INL/EXT-06-01183

Revision 1

# Criticality Safety Basics for INL FMHs and CSOs

April 2012

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-06-01183
Revision 1

# Criticality Safety Basics for INL FMHs and CSOs

April 2012

Idaho National Laboratory
Criticality Safety Engineering
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

# FOREWORD

Nuclear power is a valuable and efficient energy alternative in our energy-intensive society. However, material that can generate nuclear power has properties that require this material be handled with caution. If improperly handled, a criticality accident could result, which could severely harm workers.

This document is a modular self-study guide about Criticality Safety Principles. This guide's purpose it to help you work safely in areas where fissionable nuclear materials may be present, avoiding the severe radiological and programmatic impacts of a criticality accident. It is designed to stress the fundamental physical concepts behind criticality controls and the importance of criticality safety when handling fissionable materials outside nuclear reactors.

This study guide was developed for fissionable-material-handler and criticality-safety-officer candidates to use with related web-based course 00INL189, BEA Criticality Safety Principles, and to help prepare for the course exams. These individuals must understand basic information presented here.

This guide may also be useful to other Idaho National Laboratory personnel who must know criticality safety basics to perform their assignments safely or to design critically safe equipment or operations.

This guide also includes additional information that will not be included in 00INL189 tests. The additional information is in appendices and paragraphs with headings that begin with "Did you know," or with, "Been there. Done that!" Fissionable-material-handler and criticality-safety-officer candidates may review additional information at their own discretion.

This guide is revised as needed to reflect program changes, user requests, and better information. Issued in 2006, Revision 0 established the basic text and integrated various programs from former contractors. Revision 1 incorporates operation and program changes implemented since 2006. It also incorporates suggestions, clarifications, and additional information from readers and from personnel who took course 00INL189. Revision 1 also completely reorganized the training to better emphasize physical concepts behind the criticality controls that fissionable material handlers and criticality safety officers must understand. The reorganization is based on and consistent with changes made to course 00INL189 due to a review of course exam results and to discussions with personnel who conduct area-specific training.

The photographs on the cover and this page were taken on July 14, 2010 during receipt and repackaging of new fuel elements for the Neutron Radiography Reactor (NRAD). On the cover, a fissionable material handler (FMH) prepares to repackage an element.

The TN-BGC-1 shipping container (birdcage) used to ship the elements from France to the Hot Fuels Examination Facility (HFEF) at the Materials and Fuels Complex (MFC). This type of container is often called a *birdcage* because the payload container is surrounded by a cage.

The FMH inserts an element into a 55 gallon fuel storage drum.

The interior of the 55 gallon fuel storage drum with a few of the new elements.

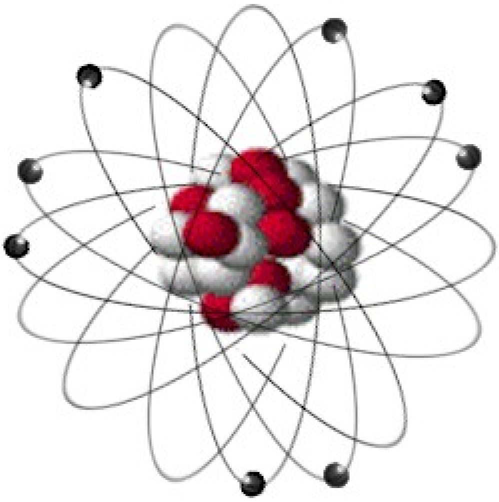
# CONTENTS

# ACRONYMS

| | |
|---|---|
| ANS | American Nuclear Society, La Grange Park, Illinois, USA |
| ANSI | American National Standards Institute |
| ATR | Advanced Test Reactor at the ATR Complex, which is at INL |
| ATRC | ATR Critical Facility at ATR Complex, which is at INL |
| CAS | criticality (accident) alarm system |
| CCA | criticality control area |
| CFR | Code of Federal Regulations |
| cm | centimeter |
| CSE | criticality safety evaluation |
| CSO | criticality safety officer |
| DOE | United States Department of Energy, Washington D. C. |
| DOT | United States Department of Transportation, Washington D. C. |
| EDMS | electronic document management system (http://edms.inel.gov/inl_index.html) |
| FMH | fissionable material handler |
| g | gram |
| in. | inch(es) |
| INL | Idaho National Laboratory, Idaho Falls and Scoville, Idaho, USA (the DOE site and a DOE contract). |
| kg | kilogram |
| L | liter(s) |
| lbs | pounds |
| LRD | laboratory requirements document |
| LWP | lab-wide procedure |
| m | meter(s) |
| MFC | Materials & Fuels Complex at INL. |
| NRAD | Neutron Radiography Reactor at MFC |
| NRC | United States Nuclear Regulatory Commission: Washington D. C. This is a different acronym definition than used in Appendix A of this guide. |
| NS | nuclear safety |
| rem | radiation equivalent man |
| rev | revision |
| U(*xx*) | enriched uranium, where *xx* is the % (usually weight percent) of U-235 in the uranium |

# MODULE 1 ATOMS AND NEUTRONS

## Introduction



Understanding fundamental criticality safety principles begins with the elemental building block of matter, the atom. A basic knowledge of the atom, its parts, and some behavior of one of these parts, the neutron, lays the foundation for understanding the fission process. (Except for the emphasis on neutrons, much of this information is also covered in radiological safety training.)

## Objectives

Explain the basic structure of an atom.

Define *isotope* and *mass number*.

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

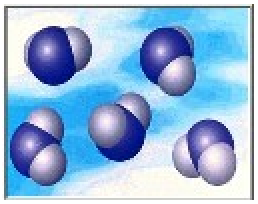
Describe neutron scatter and its effect on the energy (speed) of a free neutron.

Identify two possible results of a neutron absorption event.

### My Notes:

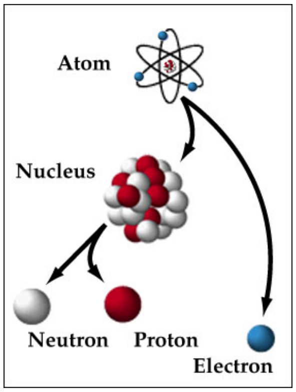
# Topic 1.1 The Atom and Its Parts

## 1.1.1 Molecules and Atoms



Depiction of water molecules

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 are no longer 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 the sketch to the right. The core is called the *nucleus*.

**Did you know …**

**That models of the atom have changed dramatically in just over a century?** The Rutherford-Bohr model used here was developed in the early 1900s. It is not the most current model, but it is easy to visualize and adequate for this study guide.

## 1.1.2 Inside an Atomic Nucleus: Protons and Neutrons

An atom's nucleus contains one or more *protons* and may contain one or more *neutrons*. They are very similar in size and mass but differ in electrical charge.

Protons are positively charged particles. Protons are important because the number of protons determines the chemical identity of the element.

Neutrons do not have an electrical charge; they are electrically neutral. Neutrons are very important to criticality safety, as will be described later in this and other modules.

Overall, the nucleus has a net positive charge

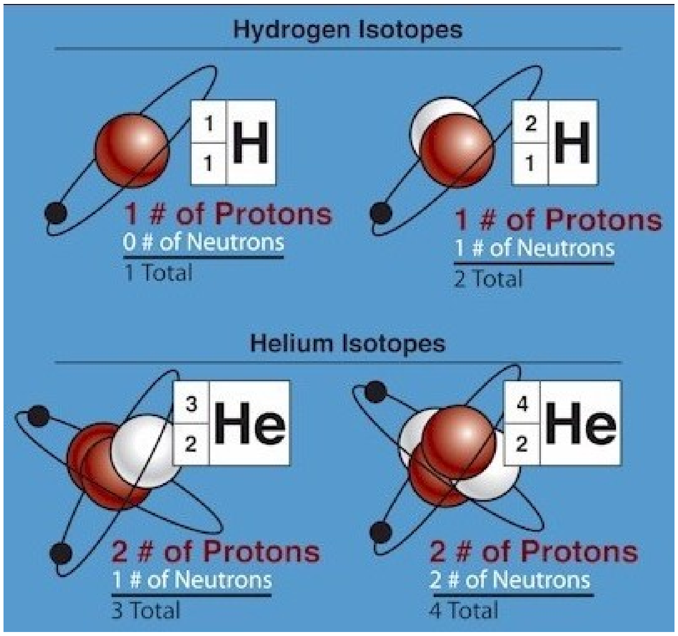
## 1.1.3 Outside an Atomic Nucleus: Electrons

Very small, subatomic 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.

**Did you know …**

**That ions are atoms with a net electrical charge?** An ion is an atom that has more or fewer electrons than protons. Ions are mentioned here because a criticality produces ionizing radiation (specifically, radiation that can produce ions in the matter with which it interacts). However, ions are not important in causing or preventing a criticality accident.

## 1.1.4 Atomic Number



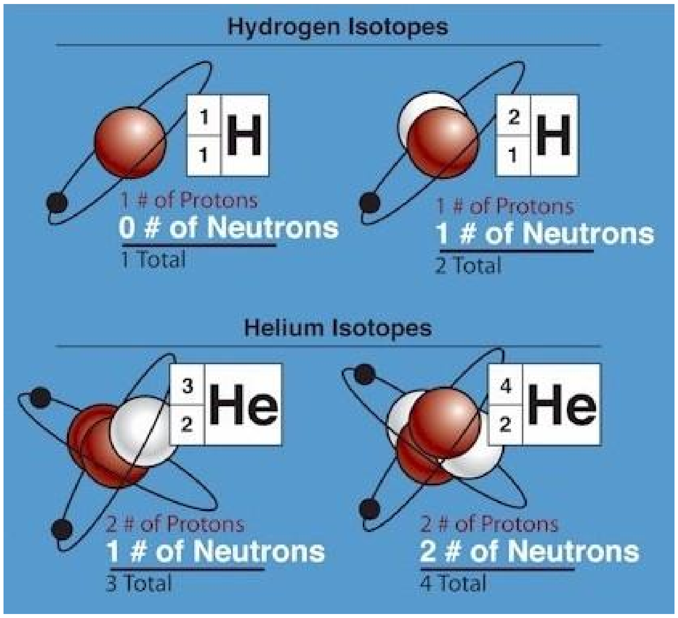
The chemical identity of an element is determined by its atomic number. The *atomic number* is the number of protons in an atomic nucleus. Each element has its own unique atomic number. For example, all hydrogen atoms have one proton and all helium atoms have two protons as indicated by the figure to the right.

Chemical symbols sometimes include numerals to identify the atomic number or other information. The exaggerated illustration to the right shows superscripted and subscripted numerals before the alphabetic chemical symbol. The subscripted numeral is the atomic number. In some sense, an element's atomic number provides the same information as its alphabetic chemical symbol.

**Did you know …**

**That the atomic number is also known as the proton number or the element number?** The reason for the name *proton number* is obvious. The name *element number* developed because typical, modern periodic tables of the elements and charts of nuclides order the elements by atomic number.

## 1.1.5 Isotopes



Different atoms of an element can have different numbers of neutrons in their nuclei. Atoms of the same element that differ only by 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.

As examples, the figure to the right shows the two most common hydrogen and helium isotopes. All hydrogen atoms have one proton each, but the most common hydrogen isotope has no neutrons and the second most common hydrogen isotope has one neutron. As another example, all helium atoms have two protons each, but one stable helium isotope has one neutron and another stable helium isotope has two neutrons.

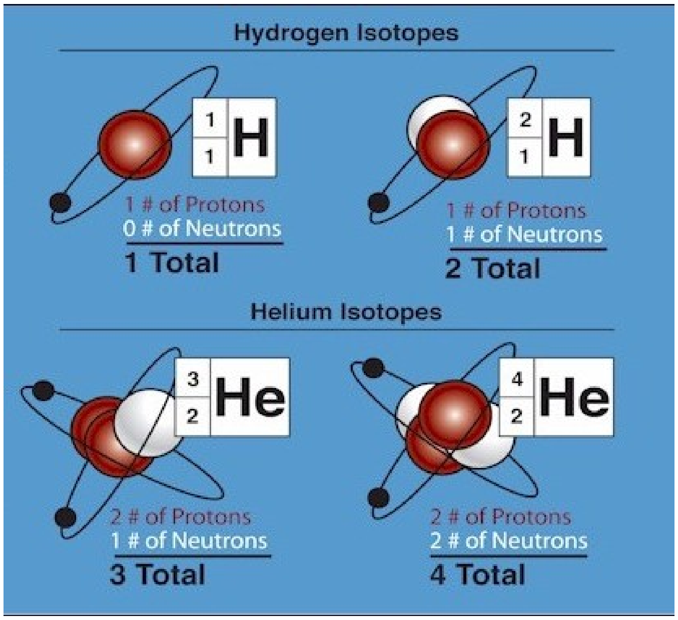
Some isotopes of an element are more important to criticality safety than others. For example, INL criticality safety is more concerned with U-233 and U-235 than with U-238.

**Did you know …**

- **That sometimes you might hear an *isotope* called a *nuclide*?** The words are often used interchangeably at INL and elsewhere, but their definitions differ subtly. This subtle difference is ignored here because it will not affect FMHs and CSOs.
- **That the number of neutrons in a nucleus affects the stability of the nucleus?** For example, uranium has several isotopes that radioactively decay at dramatically different rates. The isotope U-234 with 142 neutrons decays much more rapidly than U-235 with 143 neutrons and U-235 decays much more rapidly than U-238 with 146 neutrons.
- **That, unlike most isotopes, two of the three hydrogen isotopes have special names?** The rarest of the three, H-3, is called *tritium* for its three nucleons (one proton and two neutrons). Similarly, the H-2 isotope is called *deuterium* for its two nucleons (one proton and one neutron). The H-1 isotope has no special name, but more than 99% of natural hydrogen is H-1.

## 1.1.6 Mass Number

Each isotope or nuclide can be identified numerically by its mass number, which is the total number of protons and neutrons in an atom's nucleus. For example



- H-1 or $^{1}H$ or $H^{1}$ has a mass number of one because it has one proton and no neutrons;
- H-2 or $^{2}H$ or $H^{2}$ has a mass number of two because it has one proton and one neutron;
- He-3 or $^{3}He$ or $He^{3}$ has a mass number of three because it has two protons and one neutron; and
- He-4 or $^{4}He$ of $He^{4}$ has a mass number of four because it has two protons and two neutrons.

As indicated in the examples, an isotope's mass number might appear as a superscripted numeral before or after its alphabetic chemical symbol or as a hyphenated numeral after its alphabetic chemical symbol.

An atomic mass number is not, in and of itself, sufficient to identify an isotope uniquely. Different isotopes might have the same mass number. For example, americium and plutonium each have an isotope with a mass number of 242. Usually, we also use the alphabetic chemical symbol to identify an isotope. In this example, the isotopes are identified as Am-242 and Pu-242.

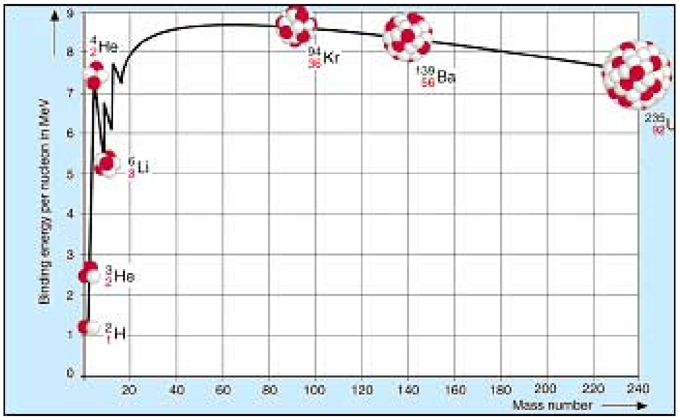
**Did you know …**

- **That an isotope's atomic mass number is almost equal to its *atomic weight*?** Their values are not truly identical. However, the atomic mass number is a very good approximation of atomic weight. That is why the two terms are sometimes used interchangeably.
- **That an element's atomic number or mass number can sometimes indicate if the element is radioactive?** The heavier the element, the more likely repulsive forces between protons in the nucleus will overcome the nucleus' binding energy. At atomic number 83 (bismuth), a point is reached where more neutrons can no longer maintain a stable nucleus. Therefore, heavy elements are radioactive.

  Very heavy elements are not only radioactive, they are also more prone to split (fission) and cause a nuclear chain reaction of fissions. (Module 3)
- **That, in general, a heavy atom has a higher neutron to proton ratio than a light atom?** In light atoms, the number of neutrons in the nucleus is approximately the same as the number of protons. In heavy atoms, the number of neutrons can be up to 1.6 times more than the number of protons. For example, He-4 has two protons and two neutrons (ratio = 1); U-238 has 92 protons and 146 neutrons (ratio ≈ 1.6).

  Neutrons help hold a nucleus together. In heavy atoms, more neutrons are needed to compensate for the electrically repulsive force of more protons. (Particles with the same electrical charge, such as two or more protons, repel each other.)

Shared energy between neutrons and positively charged protons keeps electrically 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*. The figure to the right shows the binding energy needed to keep a nucleus together as a function of mass number.

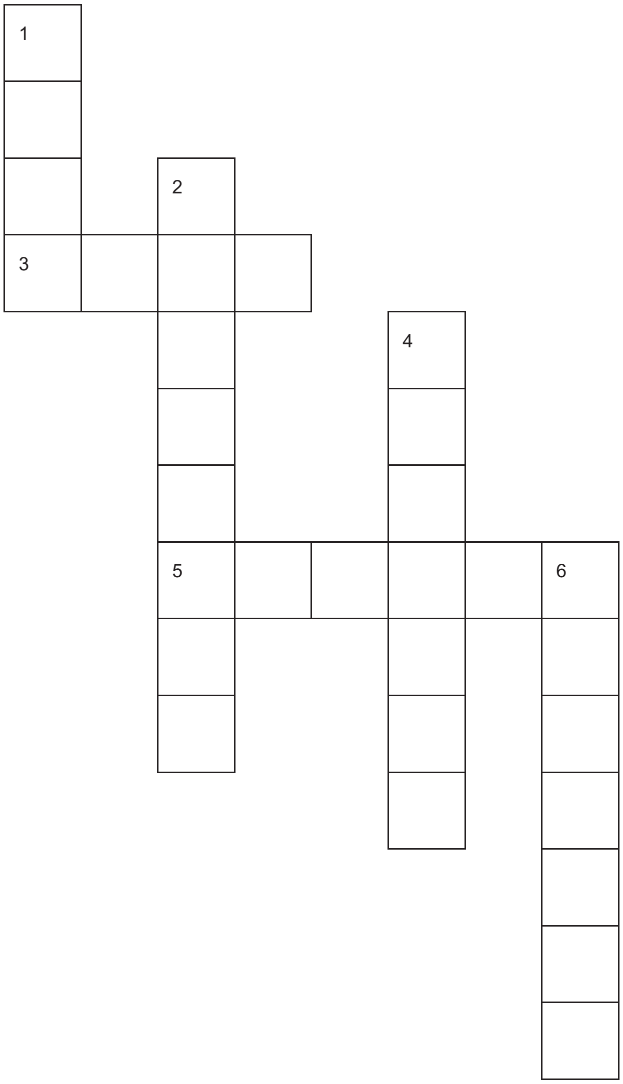


Binding energy as a function of atomic mass number

## My Notes:

## Review Questions

*Complete the following crossword puzzle. (Puzzle designed with Discovery Education's Puzzlemaker, http://discoveryeducation.com)*



ACROSS

3. An atom's ____ number is the total number of protons and neutrons in its nucleus.
5. A positively charged particle in an atom's nucleus.

DOWN

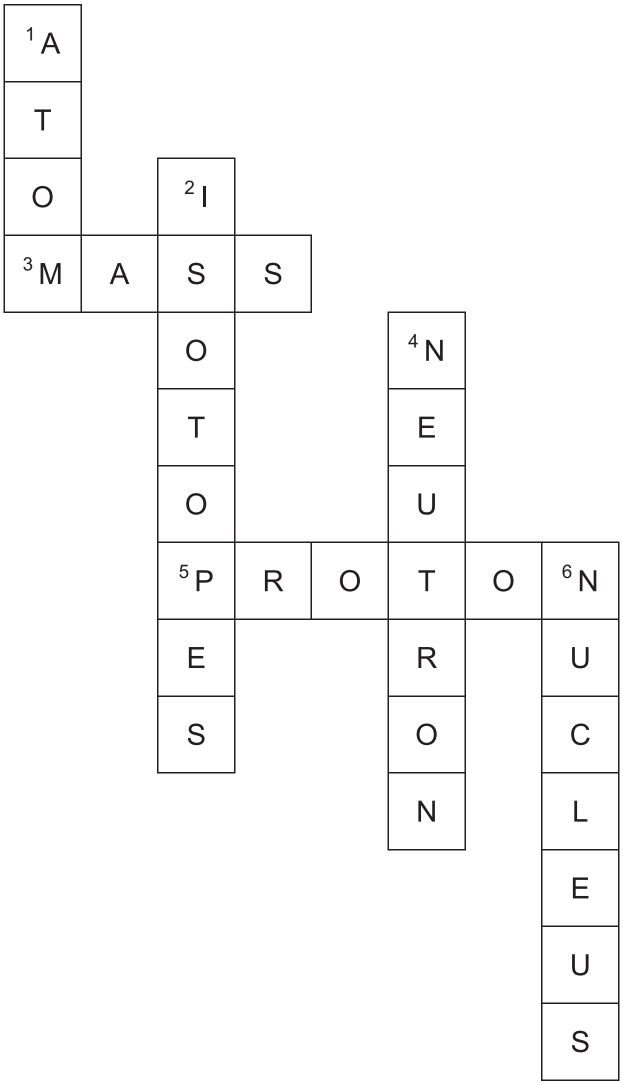
1. The smallest component of an element having all the properties of that element.
2. Atoms that have the same number of protons, but different numbers of neutrons.
4. An electrically neutral particle in an atom's nucleus.
6. The core of an atom, composed of protons and neutrons.

*Complete each statement in the left column by placing the letter of an answer from the right column in the appropriate box. Note that some answers will be used more than once and some answers will not be used.*

| | | | |
|---|---|---|---|
| ☐ | Within an atom, electrons are located ____ the nucleus | A | 92 |
| ☐ | Within an atom, neutrons are located ____ the nucleus | B | 94 |
| ☐ | Within an atom, protons are located ____ the nucleus | C | 144 |
| ☐ | All uranium isotopes have the same number of ____. | D | 236 |
| ☐ | Plutonium isotopes Pu-238, Pu-239, Pu-240, and Pu-241 differ by their number of _____. | E | 238 |
| ☐ | ____ have about the same mass and size as protons. | F | inside |
| ☐ | With 92 protons and 144 neutrons, uranium isotope U-236 has a mass number of ___. | G | outside |
| ☐ | With 94 protons and 144 neutrons, plutonium isotope Pu-238 has a mass number of ___. | H | electrons |
| ☐ | ____ have a positive electrical charge. | I | neutrons |
| ☐ | ____ have a negative electrical charge. | J | protons |
| ☐ | _____ have no electrical charge; they are neutral. | K | isotopes |

## Review-Question Answers

*Answers to the criss-cross puzzle.*



ACROSS

3. An atom's _____ number is the total number of protons and neutrons in its nucleus.
5. A positively charged particle in an atom's nucleus.

DOWN

1. The smallest component of an element having all the properties of that element.
2. Atoms that have the same number of protons, but different numbers of neutrons.
4. An electrically neutral particle in an atom's nucleus.
6. The core of an atom, composed of protons and neutrons.

*Answers to the matching exercise*

| | | | |
|---|---|---|---|
| **G** | Within an atom, electrons are located ____ the nucleus | A | 92 |
| **F** | Within an atom, neutrons are located ____ the nucleus | B | 94 |
| **F** | Within an atom, protons are located ____ the nucleus | C | 144 |
| **J** | All uranium isotopes have the same number of ____. | D | 236 |
| **I** | Plutonium isotopes Pu-238, Pu-239, Pu-240, and Pu-241 differ by their number of _____. | E | 238 |
| **I** | ____ have about the same mass and size as protons. | F | inside |
| **D** | With 92 protons and 144 neutrons, uranium isotope U-236 has a mass number of ___. | G | outside |
| **E** | With 94 protons and 144 neutrons, plutonium isotope Pu-238 has a mass number of ___. | H | electrons |
| **J** | ____ have a positive electrical charge. | I | neutrons |
| **H** | ____ have a negative electrical charge. | J | protons |
| **I** | _____ have no electrical charge; they are neutral. | K | isotopes |

## Topic 1.2 Neutron Interactions

A free neutron exists because it was born (emitted or released) during radioactive decay or nuclear fission.

A neutron is free for a very short time. During that time, it travels.

To help understand what might happen to a neutron in whatever system interests us, think of the neutron as a bullet that is fired in a random direction and the system as a large room in which there are many well spaced objects, including boxes that contain more bullets. The room's objects represent nuclei in our system; its walls and anything outside the room represent things around our system. Some things that might happen with the bullet are similar to what might happen with the neutron:

- The bullet might exit the room without hitting anything in the room and without ricochet back into the room. In this case, the bullet escaped without interacting with something in the room. Similarly, a neutron might escape the system of interest without colliding with a nucleus. We count such an event as neutron escape (or leakage), but not as neutron interaction.
- The bullet might hit an object in the room, interacting with that object. Bullet interaction depends in part on the bullet's speed and the object's physical characteristics. Similarly, a neutron might collide with a nucleus in the system, interacting with the nucleus. Neutron interaction depends in part on the neutron's energy (speed) and the nucleus' characteristics. Two interactions are of interest here:
    - The bullet might hit an object and ricochet off. Similarly, a neutron might collide with a nucleus and "bounce off" (scatter). This type of neutron interaction is called ***neutron scatter***.
    - The bullet might hit an object, penetrate it to some depth, and stay in the object. Similarly, a neutron might collide with a nucleus and become part of the nucleus. This type of neutron interaction is called ***neutron absorption***.

