel, are also good _____. reflectors

7. All good moderators are also good _____. reflectors

8. A _____ slows down a neutron by absorbing some of its energy. moderator

9. _____ are materials that readily absorb neutrons. neutron absorbers, nuclear absorbers, neutron poisons, or nuclear poisons

10. Interaction can be dangerous because neutrons _____ from one mass of fissile material can enter another mass, resulting in a criticality. leaking

11. Interaction is usually minimized by keeping fissile materials an adequate _____ apart. distance

12. For criticality safety purposes, _____ describes the mass of a fissile isotope in a material volume. concentration

13 As with concentration, the higher the fissile material _____, density

the less it takes to cause a criticality.

14 _____ is important because, for a constant volume, the larger shape

the surface-to-volume ratio, the more the neutron leakage.

15 _____ or volume is also a criticality control factor. size

16 Identify factors represented by the mnemonic *mermaids*.

S = shape and size
D = density and concentration
I = interaction
A = absorption
M = moderation
R = reflection
B = enrichment
M = mass

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Part 2 Application

Part 2 describes applied criticality safety, specifically the INEEL Criticality Safety Program, in two lessons. General administrative information, limits, responses, and definitions are presented here. A few area-specific program examples are also presented to assist readers in understanding the program's general concepts.

Fissile Material Handler candidates are required to understand general concepts of the INEEL program, know general responses to abnormal and emergency criticality safety conditions, and be able to identify and locate the main program document. Although candidates should read and understand at least two application examples, no testing on examples is planned.

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Lesson 4 INEEL Criticality Safety Program

Introduction

All fissile materials at INEEL nonreactor facilities and outside reactors at INEEL reactor facilities must be maintained at a subcritical level. Also, since criticality accidents can and have occurred, means for detecting and responding to such accidents are important. Criticality safety therefore includes prevention and mitigation of criticality accidents.

This chapter describes general administrative practices for criticality safety at the INEEL. Review questions are provided at the end of this chapter to test your comprehension.

Objectives

- Identify the primary LMITCO criticality safety program document.
- State who is allowed to handle fissile material.
- Describe what a margin of safety is.
- Explain how engineering controls and administrative controls are used in criticality safety.
- Describe general actions to take if you think a criticality safety control has failed or might be inadequate.
- Describe the double contingency principle.
- Identify the fissile material label.
- Describe what a CCA is and how it is posted.
- State mass limits for each type of CCA.
- State how a criticality accident is detected in an unshielded or partially shielded area.
- Describe our CAS alarm and proper response to it.
- Discuss lessons learned from historical criticality accidents.

Topic 4.1 Program Manual

PRD 112, *Criticality Safety Program Requirements Manual*, establishes our criticality safety program by identifying general requirements used at INEEL to ensure nuclear criticality safety. Manual topics include: responsibilities, criticality safety principles and criteria, material limits and procedural controls, documents and records, posting and labeling, shipping and transfers, training, audits and appraisals, control violations, and emergencies.

Manual requirements are implemented by procedures in lower tier documents. All employees who process, handle, store, or are responsible for fissile material are individually responsible for knowing, understanding, and strictly adhering to requirements that apply to their respective assignments.

Additional Information

At the time this guide revision was prepared, the *Criticality Safety Program Requirements Manual* was part of company wide Manual 10B - Engineering and Research. PRD 112 can be accessed on INEEL's intranet:

Topic 4.2 Fissile Material Handlers

With few exceptions, *only* qualified Fissile Material Handlers (FMHs) are allowed to handle, manipulate, store, or move significant quantities of fissile material, or items *containing* significant quantities of fissile materials.

Additional Information

Exceptions include Reactor Operators whose training includes necessary FMH knowledge and skill items, FMH candidates performing tasks under the active supervision of a qualified FMH, and personnel handling properly loaded, sealed, and labeled fissile material shipping packages.

This requirement is established to help ensure those who handle fissile material have sufficient knowledge and skill to protect themselves and their co-workers from a criticality accident. Successfully completing training associated with this guide and/or computer-based criticality safety training, is *one* of several steps needed to qualify as an FMH.

Topic 4.3 Criticality Controls and Limits

4.3.1 General

It is imperative anyone who handles or works with fissile material fully understands criticality control methods applicable to his or her assignment. An

individual must always think before making any changes in geometry or mass in any system containing fissile material.

A *criticality control* is a method for controlling a criticality control factor to ensure a system is subcritical. Often a control is expressed as a *limit* on the parameter being controlled. In addition, a control is usually identified by the factor or parameter being controlled. For example, a criticality control that limits moderators is often called a moderator limit or a moderator control.

Additional Information

Detailed analyses are performed to determine criticality controls. Controls must be designed to accommodate the worst credible change in conditions. For example, design controls would consider worst case corrosion, if criticality safety credit were taken for material exposed to a corrosive environment. As another example, handling limits consider worst case credible over-batching if personnel limit quantities in accordance with procedures and/or postings.

The type and number of controls vary with the system considered. Because most controls are very system specific, details are identified in system-specific training, for example, in on-the-job training.

Critical limits, sometimes called failure limits, represent quantities or dimensions needed before a self-sustaining chain reaction is possible. Depending on other conditions, operation at a critical limit does not guarantee the system will be critical. On the other hand, depending on these other conditions, the operation *could* be critical.

Critical limits are not the same as criticality limits, criticality safety limits, or criticality controls. These other limits and controls are used in actual practice to ensure one operates within an envelope of subcritical conditions.

Criticality control methods are often classified in two general categories: *engineering controls* and *administrative controls*.

4.3.2

Engineering Controls

An engineering (or engineered) control is a physical design that reliably serves as a criticality safety control. Examples include geometrically favorable equipment, permanently fixed neutron absorbers, and storage positions sized to prevent over-batching.

Additional Information

Engineering controls must be carefully selected because some candidates are reliable and others are not reliable enough. A seismically qualified, small-diameter, stainless steel cylindrical tank is usually very reliable. However, a valve is less reliable because industry experience proves all valves eventually leak. A physical design that is not reliable enough does not qualify as an engineered control.

Engineering-control reliability is also affected by administrative components to correctly install and appropriately maintain the item. Good engineered-controls are easily verified during or after manufacture and require relatively little maintenance.

4.3.3

Administrative Controls

An administrative control is a criticality control that relies on human actions for its implementation. Administrative controls are human-based and subject to error in application. Examples include limits on fuel piece quantity, total fissile mass, concentration, and volume (for example, vessel fill level, using a specific container when others are available, or when open containers are in an area).

Administrative controls are less desirable than engineering controls. However, even geometrically favorable devices are subject to misuse and failure. Therefore, some administrative control or support is required for essentially all operations.

4.3.4

Preferred Control Methods

As you can imagine, there are many ways to control each one, or some combination, of the eight criticality control factors studied in Lesson 3. *Control reliability is one of the most important factors considered* by designers, criticality safety personnel, and safety analysts who must recommend or select criticality controls for a specific application.

Additional Information

In order of preference, criticality control methods are:

- *Favorable geometry*, where equipment or systems are subcritical by virtue of neutron leakage under worst credible conditions, including filling to maximum capacity. This is an engineering control. Its basis is described in Topic 3.8, and especially subtopic 3.8.2.
- *Permanently fixed neutron-absorbing materials* (poisons), where favorable geometry is not practicable. This is the next preferred method of control. It is used in combination with geometry parameters. The absorber with its geometry is an engineering control. Its basis is described in Topic 3.5.

When neutron absorbers are used for criticality safety, design must provide for a positive means to verify their continued presence under all credible conditions. Verifying a neutron absorber's continued presence and replacing it as necessary are essential administrative components supporting this engineering control.

- *Administrative controls* on fissile mass or concentration, moderators, use of soluble and/or temporary poisons, presence of movable shielding material, etc., where the two above criticality control methods are not practicable.

Reliance solely on administrative controls is strongly discouraged. Where practical, administrative controls are supported by engineered, safety-significant features or instruments to reduce occurrence and significance of human errors.

In each case, these controls are employed only when combined with safety margins to accommodate the maximum credible change of conditions.

4.3.5 ***Conforming to Limits and Controls***

All fissile materials at INEEL non-reactor facilities must be maintained at a subcritical level. This can be achieved only through *strict adherence* to criticality safety controls and procedures. Although criticality in a reactor is usually expected and desirable, it is never desirable outside a reactor. There are also times when activities at a reactor, such as refueling, must be maintained subcritical.

Unintentional criticality can be caused by carelessness in treating, disposing, handling, shipping, or storing fissile material. *Most criticality accidents involve human errors and/or procedure violations*, including failure to obtain a procedure or instructions.

Remember, criticality safety requirements are established to protect your life and the lives of your coworkers. Secondarily, maintaining a safely subcritical condition helps to protect your job.

Information about criticality controls, limits, and their bases is provided in area-specific safety analyses and associated supporting documents. Administrative controls are implemented by procedures. Those controls and their bases should be explained in your area-specific training.

4.3.6 ***Criticality Control Failures and Limit Violations***

Although failures are unusual, criticality controls can and do fail in various ways. For example, a criticality control might be rendered ineffective through failure to appropriately design, identify, implement, comply with, or maintain the control if administrative components are involved. A criticality control might also be rendered ineffective through failure of some important physical component if the control is an engineered control (for example, a structural component might break or leak).

Most control failures involve procedural violations. And some criticality accidents occurred partially because, or were made worse by, inappropriate action to correct a failed condition. (See Part 3.)

At the INEEL you should *immediately stop and notify your supervisor or manager, or the area's supervisor or manager* if you think a criticality control has failed or might be inadequate. Follow procedures (part of your annual ES&H training) for securing the area, keeping yourself and others safe, and preserving the scene. There will *not* be an imminent safety hazard in most cases. However, if you believe an imminent safety hazard exists, exercise your stop work authority (PRD-1004, *Stop Work Authority*, which can be accessed on INEEL's intranet).

Additional Information

The Wood River Junction (Topic 6.13) and a Siberian Chemical Combine (Topic 6.8) criticality accidents are classic examples of accidents partially caused by procedure violations and then made worse by inappropriate response.

Topic 4.4 Double Contingency**4.4.1 *Definition***

The double-contingency principle is an accepted nuclear industry guide for proper protection against operational abnormalities. It requires sufficient safety such that no single event, regardless of its independent probability, can result in a criticality accident. In other words, **“Process designs shall incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent events occur before a criticality accident is possible.”** Notice that a critical condition is possible but *not guaranteed* if both changes occur.

All fissile material operations at INEEL must satisfy the double-contingency principle. This principle must be implemented for *each* credible criticality accident scenario. If there are multiple criticality scenarios for a system, more than two changes might be identified for that system because a change that contributes to one scenario might not contribute to another scenario.

INEEL double contingency implementation examples are discussed in Lesson 4. Readers are *encouraged* to review **at least two** examples.

Additional Information, Contingencies and Controls

DOE’s double contingency statement reads, in full, “Process designs shall incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible. Protection is provided by either (i) the control of two independent process parameters (which is the preferred approach, when practical, to prevent common mode failure), or (ii) a system of multiple controls on a single process parameter. The number of controls required upon a single controlled process parameter shall be based on control reliability and any features that mitigate the consequences of control failure. In all cases, no single credible event or failure shall result in the potential for a criticality accident.” [DOE O 420.1, section 4.3.3d(1)]

Consistent with early criticality safety definitions, INEEL personnel currently **define contingency as the controlled parameter or factor** (Lesson 3), rather than as the control on a parameter. However, remember DOE also allows the double contingency principle to be satisfied by multiple controls on a single parameter. This subtle distinction can greatly affect our nomenclature. For example, we must satisfy the double contingency principle but, in some cases, the principle is satisfied by multiple, reliable, independent controls on a single contingency rather than by two independent contingencies.

Additional Information, Credible, Incredible, Etc.

Words like *credible*, *incredible*, *likely*, *unlikely*, and *extremely unlikely* are used in criticality-safety, criticality-safety-contingency, criticality-accident, and criticality-accident-scenario discussions. These

words indicate a *probability* that a particular event might or might not occur, but exact definitions vary with subject, regulator, implementing organization, and author. Readers should keep in mind that *none* of these terms *guarantee* a particular event, or chain of events, will or will not occur.

Understand that an *incredible* event is not impossible. It might occur. If it does, *incredible* was not necessarily an inappropriate probability description. For example, an *incredible* event is often defined as one with an occurrence probability of 10^{-6} per year. In many lotteries the probability a specific person will win is usually *significantly less* than 10^{-6} (an *incredible* occurrence) but the probability that at least one person will eventually win is usually close to 1.00 (an *almost guaranteed* occurrence).

4.4.2 Safety Margin

In its simplest terms, a **safety margin** is the difference between **normal or expected conditions and conditions that are known or assumed to be unsafe**. Implementing the double contingency principle is an example of implementing a criticality safety margin; one unlikely event reduces the margin but does not eliminate it. In addition, a criticality safety margin is sometimes expressed in terms of calculated k_{eff} s (Topic 2.5) associated with normal conditions and with conditions after specific control(s) fail.

Topic 4.5 Fissile Material Labels

Form L-0431.07 (Figure 8) is a fissile material label recommended for labeling fissile material or its containers where practical. (Container size, material storage method, etc. affect practicality.)

| | | |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|------------------------|
| 431.07 02-97 Rev. #01 | | |
| FISSILE MATERIAL LABEL | | |
|  CAUTION FISSILE | Project or Log No. Sample or Container No. | |
| | Gross Wt.* Fissile Isotope | Net Wt. Isotope Wt. |
| Material Description: (Additional) | | |
| <small>*For mixtures of fissile nuclides, each gram of ^{233}U, ^{239}Pu and ^{241}Pu can be counted as two grams of ^{235}U.</small> | | |
| Owner | | Date |
| REMOVE WHEN EMPTIED | | |

Figure 8 Fissile Material Label

Additional Information

The Fissile Material Label is available from Forms Control and from the INEEL Criticality Safety organization.



Figure 9 Fissile Material Symbol

Each Fissile Material Label includes a fissile material symbol, shown on the left, which should be recognized by all who work with or around nuclear materials. *Do not touch items labeled with this symbol unless you have appropriate training*



Figure 10 Radioactive Material Symbol

Established by the American Health Physics Society, the fissile material symbol is intentionally similar to the radioactive material symbol, shown to the left. They are similar because fissile material is radioactive, *even if a fissile material's activity is too low to be a radiological concern*.

Topic 4.6 Criticality Control Areas

Administrative control of fissile material is evident with and administered through established Criticality Control Areas (CCAs). INEEL laboratory and plant areas that are *allowed* to contain significant quantities (more than 15 grams) of fissile material must be designated as CCAs, with clearly defined boundaries and criticality safety controls. Reasons for defining significant quantity as more than 15g of fissile material are discussed in Topic 5.3.

Additional Information

CCAs are established in accordance with company-wide procedure MCP-2818, *Establishing, Maintaining, and Deleting Criticality Control Areas*. This procedure can be accessed on INEEL's intranet.

There are two types of CCAs: *Mass Limit* and *Procedure*.

4.6.1

CCA Identification Signs

Each CCA is posted with a CCA identification sign which, where appropriate, should appear near entrances to each CCA.

Each CCA identification sign identifies person(s), called CCA Custodian(s), responsible for fissile material in that area. Instructions for specific limitations on quantity and movement of fissile material into the CCA also appear on the sign.

In some Procedure CCAs there might be a restriction on using water to fight a fire in the area, since water is a moderator. In such areas the CCA sign, and other signs, remind firefighters of fire-fighting restrictions for the area.