**Did you know …**

- **That free neutrons are commonly divided into three groups: fast, intermediate, and slow?** Each group is defined by a range of kinetic energy or travel velocity. Fast neutrons have more energy than intermediate neutrons, which, in turn, have more energy than slow neutrons.
- **That *slow neutrons* are sometimes called *thermal neutrons* and *intermediate neutrons* are sometimes called *epithermal neutrons*.** Such use is not completely accurate because, in each case, definitions differ subtly. However, the differences do not affect FMHs or CSOs.

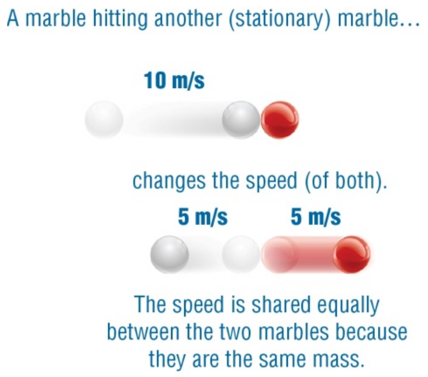
## 1.2.1 Neutron Scattering

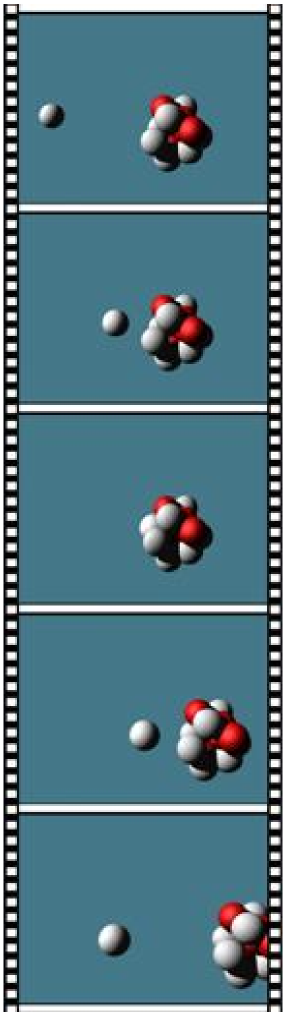
Just as our bullet might ricochet off an object or wall, a neutron might collide with and “bounce off” a nucleus. The neutron interaction is called *neutron scattering* because it changes the direction in which a free neutron travels. The change of direction can be important, resulting in the neutron staying in, or returning to, a material of interest.

The speed (energy) of the free neutron might also change during a neutron scatter event. The change depends on characteristics of the target nucleus:

- A neutron that collides with and bounces off a heavy (large) nucleus tends to slow down very little. The neutron loses very little energy due to the scatter event. This event is much like a marble colliding with a stationery bowling ball. The marble ricochets, losing very little speed and the bowling ball barely moves.

- A neutron that collides with and bounces off a light (small) nucleus tends to slow down significantly because the nucleus absorbs a significant amount of the neutron’s energy. The lighter the nucleus, the more the neutron tends to slow down. If the nucleus is very light (for example, an H-1 nucleus), we can picture the interaction as a marble striking another marble. This slowing-down phenomenon can be very important for reasons described in a later module.





Above, a depiction of a neutron colliding with a light nucleus.

**Did you know …**

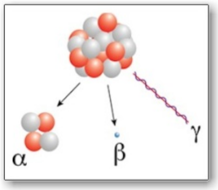
- **That scattering is the most likely interaction a fast or intermediate neutron will experience?** Neutrons emitted by fission are born fast. Such a neutron typically goes through multiple scatter events before it is absorbed.
- **That, for neutron scattering, light nuclei usually have an atomic number less than 25?** A neutron will normally slow down, at least a little, if it collides with a nucleus with an atomic number less than 25.

## 1.2.2 Neutron Absorption

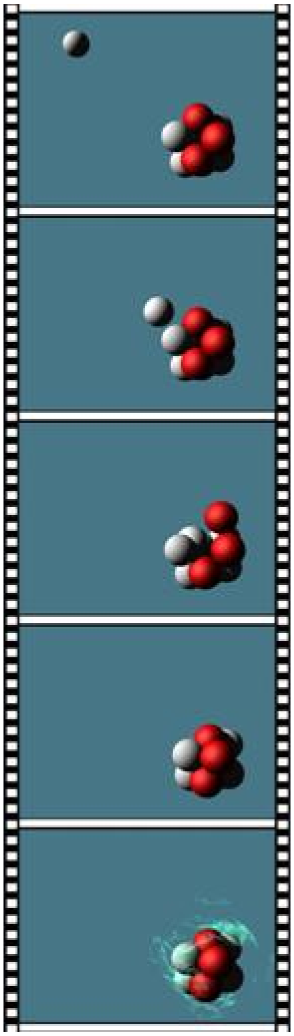
*Neutron absorption* occurs when a neutron collides with a nucleus and becomes part of that nucleus. To picture the process, imagine our bullet penetrating, but not passing through, an object. The object is small enough that, as it absorbs the bullet's energy, the object becomes momentarily unstable. Similarly, a nucleus that absorbs a neutron is unstable.

Depending on its characteristics, the unstable nucleus will become more stable through one of two phenomena:

- The unstable nucleus might undergo ***radioactive decay***, releasing energy in one or more steps. Depending on its characteristics, the nucleus will emit alpha (α), beta (β), and/or gamma (γ) radiation. No free neutrons are emitted in these cases. This type of neutron absorption, illustrated to the right, can be important to criticality safety, as described in a later module. In our bullet analogy, the object that the bullet penetrated wobbles or falls over and some small pieces of the object break off.



- The nucleus might *fission*, splitting into two fission fragments, releasing energy, radiation, and neutrons. In our bullet analogy, imagine the bullet penetrates a box of bullets, causing the box to split into two pieces and release a few bullets. This analogy is better if we imagine that released bullets move as if they were fired. Nuclear fission is discussed further in the next module.



Above, a depiction of neutron capture in a B-10 nucleus (depiction ends before radioactive decay)

**Did you know …**

- **That you can find more information about radiation?** Consult one or more of the following:
  - The Radiological Worker Training Study Guide.
  - 00TRN74, General Employee Radiological Training (GERT)
  - 00TRN213, Radiological Worker I
  - 00TRN211, Radiological Worker II
- **That neutron absorption creates an unstable nucleus, even if the unstable nucleus has a naturally occurring, stable counterpart?** The compound nucleus has excess energy because of the neutron's energy and the nucleus's *mass defect* (the compound nucleus does not have the same mass as its stable counterpart).

  Consider the boron isotopes B-10 and B-11. Each isotope has five protons; B-10 has five neutrons while B-11 has six neutrons. Naturally occurring, stable B-10 has a mass of 10.0123790 atomic mass units (amu). Naturally occurring, stable B-11 has a mass of 11.0093055 amu. But the mass of a B-10 atom plus the mass of one neutron is equal to 11.0216019 amu. The 0.01229640 amu difference is equivalent to energy (remember $E=mc^2$); it makes the compound nucleus unstable.

  In this case, the unstable nucleus undergoes radioactive decay to reduce this excess energy. It emits a gamma ray and an alpha particle, becoming a lithium-7 (Li-7) ion.

**My Notes:**

## Review Questions

*Select all choices that apply.*

1. Which of the following are major ways in which a free neutron can interact with an atomic nucleus?
    a. neutron decay
    b. neutron scatter
    c. neutron exchange
    d. neutron absorption
    e. neutron dance

2. Which of the following best describes neutron absorption?
    a. a free neutron collides with and becomes part of a nucleus
    b. a free neutron decays, emitting an electron and electron antineutrino and becoming a proton
    c. a proton captures an electron, becoming a neutron
    d. a free neutron loses energy
    e. a free neutron travels in a different direction

3. What happens due to a neutron scatter event with a very light atomic nucleus?
    a. the neutron speed (energy) changes very little, if at all
    b. the direction the neutron travels changes
    c. the neutron slows down (loses energy)
    d. the neutron is captured
    e. nothing

4. What happens due to a neutron scatter event with a very heavy atomic nucleus?
    a. the neutron speed (energy) changes very little, if at all
    b. the direction the neutron travels changes
    c. the neutron slows down (loses energy)
    d. the neutron is captured
    e. nothing

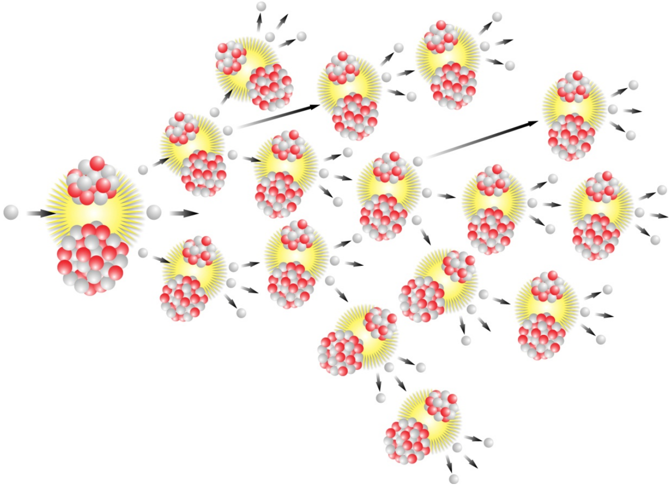
5. Neutron absorption can result in which of the following?
    a. neutron exchange
    b. nuclear fission
    c. nuclear fusion
    d. neutron capture followed by radioactive decay of the nucleus
    e. nothing

## Review-Question Answers

1. b, d     2. a     3. b, c     4. a, b     5. b, d

# MODULE 2 FISSION AND CHAIN REACTIONS

## Introduction



To understand nuclear criticality, one must also understand some basics of the nuclear fission process: what nuclear fission is, how one fission can lead to a chain of fissions, materials that can sustain a fission chain reaction, and what kinds of fission chain reactions are safe and unsafe.

## Objectives

Describe a *nuclear fission* and a *nuclear fission chain reaction*.

Describe *fissionable material*.

Identify *fissionable nuclides of concern* at INL.

Define *subcritical*, *critical*, and *supercritical* in general terms.

### My Notes:

# Topic 2.1 Nuclear Fission

*Nuclear fission* is a phenomenon in which an unstable atomic nucleus splits into two fragments, releasing energy, radiation and neutrons.

A nuclear fission can occur spontaneously. However, criticality safety is mostly concerned with fissions that occur because the nucleus absorbed a neutron (specifically, neutron-induced fission).

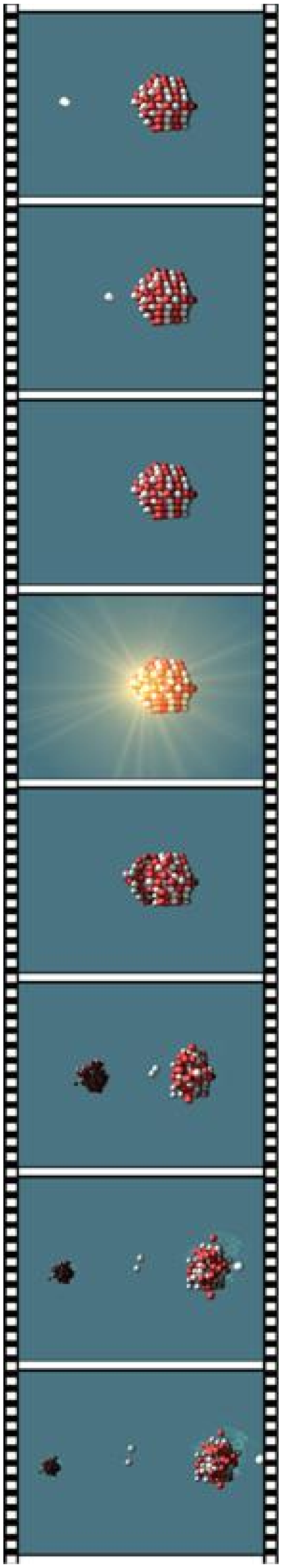
Fission fragments are more stable than the original nucleus, but they are still unstable. They are radioactive. They become more stable through radioactive decay. Fission fragments and their radioactive decay can be a health hazard if enough nuclei fission. This hazard will be discussed more in Topic 6.2. This hazard is also discussed in Radiological Worker Training.

Nuclear fission releases energy, the amount of which can be calculated using Einstein's formula, $E = mc^2$. Energy is also released as fission fragments decay. Released particles (neutrons, fission fragments, and decay products) also have a lot of kinetic energy that, through friction, create heat. This energy is desirable in a commercial nuclear reactor because much of it can be converted into electrical energy.

Nuclear fission also releases free neutrons, which does not occur with non-nuclear fission. These released neutrons are important because they can go on to cause additional fissions.

Free neutrons are a form of radiation. This radiation can also be a health hazard if enough nuclei fission.

Nuclear fission and associated radiation and radioactive decay also generate heat. However, the amount of heat might be too small for a person to feel unless the reactions are controlled.



Above, a depiction of nuclear fission

**Did you know …**

**That fission fragments vary in size and composition?** Over 40 different fragments pairs can be produced by U-235 fissions. Two pairs are indentified in equations below:

U-235 + neutron → U-236 → Sr-90 + Xe-142 + 4 neutrons

U-235 + neutron → U-236 → Kr-92 + Ba-141 + 3 neutrons

Atomic masses of nearly all nuclear fission fragments fall into two broad groups:

- The light group has mass numbers from 80 to 110.
- The heavy group has mass numbers from 125 to 155.

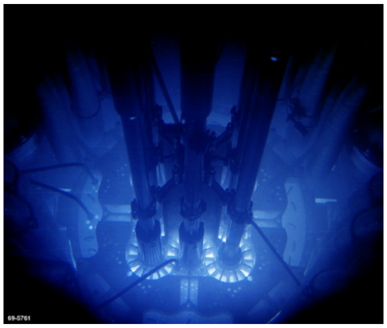
In equations above, strontium and krypton are light fragments, while xenon and barium are heavy fragments.

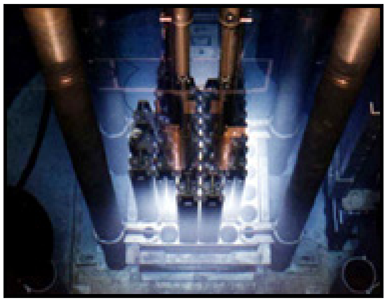
## Topic 2.2 Fission Chain Reaction

You can imagine how one fission event can initiate a chain reaction of fissions. The chain might be short, with few fission events. Or it might be long, with very many fission events. The length of the chain reaction depends on many factors, eight of which will be described in the next module.

If the fission chain reaction is long enough, 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, critical assemblies, and some nuclear experiments. INL has had 52 nuclear reactors, but only three are now allowed to operate: the ATR (right top), ATRC, and NRAD (right bottom). A critical condition should not occur anywhere else at INL these days.


Critical condition in ATR


Critical condition in NRAD

## Topic 2.3 Fissionable Material and Fissionable Isotopes

Materials that can sustain a nuclear fission chain reaction are called *fissionable materials* at INL. Nuclear fuels are examples of fissionable material. Plutonium used in radioisotope thermal generators can also be fissionable material.

Fissionable materials contain a significant quantity (mass, density, and/or concentration) of one or more fissionable isotopes. A *fissionable isotope* (or *fissionable nuclide*) is an isotope or nuclide that can undergo nuclear fission. Most unstable, heavy isotopes are fissionable. Most such isotopes are not available at INL in the forms, purities, and quantities that pose a criticality hazard.


Nuclear fuels are examples of fissionable material. These uranium-aluminum fuels have a significant quantity of U-235.

The fissionable nuclides that could pose a criticality hazard at INL are isotopes of uranium (U), plutonium (Pu), neptunium (Np), and americium (Am):

**U-233 U-235 Pu-239 Pu-241**

**Np-237 Pu-238 Am-241**

We call these seven isotopes the *fissionable nuclides of concern*.

A fissionable material that contains a significant quantity of one or more of these seven isotopes is a criticality concern at INL.

**Did you know …**

- **That a fissionable material can contain non-fissionable isotopes?** For example, many commercial reactors use oxide fuels, primarily $UO_2$. The fuel is fissionable, but its oxygen is not.
- **That a non-fissionable material can contain fissionable isotopes?** The material is non-fissionable because it does not have enough fissionable isotopes to sustain a fission chain reaction. Further, there is no plausible, inadvertent mechanism at INL to make the material critical. For example, natural uranium contains U-235 and is used as a nuclear fuel in CANDU reactors. But natural uranium is not a fissionable material at INL. INL does not have sufficient quantities of such other materials, and does not have the configurations, necessary for criticality.
- **That you might sometimes hear the word *fissile*, instead of *fissionable*?** In 2006, INL Criticality Safety decided that, at INL, we will use synonymous, nontechnical definitions for *fissionable* and *fissile*. Therefore, INL FMHs and CSOs need not worry about other definitions here, even if some people use the terms as if they are not synonymous.

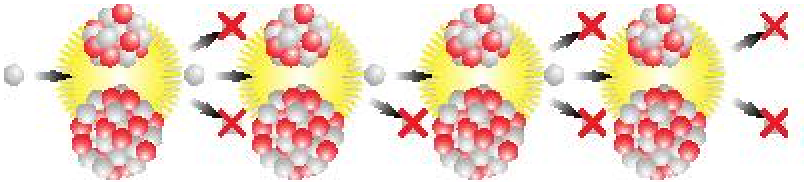
  Definitions for *fissionable* and *fissile* vary within the nuclear community and in non-technical use. Synonymous definitions are common and sometimes deeply ingrained in non-technical use, early nuclear literature, and some regions and disciplines. Other definitions depend on one or more characteristics. For more information, read: Norman L. Pruvost, J. Eric Lynn, and Charles D. Harmon III, "The Heritage and Usage of the Words *Fissionable* and *Fissile* in Criticality," Los Alamos National Laboratory Report LA-UR-04-6514, September 2004.
- **That some materials can be used to produce fissionable materials?** Such a material is called fertile material because it can breed readily fissionable material. Consider, for example, a material that contains Th-232. If a Th-232 atom captures a neutron, it becomes Th-233 and then, through radioactive decay, it becomes U-233. However, the material with U-233 must be processed to change it into a form that qualifies as fissionable material.

## Topic 2.4 Types of Fission Chain Reactions

One or more nuclear fission chain reactions might occur in almost any material or system. A few short chain reactions are safe. Many self-sustaining reactions are not safe if they occur inadvertently or outside of a reactor. We use the words *subcritical*, *critical*, and *supercritical* to describe a system with respect to criticality.

### 2.4.1 Subcritical

A *subcritical* material or system is one in which fission chain reactions ***are not*** self-sustaining. Any nuclear fission chain reaction is very brief. Each fission event, on the average, results in less than one new fission event. On the average, fewer free neutrons go on to cause more fissions than escape or are captured without causing fission. The production of free neutrons that go on to cause fission is less than the loss of free neutrons by escape or absorption.



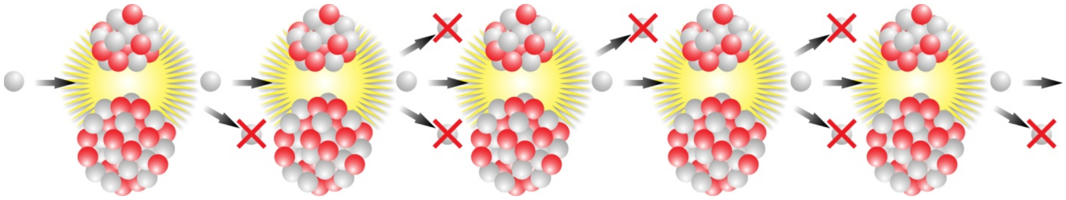
A depiction of a subcritical nuclear fission chain reaction. Crossed out neutrons are neutrons that were absorbed without causing fission or that escaped.

Except for ATR, ATRC, and NRAD, all systems and fissionable materials at INL must be kept subcritical. Even ATR, ATRC, and NRAD must be kept subcritical at times.

A stable, very subcritical condition is safe from a criticality safety perspective.

## 2.4.2 Critical

A *critical* material or system is one in which fission chain reactions ***are*** self-sustaining. Each fission event, on the average, results in one new fission event. An average of exactly one neutron from each fission event goes on to cause another fission event. Other free neutrons escape or are captured without causing fission. The production of free neutrons that go on to cause fission equals the loss of free neutrons by escape or absorption.



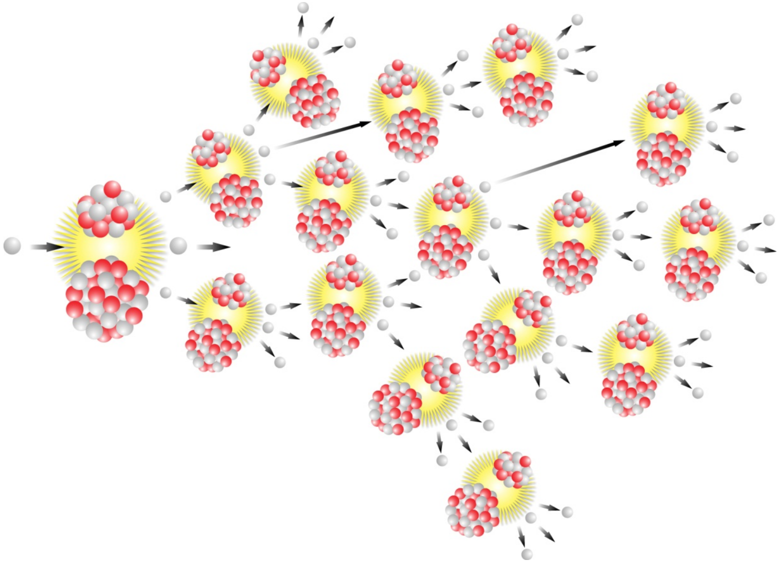
A depiction of a critical nuclear fission chain reaction.

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.) A criticality accident can have very serious consequences.

A critical condition is unsafe if personnel are not well shielded. Outside of a reactor, a critical condition is undesirable even if there is enough shielding to protect people. At INL, a critical condition is undesirable unless the condition intentionally occurs in the ATR, ATRC, or NRAD.

## 2.4.3 Supercritical

A *supercritical* material or system is one in which fission chain reactions ***are*** self-sustaining and the number of chain reactions is increasing. Each fission event, on the average, results in more than one new fission event. More neutrons cause fissions than escape or are captured without causing fission. The production of free neutrons that go on to cause fission exceeds the loss of free neutrons by escape or absorption. The free neutron population grows rapidly, usually in a fraction of a second.



A depiction of a supercritical nuclear fission chain reaction.

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. Each excursion is typically called a *burst* or *spike* or *pulse*. This is the type of criticality accident that is of most concern at INL.

A supercritical condition is unsafe if people are not well shielded. A supercritical condition outside a reactor is undesirable even if people are well shielded.

**Did you know …**

- **That supercritical accidents occurred in nuclear reactors, with fissionable ingots, and in systems for processing fissionable solution, powder, or gas?** To date, nobody has experienced a criticality accident with material in a storage system or with true waste materials, but such accidents may be considered credible in some non-INL facilities.
- **That a supercritical condition normally does not last long?** Out-of-reactor accidents usually releases enough energy to displace or boil or melt material into a subcritical configuration within seconds.

### 2.4.4 Information for Criticality Safety Officers

*NOTE: Fissionable material handlers will not be tested on this information as part of course 00INL189.*

The degree to which a system is subcritical, critical, or supercritical can be expressed numerically. Criticality safety engineers use a formula to determine the number. At its simplest, the formula compares the rate at which neutrons are produced to the rate at which neutrons are lost (captured or escaped). The result is a ratio that is less than one (subcritical), equal to one (critical), of greater than one (supercritical). This ratio is the *effective neutron multiplication factor*, which is abbreviated as k-effective, k-eff, or $k_{eff}$.

The INL Criticality Safety Program Manual, LRD-18001, specifies some requirements for acceptable k-eff values, the methods by which k-eff is calculated, and the validation of k-eff calculations.

**My Notes:**

## Review Questions

*Match concepts in the left column with their descriptions in the right column by entering the letter of the description in the box by the concept.*

☐ nuclear fission

☐ fissionable material

☐ fissionable nuclides of concern

☐ subcritical

☐ critical

☐ supercritical

☐ fission chain reaction

A fission chain reactions are self-sustaining and the number of free neutrons is increasing

B fission chain reactions are self-sustaining and the average number of free neutrons is constant

C material capable of sustaining fission chain reactions

D fission chain reactions are not self sustaining

E one or more neutrons from one nuclear fission cause one or more additional nuclear fissions

F the splitting of an atomic nucleus into two fragments, releasing energy and free neutrons

G U-233, U-235, Np-237, Pu-238, Pu-239, Pu-241, Am-241

*Considering operations outside of the ATR, ATRC, and NRAD reactors, match the concept in the left column with a description in the right column.*

☐ very subcritical

☐ critical

☐ supercritical

A safe

B unsafe or undesirable

*For Criticality Safety Officers Only. Match the concept in the left column with a description in the right column.*

☐ subcritical

☐ critical

☐ supercritical

A k-eff is equal to 1.00

B k-eff is greater than 1.00

C k-eff is less than 1.00

## Review-Question Answers

| | | | |
|---|---|---|---|
| F | nuclear fission | A | fission chain reactions are self-sustaining and the number of free neutrons is increasing |
| C | fissionable material | B | fission chain reactions are self-sustaining and the average number of free neutrons is constant |
| G | fissionable nuclides of concern | C | material capable of sustaining fission chain reactions |
| D | subcritical | D | fission chain reactions are not self sustaining |
| B | critical | E | one or more neutrons from one nuclear fission cause one or more additional nuclear fissions |
| A | supercritical | F | the splitting of an atomic nucleus into two fragments, releasing energy and free neutrons |
| E | fission chain reaction | G | U-233, U-235, Np-237, Pu-238, Pu-239, Pu-241, Am-241 |

---

| | | | |
|---|---|---|---|
| A | very subcritical | A | safe |
| B | critical | B | unsafe or undesirable |
| B | supercritical | | |

---

| | | | |
|---|---|---|---|
| C | subcritical | A | k-eff is equal to 1.00 |
| A | critical | B | k-eff is greater than 1.00 |
| B | supercritical | C | k-eff is less than 1.00 |

# MODULE 3 CRITICALITY CONTROL FACTORS

## Introduction

A critical condition is not easy to create. Many factors or parameters work together to achieve a critical mass of fissionable material. These parameters are called *criticality control factors*. Each factor is a physical characteristic that can be controlled to prevent or help prevent a criticality accident.

Understanding these factors is fundamental to understanding criticality safety. These factors can be grouped together in a variety of ways. Here, we divide the factors that are important at INL into eight categories to use the mnemonic *mermaids*:

| | |
|---|---|
| **M** | Mass |
| **E** | Enrichment |
| **R** | Reflection |
| **M** | Moderation |
| **A** | Absorption (capture) |
| **I** | Interaction |
| **D** | Density and Concentration |
| **S** | Shape (geometry) |

All eight factors work together, but we will examine them individually.

Other factors can be identified. However, INL issues associated with these other factors can be described in terms of factors already included in the *mermaids* mnemonic.

Area-specific training or mentoring will identify which factors are most important in your area.

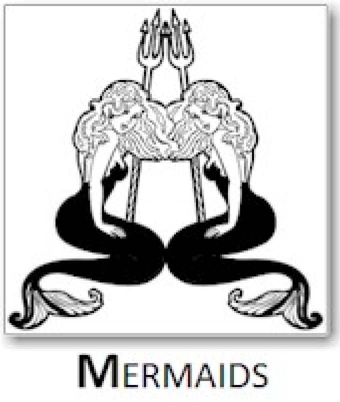
## Objectives

Identify eight criticality control factors and describe how a critical condition is affected by each factor.

### My Notes:

## Topic 3.1 Mass

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



The fewer fissionable isotopes present, the less chance a free neutron will cause a nuclear fission. Increasing the fissionable mass increases the chance that the material can be made critical.

A critical mass is the amount of a nuclide or material necessary to achieve nuclear criticality for specific conditions. The amount is typically measured in grams or kilograms. The effects of other criticality control factors are often described in terms of increasing or decreasing a critical mass.

The minimum critical mass under very specific conditions is well known for some fissionable nuclides of concern at INL (U-233, U-235, and Pu-239). Minimum critical masses for other fissionable nuclides are not so well defined (Np-237, Pu-238, and Am-241).

For fissionable material, less mass is safer; too much mass is unsafe. At INL, fissionable masses are kept as small as practical, limiting the amount of material allowed to accumulate at any one location.

**Did you know …**

- **That the minimum critical mass can be small?** The photograph to the right illustrates minimum critical mass models of a Pu-239 sphere (in the model's hand) and U-235 sphere, without their infinite water reflectors. (Reflectors are described in Topic 3.3.)
- **That a minimum critical mass is the smallest mass of fissionable material that will support a chain reaction *under specified conditions*?** As you can see from the table below, the minimum critical mass of a nearly isotopically pure material can be very small.

**Minimum Critical Mass Estimates (kg)**

| infinite water reflection (Pruvost & Paxton, LA-12808) | U-233 | U-235 | Pu-239 |
|---|---|---|---|
| One aqueous solution sphere | 0.54 | 0.80 | 0.50 |
| One solid metal sphere | 7.6 | 22.8 | 5.2 |

### More Minimum Critical Mass Estimates (kg)

| (Standard ANS-8.15-1981 R1995) | Np-237 | Pu-238 | Am-241 |
|---|---|---|---|
| Bare solid sphere | 56 to 88 | 7.1 to 12 | 58 to 98 |
| Water reflected solid sphere | 51 to 83 | 6.1 to 10.5 | |
| Steel reflected solid sphere | 33 to 55 | 4.2 to 6.9 | 34 to 60 |

- **That we sometimes limit fissionable mass by limiting something else?** Limiting the number of pieces, concentration, density, or size of a material can limit the material's mass.
    - Consider ATR fuel elements as an example. Fuel fabrication specifications for the Mark VII elements require that each element contain no more than 1085 grams of U-235. A fuel handling limit of three elements effectively limits such activities to 3255 grams of U-235. Of course, this example limit restricts more than U-235 because ATR elements have a specific shape, enrichment, and distribution of uranium in aluminum.
    - Consider volume as another example. If a material's density or concentration is constant, or limited, then limiting the material's volume also limits its mass. A minimum critical volume is the smallest volume of a particular fissionable material that will support a chain reaction *under specified conditions*. As you can see from the next table, minimum critical volumes for isotopically pure materials are small.

### Minimum Critical Volume Estimates (L)

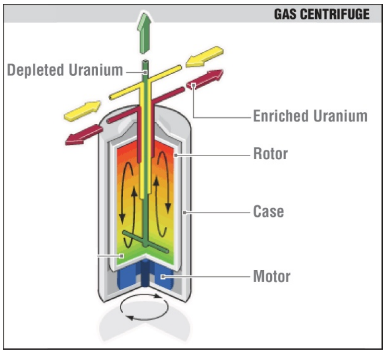
| infinite water reflection (from Pruvost & Paxton, LA-12808) | U-233 | U-235 | Pu-238 |
|---|---|---|---|
| 10 kg/L aqueous solution sphere | 0.85 | 2.3 | 0.90 |
| metal sphere | 0.42 | 1.1 | 0.28 |

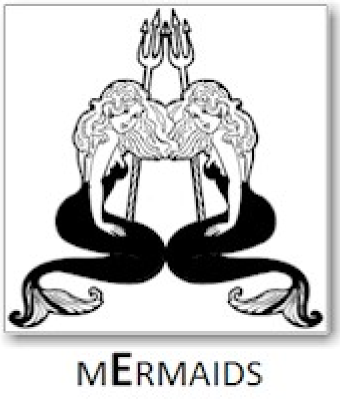
**Been there, done that.**

Most criticality accidents involved fissionable masses that either exceeded an established limit or accumulated in an uncontrolled manner and/or location. Appendix A summarizes many of these accidents.

## My Notes:

## Topic 3.2 Enrichment





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

Enrichment is usually identified as a weight percent. For uranium, it is the ratio of U-235 mass to total uranium mass. Increasing enrichment decreases critical mass. Consider, for example that, after conversion, INL's NRAD reactor operated with about 9.0 kg U-235 total during 2011 and almost 20% enriched fuel. Before conversion it operated with about 7.5 kg U-235 total and about 70% enriched fuel.

### Did you know …

**That most criticality safety limits at INL are established so that FMHs need not track enrichment?** Some such limits are based on 100% enrichment. Other limits are based on the highest credible enrichment for the materials allowed in the relevant area. For example, during the NRAD conversion project, personnel handled the fuel using limits developed for the 70% enriched elements rather than using two sets of enrichment-dependent limits.

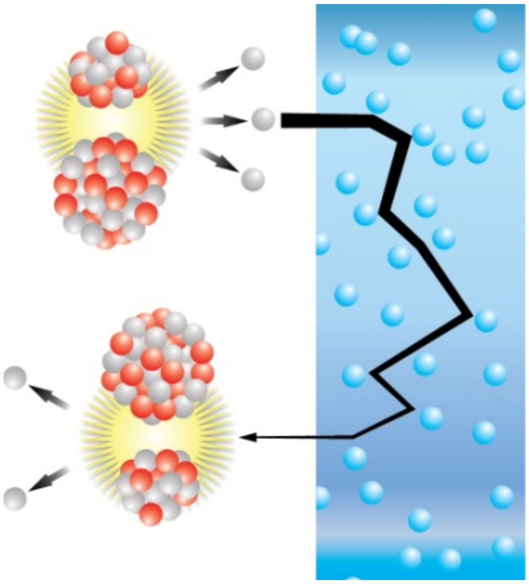
### Been there, done that.

Most, but not all, criticality accidents involved highly enriched uranium or plutonium. But lower enriched systems are not automatically critically safe. The Electrostal Fuel Fabrication Plant accident (Subtopic A.1.15) involved low enriched uranium (6.5%). A Siberian Chemical Combine accident (Subtopic A.1.9) involved intermediate enriched uranium (22.6%). The JCO accident (Subtopic A.1.22) also involved intermediate enriched uranium (18.8%).

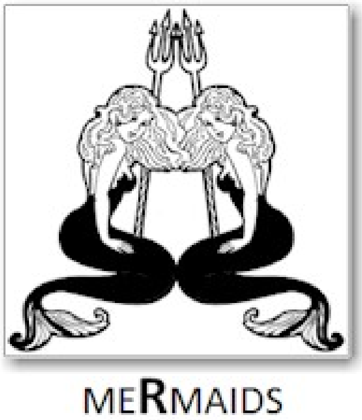
Enrichment might have been a contributing factor in other accidents. For example, the slab tanks in which the 1997 Novosibirsk Chemical Concentrates Plant accident occurred were specifically designed for a lower enrichment than was processed at the time of the accident (Subtopic A.1.21).

## My Notes:

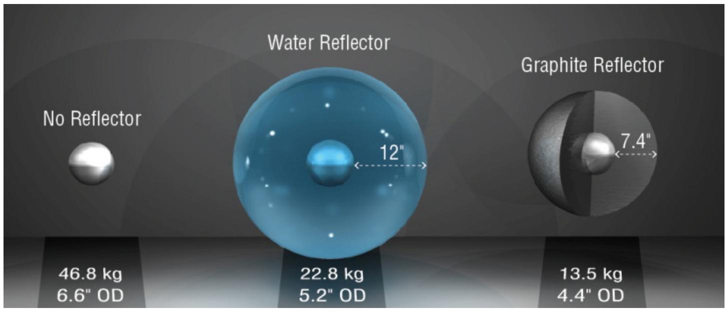
## Topic 3.3 Reflection



A depiction of neutron reflection.



Reflection is neutron scattering in which neutrons are directed back into fissionable material from which they escaped. Many neutrons normally escape if there is no reflector around the fissionable material or system. By returning a neutron to the material or system, a reflector provides additional opportunities for the neutron to cause fission.



Critical spheres of U-235 metal with and without neutron reflection

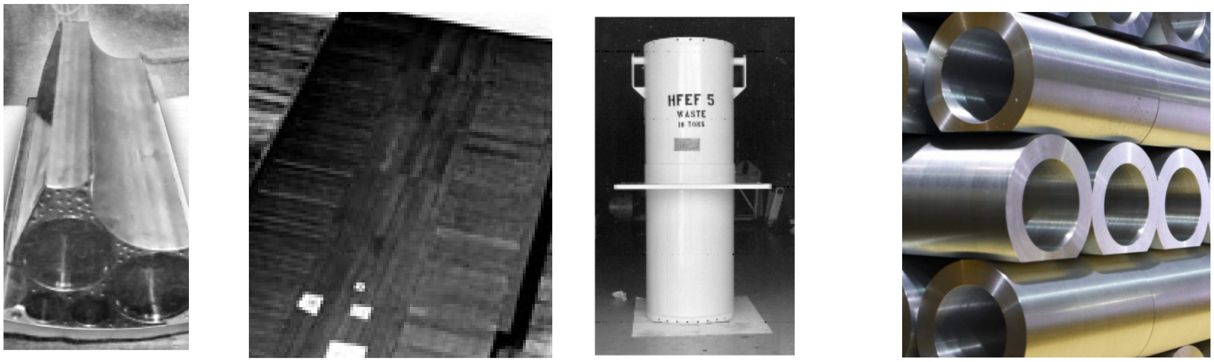
Increasing reflection decreases the critical mass. Consider a sphere of pure U-235 metal with and without a tight fitting reflector around it. The sphere requires about 46.8 kg to be critical without a reflector. It requires 22.8 kg to be critical with a 12 in. thick water reflector. And it requires 13.5 kg to be critical with a 7.4 in. thick graphite reflector.

Almost any material will reflect neutrons. But the best reflectors do not absorb neutrons well; they mostly bounce neutrons back. Examples include materials with hydrogen and/or carbon such as water, polyethylene, wood, paraffin, paper, polyethylene, and graphite. The human body, with its high content of water and carbon compounds, is all too often an excellent reflector. Criticality safety at INL ***typically*** considers the effects of an infinite, tight fitting, water reflector.

Other good reflectors include tungsten, aluminum, and beryllium.

Radiation shielding materials can be excellent neutron reflectors when located very close to fissionable material. Examples include lead, steel, concrete, water, and polyethylene. Therefore, shielding materials may be restricted in areas with much fissionable material unless the shielding materials are specifically evaluated. Such evaluations are necessary to determine fissionable material limits compatible with radiation shielding.

Hydrogenous material such as water, oil, concrete and people can be good reflectors.



Beryllium (e.g. ATR reflector), graphite (e.g CP-1 layer 3), thick lead (e.g. HFEF-5 cask ), and thick steel (e.g. pipe) can also be good neutron reflectors.

However, the presence of a reflector material, in and of itself, does not necessarily make a system unsafe. Typically, the reflector must be close enough to the fissionable material and must be thick enough to be effective.

**Did you know …**

**That some reflectors are so efficient that we call them *special reflectors*?** Criticality safety limits are typically established assuming water reflection because water is an efficient, commonly available, neutron reflector. Materials that reflect neutrons better than water are special reflectors at INL. Very thick lead, concrete, and/or steel walls are examples of special reflectors.

**Been there, done that.**

Mistakes made with neutron reflectors led directly to the two Los Alamos Scientific Laboratory accidents with a plutonium sphere (Subtopics A.2.1 and A.2.2) and to the Russian VNIIEF uranium-sphere criticality accident (Subtopic A.2.14). Neutron reflection by humans was a factor in an accident at a Mayak Production Association plant (Subtopic A.1.3). Neutron reflection by a vessel water jacket played an important role in the JCO criticality accident (Subtopic A.1.22).

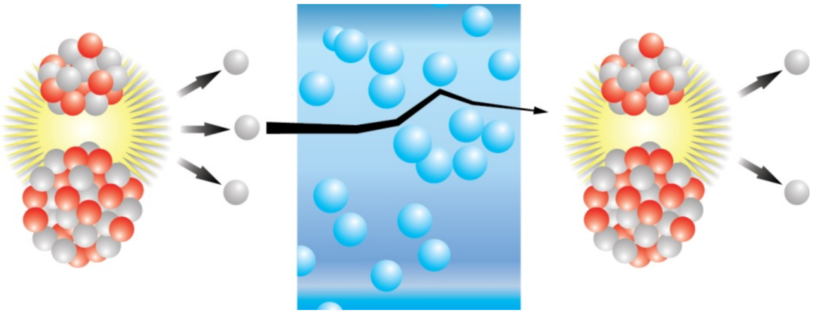
## My Notes:

## Topic 3.4 Moderation

MERMAIDS

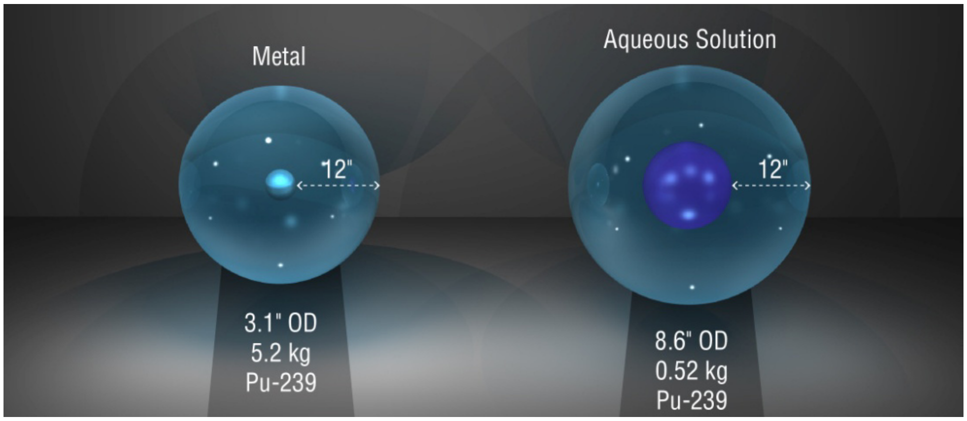
Fission neutrons are born fast, but slow neutrons are more likely than fast neutrons to cause fissions in U-233, U-235, Pu-239, and/or Pu-241. Therefore, a critical condition is more likely with these materials when there is an efficient mechanism to slow neutrons.

Moderation is neutron scattering in which the neutron loses energy. Fission neutrons are slowed, but not absorbed, through collisions with small (light) nuclei. Moderators make a self-sustained fission chain reaction more likely because more slow neutrons are available to cause fissions.



A depiction of neutron moderation: a free neutron is released during fission, slows down as it scatters off light nuclei, and is then slow enough to be readily absorbed in a fissionable isotope, causing another fission.

Up to a point, mixing a moderator into a system of U-233, U-235, Pu-239, and/or Pu-241 decreases the critical mass. Consider, for example, that the critical mass for a water-reflected, sphere of pure Pu-239 metal is about 5.2 kg of Pu-239, but the critical mass for a water reflected, perfectly mixed, solution sphere of Pu-239 and exactly the right amount of water is about 0.52 kg of Pu-239.



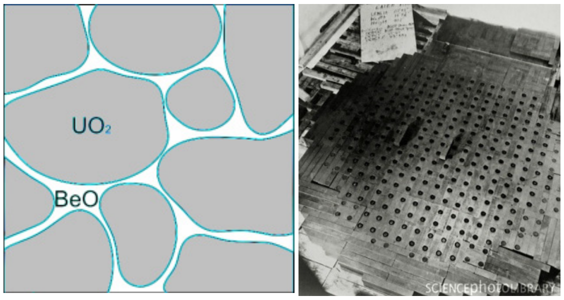
A depiction of critical sphere of Pu-239 in water. The metal sphere has no moderator and therefore requires more Pu-239 to be critical. [Reference: LA-10860-MS]

Note that moderation tends to reduce the critical mass of some, but not all, fissionable isotopes. Moderation is a concern at INL for fissionable materials that contain U-233, U-235, Pu-239, and/or Pu-241. These are the most common fissionable isotopes at the INL site. However, moderation tends to increase the critical mass of some fissionable isotopes. Examples include Np-237, Pu-238, and Am-241. These three isotopes are much more likely to absorb a fast neutron and fission than to absorb a slow neutron.

Light elements can be effective moderators because their nuclei are roughly the same size and mass as a neutron. When colliding with these nuclides, neutrons slow down much like marbles hitting other marbles, as mentioned in Subtopic 2.2.1 and shown on page 12.

Therefore, most effective neutron moderators are composed of very light elements, including hydrogen (especially its isotope deuterium), beryllium, helium, carbon, and oxygen. All materials containing hydrogen and many materials containing carbon can be good moderators. Such materials include water, plastic, paraffin, oil, and graphite.

Hydrogenous materials (such as water, oil, paraffin and plastic) can be good moderators.



Berylium (e.g. Be-U fuel) or graphite (e.g. CP-1 layer 10) can also be good neutron moderators.

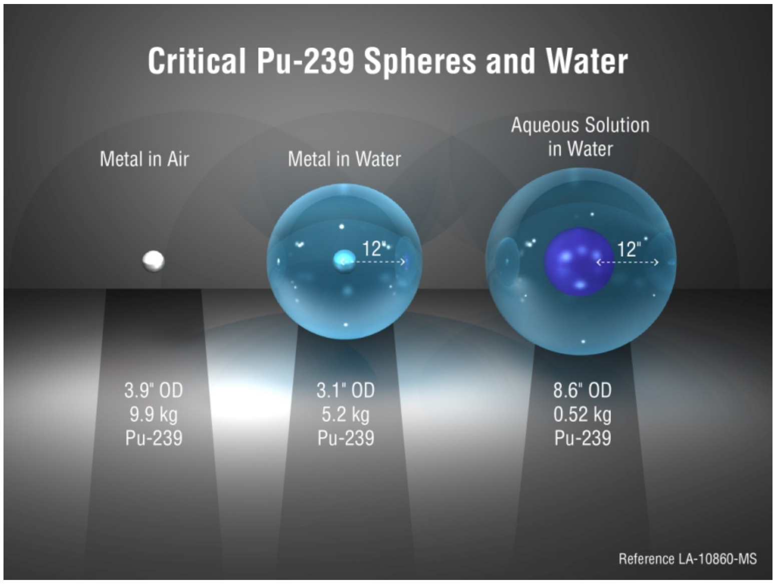
Just adding a moderator to a U-233, U-235, Pu-239, and/or Pu-241 system does not necessarily make the system unsafe. The moderator must be adequately mixed with fissionable material to be effective. Fissionable solution is an example of such mixing. A fuel-rod array in water, paraffin, plastic, or graphite is another example of such mixing. With the possible exception of hands, humans are rarely effective moderators because humans do not mix with fissionable material. Similarly, water that is not held in or between fissionable materials is usually not an effective moderator.

**Did you know …**

- **That neutron reflection (previous topic) might occur as part of a neutron moderation interaction?** The possibility of both occurring depends on the nature of the nucleus with which the neutron collided. However, we examine these control factors separately.
- **That fire suppression methods must be considered before limiting moderators in a CCA?** Water is the most commonly used and effective fire suppressant, but moderator limits almost

always involve restricting fire-fighting methods. Fire suppression restrictions are never imposed lightly because, in many operations, fires are more likely to occur, and can be more destructive, than criticality accidents.

- **That some people use qualitative terms to describe moderator quantity?** These terms are based on a recognition that, before colliding with a fissionable nucleus, a neutron might slow down too much, too little, or just enough to be easily absorbed in a fissionable nucleus:
  - *Optimum moderation* means there is just enough moderator to slow neutrons, maximizing their chance of being absorbed in fissionable nuclei.
  - *Over-moderation* means there is significantly more than an optimum amount of a moderator. If there is too much moderator, neutrons will probably be absorbed without causing fission.
  - *Under-moderation* means there is significantly less than an optimum amount of moderator. In such cases, neutrons escape before they are slow enough to be readily absorbed in fissionable nuclides.
- **That combining water reflection and moderation can reduce a critical mass significantly?** Consider Pu-239 as an example:

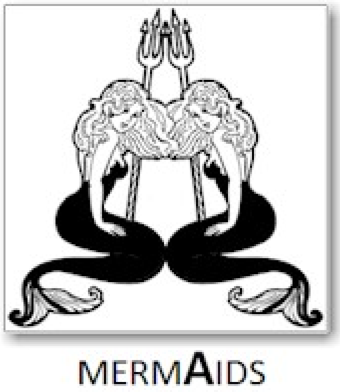


**Been there, done that.**

Neutron moderators played an important role in criticality accidents at the Machine Building Plant (Subtopic A.1.15), Boris Kidrič [Kidrich] Institute critical facility (Subtopic A.2.7), VENUS critical facility (Subtopic A.2.11), and RA-2 Reactor (Subtopic A.2.13) criticality accidents.

## My Notes:

## Topic 3.5 Absorption (neutron capture)



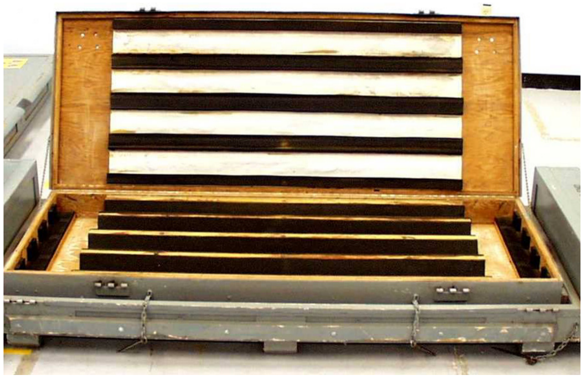
If it does not result in fission, neutron absorption removes a neutron from a fissionable system.

Such neutron absorption decreases the number of neutrons available to produce additional fissions. Such neutron absorption tends to increase a system's critical mass.

To some degree, all materials can absorb neutrons without fissioning, even fissionable isotopes. However, some materials are especially good at it. *Neutron absorbers* are materials that readily absorb neutrons without undergoing fission. Neutron absorbers are sometimes called *neutron* or *nuclear poisons*.

Boron, cadmium, hafnium, gadolinium, and lithium are strong neutron absorbers. Under certain conditions, steel and water can also be good neutron absorbers, but they are not usually identified as such.

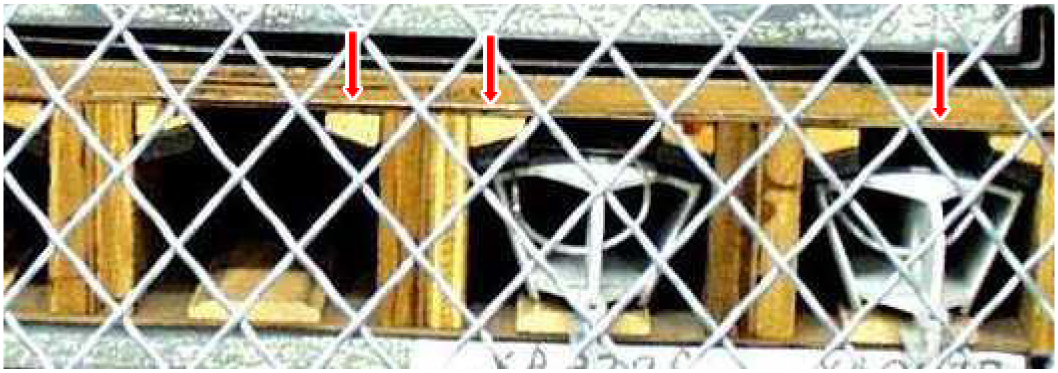
INL uses several neutron absorbers. Boron in the form of boron-carbide is the absorber in NRAD control rods. Hafnium metal is the absorber in ATR safety rods, outer shim control cylinders, regulating rods, and certain neck shims. Cadmium sheet metal is used in the four-element ATR fresh fuel shipping container and in ATR fuel storage racks.



The four-element ATR fresh fuel shipping container has polyethylene-backed cadmium to absorb neutrons.

Neutron absorbers must be located appropriately to be effective. Usually that means the absorber must be mixed in with the fissionable material or it must be located between units of fissionable material. In the ATR fuel storage racks, for example, the neutron absorber cadmium is placed between rows of fuel to reduce neutron interaction between adjacent rows.

Care must be used when adding a neutron absorber to a barely subcritical system. That is because neutron absorbers reflect some neutrons, even though absorbers are poor neutron reflectors.



Arrows point to the edge of cadmium sheet metal in ATR fuel storage racks. The cadmium absorbs neutrons that would otherwise interact between rows of fuel.