Additional Information

CCA identification signs are available from the INEEL Criticality Safety organization.

4.6.2**Mass Limit CCAs**

Mass Limit CCAs must be established by management and approved by the Criticality Safety Supervisor. **Mass Limit CCAs are locations in which more than 15g and no more than 350g ^{235}U , 250g ^{233}U , or 250g ^{239}Pu is allowed.** Reasons for these specific limits are discussed in Topic 5.2. If fissile isotopes are combined, each gram of ^{233}U and each gram of ^{239}Pu are counted as two grams of ^{235}U . The quantity of special reflectors (such as lead, carbon, and beryllium) in Mass Limit CCAs is also limited.

Figure 11 shows a blank Mass Limit CCA sign, Form 431.08.

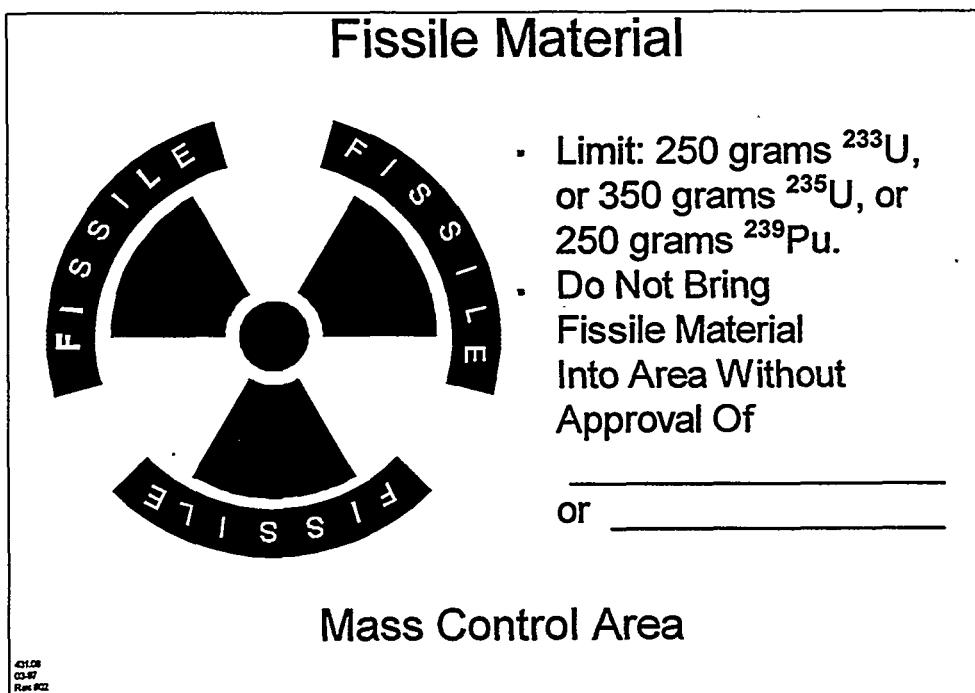


Figure 11 Mass Limit CCA Identification Sign

Additional Information

Mass Limit CCAs are typically established in INEEL analytical laboratories.

Specific procedures for organizations that have Mass Limit CCA(s) implement criticality safety controls for those CCAs. Although mass limits are implemented by procedures, a Mass Limit CCA is *not* a Procedure CCA. Instead, Mass Limit CCAs represent an acceptable general INEEL-wide fissile material control system for which specific limitations on concentration, volume, or neutron absorbers are not necessary.

4.6.3

Procedure CCAs

Procedure CCAs are established to handle and store larger quantities of fissile material. Procedure CCAs are areas that may contain more than 350 grams ^{235}U , 250g ^{233}U , or 250g ^{239}Pu , and in which fissile material is controlled by approved procedures. Procedure CCAs require approved criticality safety evaluation and safety analysis.

Figure 12 shows a blank Procedure CCA sign, Form 431.09.

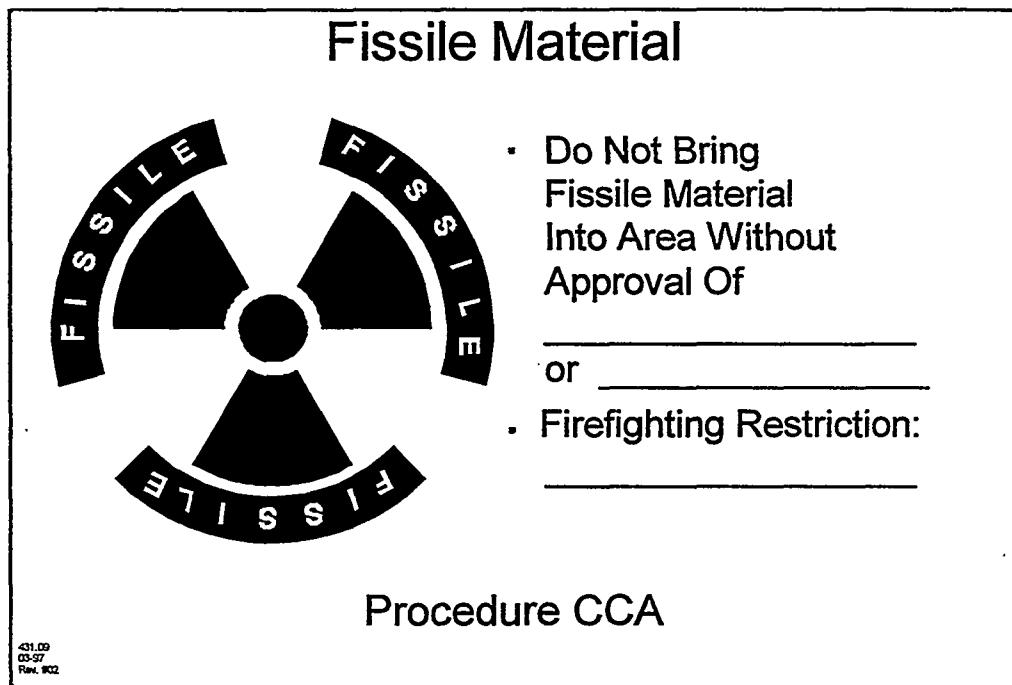


Figure 12 Procedure CCA Identification Sign

Additional Information

Procedure CCAs are typically established for nuclear fuel storage areas.

Topic 4.7 Criticality Alarm Systems

You cannot tell if a criticality is about to happen. Your senses cannot detect a criticality until it is too late. In many cases your senses cannot detect a criticality even after it is too late.

Instruments are used at INEEL to warn personnel at risk if a criticality occurred outside of a reactor. However, these instruments provide a warning only *after* the first supercritical pulse. The best way to avoid radiation exposure from a criticality accident is, of course, to prevent the accident from happening.

At the INEEL, *unshielded and partially shielded operations* in areas where an out-of-reactor criticality accident is credible are monitored by a *Criticality Alarm System (CAS)*. Each CAS is designed to alarm immediately in the event of a criticality accident in its area. The INEEL CAS alarm is a **high-low alternating tone (warbler)**. It is a special kind of evacuation alarm. It will automatically sound in the building where the accident occurred. You should learn if your area is covered by a CAS, and the sound of that CAS's alarm, as part of your on-the-job, access, and/or area-specific training.

If a CAS alarm sounds in your area, quickly evacuate the immediate area and assemble at your designated staging area. Do not run. (Running increases your chances of falling, which can increase your exposure by delaying or disabling your evacuation.) Do not enter or approach buildings in which a criticality alarm is sounding.

Additional Information

In the event of an unshielded or partially shielded criticality accident, any nearby *Remote Area Monitors (RAMs)* and *Constant Air Monitors (CAMS)* will probably alarm also. In some INEEL areas, CASs will also activate a *plant evacuation alarm*.

Immediate evacuation was an important factor in protecting nearby workers during most unshielded criticality accidents. (See Lesson 6.)

However, CASs are not installed or continuously operated in all INEEL areas with fissile material. In such cases, non-installation or non-continuous operation is justified by at least one of the following reasons:

- a criticality accident is not credible (occurrence probability is *acceptably* low, but *not necessarily* zero) for operations for which an operable CAS is not required, or
- an accident is credible, but people would be adequately protected without immediate evacuation (for example, such protection can be provided by very thick concrete or deep water). In such cases, alternate detection methods and response actions are permitted.

Adequate protection is defined differently depending on safety discipline, identified risk, management policies, and regulator. To determine if a CAS is needed for a specific INEEL operation, we usually define *adequate protection* in terms of the underlying reason for having a CAS: avoid lethal personnel radiation exposure from a criticality accident. INEEL management could, and often does, define

adequate protection differently for other purposes for the same operation (for example, the ALARA principle affects definitions for radiological control purposes during normal operations).

Topic 4.8 Lessons Learned from Criticality Accidents

4.8.1 Accident Experiences

Part 3 reviews criticality accident histories and respective lessons-learned to help workers recognize unanticipated conditions and improve vigilance. Readers are encouraged to review **at least two** accident histories, selected for applicability to your work areas and areas you visit. Consult with your trainer if you do not know which histories are most applicable.

As of the time this document was prepared, reviews included all twenty reported out-of-reactor criticality accidents and, from a significant database of unintentional reactor and assembly excursions, eight in-reactor accidents. Reviews do not include accidents in fuel storage or in solid waste systems because none have been reported. This does *not* mean fuel storage and waste system criticality accidents are incredible. Rather, it reflects the comparative ease by which adequate controls can be established and maintained for such systems.

The few out-of-reactor criticality accidents experienced in over 50 years of fissile material handling and nuclear reactor operations are insufficient to give a comprehensive picture of criticality scenarios and their consequence range. Nevertheless, we learn what we can from these accidents, from near-miss (or near-hit) incidents, and from experiments specifically designed to mimic some accident characteristics.

4.8.2 Lessons Common to Most Accidents

Each accident resulted from a *chain of events*, none of which was harmful by itself. Human error and/or procedure violations were *major* factors in these chains, causing accidents and/or contributing to accident magnitudes. Interrupting almost any link in a chain would prevent or reduce the respective accident.

None of these accidents involved unpredictable or inexplicable phenomena. Although the event chain leading to an accident was not necessarily predicted, conditions that resulted in a critical excursion were known to be unsafe. In fact, safe conditions were usually well described and documented beforehand, and anything outside those conditions was considered unsafe or critical.

Out-of-reactor accidents and most in-reactor accidents produced minimal equipment damage and no radiation exposure to the general public. Sufficient

energy to cause widespread dispersion of fission-produced contamination requires very unusual conditions.

Quantitative controls and adequate material accountability are key components in criticality accident prevention. However, because of human errors, geometrically favorable equipment and engineered controls are the most reliable method to prevent accidents.

Immediate evacuation is an effective protective measure for most people at risk from a criticality accident. Evacuation routes should lead workers away from, rather than through, high-risk areas and should minimize risks from other sources.

4.8.3

Other Important Lessons

Responder reentry into an accident scene should be undertaken only after accident causes are identified and reliable measures are in place to control the situation. Multiple critical pulses are not uncommon, and a quasi-steady-state reaction is not impossible. Although most criticality accidents will self-terminate, *appropriate* human intervention might be needed. Well-meaning but poorly planned actions can initiate additional critical excursions.

Most accidents occurred between 1958 and 1962. This is partially attributed to increased production without facility growth. Plants originally designed for moderate capacity and with minimal criticality safety guidance were used for increased throughput and a wider variety of operations. Thus, accident potential increased even during the accident-free period before 1957. There was little incentive to improve criticality safety until accidents occurred.

After these early accidents, more precise guiding data were collected and techniques for criticality control were refined. Criticality safety became a respected field. Accident record improvement was a natural consequence. However, recent accidents in Novosibirsk (May 1997, Topic 6.20) and at Arzamas-16 (June 1997, Topic 7.8) remind us that criticality safety controls, standards, and vigilance must be maintained.

Most out-of-reactor excursions occurred in *moderated fluids* (solutions, powders, gasses, etc.) of plutonium or highly enriched uranium. Small critical masses, high mobility, ease of fluid exchange, and ease of introducing water or of concentrating solutions invite critical excursions in unexpected locations.

By contrast, solids have larger critical masses, but certain solid-material accidents are more likely to be violent (involve significantly larger energy releases). Fortunately solid-material movement is more apparent, more easily controlled, and generally more readily foreseen. Criticality control is usually straightforward

and can be emphasized in plant design and operations. Administrative criticality controls are also simpler and often easier to implement.

Although most out-of-reactor accidents involved highly enriched fissile material, one accident involved low enriched material and another involved a very low intermediate enrichment.

Review Questions

1 The LMITCO Criticality Safety Program Requirements Manual, PRD 112, establishes general INEEL criticality safety requirements.

2 With few exceptions only a(n) _____ may handle fissile material. Fissile Material Handler

3 Why are engineered controls preferred over administrative controls? Engineered Controls Preferred

4 What should you do if you think a criticality control has failed or is inadequate? Immediate Stop and Notify Your Supervisor or Manager

5 State the double contingency principle. Double Contingency Principle

6 A _____ CCA may contain up to 350 grams of ^{235}U . Mass Limit

7 A _____ CCA may contain more than 350 grams of ^{235}U . Procedure

8 If a CAS alarm sounds in your area, you must _____ the building and area immediately. Evacuate

9 Each historical criticality accident was caused by a _____ of events. Chain of Series

10 Which of the following is the fissile material symbol? q

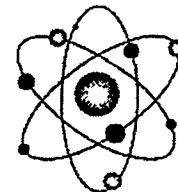
a



b



c



11 Which of the following is a CCA sign? e

Fissile Material

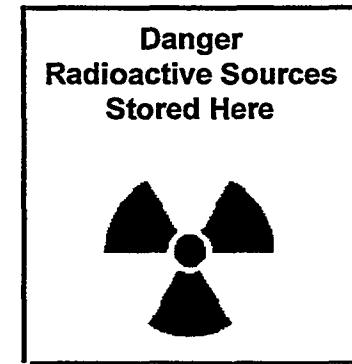
• Limit: 250 grams ^{233}U ,
or 350 grams ^{235}U , or
250 grams ^{239}Pu .

• Do Not Bring
Fissile Material
Into Area Without
Approval Of

or _____

Mass Control Area

a



b

431.07
02-97
Rev. #01

FISSILE MATERIAL LABEL

| CAUTION | Project or Log No. | | Sample or Container No. | |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------|-------------------------|--|
| | Gross Wt.* | Net Wt. | Element Wt. | |
| Fissile Isotope | Isotope Wt. | | | |
| Material Description: (Additional) | | | | |
| *For mixtures of fissile nuclides, each gram of ^{233}U , ^{237}Pu and ^{241}Pu can be counted as two grams of ^{235}U . | | | | |
| Owner | Date | | | |
| REMOVE WHEN EMPTIED | | | | |

c

Lesson 5 INEEL Criticality Control Examples

Introduction

Now that you understand a little criticality safety theory, you are ready to see how to apply it in the workplace. A few sample cases from the INEEL were selected to review in detail:

- 55-gallon drums
- Shipping packages
- 15g fissile material limit
- Mass Limit CCAs (350g ^{235}U limit)
- 380g fissile limit for waste containers (RWMC)
- ATR fuel handling in the ATR facility
- Fuel handling in FSA

You should review at least two examples, selected for applicability to your work assignments or areas in which you work. Your trainer can identify such examples.

These examples demonstrate how criticality controls are applied at the INEEL. Examples emphasize administrative controls because FMHs are relied upon most, and are most responsible, for implementing administrative controls. Although engineered controls are the preferred control method, they are not emphasized here because FMHs do not affect engineered-control implementation much. Examples are primarily based on referenced documents (Appendix A) and might be updated less frequently than the cited documents. Readers who work in an area used for an example should rely on area-specific training and procedures to identify controls currently in effect.

Objectives

No specific objectives are identified. This lesson is intended to reinforce information you learned in previous lessons.

Topic 5.1 55-Gallon Drums

A standard 55-gallon drum is a carbon or stainless steel cylinder, about 22 inches in diameter and about 34 inches high. Its physical capacity is about 56 gallons. A very similar drum, designed with metric units, is used in other countries and sometimes in the U.S.

Fifty-five gallon drums are used in many industries, businesses, and laboratories, including the INEEL. Their presence and size make these drums a criticality safety concern in areas with fissile material.

5.1.1

Generic Containers and Fissile Material

A 55-gallon drum is *not* a geometrically favorable container for most fissile materials. It is larger than many critical assemblies. In addition, the Y-12 criticality accident (Topic 6.3) occurred in a minimally reflected 55-gallon drum.

Unless the drum is modified, its diameter, height, and volume exceed critical limits for most fissile isotopes in many conditions. Consider an isolated, non-leaking drum containing a wet fissile fluid. This model envelopes many material forms, including multiple metal pieces. Table 5 lists minimum critical mass, fill height, and concentration from preliminary calculations for a water-moderated and -reflected drum. Because this hypothetical material assumes the drum's shape, minimum critical masses are significantly higher than general values listed in Table 1. However, because this drum's diameter is so large, minimum critical heights and concentrations are the same as general values listed in Table 2 and Table 3.

Table 5 Estimated Minimum Critical Parameters for a 55-Gallon Drum

(water-reflected mix of water and fissile isotope, 10kg/L maximum concentration)

| | 233U | 235U | 239Pu |
|----------------------------------|------|------|-------|
| Mass (kg) | 1.30 | 1.54 | 0.77 |
| Concentration (g/L) | 11.3 | 12.1 | 7.17 |
| Fill Height (cm) | 0.99 | 2.5 | 1.3 |
| Volume (L) based on above height | 2.4 | 6.1 | 3.2 |

Without modification, administratively controlled limits are required for criticality safety. Such limits either apply to the area as a whole and envelope any container (for example, limits in a Mass Limit CCA), or specifically address large container

use (for example, prohibit their presence, limit them to shipping packages, and/or limit their loading).

5.1.2

Fissile Material Shipping Packages

Fifty-five gallon drums are used as part of many fissile material shipping packages. Often fissile material is contained in a 5-inch diameter inner container, centered by packing material inside the drum. If subject material is ^{235}U , this design:

- takes advantage of a ^{235}U single parameter subcritical limit for a single drum (geometry control; compare 5 inches for realistic solutions of uranyl nitrate and uranyl fluoride to the minimum critical diameters for ideal ^{235}U -water mixes listed in Table 3), and
- provides about 17 inches surface-to-surface between inner containers for side-by-side drums (interaction control).

If packaging components and their assembly are reliable enough to maintain these dimensions under normal and credible abnormal conditions, this design is subcritical for many fissile materials.

However, this design is not ideal. It does not accommodate large fissile pieces. It is inefficient for very dilute fissile materials. And it is often considered inadequate for most fissile solutions and gasses.

Shipping packages will be reviewed in more detail the next topic.

Topic 5.2

Shipping Packages in General

The general public might get closer to fissile material during shipment than at any other time. Fissile material shipping regulations therefore specify rigorous tests that packages must pass before receiving a license. Abnormal condition tests are usually more strenuous and damaging than credible accident conditions inside most non-reactor nuclear facilities. For example, after surviving a 30-foot drop, shipping packages are subjected to a thermal (fire) test. Fissile material shipping packages must remain critically safe throughout.

NRC- and DOT-established controls are often convenient to implement when INEEL material can or must be stored in its shipping packages. It also helps to understand the basis for these limits so that a CCA can be established readily in the event fissile material shipping packages must be stored temporarily.

Additional Information

DOT fissile material transportation requirements are specified in 49 CFR 173, Subpart I. These requirements often apply to packages we call DOT drums.

NRC fissile material transportation requirements are specified in 10 CFR 71, which may be accessed through URL <http://www.nrc.gov/NRC/CFR/PART071/index.html>. These requirements usually apply to shipping packages at INEEL that are not DOT drums.

The most frequently used requirements involve a value often called the Transport Index (TI). Each TI is the most conservative value of indices separately determined for radiological and criticality safety purposes. The index assigned solely based on criticality safety is now often called a Criticality Index (CI). CI meaning and use are reviewed here but methods for assigning a CI are beyond this guide's scope.

A CI is a value assigned to a fissile material shipping package such that an array of identical shipping packages will be subcritical for all normal and credible abnormal transport conditions if the cumulative CI does not exceed 50. For example, if subject packages have a CI of 0.4, usually up to 250 packages are allowed to be transported together. Enveloped abnormal transport conditions include double batching (for example, two shipments parked side by side), severe package damage followed by fire and fire-fighting, dropping material into rivers, etc. No limit is placed on moderators or reflectors outside the package as long as packages are properly loaded and closed. No limits are placed on package position(s) in the array, array location, or overall array dimensions. Note that federal regulations also allow a maximum CI value of 100 when special exclusive-use controls are invoked because double batching is considered incredible in such cases.

INEEL normal and credible abnormal dry storage conditions are very benign compared to NRC-defined, DOT-endorsed, abnormal shipping conditions. An array of fissile material shipping packages should therefore be critically safe in normally dry INEEL storage if the array is critically safe for shipping.

A TI limit of 50 can usually be imposed on arrays of fissile material shipping packages in storage, assuming:

- neutron interaction between fissile material in the array and any material near the array is negligible, and
- shipping packages continue to comply with any requirements applicable to fissile material storage. For example, package integrity must be preserved and devices to retain fissile material must be used properly. However, it might not be necessary to complete certain inspections or periodic maintenance items.

In these cases the organization that holds the shipping package license, or the package's certificate of compliance, usually completes double contingency analysis for shipping and INEEL applies that analysis, supplementing it if necessary.

Usually a fuel receipt coordinator or facility-support staff member must assure a criticality index was properly assigned. FMHs and their supervisors are required to ensure shipping-package arrays do not exceed the TI=50 (or TI=100) limit.

Most individual shipping packages stored at the INEEL have very low criticality indices (0.1 to 1.0). Therefore, industrial safety concerns and storage area size are often more limiting factors than a TI limit.

Non-FMHs are sometimes allowed to move fissile material shipping packages. DOT, DOE, and NRC do not require people who move sealed packages onto and off of vehicles, and people who drive those vehicles, to be fissile material handlers. However, packages must be appropriately sealed before these people handle the packages. Personnel who handle appropriately sealed packages at the INEEL are therefore not required to be FMHs. However, these people often must have active FMH supervision for other reasons (for example, large quantities of other fissile material nearby).

Topic 5.3 Significant Quantity (15g Fissile Material)

Needs for criticality safety controls are considered when fissile material is allowed to exceed 15 grams. For example, any area allowed to contain more than 15g of fissile material must be designated a CCA unless an approved, documented analysis demonstrates a criticality accident is incredible. Why is *significant quantity* defined as such a small value, especially when 15g of ^{233}U , ^{235}U , or Pu is not a criticality concern, in and of itself? The answer has several parts:

- Fifteen grams is the quantity of unirradiated fissile material that can be mailed or shipped without special controls, based on nationally accepted DOT and NRC precedents and requirements [for example, 10CFR71.53(a)(1)]. However, these same precedents and requirements indicate criticality safety should be addressed if fissile material exceeds 15g. When establishing these requirements, regulators considered a wide variety of fissile material forms, independent organizations that might need to move such material, large fissile material quantities throughout the U.S., methods for moving such material, and public concern about nuclear safety.

Similar considerations apply at the INEEL on a smaller scale. However, it is very difficult to justify a significantly larger value at which controls begin because INEEL's scale is still quite large.

- Consistency with the NRC exemption limits helps ensure we do not inadvertently ship or receive material in violation of the 15g threshold.
- A *significant quantity* of material must be such that non-FMHs with lesser quantities cannot significantly reduce safety by moving their material or bringing it into a CCA. Demonstrating safety under such conditions is relatively simple if we are talking about one or two people, each with custody of 10 or 15g. The demonstration rapidly becomes more difficult as the number of persons and/or value of *significant quantity* of fissile material increases.
- A *significant quantity* should be such that an FMH may occasionally handle less than a significant quantity of fissile material in a CCA without requiring detailed analysis to demonstrate criticality safety. In this case, CCA limits are satisfied but one recognizes that it does not necessarily increase safety and is not always cost effective to analyze one-shot operations with a *very small* sample or source. Problems with defining when a *very small* quantity becomes a *significant quantity* for such cases are similar to problems in defining *significant quantity* in the previous bullet.

Hence, at INEEL we define *significant quantity* of fissile material as fissile material in excess of 15g ^{235}U , ^{233}U , or ^{239}Pu .

Topic 5.4 Mass Limit CCA Fissile Limits

Mass Limit Criticality Control Areas are allowed to contain any form of fissile material that does not exceed generic mass limits: 250g ^{233}U , 350g ^{235}U , 250g ^{239}Pu , or, if more than one fissile isotope is involved, the equivalent of 350g ^{235}U where each gram of non- ^{235}U is counted as two grams ^{235}U . Limits are based on minimum expected critical masses for water-reflected and moderated ^{233}U , ^{235}U , and ^{239}Pu . Analyses for Mass Limit CCAs are generic to simplify criticality safety application in areas where fissile materials are not needed in large quantities.

We will first discuss the ^{235}U limit because ^{235}U is the most abundant fissile isotope at INEEL. Note this is a single control-parameter system and controls are meant to apply to any system with a relatively small amount of ^{235}U .

For control by mass alone, we comply with a traditional best management practice, and DOE-ID-directed requirement: *a mass limit cannot exceed 45% of the minimum critical mass, if an over-batch is credible*. This requirement identifies acceptable controls to implement the double contingency principle for such cases:

- Violating the mass limit once is an unlikely event but could result in the presence of 90% of the minimum critical mass. In this case we assume ^{235}U is optimally configured, moderated, etc. because there are no controls on arrangement, moderator, etc.
- A second failure to comply with mass limits is independent of the first.

We must assume an over-batch is credible in such areas because mass limit is an administrative control, we want no additional controls on fissile material, and ^{235}U is available at the INEEL in very many forms, shapes, sizes, and quantities.

Based on experiment extrapolation and many calculations, 800-820g is the minimum critical mass for a sphere of *nearly* pure ^{235}U with optimum *water* moderation and reflection. A mass limit based on these values should not exceed 360g (45% of 800g). The 350g limit is a rounded-down value now used because (a) it is consistent with shipping limits based only on ^{235}U mass limits, (b) it accommodates any ^{235}U form, (c) it accommodates most commonly available moderators and reflectors, (d) it was already in use in many areas, and (e) people who already used it saw little advantage in raising their limit by 10g.

Once this 350g ^{235}U mass limit was identified, analysts ensured conditions under which the limit is valid envelope all expected operating conditions. This means:

- Controls ensure each over-batch truly is unlikely and independent. For mass limit CCAs, this depends on practices for transferring materials, which are beyond this example's scope.
- Special moderators and reflectors (materials that are more effective moderators and/or reflectors than water) are not a significant factor. An investigation into the effects of such material's presence caused us to establish mass limits for some special reflectors, which are also beyond this example's scope.
- Neutron interaction with material in adjacent or nearby CCAs does not adversely affect safety. Mass Limit CCAs are usually isolated by distance and intervening materials, for which we usually take credit when a CCA is approved. This is one reason each CCA must be approved by a central authority and must have well-defined boundaries.

Reasons for establishing 250g limits on ^{233}U and ^{239}Pu in Mass Limit CCAs are based on similar strategies and assumptions. The minimum critical mass of ^{233}U in water is about 560 to 590g. A limit of 250g ^{233}U was selected by choosing the nearest round-number less than 45% of 560g (252g). Similarly, 250g is less than

half the minimum critical mass of ^{239}Pu but, to simplify limits, we take some credit for the relatively small quantities and limited forms of plutonium at INEEL.

Topic 5.5 380g Fissile Limit in RWMC Waste Containers

Fissile material is generally considered an expensive and attractive material. Most radioactive waste should not include large or concentrated quantities of fissile material. It therefore seems reasonable to assume fissile material in radioactive waste would be quite dilute. However, we often must assume nuclear waste can contain residual fissile material of any fissile isotope reasonably available where waste originated. We also often must assume any fissile material in waste might be distributed in the worst possible configuration in a container.

RWMC criticality safety is somewhat dependent on accuracy and honesty of waste originators and shippers. However, each shipper must ensure container contents satisfy radioactive waste definitions. Each shipper must also ensure a single container and, if applicable, a container array, satisfy criticality safety requirements at his or her own facility and on the road. Although these requirements vary, resultant controls, limits, and designs are usually very similar. Considering all factors, a negligible over-batch might be credible but a larger over-batch is not.

For control by mass alone in this case, we comply with a traditional best management practice, and DOE-ID-directed requirement: *the mass limit cannot exceed 75% of the minimum critical mass, if an over-batch is not credible.* This requirement identifies acceptable controls to implement the double contingency principle for such cases:

- Violating the mass limit is an unlikely event and will result in the presence of much, much less than 100% of the minimum critical mass. Although waste fissile material is typically dilute, we assume worst case configuration, moderation, etc. because containers are relatively large and we often do not control waste shippers or originators.
- A second failure to comply with this mass limit is independent of the first.

An INEEL fissile mass limit was established and applied to each RWMC waste container based on the *lowest* value from two analyses:

- Extensive calculations that model typical RWMC radioactive waste in infinite arrays of DOT 6M drums. *If* one takes credit for typical waste distribution, a critical condition is not possible in this waste unless *each* drum has at least 800g of fissile isotopes.

- Minimum critical mass (Table 1) for a water moderated, water reflected unit.

The generic RWMC mass limit is 380g of fissile material, slightly less than 75% of a 530g critical limit for ^{239}Pu . The overall dilute nature of fissile material in radioactive waste is judged to compensate adequately for effects of intermixing fissile isotopes and including non-fissile materials that this 530g critical configuration does not address.

If controls, particularly receipt controls, are adequate to ensure limit bases remain valid, criticality accident scenarios are generally considered not credible for RWMC waste material. Therefore, some people do not call the 380g mass limit a criticality control. However, it is *very* important those who approve shipment receipts implement this limit.

Regardless of what one calls this limit, containers that exceed 380g fissile material *could* be a criticality safety concern, depending on non-compliance magnitude for each container *and* for all containers in non-compliance. One can deduce reasons for criticality safety concerns with overloaded drums by reviewing minimum critical masses for spheres (Table 1) and 55-gallon drums (Table 5).

Topic 5.6 ATR Fuel Handling and Storage at ATR

5.6.1 *Introduction*

The ATR facility in building TRA-670 includes the reactor, underwater canal with provisions for handling and storing irradiated fissile material, and the main reactor floor with provisions for handling and temporarily storing unirradiated and slightly irradiated fissile material. These areas are part of one Procedure CCA. Much fissile material handling and storage in this CCA involves intact ATR fuel elements (or assemblies).

Although other fissile material is also handled and stored in the ATR facility, this example focuses on standard ATR fuel elements. An ATR fuel element is an assembly of 19 aluminum clad uranium-aluminum-alloy plates held together by aluminum side plates with miscellaneous hardware above and below the fuel region. ATR plates are curved and nested; the assembly comprises an arc of a serpentine design.