### Did you know …

**That a neutron absorber might need a moderator to perform its function?** Cadmium, boron, and gadolinium do not absorb fast neutrons well, but they absorb slow neutrons *very* effectively. In some cases, moderator is included as part of the design (for example, the ATR four element fresh fuel shipping container). In other cases, the additional moderator that promotes fission is also sufficient to make the neutron absorber effective.

### Been there, done that.

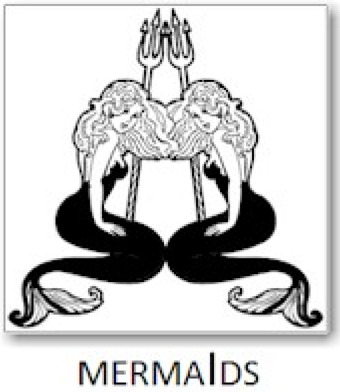
Neutron absorbers were an important factor in causing and/or terminating some criticality accidents. Several criticality accidents in reactors involved inappropriate or unplanned removal or partial removal of control rods (neutron absorbers), causing the accident. Neutron absorbers were used to terminate the chain reaction a Mayak Production Association plant (Subtopic A.1.16) and the Novosibirsk Chemical Concentrates Plant (Subtopic A.1.21). Neutron absorbers were used to ensure subcriticality (stabilize) the system after terminating a criticality accident in the JCO plant (Subtopic A.1.22).

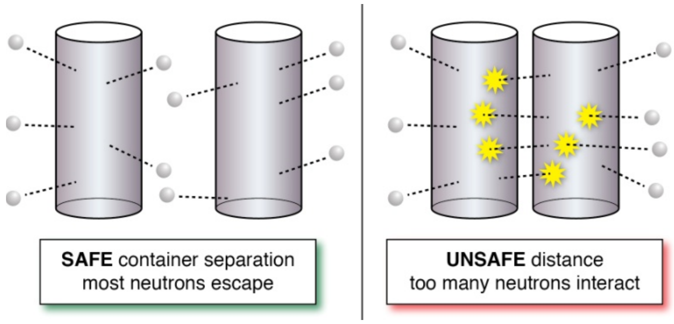
However, introducing neutron absorbers is not always effective in terminating a criticality accident. For example, injecting an absorber displaced other materials, allowing the chain reaction to continue, during the criticality accident at the Siberian Chemical Combine in 1963 (Subtopic A.1.13).

## My Notes:

## Topic 3.6 Interaction

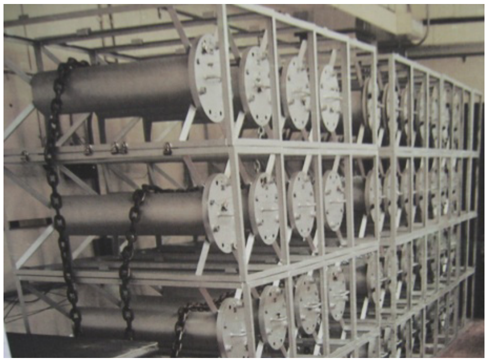
Interaction is the exchange of neutrons between two or more fuel regions or masses of fissionable material that are physically separated. Either or both masses could be subcritical alone.





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

Neutron interaction is usually controlled by separating units. In such cases, we control the distance between units. Fissionable material shipping, transfer, and storage equipment usually reduce neutron interaction by including structures that separate units of fissionable material.



“Birdcage” packages include structure to separate package contents.

ATR fuel transfer racks include broad base structures and tilted positions.

Sometimes interaction is controlled by placing a neutron absorber (Topic 3.5) between units.

### Did you know …

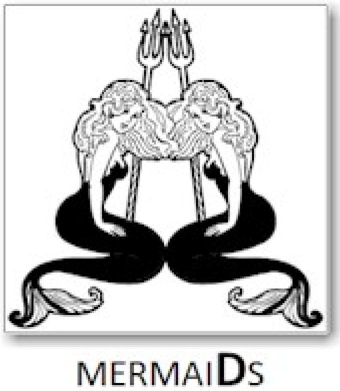
**That interaction can make a system of safe-by-geometry containers unsafe?** If interaction is not considered before grouping containers, a criticality could occur as containers are brought close together, even if each container alone is safe by geometry. Container shapes and sizes often make it too easy to place fissionable material masses too close together. (Geometry is described as a factor in Topic 3.8.)

**Been there, done that.**

**Unplanned neutron interaction between two fissionable bodies was involved in two criticality accidents.** A 1956 Los Alamos Scientific Laboratory accident involved the split halves of the Honeycomb critical assembly (Subtopic A.2.6). The 1997 Novosibirsk Chemical Concentrates Plant accident involved two slab tanks (Subtopic A.1.21).

**My Notes:**

## Topic 3.7 Density and Concentration



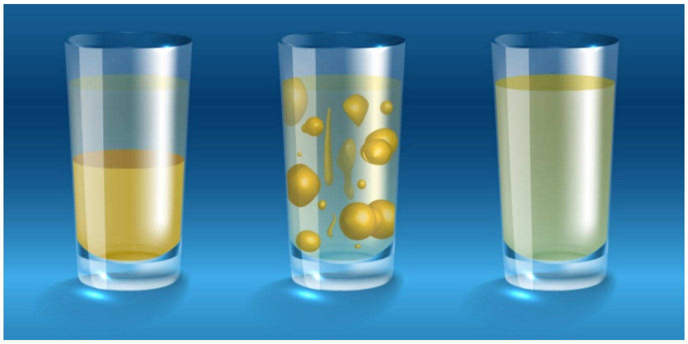
Density and concentration are similar in that they are both often expressed as a mass per unit volume (for example, g/cm$^3$, g/mL, g/L, or kg/m$^3$). The words are often used interchangeably for non-technical purposes. For our purposes and for sake of our mnemonic, such non-technical use is adequate. Therefore, for INL criticality safety training purposes, we typically use *density* and *concentration* to mean the mass of fissionable isotope(s) per unit volume of material.

The number of fissionable isotopes in a specific volume increases as the material density or element concentration increases. (This concept is illustrated below if we imagine that our fissionable isotopes are yellow.)

A series of glasses showing dilute to concentrated material, or showing light to dense solution.

Up to a point, increasing the density or concentration of a fissionable material increases the chances that a free neutron will cause a fission. Therefore, increasing the density or concentration up to that point decreases the material's critical mass.

This control factor involves the distribution of a material, or material component, through a volume. The component might actually be separate, or not mixed. At the other extreme, the components might be evenly mixed. Or the distribution might be somewhere in-between, or unevenly mixed. The graphic below illustrates this concept.



An example of unmixed, unevenly mixed, and evenly mixed materials

The distribution of fissionable isotopes in a material might affect the material's critical mass. Examples in this guide assume the distribution is as evenly mixed as possible for the materials involved.

INL criticality safety that relies on density or concentration incorporates the effects of worst case distribution when practical. However, there is at least one case in which FMH monitoring and action are necessary to ensure the appropriate material component distribution. Area-specific training addresses this issue for FMHs who may encounter this case.

**Did you know …**

- **That there is a technical difference in the definitions of concentration and density?** *Concentration* refers to the mass of a particular material component per unit volume of material. *Density* is the ratio of an item's total mass to its total volume. For example, a plutonium nitrate solution might have a plutonium concentration of 300 g/L (300 g/cm$^3$) and a solution density of 1.438 g/L (1.438 g/cm$^3$).
- **That a minimum critical concentration is the smallest concentration of fissionable solution that will support a chain reaction *under specified conditions*?** However, as you can see from the table below, a minimum critical concentration for an isotopically pure material can be very dilute, except when compared to many waste materials.

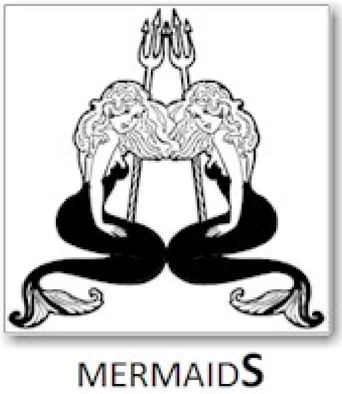
### Minimum Critical Concentration Estimates (g/L)

| infinite water reflection (from Pruvost and Paxton, LA-12808) | U-233 | U-235 | Pu-238 |
|---|---|---|---|
| aqueous solution | 11.3 | 12.1 | 7.17 |

**My Notes:**

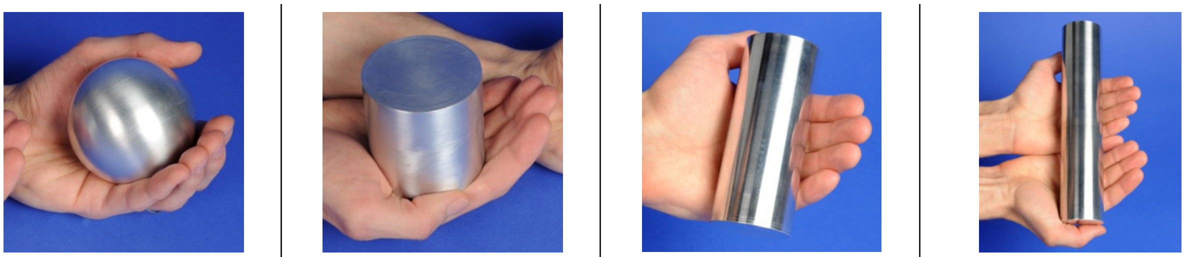
## Topic 3.8 Shape (geometry)

Shape (geometry) can also be limited to prevent or promote a criticality. Geometry control is the preferred criticality control method in most nuclear applications that involve more than a minimum critical mass of fissionable material.



Geometry control is based on neutron leakage. For certain shapes, free-neutrons are so close to an external surface of a fissionable mass that they are more likely to escape the mass than to be absorbed in a fissionable nucleus. The percentage of free neutrons that leak out of a fissionable mass increases as the surface area of the mass increases. Increasing the surface area tends to increase the material's critical mass.

Let's consider some simple shapes for solid, Pu-239 metal at theoretical density. In the illustration below, the first three items (a sphere, a fat cylinder, and a skinny cylinder) have the same 5.2 kg mass. The sphere has the least surface area and would be critical if it were water reflected. The fat cylinder with a little more surface area would be barely subcritical if it were water reflected. The skinny cylinder with a lot more surface area would be very subcritical if it were water reflected. The fourth item is a skinny cylinder of the same material, but with a 10 kg mass. This cylinder would also be critical if water reflected. This particular increase in surface area (or decrease in diameter) increased the critical mass by 4.8 kg.



5.2 kg Pu-239 sphere
3.1 in. diameter

critical with water reflection

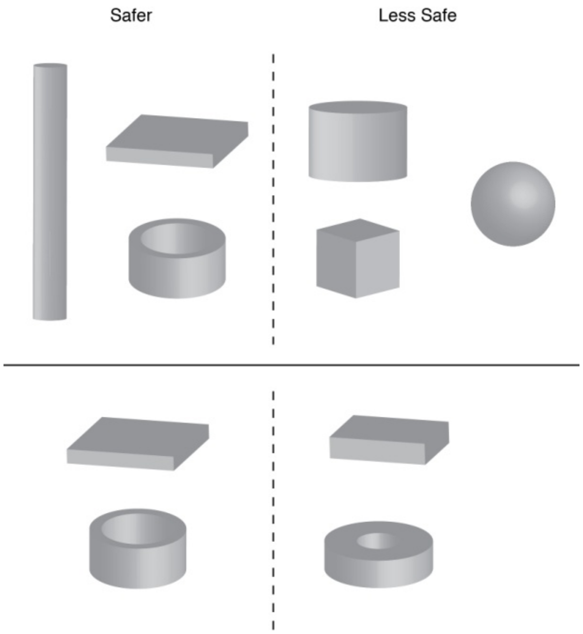
5.2 kg Pu-239 cylinder
2.8 in. diameter
2.8 in. height
barely subcritical with water reflection

5.2 kg Pu-239 cylinder
2.0 in. diameter
4.9 in. height
very subcritical with water reflection

10 kg Pu-239 cylinder
2.0 in. diameter
9.8 in. height
critical with water reflection

**Shape comparisons for Pu-239. (Numerical values are rounded-off.)**

Take the comparison farther with simple shapes for a specific material, as shown in the illustration on the next page. All of the shapes have the same volume, density and mass. As previously identified, a sphere has the least surface area and is least safe. A fat cylinder with the same height as diameter is a little safer than a sphere because it has a little more surface area. A cube is a little safer than a fat cylinder for the same reason. A skinny cylinder, a slab, and an annulus are much safer than a cube because each has much more surface area. Similarly, a thin slab is safer than a thick slab and a thin annulus is safer than a thick annulus.



Criticality safety comparison of common shapes.

A fissionable mass or item can be safe-by-geometry if it has a shape that is sufficiently subcritical for any of its credible contents and if that shape is robust enough to not deform. The safe-by-geometry determination might be based on a single item (for example, one cylindrical tank) or for a specified number of such items (for example, a bank of cylindrical tanks). It is important to know the basis for the safe-by-geometry determination if the item can be moved or the contents can be changed.

**Did you know …**

- **That a minimum critical dimension is the shape-dependent smallest dimension for a fissionable material that will support a chain reaction *under specified conditions*?** Some minimum critical dimensions for isotopically pure materials are very small.

**Minimum Critical Dimension Estimates (cm)**

| infinite water reflection (from Pruvost & Paxton, LA-12808) | 1 unit of aqueous solution, with a 10 kg/L concentration | | | 1 metal unit | | |
|---|---|---|---|---|---|---|
| | U-233 | U-235 | Pu-238 | U-233 | U-235 | Pu-238 |
| 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 |

- **That this shape factor can be summarized mathematically for an object?** When comparing general shapes we calculate the ratio of an object's surface area to its volume. In general, an object with a larger ratio is more favorable than an object with a smaller ratio. If the general shape is fixed, we can compare ratios of the shape's dimensions. For example, height-to-diameter ratios are very useful when comparing cylinders to each other. A cylinder's dimensions become less safe as its height-to-diameter ratio approaches one.

**Been there, done that.**

Geometry was an important factor in most out-of-reactor criticality accidents. In many cases, the accident vessel was not meant to contain fissionable liquid, the type of fissionable liquid, or the concentration of fissionable liquid that it contained at the time of the accident. In a few cases, a vessel was declared safe-by-geometry without considering that the vessel had a greater physical capacity than the expected maximum volume of the approved contents. And one accident (Subtopic A.1.21) involved slab tanks that bulged over years of service.

## My Notes:

## Review Questions

*Match each control factor in the left column with its best description in the right column by placing the description letter in the appropriate box.*

☐ Mass
☐ Enrichment
☐ Reflection
☐ Moderation
☐ Absorption
☐ Interaction
☐ Density and concentration
☐ Shape (geometry)

A A physical characteristic important to criticality safety because increasing the surface area allows more neutrons to escape.

B The mass of a material, or one of its constituents, compared to its volume.

C A process in which an escaped neutron returns to a fissionable material through one or more neutron-scatter events.

D The quantity of fissionable material or fissionable nuclides typically measured in grams of kilograms.

E A process in which a neutron is removed from a chain reaction by becoming part of a nucleus without causing fission.

F A process in which neutrons from one fissionable mass enter another fissionable mass.

G A process in which a neutron slows down through one or more neutron-scatter events.

H The amount of U-235 in uranium, when the amount has been artificially increased.

*Select the best answer option.*

1. Personnel will learn which criticality control factors are important to their area from:
    a. Radiological worker training
    b. Site access training
    c. Area-specific training or mentoring
    d. ES&H training

*Match each action in the left column with its effect in the right column.*

- ☐ Increasing the enrichment of uranium tends to …
- ☐ Increasing neutron reflection (adding an effective neutron reflector) tends to …
- ☐ Up to a point, adding moderation to U-233, U-235, Pu-239, and/or Pu-241 tends to …
- ☐ Increasing neutron absorption by appropriately adding a neutron absorber tends to …
- ☐ For the sum of fissionable material, increasing the distance between two units of fissionable material tends to …
- ☐ Up to a point, increasing the density of a fissionable material (or the concentration of a fissionable isotope) tends to …
- ☐ For the same density and volume, increasing the surface area of a fissionable material tends to …

A decrease the critical mass

B increase the critical mass

C have no affect on the critical mass

*Match each material in the left column with its ‘best’ type(s) in the right column.*

- ☐ boron
- ☐ cadmium
- ☐ concrete
- ☐ graphite
- ☐ hafnium
- ☐ lead
- ☐ water

A neutron absorber only

B neutron moderator and reflector

C neutron moderator only

D neutron reflector only

*Complete each sentence in the left column with the correct phrase from the right column. Assume in each case that all other things are equal.*

☐ A large mass of fissionable material is _______ a small mass of the same material.

☐ For the same mass of U-235, a high enrichment is _______ a low enrichment.

☐ The presence of a tight fitting neutron reflector is _______ no reflector.

☐ Up to a point, distributing a moderator through a system of U-233, U-235, Pu-239 and/or Pu-241 is _______ the system without moderator.

☐ Neutron absorber distributed between units of fissionable material is _______ the units without absorber.

☐ Placing units of fissionable material close together is _______ placing the units far apart.

☐ Up to a point, increasing the concentration of fissionable isotopes is _______ decreasing the concentration.

☐ A spherical shape is _______ a tall skinny cylinder.

| | |
|---|---|
| A | less safe than |
| B | safer than |
| C | as safe as |

*Select the best answer option.*

2. What are criticality control factors?
   a. Physical characteristics of fissionable materials or systems that contain fissionable material, that can be controlled to prevent a criticality accident.
   b. Areas that allow fissionable materials to be stored.
   c. The amount of fissionable isotopes in a specific volume.
   d. All of the above.

## Review-Question Answers

*Control factor matching exercise:*

| | |
|---|---|
| D | Mass |
| G | Enrichment |
| C | Reflection |
| G | Moderation |
| E | Absorption |
| F | Interaction |
| B | Density and concentration |
| A | Shape (geometry) |

| | |
|---|---|
| A | A physical characteristic important to criticality safety because increasing the surface area allows more neutrons to escape. |
| B | The mass of a material, or one of its constituents, compared to its volume. |
| C | A process in which an escaped neutron returns to a fissionable material through one or more neutron-scatter events. |
| D | The quantity of fissionable material or fissionable nuclides typically measured in grams of kilograms. |
| E | A process in which a neutron is removed from a chain reaction by becoming part of a nucleus without causing fission. |
| F | A process in which neutrons from one fissionable mass enter another fissionable mass. |
| G | A process in which a neutron slows down through one or more neutron-scatter events. |
| H | The amount of U-235 in uranium, when the amount has been artificially increased. |

*Multiple-choice exercise:*

1. Personnel will learn which criticality control factors are important to their area from:
    a. Radiological worker training
    b. Site access training
    **c. Area-specific training or mentoring**
    d. ES&H training

*Action matching exercise:*

| | |
|---|---|
| **A** | Increasing the enrichment of uranium tends to … |
| **A** | Increasing neutron reflection (adding an effective neutron reflector) tends to … |
| **A** | Up to a point, adding moderation to U-233, U-235, Pu-239, and/or Pu-241 tends to … |
| **B** | Increasing neutron absorption by appropriately adding a neutron absorber tends to … |
| **B** | For the sum of fissionable material, increasing the distance between two units of fissionable material tends to … |
| **A** | Up to a point, increasing the density of a fissionable material (or the concentration of a fissionable isotope) tends to … |
| **B** | For the same density and volume, increasing the surface area of a fissionable material tends to … |

| | |
|---|---|
| A | decrease the critical mass |
| B | increase the critical mass |
| C | have no affect on the critical mass |

*Material-type matching exercise:*

| | |
|---|---|
| **A** | boron |
| **A** | cadmium |
| **D** | concrete |
| **B** | graphite |
| **A** | hafnium |
| **D** | lead |
| **B** | water |

| | |
|---|---|
| A | neutron absorber |
| B | neutron moderator and reflector |
| C | neutron moderator |
| D | neutron reflector |

*Sentence completion exercise:*

| | |
|---|---|
| **A** | A large mass of fissionable material is _______ a small mass of the same material. |
| **A** | For the same mass of U-235, a high enrichment is _______ a low enrichment. |
| **A** | The presence of a tight fitting neutron reflector is _______ no reflector. |
| **A** | Up to a point, distributing a moderator through a system of U-233, U-235, Pu-239 and/or Pu-241 is _______ the system without moderator. |
| **B** | Neutron absorber distributed between units of fissionable material is _______ the units without absorber. |
| **A** | Placing units of fissionable material close together is _______ placing the units far apart. |
| **A** | Up to a point, increasing the concentration of fissionable isotopes is _______ decreasing the concentration. |
| **A** | A spherical shape is _______ a tall skinny cylinder. |

| | |
|---|---|
| A | less safe than |
| B | safer than |
| C | as safe as |

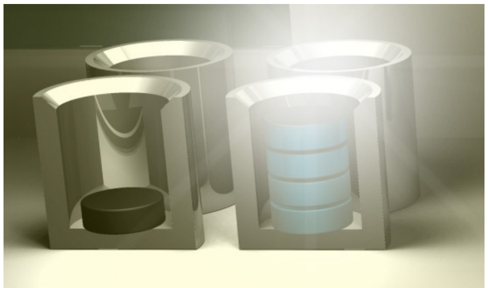
*Multiple-choice exercise:*

2. What are criticality control factors?
   **a. Physical characteristics of fissionable materials or systems that contain fissionable material, that can be controlled to prevent a criticality accident.**
   b. Areas that allow fissionable materials to be stored.
   c. The amount of fissionable isotopes in a specific volume.
   d. All of the above.

# MODULE 4 CRITICALITY ACCIDENTS AND RISKS

## Introduction

Criticality accidents can and have occurred. A criticality accident can have serious adverse consequences for people who are very near its source and/or do not respond appropriately. Such an accident can also have very serious programmatic consequences. However, accidents outside of a nuclear reactor tend to produce little radiological contamination or property damage.



## Objectives

Define *criticality accident*.

Identify one basic factor in the cause of many historical criticality accidents.

Identify some characteristics of a criticality accident.

### My Notes:

# Topic 4.1 Criticality Accidents

## 4.1.1 What is a Criticality Accident?

A criticality accident is an inadvertent critical or supercritical nuclear fission chain reaction. An uncontrolled critical or supercritical condition might also be considered a criticality accident. Criticality safety is concerned with criticality accidents that occur or could occur outside of nuclear reactors. (Reactor safety addresses criticality accidents in nuclear reactors, as well as other hazards.)

This was not a criticality accident. It was not inadvertent. Also, it was not uncontrolled.

Criticality accidents are most serious when they occur in locations that do not have sufficient shielding to protect personnel. However, any criticality accident represents a loss of control(s) that has a potential for significant adverse consequences.

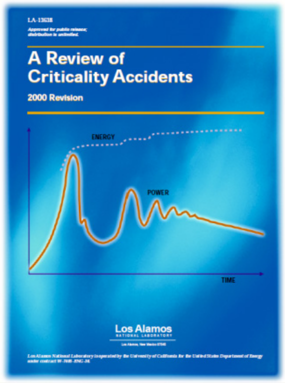
A criticality accident can occur without an easily recognized warning. There might be no sound, no vibration, no flash, no significant heat, nothing.

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.

## 4.1.2 Experience

Criticality accidents can vary greatly in magnitude, duration, and effects.

We know this because of the sixty criticality accidents that have been reported world-wide since the 1940s (Appendix A and "A Review of Criticality Accidents," Los Alamos National Laboratory report LA-13638). We can also derive information from calculations and experiments that model important features of criticality accidents. In addition, we gather information from best management practices, successful operations, and near-miss events. Sometimes we gather valuable accident-related information from other fields (for example, radiological, chemical, and/or industrial safety).



LA-13638

A Review of Criticality Accidents

2000 Revision

Los Alamos
NATIONAL LABORATORY

Report describing 60 criticality accidents.

At INL we incorporate resultant lessons learned into our criticality safety program to help accomplish our purpose of preventing and mitigating criticality accidents. We also incorporated information about criticality accident characteristics and accident-response experiences into INL emergency planning to help mitigate criticality accidents.

**Did you know …**

**That three criticality accidents occurred in recent years?** The 1997 accidents at the Novosibirsk Chemical Concentrates Plant (Subtopic A.1.21) and VNIIEF (Subtopic A.2.14) in Russia and the 1999 accident at the JCO Plant (Subtopic A.1.22) in Japan remind us that criticality safety controls, standards, and vigilance must be maintained.

### 4.1.3 Causes

Human error was a major factor in most criticality accidents

Most historical criticality accidents share similarities in their causes. Each accident results from a chain of events, none of which was harmful by itself. Interrupting almost any link in a chain would prevent or reduce the respective accident.

INL personnel consider historical criticality accidents and their causes when deriving criticality safety controls for a specific operation or area, but with a broader application.

Some accidents involve equipment failure, poorly designed equipment, or poorly designed controls. In most cases, human error is a major factor. Many human errors came about because personnel tried to improve some part of an activity without adequately considering criticality safety. Some of those errors came about because personnel did not understand enough about criticality control factors. In a few cases, personnel who agreed a process was safe did not adequately consider human behavior.

None of these historical accidents involved unpredictable or inexplicable nuclear 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.

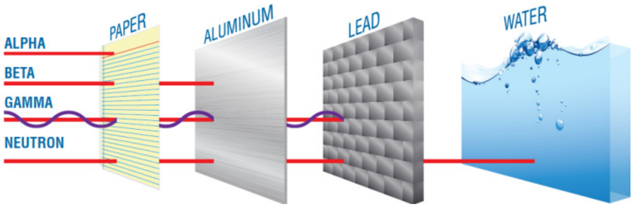
Fissionable material handlers and criticality safety officers with adequate knowledge, awareness, information, and understanding can prevent most criticality accidents by complying with established criticality controls, maintaining a questioning attitude, recognizing unsafe behaviors and conditions, and helping to improve their operations and controls.

**Did you know …**

**That most process (out of reactor) criticality accidents occurred with similar materials?** Most of these 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). 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 controls are also simpler and often easier to implement.
>
> However, do not become complacent with solid and/or low enriched material. One criticality accident occurred with low enriched uranium (Subtopic A.1.15), two occurred with intermediate enriched uranium (Subtopics A.1.9 and A.1.22), and a fourth occurred with plutonium ingots (Subtopic A.1.20).