Criticality safety limits are usually based on calculations that model the fuel geometry as precisely as practical for the calculation code used. To envelope all anticipated fuel loadings and manufacturing tolerances, the models include from 1075 to 1100g ^{235}U per element, and neglect all burnable neutron absorber.

Controls are in place to ensure that evaluations and limits are updated as necessary for design or manufacturing changes.

Unirradiated and slightly irradiated ATR fuel elements are typically received in fresh fuel shipping boxes or ATR fuel transfer racks. The fuel is typically staged on the facility's ground-level floor before being transferred underwater. Once underwater, a fuel element is loaded into the reactor in the reactor vessel or into a fuel storage rack in the reactor canal. Elements are transferred between the reactor and storage racks as needed to support various programs and tests. Once an element is considered to be spent fuel it is stored in a rack at least until appropriately cooled. Spent fuel is eventually transferred out of the ATR facility in shielded casks. This example is limited to activities with ATR fuel elements outside of the reactor vessel.

Readers might be interested in comparing this example with the example in Topic 5.7, FSA Fuel Handling and Storage. That example addresses fuel handling and storage at an underwater storage facility designed to handle much more and many different fuels than the ATR facility. Some safety concerns, controls, and implementation methods are the same. However, there are differences because these systems developed for different missions, under different management, and occasionally with different regulator and management interpretations of certain requirements.

5.6.2

ATR Fuel Handling Outside the Reactor Vessel

In the ATR facility criticality safety controls for fuel handling can be categorized by fissile material type and by facility area. This example is concerned only with ATR fuel element handling on the facility ground floor (a normally dry area) and in the underwater canal.

Both areas use administrative criticality controls. Controls common to this example's areas are:

- All fuel handling must be completed with at least two people with appropriate training. The limit better ensures understanding of and compliance with safety requirements.
- No more than four fuel elements are permitted out of approved storage at one time. This limit is 75% of the calculated minimum critical number of elements in water. The limit is an extremely small percentage of the minimum critical number of elements in air. However, there are no criticality safety controls established for moderators or moderator containers.

- No more than one type of fissile material is permitted out of approved storage at any one time. (Flux monitors and similar measuring devices are excluded from this requirement as long as the fissile material mass limits are followed for the fissile material form in its proximity.)

The second and third requirements above are separately stated for each area. Current practice applies these limits to the ATR facility as a whole, rather than to each area separately. For example, if ATR fuel elements were out of storage in the canal, those elements would be placed in approved storage before a fueled experiment would be received on the facility floor.

5.6.3 ATR Fuel Handling, Facility Floor

No additional criticality safety requirements are established for ATR fuel handling in facility dry areas. In this case, double contingency implementation is based on the minimum critical number of elements. An over-batch of one element is considered credible. No *official* credit is taken for normally dry conditions but analysts recognize that an additional non-routine concurrent condition is the presence of water in an effective configuration.

5.6.4 ATR Fuel Handling in Canal and Canal Transfer Tube

Two additional administrative controls apply to ATR fuel handling underwater, in the canal and canal transfer tube:

- Each element out of storage must be separated by at least one foot from any other element(s) out of approved storage. This limit is based on a criticality safety *rule-of-thumb*: there is no significant neutron interaction between fissile units separated by a foot of water. (Neutrons from one unit are reflected back or absorbed before reaching another fissile unit.) This rule-of-thumb developed from calculation results and from extrapolating critical experiment data, much of which envelopes or applies to ATR fuel elements.
- The Shift Supervisor or his designated alternate must actively direct fuel handling when more than two fuel elements are outside approved storage. Because sufficient water moderator and reflector are normally present, this control provides additional assurance that fuel handling complies with limits.

5.6.5 Approved Fuel Storage, General

Several administrative controls are established for criticality safety of approved storage. Most of these controls are administrative actions to support or maintain engineered controls of the storage equipment. Criticality safety staff, safety

analysts, maintenance personnel, and fuel handlers each have roles in implementing some of these controls.

- Storage fixtures must be stable and not susceptible to tipping from credible natural phenomena or work activities.
- Allowed storage conditions must be evaluated to demonstrate that the calculated k_{eff} does not exceed 0.95 for service conditions.
- To maintain fuel configuration and cladding, and to ensure adequate water separation in underwater facilities, fuel cooling must be adequate to remove decay heat without reaching saturation temperature in the coolant.
- With the exception of equipment designed for shipping or transferring fissile materials, fissile material must be removed from a storage unit before the unit is moved.
- To avoid damage to fuel and fuel storage equipment, fuel storage must be located away from areas where heavy loads are routinely handled. Alternatively, specific locations may be established to preclude physical contact between heavy loads and materials in storage.

5.6.6

Approved Fuel Storage, Underwater Fuel Storage Racks

ATR fuel elements are stored in three types of underwater fuel storage racks. In two rack types, fuel storage positions are circular tubes, sized to hold one ATR fuel element in each tube, in a triangular-pitch array. New ATR racks have 40 tubes; CPP (or INTEC) racks have 92 tubes. In the third rack type (old ATR racks), fuel storage positions are oval-shaped tubes, sized to hold two ATR fuel elements per tube (one on either side of a center divider), in a square-pitch array. Each old ATR rack has 20 tubes (40 storage positions).

All of these racks include cadmium as a neutron absorber. However, no criticality safety credit is now taken for this cadmium because of concerns about corrosion and difficulty in demonstrating adequate cadmium is continuously present. Currently approved (1998) safety analyses indicate that, without credit for the cadmium, old ATR racks would not be critically safe if fully loaded with ATR fuel elements. Therefore, extra water spacing is provided in these racks by physically blocking every other storage tube row with cover plates.

Rack criticality safety relies on a combination of engineered controls:

- Storage rack tube size physically prevents over-batching standard ATR fuel elements.

- Neutron interaction is reduced to acceptable levels by distance between usable storage tubes.

An administrative control requiring periodic structural-integrity inspections helps ensure engineered controls continue to be effective.

5.6.7

Approved Fuel Storage, Fresh Fuel Shipping Containers

ATR fresh fuel shipping containers are approved shipping containers (Topic 5.2) used to ship and transfer unirradiated and/or slightly irradiated ATR fuel elements. The 10.75 \times 31.5 \times 93.4 inch containers are primarily constructed of wood, steel, aluminum, polyethylene and cadmium. Up to four elements fit in a 4x1x1 slab array within a container, and element position size physically prevents over-batching intact elements.⁴ Each properly loaded, maintained, and closed shipping container of ATR fuel elements is assigned a transport (and criticality) index of 4.2. Up to 23 such containers may be shipped under exclusive-use provisions.

Polyethylene in the container moderates neutrons to ensure cadmium is an effective neutron absorber for all conditions except the unlikely event of a fire sufficient to melt these materials. This neutron absorption results in very little neutron interaction between intact containers, and little neutron interaction between fuel in a container and fuel at the face of a container.

An infinite three-dimensional array of intact containers with optimum water moderation inside elements, inside containers, and between containers is adequately subcritical ($k_{\text{eff}} \leq 0.95$) by virtue of fuel configuration and effective neutron absorption. A worst case water-reflected array of twenty-four containers with optimum water moderation inside intact elements and inside damaged containers is adequately subcritical by virtue of a combination of neutron leakage, neutron absorption, and fuel configuration.

5.6.8

Approved Fuel Storage, Other Containers

Other shipping and transport containers can be used in the ATR facility. These containers are usually shielded casks, handled one at a time. Most such containers would be loaded underwater in a specific area sufficiently far from the reactor vessel and from fuel storage equipment. Criticality safety for such containers is addressed in a separate Approved Transport Plan, and fuel handlers should be

⁴ Container lid will not close if an additional element is present or if an element is out of place.

trained on applicable parts of that plan before loading a container or moving a loaded container.

Some devices used in moving ATR fuel do not qualify as approved fuel storage although their general use, and sometimes design, is similar to containers that do qualify as approved fuel storage. Fuel in these devices is considered out-of-approved-storage and is subject to previously discussed fuel handling limits.

5.6.9

One Hypothetical Criticality Accident Scenario

Scenario: A criticality accident caused by six or more ATR fuel elements being removed from storage and assembled into a critical mass on the canal floor. The probability this scenario would occur is considered very unlikely.

Applicable controls and contingencies to prevent this criticality accident include:

- maximum four elements out of storage at once, and supervisory presence to strengthen limit implementation. Fissile mass in the specific form of ATR elements serves as a contingency in satisfying the double contingency principle for this scenario.
- minimum one foot spacing between elements out of storage to reduce neutron interaction between elements. Spacing serves as a contingency in satisfying the double contingency principle for this scenario.

Topic 5.7

FSA Fuel Handling and Storage

5.7.1

Introduction

Some criticality controls for fuel storage and handling at the FAST Fuel Storage Area (FSA) in building CPP-666 are described. General principles should be the same for other INEEL underwater fuel storage but nomenclature, specific fuels, storage configurations, and handling tools differ. However, these other INEEL facilities do not store as much fuel, as many different fuels, or both. Readers might be interested in comparing this example with the example in Topic 5.6, ATR Fuel Handling and Storage at ATR.

A variety of spent nuclear fuels containing significant amounts of ^{235}U are routinely shipped to and stored underwater at FSA. FSA provides facilities for receiving and unloading fuel shipments, repackaging some fuels, visually inspecting fuel, and storing fuel. Storage facilities consist of six interconnected storage pools, equipped with fuel storage racks. Fuel is handled and stored in the form of fuel handling units (FHUs) under at least 20 feet of water. Criticality

safety is provided by a combination of design features and administrative controls. For example, FHUs are stored in racks that are critically safe by virtue of geometry and ^{235}U density limitations.

Criticality safety during fuel handling operations is ensured by

- administrative controls restricting the amount of fuel being handled at any time, and
- mechanical means to limit fuel in either a transport device or storage rack position and to keep it in a proper configuration.

Fissile mass, geometry and density controls can be readily expressed by the number and type of fuel pieces assembled into an FHU. However, identifying and implementing FHU controls involves many people:

- Criticality safety staff and safety analysts identify a safety envelope and general fuel configurations within that envelope.
- Fuel handler support staff usually complete paperwork identifying (a) specific pieces and or FHUs that comply with general fuel configurations and (b) fuel handler instructions.
- Fuel handlers generally implement controls by following instructions. In these cases fuel handlers rarely, if ever, directly implement ^{235}U density or geometry controls.

However, *fuel handlers are ultimately responsible for recognizing when conditions, instructions, or both might not satisfy the safety envelope*. This is necessary for their own safety as well as to assure compliance with applicable rules.

Criticality safety is divided into three discussion subtopics: cask handling, fuel handling, and fuel storage. In all these discussions underwater FSA criticality safety requires FHUs be separated by at least eight inches of water at all times, except when fuel is in casks or storage racks specifically designed for closer FHU packing.

5.7.2 FSA Cask Handling

Fuels coming into FSA are received in casks. Casks must be spaced a certain minimum distance apart. The specified distance depends on casks, fuel type, and whether a cask is on the deck or underwater.

Before placing a cask in or removing it from an unloading pool, handlers must ensure no fuel is in the pool outside the cask. Dropping a cask onto an FHU in the pool will cause severe damage to the impacted fuel and might contribute to or cause a criticality accident if the FHU is over-moderated in its undamaged state.

Aside from the above accident, damaging placing a cask that contains fuel into a pool with an FHU already present could result in two FHUs being out of an approved storage position at one time. Unloading the cask before removing this previous fuel could also result in violating the basic criticality safety requirement to maintain a minimum eight-inch water separation.

Hypothetically, fuel could be spilled into a critical array in the unloading pool if the cask were dropped during maneuvering. Administrative controls require the use of closure devices on casks that contain enough fuel for this accident scenario.

5.7.3

FSA Fuel Handling

Specific requirements for fuel handling vary with the type of fuel that is being moved. However, the underlying requirement remains the same: ensure no more than 75% of the minimum critical number of fuel pieces (elements, assemblies, cans, or whatever) can credibly fall or be brought together into an optimal (maximum k_{eff}) array.

Procedures require fuel handlers to ensure that only one FHU is out of approved storage at a time (excluding fuel contained in a cask, physically isolated in packaging equipment by a criticality cage, or physically isolated in a pool by a gate). This one-FHU limit is especially important for some fuels because a true double batch of these FHUs is not critically safe if the eight-inch minimum water separation is also violated. In these fuel handling cases, administrative controls are the primary means for implementing both criticality safety contingencies (number and separation of FHUs). However, equipment limitations (for example, fuel-handling-crane speed, reliability, and travel ability) support compliance with these administrative controls.

5.7.4

FSA Fuel Storage

Three fuel storage concerns are: (a) excessive reactivity in a single FHU, (b) overbatching in a storage position, and (c) rack damage.

Excessive reactivity in a single FHU is controlled through fuel evaluation and receiving. Controls include linear uranium loading limits and requirements for a criticality safety evaluation that demonstrates compliance with the maximum single-position k_{eff} limits for rack storage.

Over-batching a storage position means there is more fuel in that position than there is supposed to be. Over-batching scenarios include: (a) intentional, (b) FHU drop or (c) placement of an FHU at the side of a rack. Intentional side by side overbatching could result if FHU components or storage position contents are misidentified or not clearly understood. Criticality controls for this scenario include:

- defining the FHU configuration,
- defining multiple-FHU configurations, if and where permitted, to be stored in a single rack storage tube,
- defining approved storage locations, and
- requiring a criticality control device, in each rack position with an FHU, to preclude side-by-side overbatching within a storage position. Such devices are usually part of the FHU, for example, the geometry of the fuel itself or a basket, bucket, or rack insert in which individual fuel piece(s) are placed.

The second over-batch concern, a dropped fuel resulting in a side by side configuration in a storage position is prevented by controlling rack lids above each rack storage tube and by using the criticality control device mentioned above. To a much lesser extent, a fixture that serves as a visual cue that a rack storage tube is not empty also contributes in minimizing this accident.

The last over-batching condition, a critical array caused by an FHU at the side of or between racks, is prevented by physically covering or limiting gaps where practical. Where such engineering controls are impractical, fuel is not stored in positions immediately adjacent to the exposed rack side.

The final area of concern is rack damage. Damage could occur from: (a) natural phenomena in excess of the design basis, which is outside analysis scope, (b) dropping an object in excess of the design basis drop load, or (c) moving racks. Moving loaded racks is prohibited, moving heavy objects is restricted, and the cask-handling (130-ton) crane is normally locked so that it cannot be moved over storage pools.

5.7.5

One Hypothetical FSA Criticality Accident Scenario

Scenario: A criticality accident caused by an excessive amount of aluminum fuel units outside a cask and not in approved storage. This scenario is considered very unlikely.

In this case, an FHU is a single element, or a specific bucket containing up to a specified number of elements. The number of elements is determined from criticality safety evaluations and is selected to not exceed 75% of the minimum critical number of elements. This number varies depending on the aluminum fuel type. The bucket type varies to accommodate the specific fuel, minimize over-batching, and minimize the number of different bucket designs needed.

In double-contingency-principle terms, the first unlikely event is failure by operating personnel to ensure that only one FHU is out of approved storage at any one time. Administrative controls limit handling to one FHU out of approved storage in the entire basin area, except elements contained in a cask or in the repackaging station, with its criticality "cage," specified for that fuel. This failure is unlikely because personnel certified in fuel handling operations, or under the direction of the supervisor, perform this operation and because compliance with this requirement must be independently verified by a second qualified person.

The second unlikely event is failure to maintain at least eight inches edge-to-edge separation between FHUs. The potential for a criticality is not present if FHUs are adequately separated. Eight inches of water is enough spacing to adequately reduce neutron interaction for these fuels. However, if FHUs are brought close together (less than eight inches), neutron interaction increases, and k_{eff} of the two FHUs could exceed 0.95. Administrative controls require that a minimum of eight inches edge-to-edge separation be maintained between FHUs. Again, personnel performing fuel handling operations are certified or under the direction of certified personnel.

In addition to the above controls, which satisfy the double-contingency principle for this scenario, other controls further reduce the potential for a criticality accident. For example, a third administrative control requires personnel to place fuel units removed from the cask into a repackaging station with its criticality cage until the FHU is ready to be moved to its storage location. The cage physically provides eight inches edge-to-edge spacing and isolates these fuel elements from other FHUs during fuel packaging operations. This third administrative control is not part of contingency-principle implementation; it is an additional control providing defense-in-depth.

Finally, there is another required, concurrent condition: FHU components or the multiple FHUs must be assembled into a critical configuration that is difficult to achieve by accident.

In conclusion, this scenario requires multiple failures of strong administrative controls. The probability of this scenario occurring is extremely unlikely.

Part 3 History

Criticality safety limits have substantial safety margins but alone they cannot prevent accidents from occurring. Not all fissile-material-handling dynamics can be anticipated. Criticality accidents are avoidable only when personnel have enough knowledge, skill, and willingness to implement controls appropriately and to recognize unanticipated conditions.

Criticality accident information can help workers recognize unanticipated conditions and improve vigilance. Therefore, Part 3 summarizes information from individual criticality accidents and their specific lessons, emphasizing the role humans played in these accidents. All reported-to-date out-of-reactor and several in-reactor criticality accidents are included. All three criticality accidents at the former Idaho Chemical Processing Plant are included as much for local interest as instruction. Reviews do not include criticality accidents in fuel storage or in solid waste systems because none have been reported. This does *not* mean such accidents are incredible.

Part 3 supplements Topic 4.8, which summarizes lessons-learned from the overall criticality accident history.

Fissile material handler candidates should review at least two accident descriptions, preferably from those most applicable to the reader's work area or an area the reader visits. However, no test questions are planned for these summaries.

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Lesson 6 Process Criticality Accidents

Summary

At the time this revision was prepared, twenty out-of-reactor criticality accidents were reported: seven in the US, one in the UK, and twelve in the Soviet Union or Russia. A thirteenth Russian accident was reported as a process accident but is here classified as an in-reactor accident (see Topic 7.4). Accident-specific lessons-learned are described here but cumulative lessons-learned were discussed in Topic 4.8.

None of these accidents were associated with nuclear fuel storage or fissile material transportation. Most occurred with aqueous solutions, including several cases in which fissile material was not supposed to be a solution or slurry. However, one occurred with solid material.

These accidents resulted in seven deaths, 40 significant radiation overexposures, no significant equipment damage, and negligible fissile material loss. In no case was there any danger to the general public.

While accident results are indeed significant, our criticality safety record is impressive compared to that of more common industrial hazards. At nuclear facility sites, risk of fatality is much higher from hazards such as motor vehicle and aircraft accidents, electric shock, falls and falling objects, burns, and non-nuclear explosions.

Although our criticality accident record is favorable, extreme care must be used to maintain it, especially in light of a somewhat distorted view the public has of nuclear accident risk.

Objectives

No specific objectives are included here. A related objective is included in Lesson 4 based on Topic 4.8: Discuss lessons learned from historical criticality accidents.

Topic 6.1 15 March 1953, Mayak Enterprise, the Urals, USSR

This accident occurred in vessels used for mixing, diluting, sampling, storing, and transferring plutonium-nitrate solutions. A concrete cell contained seven 40L, nonfavorable geometry vessels with interconnections, filters, traps, and vacuum equipment for solution transfers. Some in-cell vessels could also be connected with eight similar vessels outside the cell.

On March 15, 1953, 26L of solution containing 650g Pu divided between two in-cell vessels was to be transferred to a third vessel outside the cell. A chief operator and assistant operator connected the vessels to vacuum equipment and proceeded with the transfer.

By the end of the transfer the chief operator was next to the receiving vessel (outside the cell) and the assistant operator was near the originating vessels (inside the cell, several meters from the receiving vessel). The chief operator disconnected the hose from the receiving vessel, saw foam, and reconnected the hose. About that time, the assistant operator noticed solution had entered a glass vacuum trap.

Realizing something was wrong, these operators transferred solution from the receiving vessel to the initial vessels, diluted it, cooled it, and then transferred it to two other empty, in-cell vessels. Both operators decided not to tell authorities. However, two days later the chief operator exhibited severe radiation sickness. (Prompt medical attention probably would have alleviated or prevented many symptoms.)

Investigators determined the receiving vessel contained about 31L solution when the initial transfer was complete and that about 5L solution was missing from the cell after the accident. They believe the accident consisted of a single power burst of about 2.5×10^{17} fissions. They also estimated the chief operator received about 1000 rad, the assistant about 100 rad.

Topic 6.2 21 April 1957, Mayak Enterprise, the Urals, USSR

The second process criticality accident at the Mayak Enterprise occurred in a chamber for oxalate purification and filtration of highly enriched uranium solutions. The chamber contained a 500mm diameter (about 19.7 in.), 100L vessel equipped with heater and a stirring device, a filter, a tank, and a vacuum trap on the solution outlet line. There was no radiation monitoring equipment and, apparently, little if any shielding.

Process operations deviated significantly from requirements:

- equipment was not regularly cleaned out,
- errors were made in accounting for uranium and other ingredients,
- process vessel temperatures were not monitored, and
- filter condition was not checked.

As a result 3.4kg of oxalate precipitate accumulated in the tank. A critical condition was achieved but not known for some time.

On April 21, 1957, the operator noticed filter media had swelled. Precipitate was discharging gasses. This phenomena was observed for about ten more minutes. The reaction terminated when part of the solution was forced from the tank into the trap.

Investigators estimated a yield of 2×10^{17} fissions by averaging results from different accident scenario theories. The operator died 12 days later; five other workers developed radiation sickness.

Topic 6.3 16 June 1958, Y-12, Oak Ridge TN, USA

The Y-12 accident occurred in an area for recovering enriched uranium from scrap. A material inventory was in progress.

Workers were cleaning and leak testing a supposedly empty system of 5-inch pipes. Between emptying and washing, solution leaked into the pipes through a valve that was supposed to isolate these pipes from other process equipment.

First, concentrated fissile solution from the pipes flowed into a 55-gallon drum meant to catch wash and leak-test water. The solution was too shallow to be critical. Then water flowed into the 55-gallon drum. This water diluted the fissile solution, increased the solution fill height, and caused a criticality accident. Water continued to flow, further diluting the solution, eventually causing the system to become subcritical.

The initial critical pulse occurred with about 2.1kg ^{235}U in 56L solution followed by a succession of bursts, producing an estimated 1.3×10^{18} fissions in three minutes. Only about 10^{16} fissions occurred in the first and largest burst because flow rate was relatively low. This is consistent with observations that the reaction was not violent enough to splash solution out of the drum. Operators reported seeing a *blue flash* before evacuating.

One man, who was about 6 feet from the drum, received a radiation exposure of 461 rem. Other exposures were 428 rem at 18 feet, 413 rem at 16 feet, 341 rem at 15 feet, 298 rem at 22 feet, 86 rem at 31 feet, 68 rem at 37 feet, and 29 rem at 50 feet. Exposures and distances from the drum do not correlate closely, primarily because some evacuation routes were more favorable than others. Exposures resulted almost entirely from the initial burst (from which there was no escape), because radiation alarms activated and immediate evacuation ensued. The importance of rapid departure can be appreciated if one notes people exposed to 400 to 500 rem have about a 50% chance of survival without medical attention.

Management subsequently adopted two measures to prevent similar accidents: (1) isolate equipment by disconnecting transfer lines that might contain fissile material, and (2) permit only geometrically favorable containers for enriched uranium solutions in process areas (for example, waste baskets are perforated and standard mop buckets were replaced by geometrically favorable containers).

Topic 6.4 30 Dec. 1958, LASL, Los Alamos NM, USA

This LASL accident involved equipment for treating dilute raffinate from a plutonium recovery plant. Residual plutonium (typically 0.1g/L) and small quantities of americium were recovered from raffinate by solvent extraction in large tanks.

A material inventory was in progress and tanks (all closed) were to be emptied and cleaned, one by one. Presumably to simplify this process, residual materials and nitric acid wash solutions from four vessels were emptied into one tank, a vertical 225-gallon, 38-inch diameter vessel. Collection was possible due to many interconnecting transfer lines. Expected fissile inventory was 0.125kg for the entire system.

The excursion occurred in this large tank when its stirrer was turned on. Subsequent investigation indicates 3.27kg plutonium, in an 8-inch-thick organic layer (160L), was floating on a dilute aqueous solution (60g plutonium in 330L). Stirring initially thickened the center of the organic layer, enough to make the solution supercritical. Continued stirring mixed the organic and aqueous phases, diluting plutonium enough that criticality did not continue.

The excursion produced a single spike, about 1.5×10^{17} fissions. An operator, who was standing against the tank, received about 12,000 rem and died 36 hours later. Two men who approached the tank to help the victim received 134 rem and 53 rem. There was no damage to equipment and no contamination, although the shock displaced tank supports $\frac{3}{4}$ -inch and knocked the operator off a small ladder. A radiation alarm 175 feet away activated, and a blue flash accompanying the excursion was seen from an adjoining room.

The only explanation found for 3.3kg of plutonium in this process, is that solids accumulated gradually during seven years of operation. The entire recovery plant was scheduled to be rebuilt after six more operating months. Instead, old equipment was retired immediately.

Many changes were made afterwards. Safer equipment was installed in the rebuilt plant, as planned. Written procedures were improved for all operations and for emergencies. Emphasis on procedure compliance and nuclear safety training increased. Radiation alarms were installed to monitor all process areas. Solution transfer lines not required for a specific operation were blocked to minimize opportunities for abnormal interchanges. Neutron absorber (cadmium nitrate solution) was added to vent tanks and vacuum buffer tanks for safety in the event of inadvertent transfer. In addition, periodic surveys with portable neutron detectors were instituted to detect abnormal plutonium accumulation.

Topic 6.5 16 Oct. 1959, ICPP, Scoville ID, USA

This ICPP excursion resulted from air sparging a bank of safe-by-geometry storage cylinders that contained uranium solution (170g $^{235}\text{U}/\text{L}$). Sparging initiated a siphon that transferred about 200L solution (34kg ^{235}U) from geometrically favorable storage cylinders into a 5,000-gallon tank containing about 600L water. Criticality in this tank produced about 4×10^{19} fissions over about 20 minutes. An initial spike of about 10^{17} fissions was probably followed by smaller spikes and then by more-or-less stable solution boiling. The reaction terminated after about 400L water was distilled into another tank. No equipment was damaged.

There was no direct neutron and gamma exposure, but airborne activity spread into operating areas through vent lines and drain connections. Airborne activity triggered radiation alarms and immediate evacuation ensued. Two persons received significant beta radiation doses, 50 and 32 rad, when they evacuated through areas where off-gas system and drain lines vented. These exposures demonstrate usefulness of radiation alarms in areas that might be affected by a nuclear incident occurring elsewhere.

Action to install valves in the line was already in progress. These actions were completed before restart. Orifices were added to sparge lines to restrict air flow volume. Emergency procedures were improved and water traps were installed in vent and drain lines. Equipment and operating procedures were reviewed to establish several lines of defense against inadvertent transfers of fissile material.

Topic 6.6 5 Dec. 1960, Mayak Enterprise, the Urals, USSR

The third process criticality accident at Mayak Enterprise occurred in a chamber for plutonium-carbonate solution filtration. Chamber equipment included a chemical processing vessel, a transfer tank, a filter, and an unfavorable geometry tank. The latter was a 40L vessel with a 350mm (about 13.8 in.) diameter and 400mm (about 15.7 in.) height. There were radiation and/or criticality alarm systems in the area.

Plutonium masses were determined by measuring solution volumes and chemically analyzing solution samples. However, process records were poorly maintained. In addition, sometimes there was a 100% uncertainty in total plutonium mass results, although procedures stipulated 20% was the maximum acceptable uncertainty.

On December 5, 1960, a technician discovered a discrepancy in plutonium mass analysis for the process vessel. However, he proceeded to transfer solution to the filter without resolving this discrepancy.

A single-spike excursion occurred in the nonfavorable geometry vessel, terminated by solution surging into connecting lines. During emergency response the vacuum system was turned off. This action allowed solution to flow back into the nonfavorable geometry vessel, resulting in a second excursion.

Subsequent investigation indicated:

- the first excursion occurred with approximately 800g Pu in solution and 170g Pu precipitate,
- the estimated total yield was 10^{17} fissions, and
- several people received exposures of up to 5 rad.

Topic 6.7 25 Jan. 1961, ICPP, Scoville ID, USA

This second ICPP criticality accident occurred on January 25, 1961. System design minimized the accident's immediate physical consequences: (1) Concrete shielding protected personnel. (2) Ventilation-system design prevented airborne activity from entering work areas. (3) Equipment design prevented a destructive or persistent excursion.

Nevertheless, it was a serious occurrence at ICPP, and lessons learned were important. The incident could have had serious consequences had the shielding been less than designed.

The excursion occurred when about 40L uranyl nitrate solution (200g U/L) was forced upward from a 5-inch diameter section of an evaporator into a 24-inch diameter vapor disengagement cylinder, well above the normal solution level. Presumably, air entered associated lines during attempts to clear a plugged line and to improve pump operation. When the air bubble reached the evaporator, solution was expelled from the lower section. The excursion, thought to be a single spike, yielded 6×10^{17} fissions. Radiation triggered alarms, causing plant evacuation, but nobody received more than 100 mrem.

Inadvertent criticality in the disengagement cylinder was deemed credible before the accident. Therefore, lines led from its base to two geometrically favorable vessels, with provisions for overflow to the floor. This arrangement and other features prevented a large pressure increase and a sustained reaction. There was no equipment damage and no significant radiation exposure.

Plant operations resumed shortly after the incident. Management restricted the use of air pressure to move liquids. A borated steel grid was installed in the disengagement cylinder, and the cylinder was later replaced with a thin slab tank. Staff was reminded of the wisdom of basing system design on upset conditions.

Topic 6.8 14 Aug. 1961, Siberian Chemical Compound, USSR

The Russian criticality accident of 14 August 1961 occurred in an experimental facility of the Siberian Chemical Combine. It differs from U.S. accidents because it involved intermediate (10-60%) enriched, gaseous uranium.

This part of the experimental facility purified 22.6% enriched uranium hexafluoride (UF_6) in a line that included a main cylinder, additional vessels, a tank, and a pump with a cylindrical 60L oil vessel. Liquid nitrogen cooled the main cylinder, to cool and condense gaseous UF_6 . The main cylinder was inadequately cooled, temperature control devices were not operational, and one vessel was bypassed.

Apparently gaseous UF_6 leaked because it was inadequately cooled and process limits were not observed. Leaked gas accumulated and condensed in the pump's oil reservoir. Uranium concentration was about 400g/L at the time of the accident. Assuming the vessel was full, the mass was about 24kg U or 5.4kg ^{235}U .

Radiation alarms activated due to the excursion and staff evacuated. However, the alarm was declared false because portable gamma-dosimeters did not confirm an accident. The facility was restarted three hours later, resulting in a second excursion of the same magnitude as the first.

Both excursions shut down from temperature increase effects and oil ejection. The total yield was about 10^{16} fissions.