### 4.1.4 Radiation



A criticality accident generates four types of ionizing radiation: alpha particles, beta particles, gamma rays, and neutrons

Nuclear fission and the subsequent radioactive decay of fission fragments produce four types of ionizing radiation: neutrons, alpha particles, beta particles, and gamma rays.

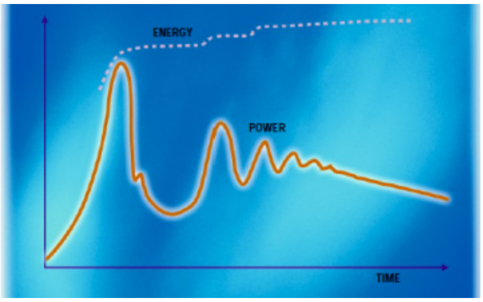
The amount of radiation generated in a local area due to a criticality accident is large, even for a small accident. A criticality accident can generate higher levels of neutron and gamma radiation in a shorter time than almost any other radiological accident.

Direct radiation from a criticality accident is a primary concern when designing mitigative features for a criticality accident, planning responses to a criticality accident, and responding to a criticality accident.

Secondary sources of radiation are also a concern. Neutrons from a criticality accident can create such sources when absorbed in surrounding materials. For example, a criticality accident can activate nitrogen in the air, zinc in certain metallic alloys, and sodium in blood. Sometimes, the secondary radioactive sources might also produce ionizing radiation. Such secondary sources are typically weak, but they are not necessarily negligible. A person exposed to such sources over many minutes or hours can receive a significant radiation dose.

### 4.1.5 Power History

The amount of energy, and consequently the amount of radiation and heat, generated during a criticality accident vary with time. It is therefore often convenient to describe criticality accidents in terms of a power history.



A criticality accident power history might include multiple bursts.

Most criticality accidents are characterized by an initial pulse, spike, or burst of power in which the power rises rapidly and then falls. Such accidents might consist of a single or multiple bursts. A burst might be followed by quasi-steady-state or slowly decreasing power or it might disperse material sufficiently to terminate the power history. However, under just the right conditions, a criticality accident can occur without producing a burst. (For example, see Table A1.)

**Been There. Done That.**

Historical criticality accidents had very different power histories:

- Many process (out-of-reactor) accidents had one or few bursts with an elapsed time of seconds to several minutes.

- The longest process accident was initiated at the Hanford Recuplex Plant on April 7, 1962 (Subtopic A.1.10). It consisted of multiple power bursts over 37 hours. It ended when enough water boiled off and organic matter, which extracted plutonium, settled.
- Many historical criticality accidents in reactors, critical assemblies, or critical experiments had one burst and lasted for much less than a minute.
- The longest criticality accident was initiated with a critical assembly at a well-shielded VNIIEF facility in Russia on June 17, 1997 (Subtopic A.2.14). It included an initial burst and a quasi-steady-state power that required human intervention to terminate. The critical condition lasted 6 days, 13 hours, and 55 minutes.

### My Notes:

## Review Questions

*Determine if the statement is true or false.*

1. A criticality accident is an inadvertent critical or supercritical nuclear fission chain reaction.
   true
   false
2. An easily recognizable warning will always precede any criticality accident.
   true
   false
3. Human error is rarely a factor in criticality accidents.
   true
   false
4. Secondary sources of radiation from a criticality accident are of no concern.
   true
   false
5. A criticality accident can generate higher levels of neutron and gamma radiation in a shorter time than almost any other radiological accident.
   true
   false
6. A criticality accident might produce no power bursts, only one power burst, or multiple power bursts.
   true
   false

## Review-Question Answers

1. true
2. false
3. false
4. false
5. true
6. true

## Topic 4.2 Criticality Accident Consequences

### 4.2.1 Medical

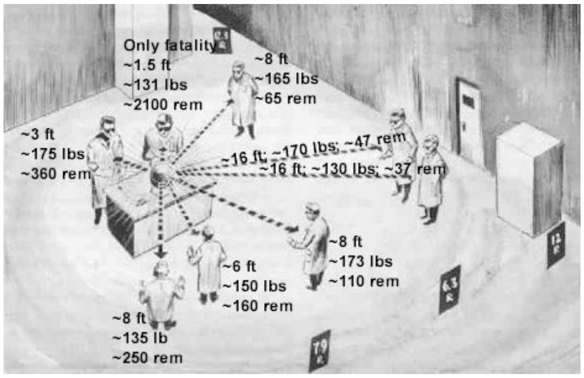
The health effects of a criticality accident vary greatly. The effects on a specific individual depend on many factors (for example, the doses a victim received to various organs, the victim's overall health, available medical resources, etc.).

One of the most important factors is the specific radiation dose to each organ and body part of the exposed person. The three major factors influencing that dose are the person's exposure time, the distance between each body part and the accident (source), and the amount of radiological shielding between the various body parts and source.

For example, consider the 60 reported criticality accidents that occurred since the 1940s (Appendix A). Collectively these accidents resulted in 21 fatalities and 29 other people with acute radiation injury. All seriously exposed individuals suffered acute radiation sickness. At least seven people suffered permanent disabilities, including at least four who underwent limb amputations.

Other people who were relatively near a critical source did not suffer such severe effects. Some people experienced mild radiation sickness without any lasting effects. And some people exhibited no visible radiation sickness and, apparently, have no long term health effects.

Assume a criticality accident consists of a single burst and nearby people evacuate immediately. A person within a few feet of the source might receive a lethal dose. A person a few feet away can probably avoid a lethal dose. A person more than ten or fifteen feet away might suffer mild radiation sickness and temporary radiation effects.

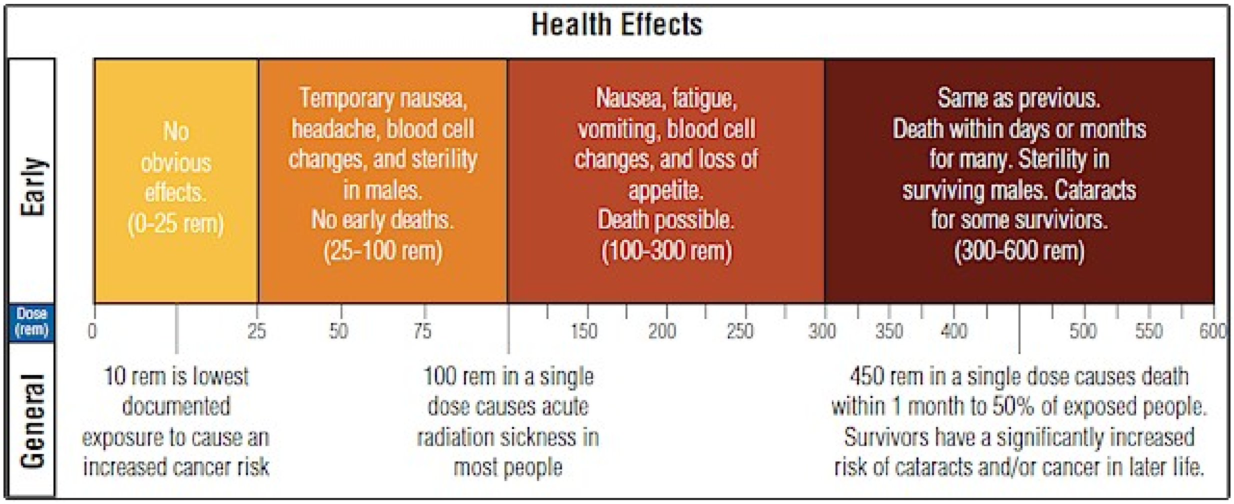


Approximate distances, sizes, and doses of personnel exposed in the 1946 criticality accident at Los Alamos.

However, predictions based on distance alone are only generalities. Consider, for example, persons exposed in 1946 and 1978. The single burst, 1946 Los Alamos Scientific Laboratory criticality accident occurred with an unmoderated, reflected plutonium sphere (Subtopic A.2.2). The sketch shows personnel locations at the time of the critical burst and their estimated whole body doses. The person closest to the source suffered severe, acute radiation sickness and died nine days later. The person about 3 feet away experienced a much milder form of radiation sickness and recovered well. The others suffered short-term radiation effects, but their symptoms were not readily visible.

The similarly energetic, single burst, 1978 Siberian Chemical Combine criticality accident occurred with unmoderated, reflected, plutonium ingots (Subtopic A.1.20). The primary victim in this Russian accident was a similar distance from the accident source as the primary victim in the 1946 accident. But there was at least a little more shielding between the Russian victim's vital organs and the critical source. He suffered severe, acute radiation sickness and his forearms were amputated, but he survived.

Although the health effects of a criticality accident vary greatly, the symptoms can be grouped together by exposure category:



Possible early and general health effects of acute radiation exposure that can occur due to a criticality accident.

In cases of very high, acute radiation doses, some potential health effects might be directly observable in the first few hours:

- Headache
- Extreme nervousness and confusion
- Nausea, diarrhea, and vomiting
- Loss of consciousness
- Convulsions

**Do you know where to get more information about the health effects of radiation exposure?**

For further information, consult one or more of the following:

- The Radiological Worker Training Study Guide
- Course 000TRN74, General Employee Radiological Training (GERT)
- Course 00TRN213, Radiological Worker I
- Course00TRN211, Radiological Worker II
- Instruction EPI-76, Emergency Radiation Exposure Control, Appendix A

### 4.2.2 Radiological Contamination

Radiological contamination might occur during the course of a criticality accident, response to the accident, or both. For example, radioactive material might be spilled, people might track contamination into previously uncontaminated zones, and/or irradiated material might be treated as if it was contaminated.

**However, radiological contamination is very local**. With the possible exception of activated, atmospheric nitrogen, radiological contamination due to a criticality accident is usually confined to the building or even the room in which the accident occurred and to persons upon whom a fissionable material splashed or spilled.

**Been there. Done that.**

No historical criticality accident has led to significant radiological contamination outside the respective facility's boundaries, except for contamination some victim(s) or responder(s) carried on or in their selves. For example, contamination spread by criticality-induced steam explosions (Subtopics A.2.4, A.2.9 and A.2.10) scattered radioactive debris locally, but no contamination was detected outside the respective facility fence line. Even in the case of the 1999 accident (Subtopic A.1.22), when news media footage showed over-reactions such as traffic police wearing personal protective equipment and residents washing down building exteriors, the presence of radioactive particles that could be attributed to the accident (as opposed to rain washing naturally radioactive particles from the air) was negligible.

### 4.2.3 Equipment Damage

Contrary to some people's opinion, a criticality accident is not like a bomb explosion. **Most criticality accidents cause little or no equipment damage.**

However, there are exceptions, especially if the accident occurs in a sealed vessel, a nuclear reactor, or a critical assembly. But even then, the damage is local.

**Been there. Done That.**

- Forty-eight of the 60 criticality accidents caused little or no damage?
  These accidents include all 22 of the process (out of reactor) accidents and 26 in-reactor accidents. In these cases, the most significant, but still minor, equipment damage typically occurred as part of a response plan to terminate the reaction. For example, a water circulation line was intentionally breached in response to the 1999 criticality accident (Subtopic A.1.22). However, sometimes the accident itself caused a little damage. For example, a 1958 criticality accident displaced the tank in which it occurred by about 3/8 inches at its supports (Subtopic A.1.5).

- Several in-reactor criticalities caused significant, but still localized damage. For example, the 1954 destructive test of the Boiling Water Research Reactor number 1 (Subtopic A.2.4), the 1961 Stationery Low-power reactor number 1 accident (Subtopic A.2.9), and the 1962 destructive Special Power Excursion Reactor Test 1D (Subtopic A.2.10) initiated steam explosions that destroyed their respective reactors, but did not severely damage their respective facilities. The 1963 Lawrence Radiation Laboratory criticality accident with the Kukla assembly initiated a fire that severely damaged the assembly itself, but nearby combustible materials did not burn or scorch.

  Energy from these other in-reactor accidents directly caused major or severe damage within the reactor, but did not damage items outside of the reactor: the 1952 Nuclear Reactor Experimental, 1952 ZPR-1, 1953 Russian Fast Neutron Physics Reactor critical assembly/machines, 1955 Experimental Breeder Reactor number 1, 1957 Godiva assembly, 1958 Heat Transfer Reactor Experiment number 3, 1968 Army Pulse Reactor Facility, and 1971 SF-3 accidents.

**My Notes:**

## Review Questions

*Complete each statement in the left column by entering the letter of the appropriate phrase from the right column in the box.*

☐ The health effects of radiation exposure due to a criticality accident _____

☐ Short term health effects might include _______.

☐ If the exposure is not lethal, long term health effects might include _____.

☐ _______ might occur as the result of an accident, but it was very local in historical accidents.

☐ Most criticality accidents result in _____.

☐ _______ are the three major factors influencing the radiological dose a person might receive as the result of a criticality accident.

A time, distance and shielding

B. radiological contamination

C. can vary greatly

D nausea, diarrhea, vomiting, loss of consciousness, and convulsions

E little or no equipment damage

F eye cataracts and cancer

## Review-Question Answers

| | |
|---|---|
| C | The health effects of radiation exposure due to a criticality accident _____ |
| D | Short term health effects might include _______. |
| F | If the exposure is not lethal, long term health effects might include _____. |
| B | _______ might occur as the result of an accident, but it was very local in historical accidents. |
| E | Most criticality accidents result in _____. |
| A | _______ are the three major factors influencing the radiological dose a person might receive as the result of a criticality accident. |

| | |
|---|---|
| A | time, distance and shielding |
| B. | radiological contamination |
| C. | can vary greatly |
| D | nausea, diarrhea, vomiting, loss of consciousness, and convulsions |
| E | little or no equipment damage |
| F | eye cataracts and cancer |

# MODULE 5 PROTECTION FROM CRITICALITY ACCIDENTS

## Introduction

INL has a Criticality Safety Program that establishes requirements to protect people from criticality accidents. Protection relies primarily on implementing, and improving, controls to prevent such accidents. Protection also includes implementing designs and planned responses that mitigate the consequences of an accident.

Fissionable material handlers and criticality safety officers are very important to the program. They are an important line of defense against a criticality accident because the program relies on them to understand, comply with, and help improve the controls. It also relies on them to respond appropriately to failed or suspect controls and to criticality alarms.

## Objectives

Identify the INL Criticality Safety Program's purpose.

Describe how the Criticality Safety Engineering Department works with line management to derive criticality controls for a facility.

Define *criticality control area* and identify the two types of CCAs.

Identify who is allowed to handle fissionable material.

Explain why a single, credible control failure does not result in a criticality accident.

Identify the fissionable material handler's role in maintaining criticality safety controls.

Explain the difference between an engineering control and an administrative control.

Describe general actions to take if you think a criticality safety control has failed or is inadequate.

State the purpose of a criticality alarm system in an area that is not well shielded.

Identify the proper response to a criticality alarm in your area.

Identify the proper response to a criticality alarm in your complex that is not in your area.

### My Notes:

# Topic 5.1 The INL Criticality Safety Program

## 5.1.1 Program Purpose

Laboratory Requirements Document

INL Criticality Safety
Program Requirements
Manual

INL
Idaho National
Laboratory

Program Description Document

INL Criticality Safety
Program

The purpose of the INL Criticality Safety Program is to protect people and the environment by preventing and mitigating criticality accidents. The program is important in preventing injurious, or even lethal, radiation exposures.

The INL Criticality Safety Program implements all relevant national, federal, and DOE requirements. The program also incorporates relevant recommendations and best management practices. In addition, the program is based on the core functions and guiding principles of the INL Integrated Safety Management System.

INL Criticality Safety Program documents are linked to the INL Criticality Safety Engineering webpage of the INL intranet (https://nucleus.inl.gov/portal/server.pt/community/inl_criticality_safety_engineering/369)

**Did you know …**

- **That the *INL Criticality Safety Program Requirements Manual*, LRD-18001, establishes our program?** We also have a program description document, PDD-18001, which describes how the various pieces fit together and summarizes roles and responsibilities within the program.
- **That there is more than one requirement source for the program?** Requirement sources include federal regulation 10 CFR 830.204(5), order DOE O 420.1B and most ANSI/ANS-8 standards (national standards for nuclear criticality safety outside of reactors). The program also includes best management practices developed at INL and elsewhere over many years of fissionable material operations.
- **That the INL Criticality Safety Program incorporates only requirements which apply to current INL operations?** Additional requirements exist, but they do not apply at this time. Criticality Safety Engineering reviews the program and its supporting documents periodically and as operations change to ensure our program is up-to-date, applicable, and sufficient.

## 5.1.2 Facility Criticality Safety and the Criticality Safety Officer

If a facility or an area has or will have fissionable material in forms or quantities that are a criticality safety concern, facility management appoints a CSO. The CSO maintains up-to-date criticality safety information relevant to his or her area(s) and duties. Area-specific training or mentoring identifies an area's CSO to workers who have not yet met him or her.

The CSO and safety analyst review a criticality safety evaluation with Criticality Safety Engineers.

The CSO works with INL Criticality Safety Engineering to ensure the facility and its operations are critically safe. Together, they identify the criticality controls necessary to prevent a criticality accident and, if appropriate, to mitigate the consequences of such an accident. They also work together to ensure the features and controls are adequate, effective, as easy to implement as practical, and updated as needed.

***Required information for CSOs, but not for FMHs:***

Before acting without supervision, a CSO must have all of the following:

- General criticality safety knowledge (for example, basic criticality safety information from training course 00INL189).
- Knowledge about the safety basis for his or her area(s).
- General familiarity with procedures, standards, and guides that direct criticality safety evaluation and analysis.

**Did you know …**

- **That, like other safety and operational considerations, criticality safety should be designed into a system from the beginning?** If criticality safety is considered early enough in a project's development, it is usually practical to develop safety controls that do not unduly impact operational efficiency.
- **That criticality-control derivation is a cooperative process?** It generally begins when a CSO asks a criticality safety engineer to help develop criteria for a proposed new operation, piece of equipment, or facility. Sometimes it begins when the CSO asks a criticality safety engineer to review a change. The process might also begin with a project-manager's request or it might begin as a result of an assessment. Or it could begin when somebody asks a question.

  Then, with the help of the CSO or project representative, criticality safety personnel review available information and any relevant, existing materials, facilities, equipment, and operations to determine if criticality control is needed. If control is needed, a criticality safety engineer evaluates the activities of interest and derives controls. The engineer uses information from and reviews by the CSO or project representative, cognizant safety analyst and others.

  With CSO assistance, criticality safety engineers update, upgrade, replace, and/or retire controls and their supporting evaluations as needed to support facility, operation and material changes.

### 5.1.3 Criticality Control Areas in General

A CCA is an area in which fissionable material must be controlled to ensure criticality safety. Each CCA must have clearly defined boundaries and criticality safety controls.

Each INL laboratory and plant area that is or will be allowed to have material that contains more than 15 grams of fissionable nuclides (Subtopic Topic 2.3) must be evaluated to determine if a CCA is needed.

If criticality controls must be implemented in an area to ensure safety, facility management must assign a CSO and establish and maintain a CCA. These actions are subject to the INL Criticality Safety Engineering Manager's approval.

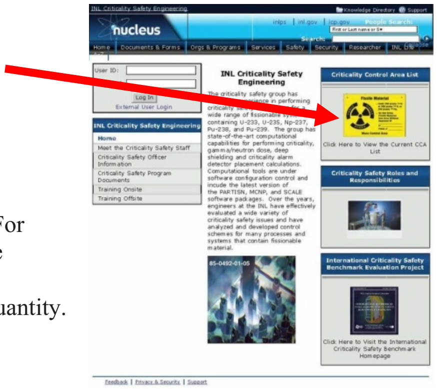
The INL Criticality Safety Program defines two types of CCAs: mass limit CCAs (Subtopic 5.1.4) and procedure CCAs (Subtopic 5.1.5). Your area-specific training or mentoring will identify the CCA type(s) relevant to your assignments.

A CCA may have one or more types of criticality safety postings:

- CCA identification.
- Firefighting restriction.
- Criticality safety limit(s).

The CSO posts such information to help people who work in or near a CCA, who might pass through a CCA while transferring fissionable material, and/or who might respond to an emergency in or near the CCA. The CSO works with Criticality Safety Engineering, management, and, typically, the workers and emergency responders to determine if postings are necessary.

You can find a current list of CCAs and their CSOs through the Criticality Safety Engineering webpage (https://nucleus.inl.gov/portal/server.pt/community/inl_criticality_safety_engineering/369)



**INL Criticality Safety Engineering**

The criticality safety group has [illegible] ience in performing criticality [illegible] for a wide range of fissionable sys[illegible] containing U-233, U-235, Np-237, Pu-238, and Pu-239. The group has state-of-the-art computational capabilities for performing criticality, gamma/neutron dose, deep shielding and criticality alarm detector placement calculations. Computational tools are under software configuration control and incude the latest version of the PARTISN, MCNP, and SCALE software packages. Over the years, engineers at the INL have effectively evaluated a wide variety of criticality safety issues and have analyzed and developed control schemes for many processes and systems that contain fissionable material.

Click Here to View the Current CCA List

Click Here to Visit the International Criticality Safety Benchmark Homepage

**Did you know …**

- **That some evaluated areas do not become CCAs?** For example, we will not establish a CCA if the fissionable nuclides would only be in forms for which a criticality accident is just not credible, no matter how large the quantity.
- **That the 15 gram threshold is loosely based on U.S. shipping and postal regulations?** People may mail 15 grams or less of unirradiated U-235 without special packaging because the U. S. Postal Service uses DOT definitions for such material. Fifteen grams is the maximum amount of fissile nuclides in packaging that can be exempted from classification as fissile material for NRC and DOT packaging and shipping regulations.
- **That CCAs are established in accordance with a lab-wide procedure?** The procedure is LWP-18003, *Establishing, Operating, and Deleting INL Criticality Control Areas (CCAs)***,** which is linked to the INL Criticality Safety webpage. It is also available on EDMS.

## 5.1.4 Mass Limit CCAs

A mass limit CCA is an area in which criticality safety is provided using generically determined mass limits on fissionable nuclides. The affects of fissionable mass on criticality safety are described in Topic 3.1.

One of two sets of limits applies to a mass limit CCA. These generic limits are fairly low because little or no safety credit is taken for other fissionable material characteristics such as form, enrichment, density, or shape. Similarly, little safety credit is taken for the presence or absence of other materials such as moderators, absorbers, or reflectors.

MASS CRITICALITY CONTROL AREA (CCA)

☐ Limit: 350 grams $^{235}$U equivalency

☐ Limit: 250 grams $^{239}$Pu or $^{233}$U equivalency

- Do Not Bring Fissile Material Into Area Without Approval Of

Name: ____________

Phone No.: ____________

431.08 05/18/2006 – Rev. 05

Extremely large quantities of beryllium, graphite, lead, or heavy water could be a problem as moderators or reflectors in a CCA. Therefore, Criticality Safety Engineering must evaluate their presence. Such evaluation is necessary because handbook data, upon which the fissionable material mass limits are based, do not incorporate the affects of such materials.

If your assignments involve a mass limit CCA, area-specific training or mentoring will identify which set of limits apply, the methods and equivalency used to track fissionable nuclides in the CCA, and the limits, if any, on large quantities of beryllium, graphite, lead, or heavy water.

**Did you know …**

- **That CCA management must choose which of the two indicated limits applies when establishing a mass limit CCA?** Management cannot have one mass limit CCA that implements both limits.
- **That the two equivalencies differ?** In both cases, all plutonium isotopes count.
    - If management chooses the U-235 equivalency, the CCA is limited to no more than 350 gram of moderated fissionable equivalent (MFE). In this case, each gram of plutonium and of U-233 counts as two grams of U-235 fissionable equivalent mass:

      $$\text{MFE} = \text{U-235 mass} + 2 \times (\text{U-233 mass} + \text{Pu mass})$$
    - If management chooses the Pu or U-233 equivalency, the CCA is limited to no more than 250 grams of total fissionable mass (TFM). Each gram of U-233, U-235, and Pu counts as one gram of fissionable equivalent mass:

      $$\text{TFM} = \text{U-235 mass} + \text{U-233 mass} + \text{Pu mass}$$
- **That mass limit CCA limits are based in large part on minimum critical mass estimates?** The following considerations originally influenced the decision to use 250 grams U-233, 350 grams U-235, and 250 grams Pu-239 as limits for mass limit CCAs:
    - The minimum critical mass estimates for a single, water reflected, aqueous solution sphere of pure $^{233}$U, U-235, or Pu-239, the masses are about 540, 800, and 500 g, respectively.
    - A best management practice recommends that, if control is by mass alone, the mass limit should not exceed 45% of the minimum critical mass. Therefore, in the unlikely event of a double-batched limit, the quantity of material would not exceed 90% of its minimum critical mass. The 45% value for pure U-233 is 243 grams; for pure U-235 is 360 grams, and for pure Pu-239 is 225 grams.
    - A limit of 350 grams U-235 was adopted for consistency with various federal regulations that were then in-effect for transporting U-235 on public roads.
    - A limit of 250 grams U-233 or Pu-239 was adopted after considering the variety, forms, and isotopic compositions of INL fissionable materials and after considering INL materials that are very effective moderators and/or reflectors.

### 5.1.5 Procedure CCAs

A procedure CCA is an area that is allowed to have more fissionable material than a mass limit CCA.

Criticality safety is achieved using controls that are determined specifically for the area, its material, and its activities.

Unlike mass limit CCAs, criticality controls may differ significantly between different procedure CCAs.


PROCEDURE CRITICALITY CONTROL AREA (CCA)

- Do Not Bring Fissile Material Into Area Without Approval Of ____________

or ____________

Phone No. ____________

- Fire Fighting Restrictions:

☐ Yes ☐ No

431.09 05/18/2006 – Rev. 05

As part of the evaluation for a procedure CCA, criticality safety personnel usually postulate area-specific criticality accident scenarios. Each scenario is a sequence or set of unlikely or improbable events that must occur to achieve a critical condition. The scenarios form bases for the area's criticality controls. Personnel who handle fissionable material in a procedure CCA learn about these derived controls and their bases in area-specific training or mentoring.