The operator, about 0.5m (20 inches) away from the pump, received about 200 rad. It is not clear from currently available literature if this exposure is from one or both excursions.

The facility was redesigned and reconstructed. Processing manuals and procedures were revised.

Topic 6.9 7 April 1962, Hanford Works, Richland WA, USA

The multipurpose Recuplex facility for plutonium recovery started as a pilot plant in 1955. With successive changes it became a production facility. Various portions of this versatile plant were contained in room-size plastic hoods (gloveboxes) to prevent external contamination. Over time plant equipment deteriorated and leaked. Even visibility through the plastic hood walls was poor. A thorough clean-up was almost complete at the time of the accident.

The 69L glass tank in which the excursion occurred was normally used to transfer dilute-streams from solvent extraction columns. This solution, which carried a fraction of a gram per liter of plutonium residues, was then directed to a secondary recovery process (similar to the raffinate treatment process of the Los Alamos accident, Topic 6.4). About 46L of solution containing 1.4 to 1.5kg plutonium was inadvertently transferred to the transfer tank and led to the excursion. Apparently most of the material was aqueous solution sucked up from a sump through a temporary clean-up line. Solution in the sump had apparently overflowed from a geometrically favorable vessel.

The incident produced about 8.2×10^{17} fissions over 37 hours, with about 20% occurring in the first half-hour. Event reconstruction indicated an initial spike of about 10^{16} fissions, followed by smaller spikes for 20 minutes, after which boiling occurred. The excursion ended after boiling off about 6L water and settling organic matter after the organic extracted plutonium from the aqueous phase.

The initial burst, accompanied by a blue flash, triggered radiation alarms. Immediate plant evacuation ensued. One man, who was 5 or 6 feet from the transfer tank, received a radiation dose of 110 rem. Another person, about 9 feet away, received 43 rem, and a third, at 26 feet received 19 rem.

A small, remotely controlled robot, equipped with television, was used during post-evacuation response. This robot, normally used for handling irradiated fuel, was used to fix the incident location, place and read meters, and operate valves.

The Recuplex plant was already scheduled for replacement. It was not reactivated after the accident. The replacement plant made fuller use of geometrically favorable equipment and neutron absorbers. It was adaptable without improvisation, and its new equipment was easier to clean. Operational flexibility requires special effort to maintain up-to-date written procedures that represent realistic practice.

Topic 6.10 7 Sept. 1962, Mayak Enterprise, the Urals, USSR

A criticality accident occurred September 7, 1962, in a chamber for dissolving plutonium metal scrap at the Mayak Enterprise. Until then scrap material was stored without measuring fissile content because the plant lacked appropriate instruments. Scrap reprocessing was based on total mass and an experience-based value of 1wt% Pu.

Scrap reprocessing included initial dissolution in nitric acid using a 100L, 450mm (about 17.7 in.) diameter dissolver vessel. The vessel was equipped with a stirring device, heater, and 5 cm (about 2 in.) thick lead shielding. The operating manual allowed operators to halt dissolution when excess acid was neutralized.

Personnel evacuated when a radiation and/or criticality alarm system activated a few minutes after completing a dissolution operation and turning off stirrer and heater. Personnel exposure was insignificant due to this evacuation and the vessel's shielding.

The first fission spike was followed by two spikes within 40 to 50 minutes. Investigation indicated there was 1.32kg Pu in the completely full dissolver. Each spike terminated because some solution was ejected. However, continued dissolution caused the second spike. Estimated total yield was 2×10^{17} fissions.

Topic 6.11 30 Jan. 1963, Siberian Chemical Compound, USSR

An accident occurred January 30, 1963, at the Siberian Chemical Combine's facility for reprocessing highly enriched uranium scrap. Scrap was divided into dissolver batches based on uranium mass, but lax recording practices allowed values to be listed either as a percentage of uranium mass or as grams uranium per kilogram scrap. As a result, a batch containing 5% uranium (50gU per 50kg scrap) was misidentified as containing 5g/kg.

The error was discovered after dissolving the batch based on solution chemical analysis. The solution was divided, transferred to two vessels, and resampled. Reanalysis was faulty and again underestimated uranium by a factor of 10

because, based on experience, nobody could believe they had such highly concentrated scrap solution.

Based on this faulty analysis, personnel transferred about 40L with a true concentration of approximately 71g/L to a 342mm (about 13.5 in.) diameter tank. Staff evacuated because an alarm activated due to the first fission spike. Four staff members who were about 10m from the tank received exposures from 6 to 17 rad.

For the first six hours the fission reaction continued as a series of power oscillations. Each spike terminated by ejecting solution into transfer lines but nuclear reaction reinitiated when solution flowed back into the tank. Then the reaction reached a quasi-steady-state plateau with unresolved fission spikes. The reaction was terminated ten hours after the first spike by transferring solution to favorable geometry vessels. The total yield was estimated at 7.9×10^{17} fissions.

Topic 6.12 13 Dec. 1963, Siberian Chemical Compound, USSR

This December 13, 1963 Russian accident differs from U.S. accidents because it reached a quasi-steady-state condition that was terminated by injecting a soluble neutron absorber into the system.

In the Combine's facility for uranium extraction, a vacuum control trap was installed on the main line for transferring highly enriched (apparently 90% or more) uranium solution. The trap was a vertical cylinder with a hemispherical bottom, with a 0.5m (20 inch) diameter and 100L volume.

Extracting agent was inadvertently transferred to the trap in small quantities and, occasionally, uranium solution accumulated in the trap due to overflows upstream. There was no method to detect or account for extracting agent, and no controls were required to prevent uranium overflows of the size experienced. Inevitably extracting agent in the trap became saturated with uranium.

The accident occurred when the trap filled with uranium solution at approximately 33g/L. The first spike was about 1.6×10^{15} fissions. A gamma detector registered 16 oscillations of decreasing intensity and periodicity over the next six hours.

Response personnel, assuming the reaction had ended, turned off the vacuum system. As a result, solution in the lines reentered the trap. After an intense peak and subsequent power oscillations, the reaction reached a quasi-steady-state. Cadmium solution, injected into the trap, terminated the reaction.

Total yield was estimated at 2×10^{17} fissions over 18 hours. Nobody was injured because nobody was near the trap when the accident began. The alarm system activated and personnel evacuated safely.

Topic 6.13 24 July 1964, Wood River Junction RI, USA

United Nuclear Corporation's scrap facilities at Wood River Junction were designed to recover enriched uranium from reactor-fuel-fabrication scrap. Operations started in March and were still preliminary in July, when the accident occurred.

Because of startup difficulties, there was an unusual accumulation of contaminated trichloromethane. There were also very concentrated ^{235}U solutions, from clean-out of a plugged evaporator. Separate bottles were used but contaminated trichloromethane and concentrated fissile solution were stored in the same kind of 5-inch diameter bottles, in the same general area.

Uranium was recovered from contaminated trichloromethane by hand agitation with sodium carbonate solution. Eventually operators improvised to speed this very tedious process. They treated the trichloromethane in an 18-inch-diameter tank intended only for makeup of sodium carbonate solution. Neither the plant superintendent nor one of three shift supervisors was aware of this practice. This geometrically unfavorable tank was the excursion site.

Apparently a bottle of concentrated solution was mistaken for trichloromethane and poured into the sodium carbonate makeup tank.

From the most plausible event reconstruction, two excursions occurred about two hours apart. The first, a single spike of about 10^{17} fissions, occurred when most of the concentrated solution had been poured into the tank. The shock splashed about one-fifth of the solution out of the tank and knocked the operator onto the floor. Workers observed a blue flash and radiation alarms activated. The victim, who ran out of the building, received a dose of about 10,000 rad and died 49 hours later. Other exposures were minor because other workers were at least 40 feet away and because everybody evacuated immediately.

Apparently the first excursion ejected enough solution that the vortex from a tank stirrer maintained a subcritical state. Two hours after the first excursion, however, two men reentered the area. They turned the stirrer off, and then on again some minutes later. Then they drained the tank. (The radiation alarm was still sounding as a result of the first burst.) Apparently, the second excursion occurred shortly after the stirrer was turned off. It could have been either a single burst or a sequence of bursts. The two who drained the tank received radiation doses of 60 to 100 rad.

The two excursions produced about 1.3×10^{17} fissions.

After the accident United Nuclear Corporation analyzed operation methods. Analysis included penetrating reviews of, and improvements to, operating procedures, criticality limits and controls, uranium accountability and material balance methods, health-physics procedures and controls, training, and emergency procedures. Geometrically favorable equipment was put into operation for recovering uranium from trichloromethane.

Topic 6.14 13 Nov. 1965, ElectrostaI Fuel Fabrication Plant, USSR

This accident involves low enriched (less than 10%) uranium powder. The process converted uranium hexafluoride, UF_6 , into uranium dioxide, UO_2 , powder. To speed load-out, the receiving vessel was equipped with a vacuum system. This system included a line with two filters and a vacuum water pump with a water vessel that had a 30cm. (12 in.) diameter and 65cm (26 in.) height. Filters were checked rarely and no instruments were used to detect uranium accumulation.

On 13 November 1965, the alarm system activated and staff evacuated. Investigation revealed both filters were punctured. Uranium powder had accumulated in the pump's water vessel. 157 kg of uranium slurry (51kg uranium enriched to 6.5%, or 3.3kg ^{235}U) were extracted from the pump vessel. The excursion consisted of one spike with an estimated 10^{15} fissions. One worker received 3.5 rad.

The uranium dioxide unloading device was dismantled.

Topic 6.15 16 Dec. 1965, Mayak Enterprise, the Urals, USSR

This accident at a Mayak Enterprise's facility for dissolving uranium scrap also involved highly enriched uranium. The accident occurred in a 450mm (about 17.7 in.) diameter dissolver vessel equipped with a vapor-water heater jacket on the outside and a pulsation device inside. Difficulties in identifying which of three unfavorable geometry dissolver vessels was involved delayed accident termination.

Staff deviated from operations manual requirements. Deviations involved material accounting, storage practices, scrap transfers, and shift change practices. For instance, some sample analysis results were reported by telephone, increasing chances for miscommunication, and scrap of differing uranium contents were stored together, increasing chances for misidentification. As a result, 2.2kg uranium was loaded into a dissolver vessel for which the minimum critical mass, according to the operation manual, was 2kg. Further, the manual indicated

1.5 hours was needed to completely dissolve a scrap batch but the operator disconnected heater and pulsator 40 minutes after startup because of a scheduled chamber cleanup.

The alarm system activated ten minutes later. Gamma detectors registered 11 spikes with increasing intervals over seven hours. The reaction was terminated by injecting cadmium solution into the tank. An estimated total of 7×10^{17} fissions occurred and the staff was exposed to small radiation doses, up to 0.03 rad.

Topic 6.16 10 Dec. 1968, Mayak Enterprise, the Urals, USSR

A criticality accident occurred December 10, 1968, while testing a new technology for plutonium extraction at the Mayak Enterprise. Incoming solutions with up to 0.4g Pu/L were being transferred to a 4,000L tank. Sample results indicated deviations from anticipated normal conditions: (1) plutonium concentration was about 0.5g/L and (2) solutions contained organic materials.

Operators assigned to remove organics from the tank used a safe-by-volume 20L glass bottle, an unfavorable geometry 60L vessel, a rubber hose, and a pump. When they filled the glass bottle, both chief operator and operator noticed their removed organic fluid had a dark-brown color, indicating high plutonium content in the organic. They poured the organic fluid into the 60L vessel.

The operator saw a flash of light when, as ordered, he poured a second bottle of organic into the 60L vessel. The building alarm activated and all personnel evacuated. However, the shift supervisor returned and tipped the 60L vessel to pour some fluid into a drain. This resulted in a second spike in the same vessel.

Yields are respectively estimated at 10^{16} and 5.0×10^{16} fissions for the first and second spikes. The shift supervisor died. The operator developed severe radiation sickness; and both legs were amputated to save his life.

Topic 6.17 24 Aug. 1970, Windscale Works, Great Britain, UK

Only a basic description of the accident at the Windscale Works on August 24, 1970 is included here. Interested readers should refer to Stratton's *A Review of Criticality Accidents* for a more complete description.

The accident occurred in a solvent extraction portion of a plutonium recovery plant with well-established controls. However, a 25-foot deep trap, or lute, installed for contamination control between a transfer tank and constant-volume feeder contributed directly to the accident. Plant designers and personnel did not realize that liquid material and plant equipment characteristics were such that any

solvent in the tank was trapped until a particular tank fill level was exceeded. Plutonium concentration in the trapped solvent slowly increased with each transfer through the tank because the trapped solvent stripped a very small quantity of plutonium (about 10g) from each aqueous batch processed. Presumably periodic plant cleanout sharply reduced the plutonium concentration without completely removing the solvent and plutonium, thereby delaying but not preventing the critical excursion. Reasons for not noticing the small loss of plutonium in each transfer, and possibly the gain of plutonium with each cleanout, are not indicated in readily available reports.

The excursion occurred upon completing a transfer of 50L solution, containing less than 300g Pu. The excursion occurred in the transfer tank, lasted less than ten seconds, and activated criticality alarms. The two people then in the plant evacuated immediately. One received an exposure of about 2 rads, the other less than 1 rad.

Investigation indicated 39L solvent, containing 2.15kg Pu were present in the tank and tank leg of the trap. Solvent degradation indicated solvent had been trapped for at least several months and possibly up to two years as its fissile concentration increased very slowly. The excursion, which produced about 10^{15} fissions, apparently initiated and shut down due to very subtle differences in aqueous and organic phase geometries as that last transfer ended.

Topic 6.18 17 Oct. 1978, ICPP, Scoville ID, USA

The most recent U.S. criticality accident was the third to occur at ICPP. The excursion occurred in the first solvent extraction cycle where uranium was extracted from spent fuel, and then scrubbed, stripped, and washed in different process columns to separate uranium from fission products. Called PUREX processing, such processes are described further in nuclear-fuel-cycle textbooks.

The excursion occurred in a scrub column. The aluminum-nitrate scrubbing-agent was diluted, from 0.7 to 0.08 molar, because water leaked through a valve to a makeup tank. Dilution went unnoticed because a low-density solution alarm was inoperable, and periodic sampling procedures were not followed.

This very low aluminum nitrate concentration caused aqueous solution to act as a stripping agent rather than a scrubbing agent. Thus, as uranium-bearing organic solvent moved through the scrub column, much of its uranium was left behind in the aqueous solution. About a month's buildup increased uranium concentration, from a usual 0.3g/L in aqueous solution (1.8g/L in organic solvent), to about 22g/L in aqueous solution in the column's lower head region.

This concentration and configuration apparently was slightly *delayed supercritical* over an extended time. (The reaction was sustained by neutrons released up to 1½ minutes after each fission. In a reactor, delayed neutrons allow a more stable power level.) Increasing temperature would normally make the system subcritical (negative reactivity feedback effect) but higher temperatures enhanced uranium extraction, thereby maintaining the supercritical condition.

Eventual operator action in response to pressure buildup resulted in a radiation spike that might have signaled a fission pulse. The excursion probably terminated due to effects of operator action, temperature feedback, or both.

The accident produced 3×10^{18} fissions without any solution release or equipment damage. Inherent shielding prevented any substantial radiation exposure to personnel.

Topic 6.19 13 Dec. 1978, Siberian Chemical Combine, USSR

This fourth Siberian Chemical Combine accident is unique because it involves metallic fissile material in a configuration not intentionally designed to be critical. Plutonium ingots were transferred in containers through glove boxes. Although ingot containers were lined with polyethylene and cadmium to reduce neutron interaction, each container could hold more than the minimum critical mass of ingots. Apparently the administrative limit was one ingot per container.