**Did you know …**

**That the derivation of criticality controls for a procedure CCA is documented in one or more criticality safety evaluations?** You can access many active evaluations as records in the INL electronic document management system (EDMS).

### 5.1.6 Fissionable Material Handlers

Facility criticality safety relies directly on people who work in the facility. In addition to the CSO, criticality safety relies on FMHs.

An FMH is a qualified person who is authorized by management to handle, move, manipulate, process, and/or store fissionable material in quantities, forms, and specific areas that require criticality controls. With few exceptions, only FMHs are allowed to perform such tasks because only FMHs are required to have the training necessary to implement the relevant controls.

An FMH must be qualified before he or she is allowed to handle fissionable material without active supervision. FMH qualification requirements are established to help ensure that those who handle fissionable material have sufficient knowledge and skill to protect themselves and their co-workers from a criticality accident. The training is divided into several categories:

FMHs complete final preparations before lowering a fuel element cluster into the NRAD reactor pool.

- General training addresses topics that all INL FMHs must know. These topics include very basic criticality safety principles, as described in course 00INL189 and this document.
- Area-specific training addresses criticality safety for the specific area(s) in which an FMH will work. It includes the controls and implementation methods used in the subject area(s). Area-specific training also addresses criticality accident scenarios postulated for the area. This training builds on the principles and information that was provided in the general criticality safety training.

  NOTE: FMH qualification is area-specific. A person qualified to handle fissionable material in one area would need to complete area-specific training for a second area before being qualified to handle fissionable material in that second area. The only exception is when the second area effectively has the same limits and implementation methods as the first area. Typically, such exceptions apply to mass limit CCAs.
- Retraining as necessary to ensure FMHs have up-to-date information, are aware of current criticality safety issues, and, if appropriate, remember basic criticality safety principles.

**Did you know …**

**That there are several common exceptions for FMH requirements?**

- People who handle no more than 15 grams of fissionable nuclides are not required to be FMHs. This 15 gram threshold is discussed as *Did-you-know* information under Subtopic 1.5.3.
- Typically, qualified reactor operators (ATR, ATRC, and NRAD operators) do not have a separate FMH qualification because their reactor operator qualification incorporates the training needed to handle fissionable material in their facility.
- People are not required to complete FMH training to handle or move a loaded and closed shipping or storage package if the package has an assigned criticality safety index (a number used for determining how many packages can be shipped or stored together). Federal law allows people such as heavy equipment operators and truck drivers to move shipping packages without criticality safety training because a criticality accident is not credible under such conditions. For analogous reasons this exception can be extended to storage packages that have a criticality safety index assigned with the Criticality Safety Engineering Manager's concurrence.
- FMH candidates are not required to complete all FMH training before performing tasks under the active supervision of a qualified FMH. The qualified FMH supplements the candidate's criticality safety knowledge as needed during task performance.

**Been there. Done that.**

Several historical accidents were caused or made worse by workers with inadequate training. Sometimes the training was inadequate because the accidents were deemed not credible. The 1964 United Nuclear Corporation accident (Subtopic A.1.14) and the 1999 Japanese JCO accidents (Subtopic A.1.22) are notable examples. Please note that not-credible accidents are usually *not credible* only if personnel implement and comply with all controls.

## My Notes:

## Review Questions

*Fill in the blanks.*

1. The INL Criticality Safety Program's purpose is to protect people by ______________________ and __________________criticality accidents.
2. The INL Criticality Safety Program is important in preventing injurious, or even lethal, ________________ ______________________.
3. Facility criticality safety relies directly on the people who ____________________ ______________________ ______________________ ____________________ .
4. The __________________ represents facility management and workers. He works with Criticality Safety Engineering personnel to ensure the facility and its operations are critically safe.
5. A/an ________________ is an area in which fissionable material must be controlled to ensure criticality safety.
6. ______________________-______________________ ______________________ or mentoring identifies the CCA type(s) relevant to a person's assignments.
7. In a/an ________________ ______________________ CCA, criticality safety is provided through generically determined mass limits on fissionable nuclides.

8. One of two sets of limits apply to a ________________ ________________ CCA.
9. In a/an ________________ CCA, criticality safety is provided by controls that are determined specifically for the area, its material, and its activities.
10. Postulated criticality accident scenarios are sequences or sets of _____________ or ______________________ ______________________ that must occur to achieve a critical condition.
11. With few exceptions, only a/an ___________________ is allowed to handle, manipulate, store, or move significant quantities of fissionable material, or items containing significant quantities of such materials.
12. To act without supervision, an FMH must complete training that includes course ______________________ and __________________ _____________________ ______________________ or mentoring. The FMH also completes retraining as necessary.
13. *For criticality safety officers only:* To act without supervision, a CSO must complete course ________ . The CSO must also have knowledge about the safety basis for his or her area(s) and a general familiarity with procedures, standards, and guides that direct criticality safety evaluation and analysis.

## Review-Question Answers

1. preventing, mitigating
2. radiation exposures
3. work in the facility
4. CSO (or Criticality Safey Officer)
5. CCA (or Criticality Control Area)
6. Area-specific training
7. mass limit
8. mass limit
9. procedure
10. unlikely, improbable
11. FMH (or Fissionable Material Handler)
12. 00INL189, area-specific training
13. 00INL189

## Topic 5.2 Accident Prevention

### 5.2.1 Criticality Controls in General

A *criticality control* is a method for limiting a criticality control factor to ensure a mass or system is subcritical. Often a control is expressed as a limit on the factor that is controlled and identified by that factor. For example, a control that limits moderators is often called a *moderator limit* or a *moderator control*.

Criticality controls are very reliable and ensure that one or more control factors are limited to maintain subcriticality. **These controls are designed to ensure that no single, credible failure will result in a criticality accident.** However, there might be no guarantee of criticality safety in the event of two or more failures.

Workers are an integral part of criticality control schemes. Familiarity with criticality factors helps workers understand their facility's criticality controls and the affects of their actions with respect to those controls. Familiarity also helps workers identify rare conditions that are outside of those controls.

It is imperative that anyone who handles or works with fissionable material complies with and fully understands criticality control methods applicable to his or her assignment.

Please think before making any changes in any feature controlled for criticality safety purposes.

Area-specific training or mentoring identifies and explains the controls (and, for procedure CCAs, the underlying criticality accident scenarios) that apply to your assigned area. If you need more information or a better explanation, don't hesitate to ask questions during training and briefings. Outside of training and briefings, please ask your area's CSO if you have a question about a control or its application. Contact a member of Criticality Safety Engineering if you need additional explanation or have additional criticality safety questions.

**Did you know …**

**That definitions for words like *credible, incredible, likely, unlikely*, *extremely unlikely*, and *beyond extremely unlikely* vary considerably?** Such words are used in many documents and discussions related to criticality safety. (For example, "criticality controls are designed to ensure that no single, credible failure will result in a criticality accident.")

These terms indicate a *probability* that a particular event might or might not occur, but exact definitions vary with subject, regulator, implementing organization, and author. Keep in mind that none of these terms are used to guarantee that a particular event, or chain of events, will or will not occur.

An incredible event is not impossible. It might occur. If it does occur, *incredible* might still be the appropriate probability description. Similarly, a likely event is not guaranteed to happen. If a likely event does not occur, *likely* might still be the appropriate probability description.

For example, let's look at a legitimate, well-run, large lottery and at typical occurrence-probability definitions. An incredible (or beyond extremely unlikely) event is often defined as one that has an occurrence probability of no more than one in a million in one year. For large lotteries, the chance a specific person will win is significantly less than one in a million. Let's assume Pat has no claim on any lottery tickets, Kelly has claim on one ticket and Sam has some claim on many more tickets than anybody else. It should be impossible for Pat to win. It is incredible, but not impossible, for Kelly to win. Similarly, it might be likely that Sam will win, but Sam's win is not guaranteed.

### 5.2.2 Engineering Controls

There are two types or categories of criticality controls: *engineering controls* and *administrative controls*.

An engineering (or engineered) control is a design feature that reliably serves as a criticality control**.** Examples include safe-by-geometry equipment, permanently fixed neutron absorbers, and storage positions sized to prevent over-batching.

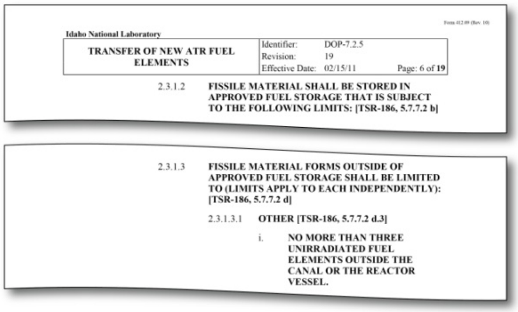
Engineering controls must be carefully selected. A physical design that is not reliable enough does not qualify as an engineering control.

Human actions can affect engineering controls to some extent. An engineering control must be adequately designed, correctly built, correctly installed, adequately maintained, and appropriately used. Consider, for example, the storage rack shown to the right. Based on its intended contents, the rack is designed to limit neutron interaction between positions and to limit overbatching within positions. However, safety also depends on workers who must place material in the storage positions in compliance with loading limit(s).

An engineering control example: seismically qualified storage rack limiting stored material size and neutron interaction.

### 5.2.3 Administrative Controls

An administrative control is a control that relies primarily on human actions for its implementation. Examples include limits on piece quantity, mass, concentration, and, sometimes, volume. These limits are typically specified in work documents. They are also posted if such posting would help workers. In some cases, the controls are included in software used to run or track an operation.



Form 412.09 (Rev. 10)

**Idaho National Laboratory**

| | | | |
|---|---|---|---|
| **TRANSFER OF NEW ATR FUEL ELEMENTS** | Identifier: | DOP-7.2.5 | |
| | Revision: | 19 | |
| | Effective Date: | 02/15/11 | Page: 6 of **19** |

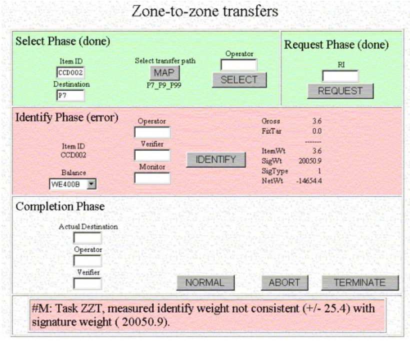
2.3.1.2 **FISSILE MATERIAL SHALL BE STORED IN APPROVED FUEL STORAGE THAT IS SUBJECT TO THE FOLLOWING LIMITS: [TSR-186, 5.7.7.2 b]**

2.3.1.3 **FISSILE MATERIAL FORMS OUTSIDE OF APPROVED FUEL STORAGE SHALL BE LIMITED TO (LIMITS APPLY TO EACH INDEPENDENTLY): [TSR-186, 5.7.7.2 d]**

2.3.1.3.1 **OTHER [TSR-186, 5.7.7.2 d.3]**

i. **NO MORE THAN THREE UNIRRADIATED FUEL ELEMENTS OUTSIDE THE CANAL OR THE REACTOR VESSEL.**

An example of administrative controls implemented in a procedure.



Zone-to-zone transfers

Select Phase (done)

Item ID: CCD002

Destination: P7

Select transfer path: P7_P9_P99

Request Phase (done)

Identify Phase (error)

Item ID: CCD002

Balance: WE400B

| | |
|---|---|
| Gross | 3.6 |
| FixTar | 0.0 |
| ItemWt | 3.6 |
| SigWt | 20050.9 |
| SigType | 1 |
| NetWt | -14654.4 |

Completion Phase

#M: Task ZZT, measured identify weight not consistent (+/- 25.4) with signature weight ( 20050.9).

An example of software that supports administative control implementation.

Administrative controls are worker-based. They are subject to error in application. They are, therefore, less desirable than engineering controls.

However, an administrative control can be reliable if workers have sufficient knowledge, skills, integrity, and concern. The control must also be conservative enough that reasonable errors do not create truly unsafe conditions.

**Did you know …**

**That we have a preference order for selecting criticality control methods?** It is based on experience with control reliability. Unsurprisingly, administrative controls are least preferred:

- *Safe-by-geometry physical designs* are most preferred.
- *Permanently fixed neutron-absorbing material* is acceptable where safe-by-geometry designs are not practicable.
- *Administrative controls with additional support* (for example, physical designs, instruments, and/or software) are acceptable if the two above methods are not practical.
- *Administrative controls with no additional support* are least preferred.

### 5.2.4 Criticality Control Failures and Limit Violations

It is physically possible to cause or contribute to an unintentional criticality through carelessness in treating, disposing, handling, moving, or storing fissionable material. Most criticality accidents involve human errors and/or procedure violations, including failure to obtain a procedure or instructions. (See Appendix A for further descriptions of these accidents.)

Failures are unusual, but controls can and do fail in various ways. For example, administrative components of a criticality control might be rendered ineffective through failure to appropriately design, identify, implement, comply with, or maintain the control. An engineering control might be rendered ineffective through failure of some important physical component (for example, a structural component might break or leak).

Remember, criticality controls are established to protect your life and the lives of your coworkers. Maintaining a subcritical condition also helps protect our projects and jobs.

If you think a criticality control has failed or might be inadequate, you should:

- Immediately take a timeout (LWP-14002, "Timeout and Stop Work Authority").
- Do not attempt to correct the situation yourself. You might make the condition worse.
- Notify the CSO and your supervisor, or the area's supervisor. (They will contact Criticality Safety Engineering.)
- Follow procedures for securing the area, while keeping yourself and others safe.

Take a timeout or stop work (LWP-14002)

- Preserve the scene – do not handle the material further or change its configuration until your concern is resolved and a path forward is identified.

Most cases will ***not*** constitute an imminent safety hazard. However, if you believe an imminent safety hazard exists, do not hesitate to exercise your stop work authority (LWP-14002).

**Did you know …**

**That a single criticality control failure or violation will not present an imminent safety hazard?** As previously mentioned, criticality safety controls are designed to ensure that no single, credible failure will result in a criticality accident. In some cases, numerous failures must occur before a criticality accident is possible. In some places, safety is not guaranteed after just a few failures. Your area specific training will identify failures that must occur.

## My Notes:

## Review Questions

*Fill in the blanks.*

1. The criticality safety engineer works with the CSO to derive ______________ and ______________________ criticality controls to prevent the accident.
2. Criticality controls are designed to ensure that no _____, _____________________ ______________________ will result in a criticality accident.
3. _____________________-______________________ ______________________ or mentoring identifies and explains the controls (and, for procedure CCAs, underlying criticality accident scenarios) that apply to your assigned area.
4. There are two general types of controls: ____________ controls and ___________ controls.
5. A/an _________________ control is a design feature that reliably serves as a criticality control**.**
6. A/an _________________ control is a control that relies primarily on human actions for its implementation.
7. _____________________ controls are less desirable than ____________________ controls.
8. A storage rack with specific storage position sizes and spacing could be an example of a/an _______________ control.
9. A vessel with a specific diameter could be an example of a/an _________________ control.
10. A limit on the mass or number of pieces that may be placed in a storage position is an example of a/an ___________________ control.
11. A requirement to use a specific container is an example of a/an ________________ control.
12. If you think a criticality control has failed or might be inadequate, you should immediately ___________ ______________________ _____________________ .
13. If you think a criticality control has failed or might be inadequate, _____________ _____________________ attempt to fix the situation yourself.
14. If you believe an imminent safety hazard exists, do not hesitate to exercise your ______________________ ______________________ _____________________ .

## Review-Question Answers

1. necessary, sufficient
2. single, unlikely control failure
3. Area-specific training
4. engineering, administrative
5. engineering
6. administrative
7. Administrative
8. engineering
9. engineering
10. administrative
11. administrative
12. take a timeout
13. do not
14. stop work authority

## Topic 5.3 Accident Mitigation

### 5.3.1 Criticality Accident Planning

If a criticality accident is credible even considering the implementation of controls, Criticality Safety Engineering personnel evaluate the postulated accident scenario(s) (mentioned in Subtopic 5.1.3) and facility features to help facility management and emergency planners identify designs, alarm systems, and response actions that would mitigate the accident.

### 5.3.2 Shielding

Some facilities have significant shielding due to the activities for which they were designed. In such cases, Criticality Safety Engineering personnel determine if the shielding is sufficient to protect people in and near the facility from the most injurious consequences of a criticality accident. If the shielding is insufficient, facility management may augment the shielding, install a criticality alarm system, or both.

The FCF and HFEF cells have enough shielding to protect personnel in the event of a criticality accident

Radiological protection personnel and emergency planners also consider the shielding as well as any radiation alarm systems or criticality alarm systems that may be installed. They then develop criticality accident response measures to include in the facility portion of the INL Emergency Plan.

### 5.3.3 Criticality Alarm Systems

A CAS is one way in which we mitigate a criticality accident if such an accident were to occur in an area with insufficient shielding. A CAS is necessary because, as previously identified, 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.

A criticality alarm system monitor at MFC. Criticality alarm activation signals a need for immediate evacuation.

The purpose of a CAS is to detect a criticality accident and produce an immediate criticality alarm. The alarm notifies people in the affected area to evacuate. Prompt evacuation protects people from exposure to materials that were irradiated by the accident and, more important if the accident is ongoing, to additional radiation from the accident. Course 00INL189 includes an exercise to demonstrate the significant difference in dose due to evacuation (increasing distance from source and limiting exposure time). **The underlying reason for having a CAS is to avoid lethal personnel radiation exposure from a criticality accident.**

A CAS is useful, but it is important to remember:

- A CAS does not warn that a criticality accident is about to happen. Instead, it warns that an accident has happened or is in progress. In other words, even with a CAS and prompt evacuation, a person could still receive a radiation dose during the first few seconds, or the first burst, of the accident.
- A CAS does not actually protect you. Instead, it provides an alarm so that you can better protect yourself. Your best protection comes from preventing the accident.

Criticality alarm sounds might vary between complexes at INL:

- The MFC criticality alarm consists of three bursts of a horn. Simultaneously, rotating blue lights will be energized both inside and outside the affected facility warning personnel that there has been a criticality in the facility and to stay away from the facility. The horn alarm should be followed by a voice announcement throughout MFC stating that a criticality has occurred at the affected facility, but the voice announcement system is not part of the CAS itself.
- As of February 2012, other INL complexes do not have facilities that require a criticality alarm system.

If an area has a CAS, area-specific training or mentoring is used to familiarize workers with the sound of that CAS and with planned evacuation route(s).

**Did you know …**

- **That you might hear radiation alarms as well as criticality alarms in the event of a criticality accident?** Typically, nearby remote area monitors (RAMs) and constant air monitors (CAMs) will also alarm.
- **That many features must be considered to ensure a CAS will fulfill its purpose?** Each CAS is designed to be very reliable. However, the system is composed of many necessary components, each of which must be maintained.

  Other factors also affect CASs. For example, a CAS might be impaired by an unanalyzed, long-term addition of radiological shielding material between a detector and the possible criticality location. Or it might be impaired by an unanalyzed, long-term addition of sound-muffling material between workers and the speakers or horns. In addition, we temporarily defeat a CAS alarm if we instruct workers to disregard alarms during testing, which explains why certain fissionable material operations might be suspended during such testing.

### 5.3.4 Responding to a Criticality Alarm

If a criticality alarm sounds, it might have been caused by an equipment malfunction, testing, or a criticality accident. However, the alarm might be your only warning of an accident. Therefore, **RESPOND TO EVERY ALARM AS REAL** until it is proven otherwise.

If a criticality alarm sounds in your area, it is important that you respond rapidly:

- Immediately stop your task. Do not try to correct any action or condition that might have caused the alarm. You might make matters worse.

Immediate evacuation in response to a criticality alarm.

- Quickly evacuate the immediate area without running. Running increases your chances of falling, which can increase your exposure by delaying or disabling your evacuation. (The next page illustrates how evacuation reduces your dose by increasing distance to the source and decreasing exposure time.)

  Evacuation routes necessarily vary due to building, facility, and complex layout. If an area has a CAS, area-specific training or mentoring is used to familiarize workers with the sound of that CAS and with the identified evacuation route(s). Area-specific training or mentoring will also describe provisions in place to warn workers of known changes to an evacuation route.
- Report to your designated assembly area and report information you have that might be important to emergency responders.
- Be prepared to take further actions as directed.

NOTE: Criticality alarm systems automatically notify personnel who will initiate other emergency response.

The response of people nearby is also important. If a CAS alarm sounds near, but not in, your area:

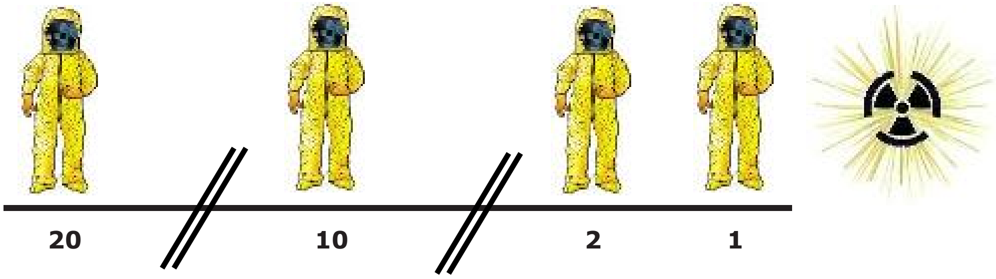
- *Stay away from a building or area in which a criticality has occurred.*
- Comply with area-specific instructions, if the area you are in has instructions for such events.
- Be prepared to take further actions as directed.

**Been there. Done that.**

- Unauthorized and unplanned response actions might make a criticality accident worse. The 1964 United Nuclear Corporation accident (Subtopic A.1.14) and the 1968 Mayak Production Association accident (Subtopic A.1.17) are classic examples of accidents partially caused by procedure violations and then made worse by inappropriate response action(s). In both cases, the person involved received an avoidable, significant dose, or additional dose, directly due to poorly planned actions
- Immediate evacuation was an important factor in protecting nearby workers during most unshielded criticality accidents. (See Topic A.1) Criticality accident history indicates that, if you do not receive a lethal dose from the initial burst of a criticality accident, evacuation can save your life. Persons who evacuate immediately avoid further radiation dose from:
  - any subsequent bursts, 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 a significant part of the possible radiation exposure from a criticality accident if people do not evacuate.

**My Notes:**



| feet: | 20 | 10 | 2 | 1 |
|---|---|---|---|---|
| <br>60 minutes | 12.50 rem | 50.00 rem | 1250 rem | 5000 rem |
| <br>15 minutes | 3.125 rem | 12.50 rem | 312.5 rem | 1250 rem |
| <br>10 minutes | 2.083 rem | 8.333 rem | 208.3 rem | 833.3 rem |
| <br>5 minutes | 1.042 rem | 4.167 rem | 104.2 rem | 416.7 rem |
| <br>1 minute | 0.2083 rem | 0.8333 rem | 20.83 rem | 83.33 rem |

Your radiological dose decreases as you increase your distances from the source (move to the left in the columns above) and decrease your time near the source (move down the rows above). In this case, the hypothetical critical source produces a steady 5000 rem/hr.

## Review Questions

*Select all choices that apply.*

1. The following features or actions help mitigate the consequences of a criticality accident:
   a. criticality accident planning
   b. radiological shielding
   c. criticality alarm systems
   d. evacuation in response to a criticality alarm
   e. restarting a facility operation
2. (*select one in this case*) The underlying purpose of having a criticality alarm systems is to
   a. comply with DOE requirements
   b. provide a means to initiate evacuation drills
   c. avoid lethal radiation exposure from a criticality accident
   d. avoid radiation exposure from any radiological accident
   e. spend money
3. A criticality alarm system:
   a. warns that a criticality accident is about to happen
   b. warns that a criticality accident has happened or is in progress
   c. protects workers
   d. provides an alarm so that workers can better protect themselves
   e. automatically notifies personnel who will initiate further emergency response
4. If a criticality alarm sounds in your area:
   a. Immediately stop your task
   b. Quickly evacuate the immediate area without running.
   c. Assist others only to the extent that it will not delay your own evacuation
   d. Report to your designated staging/assembly area.
   e. Be prepared to take further action as directed.
5. If a criticality alarm sounds near, but not in, your area:
   a. Run to help emergency responders, even if you aren't one of them.
   b. Gather near the building with the alarm to see what is happening.
   c. Comply with any area-specific instructions for such events.
   d. Be prepares to take further action as directed.
   e. Stay away from any building or area in which a criticality has occurred.

## Review-Question Answers

1. a,b,c,d
2. c
3. b,d,e
4. a,b,c,d,e
5. c,d,e

# Appendix A
# Criticality Accident History

## Introduction

Criticality safety limits typically incorporate substantial safety margins. However, limits alone cannot prevent accidents from occurring. Not all dynamics of fissionable material handling can be anticipated. Criticality accidents are avoidable only when personnel have enough knowledge, skill, and willingness to implement criticality controls appropriately and to recognize unanticipated conditions.

Criticality accident information can help workers recognize unanticipated conditions and improve vigilance. Therefore, this appendix summarizes information from individual criticality accidents and their specific lessons, emphasizing the role humans played in these accidents.

*A Review of Criticality Accidents* describes the 60 criticality accidents that were reported between 1940 and 2005. Twenty-two accidents occurred in process systems (systems that were not designed or intended to be critical, Topic.A.1). Thirty-eight accidents occurred in systems that were designed to be critical or supercritical under particular conditions (Topic.A.2).

None of these accidents occurred in fuel storage or solid waste systems. And none occurred during fissionable material transportation. This lack is not surprising, but it does *not* necessarily mean that criticality accidents in such systems are incredible or impossible.

Most criticality accidents occurred with aqueous solutions, including several cases in which the material was not supposed to be a solution or slurry. One out-of-reactor accident occurred with solid fissionable material.

These accidents resulted in nine fatalities, about 50 significant radiation overexposures, no significant equipment damage, and negligible fissionable material loss. One case included measurable exposures to the public, none of which were true overexposures. None of the cases involved actual danger to the general public, but the latter case had severe repercussions with respect to public perceptions and reactions.

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 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.

## Additional Acronyms Used In Appendix A

| | |
|---|---|
| ~ | about, approximately |
| < | less than |
| ANL | Argonne National Laboratory |
| ANL-E | ANL – East, Argonne, Illinois, USA. Currently *ANL* |
| ANL-W | ANL – West at NRTS. Currently *MFC* at INL |
| APRF | Army Pulse Reactor Facility, Aberdeen, Maryland, USA |
| BKI | Boris Kidrič [Kidrich] Institute, Vinča, Belgrade, Yugoslavia |
| BORAX-I | (or BORAX-1) Boiling Water Research Reactor number 1 at NRTS |
| CAC | Constituyentes Atomic Center (Centro Atómico Constituyentes), Constituyentes (near Buenos Aires), Argentina |
| CENS | Nuclear Studies Center of Saclay (Centre d'Études Nucleaires de Saclay), Saclay, Essone, France |
| CRL | Chalk River Laboratories, Chalk River, Ontario, Canada |
| EBR-I | Experimental Breeder Reactor number 1 at NRTS |
| fiss | fission(s) |
| FKBN | Latin-character abbreviation for name translated as *Fast Neutron Physics Reactor* [critical assemblies/machines] at VNIIEF and VNIITF |
| FKBN-2M | FKBN Modification 2 at VNIIEF |
| Gy | Gray (equivalent to 100 rad) |
| hr | hour |
| HTRE-3 | Heat Transfer Reactor Experiment number 3 at NRTS |
| HW | Hanford Works (near Richland), Washington, USA |
| ICPP | Idaho Chemical Processing Plant at NRTS/INEL. |
| INEL | Idaho National Engineering Laboratory. Formerly *NRTS*, currently *INL*. |
| JCO | JCO Fuel Fabrication Plant, Tokaimura, Ibarakiken, Japan (*JCO* is an all-uppercase character name, not an acronym) |
| KI | Kurchatov Institute of Atomic Energy, Moscow, Moscow Oblast, USSR. |
| LASL | Los Alamos Scientific Laboratory. |
| LRL | Lawrence Radiation Laboratory, Livermore, California, USA. |
| MBP | Machine Building Plant, Electrostal, Moscow Federal City, RF. Also known as the *Electrostal Fuel Fabrication Plant* |
| MeN | $M \times 10^N$ |
| min. | minute(s) |

| | |
|---|---|
| MPA | Mayak Production Association, Mayak (formerly Chelyabinsk-65), Chelyabinsk Oblast, RF. Also known as the *Mayak Enterprise* and *Mayak Plant* |
| mr | millirem |
| MSKS | not identified (critical assembly/machine), at VNIIEF |
| N/A | not applicable |
| NCCP | Novosibirsk Chemical Concentrates Plant, Novosibirsk, Novosibirsk Oblast, RF |
| NRC | Nuclear Research Center, Mol, Antwerp Province, Belgium. This is a different acronym definition than used in the main body of this guide. |
| NRTS | National Reactor Testing Station (1949-1974). Currently *INL*. |
| NRX | Nuclear Reactor Experimental at CRL |
| r | Roentgen |
| rad | radiation absorbed dose |
| rem | radiation equivalent man |
| RA-2 | [not identified, but possibly *Argentine Reactor number 2*] at CAC |
| RF | Russian Federation. Formerly *USSR* |
| SCC | Siberian Chemical Combine, Seversk, Tomsk Oblast, RF. |
| sec. | second(s) |
| SF-3 | not identified (a critical assembly/machine at KI) |
| SF-7 | not identified (a critical assembly/machine at KI) |
| SL-1 | Stationery Low-power reactor/plant number 1 at NRTS |
| sol'n | solution |
| SPERT-D1 | Special Power Excursion Reactor Test number D1 at NRTS |
| Sv | Sievert (equivalent to 100 rem) |
| UK | United Kingdom |
| UNC | United Nuclear Corporation, Wood River Junction, Rhode Island, USA |
| unk | unknown |
| USA | United States of America |
| USSR | Union of Soviet Socialist Republics |
| VENUS | Vulcain Experimental Nuclear Study at the NRC, Mol, Belgium |
| VNIIEF | Latin-character abbreviation for name translated as Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics, Sarov, Nizhny Novgorod Oblast, RF |
| VNIITF | Latin-character abbreviation for name translated as Russian Federal Nuclear Center - All-Russian Research Institute of Technical Physics, Snezhinsk, Chelyabinsk Oblast, RF |

| | |
|---|---|
| WSMR | White Sands Missile Range, New Mexico, USA |
| WW | Windscale Works, Sellafield, Cumbria, UK |
| Y-12 | Y-12 Plant, Oak Ridge, Tennessee, USA (originally code-name, not an acronym) |
| ZEEP | Zero Energy Experiment Pile, at CRL |
| ZPR-1 | Zero Power Reactor number 1, at ANL-E |

# Topic.A.1 Out-of-reactor (Process) Criticality Accidents

Table A1 lists the 22 process criticality accidents that were reported between 1940 and 2011. Seven occurred in the USA, one in the UK, thirteen in the RF or USSR, and one in Japan. Of local interest, three accidents occurred at the Idaho Chemical Processing Plant. All 22 accidents are summarized here.

## A.1.1 March 15, 1953, MPA, USSR

Controlled factors: mass (via volume, concentration), neutron absorption, interaction

Other factors: reflection (partial shielding), geometry

Excursion(s): one burst

Criticality/radiation alarm(s): none

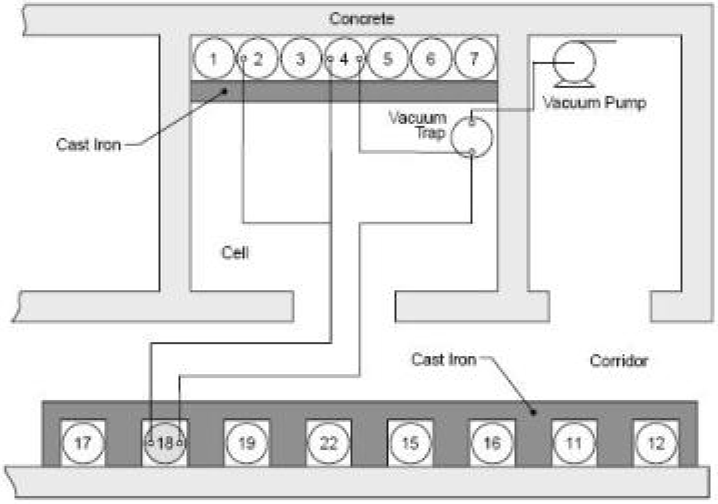
Radiation exposures: 1000, 100 rad

Radioactive contamination: none

Medical consequences: no fatalities, one case severe radiation sickness with limb amputation; no further consequences reported

Equipment/facility damage: none

Lessons-learned topics: training, human factors (available unapproved vessels, reporting, safety culture), inadvertent/ unrecorded transfer, conduct of operations (limit compliance, abnormal event reporting, overbatch), emergency planning (radiation alarms/CAS, evacuation, event reporting), design (available unapproved vessels, engineered features not sufficient in this case)



Vessel layout during the 1953 criticality accident.

This accident occurred in partially shielded vessels used for mixing, diluting, sampling, storing, and transferring plutonium-nitrate solutions.[a] A concrete cell contained seven not-safe-by-geometry vessels consecutively numbered 1 through 7. These vessels had interconnections, filters, traps, and vacuum equipment for solution transfers. Some in-cell vessels could also be connected with eight identical vessels in a corridor outside the cell. Several meters (~yards) from the in-cell vessels, the in-corridor vessels were numbered 11, 12, 15, 16, 17, 18, 19, and 22. The accident occurred in vessel 18, shown in the schematic above.

Criticality controls consisted of cadmium installed between the seven in-cell vessels, a plutonium mass limit on each vessel, and requiring that vessels 2, 4, and 6 never contain solution. However, operators were not trained in criticality safety. In addition, the area was not covered by a CAS or even by fixed radiation alarms.

---

[a] Shielding included cast iron plates around vessel arrays and the cell's concrete walls.

## Table A1. Out-of-reactor (Process) Criticality Accidents

| start date | power history ~ duration | site | alarm (b) | ~ no. of exposures(a) | | | material | volume (L) | estimated fission yields | | total (1e17 fiss.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ≥ 1 rem | ≥ 12 rad | fatal | | | first burst (1e17 fiss.) | specific burst (1e15 fiss./L) | |
| Mar. 15, 1953 | < 1 min. - 1 burst | MPA, USSR | none | 2 | 2 | 0 | Pu nitrate sol'n | 31.0 | unk | unk | ~2.0 |
| Apr. 21, 1957 | 10 min. | MPA, USSR | none | 6 | 6 | 1 | U(90) slurry | 30.0 | unk | unk | ~1.0 |
| Jan. 2, 1958 | < 1 min.- 1 burst | MPA, USSR | unk | 4 | 4 | 3 | U(90) nitrate sol'n | 58.4 | ~2.0 | 3.4 | ~2.0 |
| June 16, 1958 | 13 min. | Y-12, USA | C | 8 | 8 | 0 | U(93) nitrate sol'n | 56.0 | ~0.1 | 0.2 | 13.0 |
| Dec. 30, 1958 | 3 sec. | LASL, USA | none | 10 | 6 | 1 | Pu aqueous & organic sol'ns | 160.0 | 1.5 | 0.94 | 1.5 |
| Oct. 16, 1959 | 20 to 30 min. | NRTS, USA | R | 12 | 2 | 0 | U(~91) nitrate sol'n | 800.0 | ~1.0 | ~0.1 | 400.0 |
| Dec. 5, 1960 | 110 min.(c) | MPA, USSR | C | < 5 | 0 | 0 | Pu carbonate sol'n | 19.0 | unk | unk | ~2.5 |
| Jan. 25, 1961 | few min. | NRTS, USA. | R | 0 | 0 | 0 | U(~90) nitrate sol'n | 40.0 | ~0.6 | 1.5 | 6.0 |
| July 14, 1961 | 165 min. -2 excursions | SCC, USSR | C, R | 1 | 1 | 0 | $U(22.6)F_6$ & oil sludge | 42.9 | none | none | 0.12 |
| Apr, 7, 1962 | 37 hr.(c) | HW, USA | C | 5 | 3 | 0 | Pu sol'n | 45.0 | ~0.1 | 0.2 | 8.0 |
| Sep. 07, 1962 | 100 min.(c) | MPA, USSR | C | 0 | 0 | 0 | Pu nitrate sol'n | 80.0 | none | none | ~2.0 |
| Jan. 30, 1963 | 10 hr., 20 min.(c) | SCC, USSR | C | 4 | 1 to 3 | 0 | U(90) nitrate sol'n | 35.5 | unk | unk | 7.9 |
| Dec. 2, 1963 | 16 hr.(c) | SCC, USSR | C | 1 | 0 | 0 | U(90) organic sol'n | 64.8 | none | none | 0.16 |
| July 24, 1964 | 90 min. - 2 bursts | UNC, USA | C(d) | 5 | 3 | 1 | U(93) nitrate sol'n | 41.0 | ~1.0 | 2.4 | ~1.3 |
| Nov. 3, 1965 | unknown | MBP, USSR | C | 1 | 0 | 0 | U(6.5) oxide slurry | 100.0 | none | none | ~0.08 |
| Dec. 16, 1965 | 70 min.(c) | MPA, USSR | C | 0 | 0 | 0 | U(90) nitrate sol'n | 28.6 | none | none | ~5.5 |
| Dec. 10, 1968 | 75 min. - 3 bursts | MPA, USSR | C | 4 | 2 | 1 | Pu aqueous & organic sol'ns | 28.8 | 0.3 | 1.0 | ~1.3 |
| Aug. 24, 1970 | 5 to 10 sec. | WW, UK | C | 1 | 0 | 0 | Pu aqueous & organic sol'ns | 40.0 | none | none | 0.01 |
| Oct. 17, 1978 | 20 to 30 min. | INEL, USA | R | 0 | 0 | 0 | U(~82) nitrate sol'n | 315.5 | unk | unk | 27.0 |
| Dec. 13, 1978 | < 1 sec. - 1 burst | SCC, USSR | C | 8 | 1 to 7 | 0 | dry Pu metal ingots | 0.54 | 0.03 | 5.6 | 0.03 |
| May 15, 1997 | 26 hr. 5 min.(c) | NCCP, RF | C | 0 | 0 | 0 | U(70) oxide slurry | unk | none | none | 0.055 |
| Sep. 30, 1999 | 19 hr. 10 min.(c) | JCO, Japan | R | 3 | 3 | 2 | U(18.8) nitrate sol'n | 45.0 | ~0.5 | 1.1 | 25 |

(a) Thresholds of 1 rem and 12 rad are used here because they are, respectively, thresholds at which responders must consider protective actions for the public and at which CASs might be required. The numbers listed here do not include exposures to responders or the public. However, the only measured exposures to the public occurred with the Japanese accident in 1999: the highest exposure to any rescuer or responder was 56 rem, and the highest exposure to people who remained offsite was 2.5 rem.

(b) Alarm instruments as identified in reports: C = criticality alarm, R = radiation alarm, unk = unknown (not reported).

(c) Excursion terminated with human intervention.

(d) The criticality alarm was ineffective for the second burst because it was still sounding due to the first burst.

On March 15, 1953, in violation of procedures, vessels 2 and 4 contained solution and each of vessels 1, 3, and 4 contained more than their plutonium limit.

To accommodate scheduled transfers that day, a plan was prepared to transfer the contents of vessels 2 and 4 to vessel 18, which records indicated was empty. 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 vessel 18 and the assistant operator was near vessels 2 and 4. The chief operator disconnected the hose from the vessel 18, saw foam, felt heat, and reconnected the hose. About that time, the assistant operator noticed solution had entered a glass vacuum trap.

Realizing that something was wrong, these operators transferred solution from vessel 18 back to vessel 4, diluted it, cooled it, and then transferred it to previously empty vessels 22 and 12. A critical excursion did not occur when transferring the material back to vessel 4 because the vacuum trap had failed. Having no criticality safety training, and not recognizing that a criticality accident had occurred, both operators decided not to tell authorities. However, two days later the chief operator exhibited severe radiation sickness.[b]

Upon report of the operator's illness, an investigation began. Investigators determined that vessel 18 contained about 168% of the plutonium limit when the initial transfer was complete. Almost 27% of the plutonium in vessel 18 came from a previous, unrecorded transfer from vessel 1. Investigators also concluded the accident consisted of one power burst of about 2.5e17 fissions.

The chief operator received about 1000 rad, the assistant about 100 rad. The chief operator suffered severe radiation sickness and amputation of both legs. He died 35 years later, apparently of unrelated causes. The assistant operator apparently did not exhibit any radiation sickness symptoms.

### A.1.2 April 21, 1957, MPA, USSR

Controlled factors: mass (via volume, concentration)

Other factors: geometry, concentration

Excursion(s): multiple bursts over 10 minutes

Criticality/radiation alarm(s): none

Equipment/facility damage: none

Radioactive contamination: spill inside glove box; equipment clean up afterwards

Radiation exposure(s): 3000 rad, five exposures each less than or equal to 300 rad

Medical consequences: one fatality; five cases of radiation sickness but without apparent long-term health effects

Lessons-learned topics: training, conduct of operations (material accountability), human factors (ability and ease of monitoring important variables, undetected overbatch), design (process monitoring), change analysis (uranium precipitation, fully analyze improvements), emergency planning (radiation alarms/CAS, evacuation, multiple bursts)

The second process criticality accident at Mayak Enterprise occurred in a glovebox for purifying and filtering highly enriched (about 90%) uranium solutions. The glovebox contained a not-safe-by-geometry vessel equipped with a heater and a stirring device, a filter, a tank, and a vacuum trap on the solution outlet line. Design and layout were

---

[b] Prompt medical attention probably would have alleviated or prevented many symptoms.

determined by operational and production considerations without initial regard to ease of operation, methods for complete clean-out, etc.

Criticality safety measures consisted of a uranium mass limit for each batch, implemented through calculations based on volume and on uranium concentration in uranyl nitrate. There was no CAS, no radiation monitoring equipment and little shielding. Operators had no criticality safety training.

The accident occurred on April 21, 1957, while vacuum filtering U(90) slurry. The operator saw the filter media swell, followed by a violent gas release and precipitate ejection from the receiving vessel. She instinctively returned ejected material to the vessel by hand. She began to feel ill within seconds. Gas discharge continued for about ten more minutes, during which precipitate was ejected into the vacuum trap of an adjacent glovebox. The reaction terminated when sufficient precipitate was ejected.

Lacking relevant training, people in the room did not understand what they had observed. A radiation control officer called to the scene determined that a criticality accident had occurred based on measurements he or she took.

At the time of the accident, the receiving vessel contained 425% of the batch mass limit based on data from glovebox dismantling and equipment clean up. However, the operator had followed procedures and did not violate criticality safety controls. The uranium accumulation probably resulted from a combination of factors:

- There was no requirement to clean out equipment between scheduled times if, for each batch, the mass difference between incoming and outgoing fissionable streams was less than 5%. Also, potential fissionable-mass-accumulation was not tracked between cleanings.
- There was no in-line instrumentation for measuring uranium concentration or accumulation in the receiving vessel.
- Solution temperature was an important process variable, but there was no simple-to-use monitoring device. Temperatures were controlled by heating times.
- Solution stiochiometry was an important process variable, but concentration control was imprecise.[c] Therefore, precipitate could slowly accumulate in a hard, thin crust inside the vessel.
- It is possible that very minor filter defects could have contributed to an increased rate of precipitation accumulation. However, filters were replaced if they had visible defects or if unusually high flow rates were detected through the filters.
- There was no operationally convenient method for inspecting the inside of the receiving vessel.
- In an effort to reduce personnel exposures, procedures were changed to allow an acid flush for vessel clean out, rather than the previously required mechanical clean out.

The operator received an estimated 3000 rad dose and died 12 days after the accident. The other five people in the room received upwards of 300 rad each. All five developed radiation sickness, but recovered without apparent long-term health effects.

The excursion produced an estimated 2e17 total fissions. There was no damage. Contamination was confined within the glovebox.

---

[c] At its simplest, stoichimetry is the math behind chemistry, or the use of chemical equations. It deals with the balance between reactants (chemicals or compounds input) and products (resultant chemicals or compounds) of a chemical reaction.

The glovebox was disassembled, cleaned, and reassembled with its original equipment. A radiation meter was installed on the glovebox, procedures were revised, and enhanced operator training was implemented. Operations resumed in a few days.

### A.1.3 January 2, 1958, MPA, USSR

Controlled factors: geometry

Other factors: reflection

Excursion(s): one burst

Criticality/radiation alarm(s): none (reactor facility)

Radioactive contamination: ejected material

Radiation exposure(s): three at ~6000 rad, one at ~600 rad

Medical consequences: three fatalities; one person with radiation sickness followed by continuing long-term health problems and eventual blindness

Equipment/facility damage: little or none

Lessons-learned topics: human factors (convenience, vessel mounting, safety culture), conduct of operations (procedure compliance), design (convenience, vessel mounting, geometry), change analysis/understanding

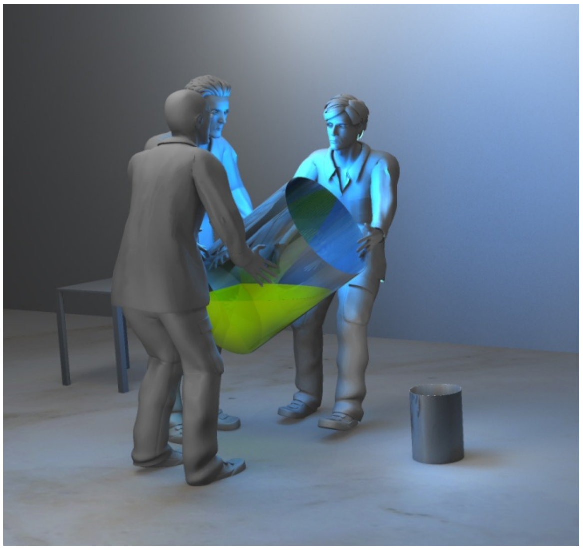
This accident occurred in a vessel used for critical experiments. However, it is categorized as a process accident because it occurred after experiments terminated, during fissionable material handling with the vessel out of its experimental configuration.

After the first two process criticality accidents at Mayak Enterprise (Subtopics A.1.1 and A.1.2), authorities established a critical experiments facility on site. Designed to measure critical parameters for highly enriched uranium solutions, equipment included a tank bolted to a stand, a neutron source, neutron detectors, a control rod, and small-diameter connecting lines. Equipment and shielding were located to minimize neutron reflection for the experiment tank. Like most reactor facilities, there was no CAS. (Critical conditions are expected and desirable at certain times. Therefore, different instrumentation is used to detect such conditions.)

The accident occurred on January 2, 1958, after the dedicated staff of four very knowledgeable team members completed the first experiment of the New Year. This was also the first experiment with a large vessel that represented process vessels on site.

After the experiment, the team initially followed procedures to drain the vessel through a line to safe-by-geometry bottles. This process was very tedious. After filling some bottles and judging the remaining solution to be highly subcritical, team members violated procedures to accelerate draining. They placed empty bottles nearby, removed the vessel’s start-up source, and unbolted the vessel. Three members manually lifted the vessel and began to tip it to pour solution into the bottles.

The team immediately noticed a flash and, simultaneously, solution ejection. (The illustration to the right depicts the accident without the solution ejection and vessel tipping.) The three experimenters dropped the vessel. All four immediately went to a change room, showered, and were transported to a hospital.



Representation of January 1958 accident

Before it was unbolted, the vessel contained fissionable solution in a poorly reflected, near-slab geometry. However, as the vessel was tipped, solution geometry changed. It became optimal with effective reflection by three humans. Apparently, a small neutron background also contributed. A single burst of about 2e17 fissions occurred.

Exposed to an estimated 6000 ± 2000 rad each, the three experimenters died five to six days later. The fourth experimenter, who was about 2.5 m (8.2 feet) from the vessel and received about 600 rad, developed acute radiation sickness, followed by continuing health problems. She developed cataracts and lost her sight some years later.

Because of the accident, the experimental facility was dismantled and the critical experiment program was discontinued.

Contributing factors included (1) violating the vessel draining procedure, (2) performing work outside the procedure (unbolting and removing the vessel), (3) experiment stand design that made it relatively easy to unbolt and remove the vessel, (4) neutron reflection by personnel, and (5) lack of operator awareness with regard to the large effects of shape changes on solutions with, originally, very small height-to-diameter ratios.

### A.1.4 June 16, 1958, Y-12, USA

Controlled factors: mass and/or concentration (waste stream)

Other factors: geometry, concentration

Excursion(s): multiple bursts over about 3 minutes

Criticality/radiation alarm(s): CAS, constant air monitors, and other radiation monitors

Radioactive contamination: material in drum

Radiation exposure(s): 461, 428, 413, 341, 298, 86, 68, and 29 rem

Medical consequences: no fatalities, three or four cases of very mild radiation sickness, no other consequences reported

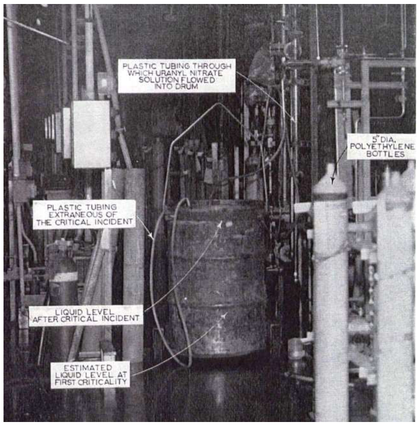
Equipment/facility damage: none

Lessons-learned topics: inadvertent transfer, design (geometry, valves leak), emergency planning (CAS, evacuation, multiple bursts), perhaps human factors (infrequently performed activities)

The Y-12 accident occurred in an area for recovering enriched uranium from scrap. The area was equipped with a CAS and radiation monitors.

On that Monday afternoon, a fissionable material inventory was in progress. It included an associated process shutdown, equipment cleaning, and restart. Parts of the system had restarted in other areas where inventory activities were complete.

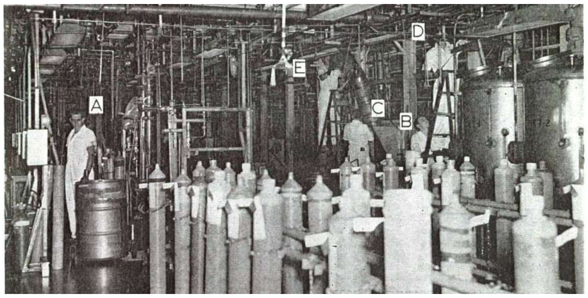
Workers were cleaning and leak testing a supposedly empty system of 5-in. pipes. Between emptying and washing, solution leaked into the pipes through a valve that was supposed to isolate these pipes from process equipment in the area that had restarted.



The 55 gallon drum after the Y-12 criticality accident.

First, concentrated fissionable solution from the pipes flowed into a 55-gallon drum meant to catch wash and leak-test water that was *supposed to* contain no more than negligible amounts of fissionable nuclides. The concentrated solution was too shallow to be critical. Then water flowed into the 55-gallon drum (shown on the right). This water diluted the fissionable 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 burst was followed by multiple, less energetic bursts, producing an estimated 1.3e18 total fissions in three minutes. No equipment was damaged and no material was spilled or ejected.



Reconstruction of initial locations of personnel during the Y-12 criticality accident.

Operators saw a flash before evacuating in response to criticality alarms that activated with the first burst. One man ("A"), who was about 6 feet from the drum, received a radiation exposure of 461 rem (365 rad). Other exposures were 341 rem (270 rad) at 15 feet ("B"), 413 rem (327 rad) at 16 feet ("D"), 428 rem (339 rad) at 18 feet ("C"), 298 rem (236 rad) at 22 feet ("E"), 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. Of these people, one survived 14½ years, another survived 17½ years, five were alive 29 years after the accident, and the status of the eighth person was unknown in the year 2000.

Operations resumed within three days. However, management adopted two measures to prevent similar accidents: (1) isolate equipment by disconnecting transfer lines that might contain fissionable material, and (2) permit only safe-by-geometry containers for enriched uranium solutions in process areas (for example, waste baskets are perforated and standard mop buckets were replaced by safe-by-geometry containers).