No instrumentation was used to monitor plutonium mass in containers. Responsibilities for material accountability were not clearly defined. And, although the operation was apparently designed for one person to perform, there were cases in which one person completed operations begun by another person, or in which several people worked at one station.

On 13 December 1978, an operator continued work begun by another operator. He transferred ingots between containers and registered container transfers to another glove box.

The critical excursion occurred while loading an ingot. The alarm system activated and personnel evacuated. Subsequent investigation revealed the accident occurred as the operator loaded a fourth ingot into one container. The fourth ingot, which had the smallest mass (less than 1kg), was ejected by the excursion. At that point the operator extracted the other ingots manually before evacuating.

The single spike yielded 3×10^{15} fissions.

Although the operator survived, he received 250 rad whole body, with up to 2000 rad to his hands. Apparently it was necessary to amputate his hands and lower arms to save his life. Many people believe such extreme measures probably would not have been needed if this operator had evacuated immediately.

Seven other persons in the general area received doses from 5 to 60 rad, apparently without permanent adverse affects.

Topic 6.20 15 May 1997, Chemical Concentrates Plant, Novosibirsk, Russia

The most recent out-of-reactor criticality accident occurred in a uranium fuel fabrication facility of the Chemical Concentrates Plant in Novosibirsk.

The excursions occurred in two parallel, vertical slab tanks. Each tank had an approximate 600L volume, 3m (9.8 ft) high by 2m (6.6 ft) long by 0.1m (3.9 in.) thick, separated by about 0.8m (2.6 ft) surface-to-surface. These tanks collect solution from a fuel etching process.

The tanks were designed to be geometrically favorable for low-enriched uranium. However, personnel who had little criticality safety experience later granted a license for up to a 36% enriched fuel. These people apparently did not understand that this slab design was not geometrically favorable for any enrichment. Worse, these tanks were apparently used for 90% or more enriched fuel, exceeding the limit, for at least a short while before the accident occurred.

Over ten years of operation, the tanks bulged near their bottoms to a maximum thickness of about 0.14m (5.5 in.). In addition, uranium-bearing sediments accumulated on tank walls during the decade. Sediment buildup was undetected and uncontrolled, involving at least 154kg total sediment mass.

The first critical pulse occurred 15 May 1997. Six pulses were observed over 26 hours, with the main pulse yielding an estimated 10^{15} fissions. Apparently pulses occurred in both tanks and neutron interaction played at least a small role in the incident. Although borated solution was injected on 15 May 1997, more soluble neutron absorber was needed to shut down the system on 16 May 1997.

No people were exposed or injured during this accident because nobody was close to the equipment at the time of the first pulse. Automatic alarms activated as designed and staff evacuated immediately.

No equipment was damaged and no environmental releases occurred. Although fire trucks responded when evacuation alarms actuated, the accident did *not* involve any fires.

Lesson 7 In-Reactor Criticality Accidents

Introduction

For this lesson reactors are defined as assemblies, facilities, and experiments designed to achieve a nuclear critical or supercritical condition, or to operate at a barely subcritical condition. It should be no surprise that a system designed to achieve critical conditions will be critical under certain conditions, regardless of the manner in which those conditions are approached. In addition, some subcritical facilities differ from critical facilities only by material quantity or concentration. Therefore, it should also be no surprise that maloperation of a subcritical facility might produce a critical condition.

Much criticality accident prevention and characterization information can be obtained from both reactor operation and reactor accidents. In addition, certain critical experiments are specifically designed to simulate parts of criticality accidents. We have much more reactor experience data than out-of-reactor accident data. However, only a few accident histories are included to illustrate certain lessons.

Objectives

No specific objectives are included here. A related objective is included in Lesson 4 based on Topic 4.8: Discuss lessons learned from historical criticality accidents.

Topic 7.1 21 Aug. 1945, LASL, Los Alamos NM, USA

One of the first criticality accidents in history occurred August 21, 1945, during a hand-stacking critical experiment with a plutonium metal sphere. The sphere is comprised of two hemispheres of delta-phase plutonium metal coated with 0.005-inch-thick nickel. The total sphere mass was 6.2kg, with a density of about 15.7g/cm^3 . The lone experimenter planned to build a subcritical assembly, with this sphere reflected on four sides by tungsten carbide. Nearby neutron counters monitored the assembly area.

The experimenter hand-stacked 4.4kg tungsten-carbide bricks to build a 263kg reflector wall. As he moved the final brick over the assembly, he noticed neutron counters indicated the assembly would be supercritical if this brick were added. As he withdrew this brick, it slipped and fell on the center of the assembly.

The assembly became supercritical on prompt neutrons. The final brick was ejected immediately and the experimenter proceeded to unstack his assembly. His exposure was about 510 rem from a yield of 10^{16} fissions. He died 28 days later.

An army guard who was in the building but not helping with the experiment received a dose of about 50 rem.

Topic 7.2 21 May 1946, LASL, Los Alamos NM, USA

Nine months after the previously described accident, an experienced scientist was demonstrating metal critical assembly and neutron reflection principles with the same plutonium sphere. In this case the reflector was comprised of two beryllium metal hemispheres. The plutonium sphere rested in the tight-fitting lower beryllium hemisphere. The scientist held the upper beryllium hemisphere with his left thumb through an opening at the polar point, with one edge of this hemisphere resting on the lower hemisphere, and with the opposite edge resting on the end of a screw driver.

The screwdriver slipped, the upper beryllium hemisphere fell into place around the plutonium sphere, and the assembly immediately went prompt critical. Either the scientist or the kinetic energy from this single pulse threw the upper beryllium hemisphere to the floor, which terminated the reaction.

All people immediately evacuated the room.

At the time safety practices were based on experimenter knowledge, skill, and experience rather than on formal analyses. These practices were implemented by oral instructions and discussions, and were not necessarily part of written

instructions. Although the demonstration seemed safe enough to all concerned beforehand, in hindsight it lacked many readily identifiable safety measures.

As a result of these two accidents, more formal and elaborate safety systems were required. New requirements included remote assembly of near-critical devices and specifying safety precautions in written instructions.

Additional Information

Although many people refer to this as the *tickling the dragon's tail accident*, neither this accident nor its equipment were part of critical experiments known as *dragon's tail experiments*. However, the same concept is the basis for both names.

Topic 7.3 3 July 1956, LASL Honeycomb Critical Assembly, Los Alamos NM, USA

Some accidents occur within operating parameters, qualifying as accidents only because criticality was (a) not intended at the time it occurred, (b) approached too quickly or slowly, or (c) produced an unexpected consequence. Often these accidents remind us of reasons for our controls and remind us that we cannot plan for or predict everything precisely.

The LASL Honeycomb Critical Assembly was a split-table machine typical of several then in existence. It is very similar to ZPPR assemblies that were operated at ANL-W.⁵ Each array of the LASL split assembly consisted of a square matrix of 576 aluminum tubes, 3 in.×3 in.×3 ft. One array was stationery, the second was aligned with the first but could be moved on a cart along tracks.

On the incident day the assembly was loaded with 58kg of uranium, enriched to 93% ^{235}U , in the form of 2- and 5-mil foils arranged between graphite slabs, with some beryllium reflector surrounding the core. The total graphite mass was 1139kg. Personnel made some minor changes to the reflector and graphite, and then left the building to complete the experiment from a remote control room.

In the control room three miles away, experimenters started the assembly cart to begin an approach to critical. Unexpectedly, the condition was approached too rapidly to take routine measurements. While the cart was moving at about

⁵ Picture two post-office-box arrays facing each other, each with deep, identical square tubes instead of boxes. Trays with nuclear fuel, reflectors, moderators, and/or experiments are placed in each tube. The assembly is made critical by decreasing distance between the two arrays. Trays and tubes are typically filled by hand but the arrays are brought together using remotely operated equipment. The entire system was typically dry; water moderation was simulated with polyethylene.

0.2 in./s, the system became prompt critical, a burst occurred, and the scram system retracted beryllium control rods and reversed the cart's motion.

The burst yield was 3.2×10^{16} fissions. There was no damage and no contamination. There were no personnel radiation exposures because of the distance between experiment and experimenters. Remote operation, incremental changes, and following procedures assured this accident did not have more severe consequences.

Topic 7.4 2 January 1958, Mayak Enterprise, the Urals, USSR

After the first two process criticality accidents at Mayak Enterprise (Topic 6.1 and Topic 6.2), authorities established a critical experiments facility on site. Designed to measure critical parameters for highly enriched uranium solutions, equipment included a tank bolted to structural members, a neutron source, neutron detectors, a control rod, and small-diameter connecting lines.

On January 2, 1958, four facility staff members completed an experiment and decided to accelerate solution draining by violating procedures. They placed favorable-geometry vessels nearby and unbolted the tank. Three people tipped the tank to pour solution into these safe vessels.

Solution geometry in the tipped tank became optimal with effective neutron reflection by three humans, resulting in a power excursion. A single spike of about 2.3×10^{17} fissions occurred, ejecting part of the solution from the tank.

The three people who tipped the tank died five to six days later. The fourth staff member, who was about 3m from the tank, developed radiation sickness resulting in blindness.

Subsequent investigation indicated that, in addition to procedure violations, criticality safety measures were inadequate. As a result, the experimental facility was dismantled.

Topic 7.5 15 Oct. 1958, Boris Kidrich Institute, Vinca Yugoslavia

The critical facility at the Boris Kidrich Institute in Vinca, Yugoslavia, was composed of an unreflected matrix of aluminum-clad natural uranium rods moderated with heavy water. Two cadmium safety rods were installed but not interlocked with the assembly's flux recorder. Water level was normally used to control system reactivity; the normal critical height was 178cm.

A *subcritical* foil-counting experiment was in progress at the time of the accident. A *barely* subcritical neutron multiplication was desirable to maximize foil activation. Neutron multiplication was increased by increasing the height of heavy water in the reactor tank in a series of steps. On the last step two of the BF_3 chambers performed as before (leveling off at a higher signal level), but the third chamber behaved erratically and was disconnected.

After the assembly was operated this way for five to eight minutes, an experimenter smelled ozone and realized the system must be supercritical at some unknown power level. Cadmium safety rods were used to terminate the reaction.

Investigation indicated chambers that were thought to be working properly had saturated. They read a constant maximum value although assembly power level was increasing steadily.

Personnel exposures were intense, estimated at 205, 320, 410, 415, 422, and 433 rem. Of the six persons present, one died and five suffered severe, but temporary, radiation sickness. The critical assembly withstood an energy release of 80 MJ (about 2.6×10^{18} fissions) with no reported damage.

Topic 7.6 30 Dec. 1965, VENUS Critical Facility, Mol, Belgium

VENUS was a tank-type, water-moderated, critical assembly machine. Its heavy water (D_2O)⁶ moderator could be diluted with light water (H_2O) to soften the neutron energy spectrum and maintain reactivity as fissile material was consumed. For experiments in progress, moderator and reflector were composed of 70% H_2O and 30% D_2O . The reflector extended 30 cm above the core. The fuel was UO_2 with a total 1.2×10^6 g mass and a 7% ^{235}U enrichment. Reactivity control was achieved by moving eight safety rods and two control rods, all made of neutron absorber. Eight additional absorber rods could be manually positioned in the core.

Just before the accident, all safety rods, one control rod, and seven manual absorber rods were in the core. The second control rod was being inserted. In this configuration the reactor was subcritical by one safety rod and one control rod.

⁶ Different hydrogen isotopes make light and heavy water. The most abundant hydrogen isotope has one proton and no neutrons in its nucleus, is typically represented with the chemical symbol H, and is the isotope in light water. Deuterium is a less common hydrogen isotope with one proton and one neutron in its nucleus, is often represented with the chemical symbol D, and is the isotope in heavy water.

A reactor operator devised a plan to achieve the new rod pattern desired for the experiment. The operator decided to complete inserting the second control rod and then insert the last manual rod. Then, as the reactor should have been subcritical by one safety rod, two control rods, and one manual rod, the operator thought a different manual rod could be removed. The reactor could then be made critical by lifting two safety rods. This plan required one man to insert one manual rod and extract another. The plan did not implement a key reactor safety rule: manual rod manipulation was prohibited unless water was first emptied from the reactor vessel.

The operator ordered a technician to implement this plan. The technician did not wait until the moving control rod reached its seated position, and he started the manipulation in the wrong order. He began extracting the specified manual rod rather than inserting the last manual rod.

The reactor became critical as the manual rod was extracted. The technician's left foot was projecting over the tank edge, resting on a grid about 5 cm above the reflector. His right foot and leg were somewhat behind him and partially shielded. He noticed a glow in the bottom of the reactor, immediately dropped the rod, and left the room.

The energy release was about 13 MJ (4.3×10^{17} fissions). The excursion apparently terminated due to the dropped manual rod. However, vessel water was automatically dumped, an action that might have accelerated the shutdown.

No steam was created; there was no fuel damage; and there was no contamination. However, the technician received a severe radiation dose, primarily from gamma rays. Rough estimates based on numerous measurements in a phantom indicate he received 300 to 400 rem to his head, 500 rem to his chest, 1750 rem to his left ankle, and possibly near 4000 rem to the toes on his left foot. Medical intervention was successful; the patient recovered, although his left foot had to be amputated.

Topic 7.7 23 Sept. 1983, RA-2 Facility, Buenos Aires, Argentina

The RA-2 reactor was a pool reactor with MTR-type fuel elements. Control rods were like fuel elements, except two of 19 fuel plates were replaced with cadmium plates. The reactor had a water moderator and a graphite reflector. Safety requirements included instructions to drain reactor water before making any fuel configuration changes if people were present.

A technician, who was a qualified operator with 14 years experience, was alone in the reactor room making a fuel configuration change. The moderator had not

been drained, in violation of procedures. Also contrary to safe practices, two fuel elements were placed just outside the graphite instead of being removed from the tank. Two control elements without cadmium plates were to be placed in the fuel configuration.

Apparently the reactor went critical as the second control element was inserted. The excursion consisted of a single pulse yielding about 3 to 4.5×10^{17} fissions.

The operator received an absorbed dose of about 2000 rad gamma and 1700 rad neutron. He survived two days. Two people in the control room received exposures of about 15 rad neutron and 20 rad gamma. Six others received lesser exposures down to 1 rad, and nine received less than 1 rad.

Topic 7.8 16 June 1997, Arzamas-16, Sarov, Russia

Most information about this accident is gleaned from news media accounts. Readers are warned that such accounts are written for a non-technical audience and are often sensationalized.

On 16 June 1997 a scientist was preparing a spherical, metallic, critical assembly with a highly enriched uranium core and a copper reflector, in a well-shielded experiment room in an underground bunker. He was one of Russia's most senior and experienced scientists in critical experiment assembly, operation, and measurement. Assembly pieces were primarily nested hemispheres of varying thicknesses, a design strategy that allows for a broad range of different experiment configurations.

The accident resulted from a chain of mistakes and violations of established practice, but it is unclear which practices were included in written instructions. Apparently the scientist designed this experiment himself and miscalculated. He did not have his manager's approval, but some reports indicate he had sufficient authorization without management review. The scientist acted as both senior supervisor and senior control engineer, which was permitted although, in hindsight, these assignments were supposed to provide independent checks on actions and decisions. He also did not use a start-up source, which would result in severely underestimating an approach-to-critical if using typical neutron multiplication measurements. Some responders indicated this scientist used only the lower half of a vertical split-table experiment structure (half of the experiment should have been built on the stationary upper portion, half on the movable lower portion, and then the two portions should have been brought together remotely). He wore slippery gloves while assembling the experiment, but these gloves were standard wear for such work. Finally, the scientist was alone in the experiment

room at the time of the accident, an atypical condition for which he was apparently authorized.

On Tuesday, 17 June 1997, the scientist began assembling a critical experiment. At 1050 hours he tried to place the next to the last copper shell, before leaving to add the last shell remotely. Apparently the assembly went prompt critical either just before the shell was in place, causing the scientist to drop the shell he held, or he dropped the shell onto the assembly causing it to go prompt critical.

The scientist apparently tried to disassemble the experiment but it was out of reach (having dropped, been knocked down, or been withdrawn as the structure scrammed) or he could not get a good enough grip on the assembly. He then evacuated the building, closed its door, and reported to authorities before losing consciousness.

Initial pulses are usually sufficient to force pieces apart, causing systems to shutdown. However, this assembly apparently settled into a steady or quasi-steady state. One report indicates a thin coating on assembly pieces melted enough in the initial burst to fuse pieces together. News reports indicate radiation levels in the room exceeded 1000 roentgen, and room temperature exceeded 100°C, but assembly power was scarcely more than typical for a household appliance such as an iron. According to news reports, the critical reaction was terminated sometime Monday, 23 June 1997, approximately six days after the initial burst.

Technical response included immediately evacuating the general area near the bunker and a variety of activities to ensure there was no danger to anybody outside the bunker. Responders were able to take time developing and testing further response actions because the assembly was well shielded. They used a robot for reconnaissance, measurements, removing other fissile material, and experiment disassembly. Responders rehearsed actions in a mock-up specifically built for this response. Unfortunately, a cable snapped during a final rehearsal and seriously injured two engineers.

The scientist's radiation exposure was initially reported as about 300 rem. However, post-investigation estimates indicate his total neutron and gamma dose was about 5000 rad. Despite aggressive medical treatment, the scientist died after 87 hours (almost four days).

A second person was present during some of the experiment, but he exited the experiment room minutes before the accident. He apparently received some radiation exposure and was treated on-site.

Appendix A References

Listed alphabetically by document number where numbers are most commonly used in common speech to identify the document. Other documents are included alphabetically by authoring organization or author's family name.

The most recent revision or issue of these documents is usually the one in effect. The in-effect revision or issue must be applied in actual operations. Issue dates and revisions are included here only to indicate which version was in effect at the time this guide revision was written.

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Appendix B Definitions

In most cases non-technical or simplified technical definitions are listed. If both non-technical and technical definitions are often used at INEEL, both are listed. In such cases non-technical definitions are usually acceptable. Definitions listed here are adequate for basic criticality safety training. However some of these non-technical definitions are not appropriate for criticality safety analyses. Similarly, some criticality safety definitions are not appropriate for non-criticality-safety purposes.

absorber, neutron – material or object that readily captures neutrons. (Topic 3.5)

absorption, neutron – phenomena in which a free neutron collides with and becomes part of an atomic nucleus. The resultant nucleus has excess energy it eliminates either through radioactive decay or fission. (Subtopic 1.3.3)

administrative control – criticality control that relies on human actions for its implementation. (Subtopic 4.3.3)

atom – smallest component of a chemical element having all chemical properties of that element. (Subtopic 1.1.1)

atomic mass – mass of an atomic or subatomic particle, typically expressed in terms of an atomic mass unit (amu)

atomic number – number of protons in an atomic nucleus. (Subtopic 1.1.4)

atomic weight – see *atomic mass*

binding energy or force – force between neutrons and protons, which holds an atomic nucleus together. (Subtopic 1.2.1)

cask – a shielded container to store, transfer, or transport radioactive material.

Cerenkov radiation – electromagnetic radiation emitted by charged particles moving through a material at a velocity greater than the speed of light in that material. Cerenkov radiation causes the blue glow seen in some spent fuel storage basins (water is the material in these cases) and the blue flash sometimes seen from a criticality accident (fluid in a person's eye is the material in these cases).

chain reaction, nuclear – reaction in which a fission of one atomic nucleus leads to fission in one or more other atomic nuclei. (Lesson 2)

concentration – (1) technically, ratio of a material component's mass to the material's volume; (2) non-technically synonymous with density. (Topic 3.7)

contingency – criticality control factor or parameter (Lesson 3) that is controlled in a specific operation to prevent a criticality accident. (Topic 4.4)

control – a mechanism or method devised to ensure one or more criticality safety parameters or factors (Lesson 3) are maintained within acceptable limits. The subcritical margin, or margin of criticality safety, is influenced when the value of the controlled parameter is varied. (Topic 4.3)

critical – (1) condition characterized by at least one self-sustaining nuclear fission chain reaction (each fission produces, on the average, one neutron that causes an additional fission) (subtopic 2.4.2); (2) having a k_{eff} equal to 1.0. (Topic 2.5)

critical mass – minimum mass of a fissile material that will support a self-sustaining nuclear chain reaction under specified conditions. (Topic 3.1)

criticality accident – release of energy as a result of inadvertently producing a self-sustaining or divergent neutron chain reaction

criticality alarm system (CAS) – a network of gamma and/or neutron sensitive detectors connected to audible alarms. The system monitors a specific area and signals immediate evacuation of personnel if a criticality accident occurs in that area. (Topic 4.7)

criticality control area (CCA) – INEEL laboratory or plant area *allowed* to contain significant quantities of fissile material. (Topic 4.6)

criticality detection system (CDS) – a system by which a well-shielded area can be monitored to detect and warn if a criticality accident is or has occurred in that area. The warning signal need not be immediate because personnel would not be at immediate risk. (mentioned in Topic 4.7)

criticality safety – protection against the consequences of an inadvertent, self-sustaining nuclear chain reaction, preferably by preventing the reaction. Protection includes physical protection, training, procedures, emergency response, and other precautions.

delayed neutrons – neutrons released up to 1½ minutes after a fission event. In a reactor, delayed neutrons can be controlled to allow a more stable power level.

density – (1) technically, ratio of a material's mass to its volume; (2) non-technically synonymous with concentration. (Topic 3.7)

electron – subatomic particle having a single negative electrical charge, typically found orbiting an atomic nucleus. (Subtopic 1.1.3)

element – substance that cannot be decomposed into simpler substances by chemical means

engineered, or engineering, control – physical design that reliably serves as a criticality safety control. (Subtopic 4.3.2)

enrichment – quantity by which a specific isotope is increased above that which occurs naturally. (Topic 3.2)

epithermal, or intermediate, neutron – technically, a free neutron with an energy between fast and thermal neutron energies (typically 1 eV and 0.1 MeV).

factor, criticality control – a parameter (physical characteristic or feature) that can be controlled to prevent a criticality accident. (Lesson 3)

favorable geometry – equipment or systems that are subcritical by virtue of neutron leakage under worst credible conditions. For example, a favorable geometry vessel would be subcritical when fully reflected and filled to capacity with worst case fissile material and moderator combination, even after experiencing worst credible deterioration (corrosion, wall deformation, etc.). However, a vessel would not be a favorable geometry vessel if its dimensions exceeds the fissile material's subcritical dimensions and its physical capacity exceeds the material's subcritical volume. Similarly, a vessel would not be a favorable geometry vessel if credible deformation could exceed the vessel's subcritical dimensions. (Mentioned in Topic 3.8)

fast neutron – free neutron with high energy (typically defined as 0.1 MeV or greater). Such neutrons travel at very high velocities and are therefore called fast neutrons. Nuclear fission produces most free neutrons and these neutrons almost always are released as fast neutrons. A few materials that can fission will only fission with fast neutrons.

fertile – capable of absorbing a neutron and, through radioactive decay, becoming fissile. (mentioned in Topic 2.3)

fissible – (1) isotope requiring fast neutrons for nuclear fission; (2) element or material containing fissible isotopes. Term is proposed but not yet widely accepted. (mentioned in Topic 2.3)

fissile – (1) non-technically, capable of nuclear fission (synonymous with fissionable); (2) technically, capable of nuclear fission at any neutron energy but most especially at thermal neutron energies. (Topic 2.3)

fissile material – material containing fissile isotopes. Principle fissile isotopes are U-233, U-235, Pu-239, and Pu-241. (Topic 2.3)

fissile material handler (FMH) – person appointed by management and currently certified or qualified to handle, process, store, or otherwise manipulate more than a significant quantity of fissile material. FMHs must periodically satisfy specific training and medical requirements to maintain their certification or qualification. (Topic 4.2)

fission or nuclear fission – splitting an atomic nucleus into lighter nuclei, thereby releasing energy in the form of heat, kinetic energy, and radiation (gamma and neutron). (Topic 2.2)

fissionable – (1) non-technically synonymous with fissile; (2) current non-technical and technical definition: capable of nuclear fission; (3) one partially obsolete technical definition: requiring fast neutrons for nuclear fission; (4) Order DOE O 420.1 defines the following isotopes (see definition) as *Fissionable Nuclides of Criticality Concern*: ^{233}U , ^{235}U , and ^{239}Pu existing in quantities and forms that lead to the major focus of nuclear criticality safety; ^{237}Np , ^{238}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , ^{241}Am , ^{242}Am , ^{243}Am , ^{243}Cm , ^{244}Cm , ^{245}Cm , ^{247}Cm , ^{249}Cf , and ^{251}Cf ; and ^{231}Pa , ^{232}U , ^{234}U , ^{246}Cm , ^{250}Cf , ^{252}Cf , and ^{254}Es existing in isolated quantities less than potential minimum critical mass (per ANSI/ANS-8.15-1981). (Topic 2.3)

fissionable material – material containing fissionable isotopes. (Topic 2.3)

fuel, nuclear – material containing fissile material(s) which, when placed in a reactor or critical assembly enables a self-sustaining nuclear chain reaction to be achieved. If nuclear fuel comprises the bulk of fissile material in a facility, all fissile material in the facility might be called nuclear fuel.

fuel handling – fissile material handling involving nuclear fuel.

interaction – (1) phenomena in which a free neutron interacts with an atomic nucleus (Topic 1.3); (2) neutron exchange between fissile material bodies or systems (Topic 3.6).

isotopes – (1) technically, atoms having the same atomic number but different atomic masses (for example, ^{233}U , ^{235}U and ^{238}U are all uranium isotopes). (Subtopic 1.1.5) (2) non-technically, often used synonymously with nuclides (see definition).

k_{eff}, k-eff, or k-effective – neutron multiplication factor (ratio of the rate at which fission neutrons are produced to the rate at which neutrons are absorbed or escape). (Topic 2.5)

labeling – placement of clear and positive identifying markings on specific units or batches of fissile material (containers, pieces, etc.) to prevent material from being mistaken for other material and to identify the amount present. (Topic 4.5)

limit – an upper or lower bound placed on a criticality control parameter. For example, a maximum 350g ^{235}U (fissile mass), minimum 10g/L ^{10}B (soluble neutron absorber concentration), maximum 5.0 in. diameter (geometry), or minimum 8.25 in. separation (interaction)

mass – quantity of matter in an object regardless of forces acting on the object, typically expressed in terms of grams or kilograms. Topic 3.1 discusses fissile mass as a criticality control factor.

Mass Limit CCA – location in which more than 15g, but no more than 350g ^{235}U , 250g ^{233}U , or 250g ^{239}Pu is allowed. If fissile isotopes are combined, each gram of ^{233}U and each gram of ^{239}Pu

are counted as two grams of ^{235}U . The quantity of special reflectors is also limited. (Subtopic 4.6.2 and Topic 5.2)

may – is/are allowed to (intentionally denoting permission). Using *may* to indicate a possibility, condition, or contingency is discouraged for most criticality safety applications, to avoid confusion with using *may* to indicate permission.

moderation, neutron – neutron scatter phenomena in which free neutrons both change their travel direction and lose kinetic energy as a result of colliding with atomic nuclei. (Topic 3.4)

moderator – material that reduces neutron kinetic energy by neutron scattering collisions without appreciable neutron absorption. (Topic 3.4)

molecule – smallest component of a chemical compound having all the chemical and physical properties of that compound. (Subtopic 1.1.1)

neutron – subatomic particle having no electrical charge, typically found in an atomic nucleus. (Subtopic 1.1.2 and Topic 1.3)

neutron, free – a neutron that is not part of a specific atomic nucleus, freed as result of nuclear fission.

neutron multiplication factor – see k_{eff} , $k\text{-eff}$, or $k\text{-effective}$.

nuclear accident dosimeter (NAD) – device which, when retrieved, provides neutron and gamma dose information following an criticality accident or other serious radiation event. NADs are strategically placed in areas where CASs are required.

nuclide – (1) originally, an atomic species in which all atoms have the same atomic mass and number. (2) non-technically, synonymous with isotope. (3) non-technically, an atomic species in which all atoms are alike and/or a molecular species in which all molecules are alike.

parameter – a physical characteristic of a material or system, especially one that can be controlled to prevent a criticality accident. (Lesson 3)

poison, neutron – see *absorber, neutron*

posting – placement of signs to indicate the presence of fissile material, to designate work and storage areas, or to provide instruction or warning to personnel. Topic 4.6 includes information on CCA posting.

Procedure CCA – location in which more than 350g ^{235}U , 250g ^{233}U , or 250g ^{239}Pu is allowed. Fissile material is controlled by approved procedures. Procedure CCAs require approved criticality safety evaluation and safety analysis. (Subtopic 4.6.3)

prompt critical – a nuclear critical condition achieved with prompt neutrons.

prompt neutrons – neutrons released immediately in a nuclear fission event.

proton – subatomic particle having a single positive electrical charge, typically found in an atomic nucleus. (Subtopic 1.1.2)

reflection, neutron – neutron scattering phenomena in which free neutrons that would otherwise escape a fissile system return to the system as a result of colliding with atomic nuclei in a reflector. (Topic 3.3)

reflector – a material or object that reflects incident neutron back into a fissile material or system. Good reflectors include concrete, heavy metals, beryllium, and hydrogenous materials (for example, water and plastics). (Topic 3.3)

scatter, neutron – phenomena in which free neutron collides with and bounces off an atomic nucleus. As a result the neutron changes its travel direction and might lose some energy. (Subtopic 1.3.2)

significant quantity of fissile material – more than 15g ^{233}U , 15g ^{235}U , or 15g Pu. (Topic 5.3)

special moderator – material that is a more effective neutron moderator than water

special reflector – material that is a more effective neutron reflector than water

subcritical – (1) condition characterized by lack of any self-sustaining nuclear chain reactions (if nuclear fissions occur each fission, on the average, produces less than one neutron that causes an additional fission) (Subtopic 2.4.1); (2) having a k_{eff} less than 1.0. (Topic 2.5)

subcritical limit – limiting value assigned to a controlled parameter to ensure a system is subcritical under specific conditions. If based on criticality safety calculations, subcritical limits must appropriately allow for adverse affects of calculation methodology uncertainty and bias.

supercritical – (1) condition characterized by a divergent nuclear chain reaction (each nuclear fission, on the average, produces more than one neutron that causes an additional fission) (Subtopic 2.4.3); (2) having a k_{eff} greater than 1.0 (Topic 2.5)

thermal, or slow, neutron – neutron in thermal equilibrium with its surrounding material. Thermal neutron energies are typically defined as 1 eV or less. Thermal neutrons are often called slow neutrons because they travel at much lower velocities than fast neutrons. Characteristic values describing thermal neutrons are typically normalized to a neutron velocity of 2200 m/s. Most material that can fission will fission more readily with thermal neutrons. (Topic 1.3, Topic 2.3 and Topic 3.4).