### A.1.5 December 30, 1958, LASL, USA

Controlled factors: mass and/or concentration (waste stream)

Other factors: mass, geometry, concentration

Excursion(s): one burst over 3 seconds

Criticality/radiation alarms: none in the accident facility itself

Radioactive contamination: none

Radiation exposure(s): 12,000, 134, 53 rem

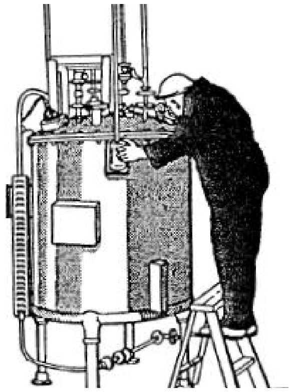
Medical consequences: one fatality, no other consequences reported

Equipment/facility damage: none, but tank supports were displaced

Lessons-learned topics: design (geometry), emergency planning (radiation alarm/CAS, evacuation), change analysis (slow buildup), conduct of operations (material accountability), human factors (administrative controls vs. engineering controls; operator familiarity with an infrequent operation)

This LASL accident involved equipment for treating dilute raffinate from a plutonium recovery plant. Residual plutonium (typically 0.1 g/L) and small quantities of americium were recovered from raffinate by solvent extraction in large tanks. The facility itself was not equipped with a CAS or radiation monitoring. However, at least one nearby facility was equipped with a CAS.

That Tuesday afternoon, a material inventory was in progress. Closed tanks 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 large tank that was safe for the entire system's expected fissionable inventory of about 125 g.

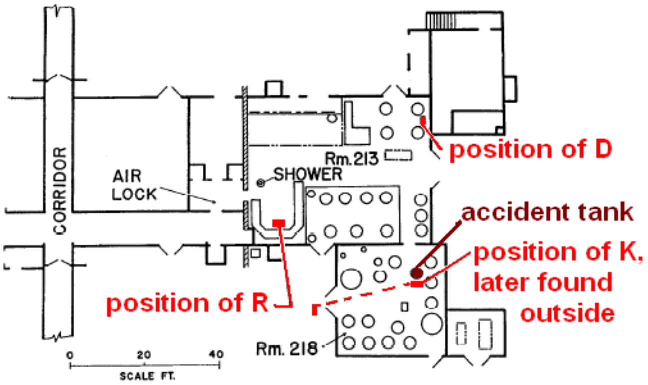


Reconstructed location of victim when the solution became critical.

The excursion occurred at 4:35 in this large tank when its stirrer was turned on and the operator was looking through a viewing port. Subsequent investigation indicates a thick layer of concentrated organic solution (3.27 kg plutonium in 160 L) was floating on a dilute aqueous solution (60 g plutonium in 330 L). Apparently, 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 the excursion did not continue.

The excursion produced a single burst, about 1.5 e17 fissions. There was no damage to equipment and no contamination, but the shock displaced tank supports about 0.1 cm (3/8 in.). A CAS about 175 feet away (in another facility) activated, and in adjoining rooms saw a light flash (not blue). The operator (K) was knocked to the ground, but he got up and left the building.

The operator received about 12,000 rem and died 36 hours later. Two men (D and R) who approached the tank to find and help the victim received 134 rem (D) and 53 rem (R). The highest dose to other operations personnel was less than 4 rem but they were more than 75 feet away and none of them approached the tank.



Initial location of operator (K) and two men who searched for him (Dec. 1958 criticality accident).

The only explanation found for 3.3 kg of plutonium in this process is that solids accumulated gradually during seven operating years. After six more operating months, the recovery plant was scheduled for rebuilding with safe-by-geometry equipment and radiation monitoring. Due to the accident, old equipment was retired immediately.

Many changes were made afterwards. Safe-by-geometry equipment was installed to significantly reduce reliance on administrative controls. 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 inadvertent transfers. 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.

### A.1.6 October 16, 1959, NRTS (ICPP), USA

Controlled factors: geometry

Other factors: concentration

Excursion(s): multiple bursts over about 20 minutes

Criticality/radiation alarm(s): constant air monitors, no CAS (well-shielded facility)

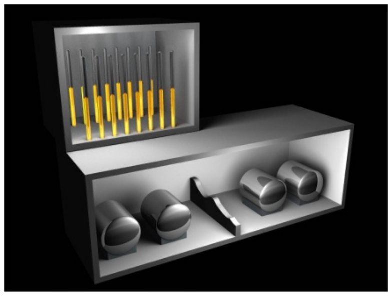
Radioactive contamination: none

Radiation exposure(s): 50 rem, 32 rem, seventeen other much smaller doses

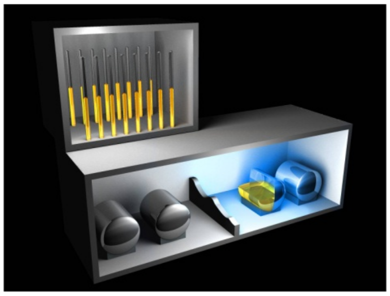
Equipment/facility damage: none

Medical consequences: no fatalities, no other consequences reported

Lessons-learned topics: design (geometry, anti-siphon measures, shielding), inadvertent transfer, human factors (infrequent operation/operator familiarity, egress routes, alarm conditioning,), conduct of operations (alarm conditioning, instrument operability), emergency planning (radiation alarms, alarm conditioning, egress routes, airborne release paths, multiple bursts)



Intended solution configuration



Configuration when the solution went critical

This accident occurred during the graveyard shift on Oct. 16, 1959. The excursion resulted from air sparging on a bank of safe-by-geometry storage cylinders that contained uranium solution (170 g U-235/L). The sparging process was used to mix solution in the cylinders to make the solution uniform throughout the cylinder bank. The pressure gauge associated with this bank did not function, and there was no other gauge by which the operator could monitor sparge airflow. The operator opened the air (sparge) valve until circumstantial evidence indicated the sparge was operating. However, the sparge was forceful enough to lift the solution so high that it siphoned solution from the cylinders into a very large, not-safe-by-geometry, waste tank that contained water. (Until this accident, it was thought that only deliberate action could transfer solution to a waste tank.)

The criticality accident in this waste tank produced about $4 \times 10^{19}$ fissions over about 20 minutes. An initial burst of about $10^{17}$ fissions was probably followed by smaller bursts and then by more-or-less stable solution boiling. The reaction terminated after about 400 L water was distilled into another tank. The large fission yield was due to solution volume and excursion duration.

Because of heavy shielding, there was no direct neutron or gamma exposure. However, airborne activity spread into operating areas through vent lines and drain connections. Airborne activity triggered local radiation alarms, but these alarms sounded relatively frequently. Therefore, evacuation was not as swift as training required. In addition, personnel followed normal egress routes rather than clearly marked evacuation routes. Consequently, a bottleneck at the exit point slowed evacuation further. (The plant had a manually activated, general evacuation system, but it was not activated.)

Two persons received significant beta radiation doses, 50 and 32 rem, when they evacuated through areas where off-gas system and drain lines vented. Seventeen other people received much smaller exposures. These exposures probably would be lower had personnel evacuated promptly using the marked routes. The exposures demonstrate the usefulness of radiation alarms in areas that might be affected by a nuclear incident occurring elsewhere.

Investigators identified several contributing factors: (1) Operators were unfamiliar with the seldom-used bank of cylinders. (2) There was no anti-siphon device in subject cylinders, although there were such devices on routinely used vessels. (3) Operating procedures were not current, although they correctly described operator actions.

No equipment was damaged, but several actions were required before restart. In-progress actions to install valves in the line were completed. Orifices were added to sparge lines to restrict airflow volume. Emergency procedures were improved and water traps were installed in vent and drain lines. Equipment and operating procedures were reviewed to establish defense-in-depth against inadvertent transfers of fissionable material.

## A.1.7 December 5, 1960, MPA, USSR

Controlled factors: mass (via volume, concentration)

Other factors: geometry

Excursion(s): multiple bursts over about 65 minutes

Criticality/radiation alarm(s): CAS (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): five ranging from 0.24 to 2.0 rem

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry, shielding/reflection), conduct of operations (procedure compliance, limit compliance, overbatch, record keeping, data falsification), emergency planning (CAS, evacuation, remote readouts, multiple bursts, material removal)

The next process criticality accident at Mayak Enterprise occurred in a system for recovering plutonium. System equipment included a first-stage processing vessel (R0) in glovebox 9; two identical, lead shielded, second-stage processing vessels (R1 and R2), a transfer tank, a filter vessel and a lead shielded, third-stage processing vessel (R3) in glovebox 10; and an unshielded, not-safe-by-geometry holding tank outside of the gloveboxes. The building had a criticality alarm system.

Criticality control for the operation relied entirely upon a mass limit for vessel R0, which typically received very low concentration waste solutions.[d] 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.

Procedures required two operators to control processes in the room, but, on Dec. 5, 1960, an operator working alone initiated a vacuum transfer from vessel R2 to the holding vessel. About 10:25 p.m., shortly after the transfer began, the operator noticed that criticality alarm detectors near the holding vessels were intermittently alarming. He left the room to report the alarms, and shortly thereafter the entire alarm system sounded continuously. All personnel evacuated to an underground tunnel per procedure.

The accident location was identified through interviews, radiation measurements taken with portable instruments, and working documents. Remote readouts oscillated, indicating multiple excursions. Responders turned off the vacuum system, as directed, in an unsuccessful attempt to terminate the excursions. Subsequently, three operators entered the room during a period of lower radiation levels and, by manipulating valves, air supplies, and the vacuum system, transferred some solution from the holding vessel to vessel R3. This terminated the excursions, but more solution had to be transferred before the system was considered safely subcritical.

The accident excursions lasted about 65 minutes, producing an estimated 2.5e17 fissions. No equipment was damaged or contaminated. During the accident response and cleanup, five individuals received doses from about 0.24 to 2.0 rem.

Subsequent investigation revealed the vessel R0 mass limit was violated so that excessive Pu eventually reached the holding vessel. On Dec. 3, 1960, vessel R0 contained 171% of its limit, but a shift production engineer deliberately changed the vessel log to show its contents in compliance with the limit. This material was processed and transferred to empty vessel R2 on Dec. 4. On Dec. 5, the same shift production engineer again violated procedures by transferring more material into vessel R2, which then contained almost a full double batch compared to the vessel R0 limit. The material was then processed through the second stage, after which the operator transferred solution to the larger-diameter holding vessel.

The holding vessel was replaced with a safe-by-geometry vessel immediately.

### A.1.8 January 25, 1961, NRTS (ICPP), USA

Controlled factors: geometry

Other factors: concentration

Excursion(s): probably one burst

Criticality/radiation alarm(s): constant air monitors and remote area monitors, but no CAS (well-shielded facility)

Radioactive contamination: none

---

[d] Adequately implemented controls on upstream vessels are often sufficient for providing safety in the downstream portions of waste systems and of batch processes.

Radiation exposure(s): none more than 0.60 rem

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry, excursion provisions, shielding, available overpressure), inadvertent transfer, human factors (operator familiarity, available overpressure), conduct of operations (communication, equipment condition), emergency planning (radiation alarms, evacuation)

This second ICPP criticality accident occurred on January 25, 1961 at 09:50. It was the fifth operating day following a yearlong shutdown and just 22 days after the fatal SL-1 accident (Subtopic A.2.9) at another complex of the same site. 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 is thought to have occurred when concentrated, high enriched, uranyl-nitrate solution was forced upward from a safe-by-geometry section of an evaporator into a not-safe-by-geometry 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 total fission yield is estimated at about 6e17 fissions. Although personnel were protected by heavy shielding, airborne release and/or radiation fields were high enough to trigger radiation alarms, initiating plant evacuation. Nobody received more than a 60 mrem dose.

Inadvertent criticality in the disengagement cylinder was deemed credible before the accident. Therefore, lines led from its base to two safe-by-geometry 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.

In addition to the disengagement head's geometry, accident investigators identified several possible contributing factors: (1) poor communications, especially about valve positions, (2) personnel unfamiliarity with equipment after a yearlong shutdown, and (3) relatively poor condition of some equipment.

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.

### A.1.9 July 14, 1961, SCC, USSR

Controlled factors: mass or concentration (via $UF_6$ temperature and oil change out)

Other factors: geometry

Excursion(s): two bursts with second due to efforts to stabilize system

Criticality/radiation alarm(s): both

Radioactive contamination: none

Radiation exposure(s): 200 rad

Medical consequences: no fatalities, no other consequences reported

Equipment/facility damage: none

Lessons-learned topics: design (geometry), conduct of operations (procedure compliance, material accountability, adequate monitoring), change analysis (affects of multiple upstream changes), emergency planning (radiation alarms/CAS, evacuation, accident possible with intermediate [fairly low] enriched uranium, multiple bursts, stabilization/recovery can cause additional excursions)

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

This part of the facility purified 22.6% enriched uranium hexafluoride ($UF_6$) in a line that included five main cylinders, three intermediate cylinders, five holding vessels, additional vessels, and a vacuum pump with a cylindrical 60 L oil vessel. Liquid nitrogen cooled the main and intermediate cylinders to cool and condense gaseous $UF_6$. During normal operations, most $UF_6$ desublimated in the main and intermediate cylinders, with very little $UF_6$ passing into a waste stream that was sent to a gas purification system via the subject vacuum pump. However, the pump's oil was changed approximately every 15 days because $UF_6$ accumulated in the oil, increasing oil density and lowering pump efficiency.

On July 1, 1961, equipment breakdowns reduced nitrogen supplies dramatically. Operating procedures were changed to require manual nitrogen charging for the five main cylinders. In addition, charging the three intermediate cylinders was discontinued, violating procedures. These actions increased the rate and amount of $UF_6$ passing into the waste stream and accumulating in the vacuum pump oil. On July 10, a process upset elsewhere resulted in more $UF_6$ being sent to the main and intermediate cylinders, which also increased the amount of $UF_6$ passing into the waste stream.

On July 14 at 04:45, a high radiation alarm sounded in the room housing the main equipment for this system, which was adjacent to the room that housed the holding vessels and vacuum pump. The building had a criticality alarm system, but its detector trip was too high to detect the very small excursion. People did not realize the radiation alarm resulted from a critical excursion in the pump oil. Per procedure, operators ceased operations and summoned a radiation control officer. The officer was unable to locate the radiation source, but noted radiation levels were rapidly decreasing. The officer authorized operation resumption.

At 07:30, an operator turned on the vacuum pump from a central panel. As he approached the equipment to open a valve between the pump and holding vessels, the criticality alarm sounded and he saw a light flash. The operator turned off the pump and immediately ran to a telephone about 200 m (~213 yards) away to inform his supervisor. Alarms sounded in three adjacent buildings, up to 320 m (350 yards) away.

An investigation determined the accident occurred in the vacuum pump oil reservoir. The first excursion was very small, probably not more than 2e14 fissions. Afterwards, the reservoir was probably barely subcritical. When the pump was turned on, the oil was forced into the central pipe of the reservoir where the second, much larger excursion occurred. This excursion shut down due to a combination of temperature increase and radiolytic gas generation, which ejected oil from the central pipe into the pump's other cavities and into gas purification equipment. The accident produced an estimated 1.2e15 total fissions. No equipment was damaged or contaminated.

Three procedure violations between July 1 and 14 directly contributed to the accident:
(1) The temperature recording instruments for the main cylinders were turned off.

(2) The main cylinders were cooled manually in a manner that produced significant temperature gradients in the cylinders and produced misleading low temperature readings. (3) Intermediate cylinder cooling was not performed.

The operator received about 200 rad, and experienced only mild radiation sickness. Nobody else received a measurable dose.

The facility was redesigned and reconstructed. Manuals and procedures were revised.

### A.1.10 April 7, 1962, HW, USA

Controlled factors: mass and/or concentration (end of clean-up)

Other factors: concentration, geometry

Excursion(s): multiple bursts over 37 hours (longest process critical excursion)

Criticality/radiation alarm(s): both

Radioactive contamination: none

Radiation exposure(s): 110, 43, 19 rem

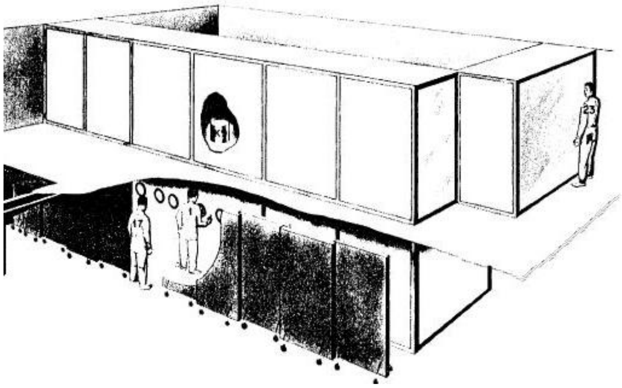
Medical consequences: no fatalities, no further consequences reported

Equipment/facility damage: none

Lessons-learned topics: design (geometry, neutron absorbers, process versatility), inadvertent transfer, human factors (infrequent operation, ability to clean), conduct of operation (plant condition), emergency planning (radiation alarms/CAS, evacuation, multiple bursts, robot)

The Hanford Works multipurpose Recuplex Facility for plutonium recovery started as a pilot plant in 1955. It eventually changed to become a production facility. Various portions of this versatile plant were contained in room-size plastic hoods to prevent external contamination. Over time, plant equipment deteriorated and leaked. Visibility through hood walls became poor. A necessary, thorough clean up was almost complete at the time of the accident.

The 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 LASL accident, Subtopic A.1.5). About 46 L of solution containing 1.4 to 1.5 kg 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 safe-by-geometry vessel.



Accident location and initial locations of personnel during the Recuplex Criticality Accident.

The incident produced about 8.2e17 fissions over 37 hours that weekend, with about 20% occurring in the first half-hour. Event reconstruction indicated an initial burst of about 1e16 fissions, followed by smaller bursts for 20 minutes, after which boiling occurred.

The excursion ended after about 6 L of water boiled off and after organic matter, which extracted plutonium from the aqueous phase, had settled.

The initial burst was accompanied by a blue flash and triggered radiation alarms. Immediate plant evacuation ensued. One man, who was 5 or 6 feet from the transfer tank, received a 110 rem radiation dose. 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 identify the precise incident location, to place and read meters, and to operate valves.

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

### A.1.11 September 7, 1962, MPA, USSR

Controlled factors: mass, concentration

Other factors: geometry, perhaps reflection

Excursion(s): three separate bursts in 100 minutes, two due to efforts to stabilize system

Criticality/radiation alarm(s): CAS (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): none

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry, instrumentation), conduct of operations (material accountability, material segregation, labels, questioning/observant attitude, procedure compliance, supervision), human factors (material segregation, labels), emergency planning (CAS, evacuation, multiple bursts, stabilization/recovery can cause additional excursions, material removal)

A criticality accident occurred just after midnight, September 7, 1962, in a chamber for dissolving plutonium metal residue at the Mayak Enterprise. Until then, scrap material was stored in one location. Operators did not measure fissionable content because the plant lacked appropriate instruments. Scrap reprocessing was based on total mass and a historical average of 1 wt% Pu, but concentration could vary significantly. In addition, relatively high concentration material was stored with low concentration material.

Residue was dissolved in nitric acid using one of two nearly identical dissolver vessels. Each vessel was equipped with a stirring device, heater, and 5 cm (~2 in.) thick lead shielding. The manual allowed operators to halt dissolution when excess acid was neutralized. They lowered excess acidity by adding more residue (apparently 1 wt% Pu).

After repairs, the first charge to vessel 2 involved relatively high concentration residue. After the dissolution run, only 3.5% of the plutonium mass was discharged in the nitrate solution. However, this sign of very incomplete dissolution was not investigated.

Instead, the second residue batch was charged. Because repairs were underway with liquid transfer lines, nitric acid was initially added to the second batch. Water was added several hours later. The addition order and the quantity violated procedures. It is likely, but not proven, that additional residue was added during this long dissolution to neutralize the solution. The clear nitrate solution was discharged.

Two more batches were processed. The third batch's solution was still acidic. During the fourth batch, another reagent was added in an unsuccessful attempt to neutralize the solution. Processing then stopped. Solution was allowed to settle.

After about 3 hours, at 00:15 on Sept. 7, 1962, the criticality alarm sounded and personnel evacuated to an underground tunnel per procedure. Blood activation analyses performed there indicated that nobody had been exposed to the accident.

All remote stabilization actions were conducted from the shift supervisor's room about 30 m (~33 yards) away. After various unsuccessful attempts, the vessel heater and stirrer were turned off, initiating a second excursion at 01:10. Further attempts were made until a third, largest, and final excursion occurred at 01:55. At that time, the heater and stirrer were turned on until the vessel was successfully drained in a two-phase process.

Investigation indicated the completely full dissolver contained approximately 300% of the criticality safety mass limit. Various factors contributed to the accident: (1) Not-safe-by-geometry equipment. (2) Charging high concentration residues when criticality safety limits were based on 1% plutonium content. (3) Inadequate isolation of high concentration from low concentration residues. (4) Adding reagents in the wrong sequence, contrary to procedures. (5) Unclear and difficult to read labels on residue cans. (6) Inadequate supervision and inadequate attention to completing material accountability documents. (7) No real-time fissionable material accounting instrumentation.

The estimated total yield was 2e17 fissions. No equipment was damaged, and only a short downtime was needed to clean up ejected solution.

### A.1.12 January 30, 1963, SCC, USSR

Controlled factors: mass (via volume and concentration)

Other factors: geometry

Excursion(s): nine separate bursts in 10 hours

Criticality/radiation alarm(s): CAS (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): four exposures from 6 to 17 rad

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry), human factors (multiple concentration units, expectations), conduct of operations (multiple concentration units, communication), emergency planning (radiation alarms/CAS, evacuation, multiple bursts, material removal)

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 recording practices allowed values to be listed either as a uranium mass fraction or as grams uranium per kilogram scrap. In addition, recycled solution concentrations were reported in g/L units, which were used to demonstrate compliance with a criticality safety mass limit for solution recycling.

On January 30, 1963, two waste containers arrived with chemical analysis results reported as a mass fraction. The supervisor for that shift erroneously recorded these results as g/kg values, underestimating the contents by a factor of 10. An operator loaded some of the material into dissolvers based on the erroneous values. Because of a shift change, a different operator completed the dissolution and transferred the solution to one of two collection vessels (64-B) where a sample was taken to determine the concentration. Later, laboratory personnel erroneously reported sample results for the other collection vessel (64-A), which happened to have a concentration about 10 times less than the subject vessel.

Relying on this erroneous data, the supervisor for the second shift decided to recycle solution in order to charge the next batch. The next batch, also subject to the original recording error, was charged to a dissolution vessel and then the contents of collection vessel 64-A were added to the dissolution vessel. The resultant solution was filtered and transferred in 10 L batches to collection vessel 64-B. The solution in the larger diameter vessel 64-B exceeded its critical height in the course of these transfers.

The first excursion occurred at 18:10 on January 30, 1963, tripping criticality alarms. Eight additional excursions, decreasing in power each time, occurred over the next approximately 10 hours. Each excursion shut down due to various factors, including thermal effects and solution ejection. Another excursion occurred each time the solution drained back into the vessel and cooled. The excursions terminated on January 31 at 04:30 when some of the solution was drained off into safe-by-geometry containers.

Staff evacuated when the criticality alarm sounded. Four staff members who were about 10 m (~11 yards) from the tank received exposures from 6 to 17 rad.

Investigators determined the system contained more than 940% of the mass limit for recycling solution. Before the filter and transfer operation to vessel 64-B, the dissolution vessel contained almost the amount needed for an unreflected criticality in that diameter of a vessel. The total yield was estimated at 7.9e17 fissions, but no equipment was damaged and no contamination resulted. The process resumed operation after no more than 12 hours.

### A.1.13 December 13, 1963, SCC, USSR

Controlled factors: geometry or size (via liquid level)

Other factors: concentration, absorption

Excursion(s): 16 bursts (11 long, weak bursts over 195 minutes, followed by four weaker bursts due to an effort to stabilize system, followed by one burst due to a later effort to further stabilize system)

Criticality/radiation alarm(s): CAS (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): all less than 5 rem

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry, detector/control effectiveness), system analysis (aqueous vs. organic vs. cadmium solution, uranium extraction, ), inadvertent transfer, emergency planning (CAS, evacuation, multiple bursts, stabilization/recovery can cause additional excursions, neutron absorber, material displacement, material removal)

This December 13, 1963, Russian accident was the second of three accidents at the Siberian Chemical Combine. The accident occurred with U(90) solution in a not-safe-by-geometry holding vessel that was one of three vessels in a vacuum system of the Combine's facility for uranium reprocessing and purification. All three vessels had not-safe-by-geometry designs for very highly enriched solution.

Small amounts of highly enriched uranium solution accumulated in the vacuum system as drops, condensate, and an occasional, inadvertent overflow from process vessels.[e] The system included two traps and a holding vessel to protect the vacuum line from corrosive solution. Level indicators on each vessel automatically initiated solution transfers, from each trap to the holding vessel or from the holding vessel to a drain line, when preset levels were exceeded. As a backup to the traps, the holding vessel's preset level was twice as high as the trap's level. The solution-transfer design relied on an initial assumption that solutions would be aqueous. However, experience indicated organic solutions also entered the vacuum line and accumulated in these vessels.

Between monthly steam cleanings, the vessels accumulated both aqueous and organic liquids that separated into layers due to the organic solution's lower density. Since organics did not actuate solution transfer, solution levels could exceed preset levels. Organic solutions could go undetected between holding vessel drainings and cleanings. Further, solutions entered from the top of each vessel, causing aqueous solutions to temporarily mix with organic solutions. While mixed, organics extracted some uranium from the aqueous solution, increasing uranium concentration in the organic layer. Since the holding vessel's preset level was higher, it could accumulate more undetected organic solution. Unknown to plant personnel, the holding vessel became mostly filled with high concentration organic solution.

On December 2, 1963, at 23:45, the area's criticality alarm system activated and personnel evacuated. The radiation detector that tripped the system was near the traps and holding vessel. Based on radiation readings, 11, long, weak excursions occurred over approximately 195 minutes. On December 3, 1963, at 03:45, personnel remotely turned off the vacuum system, which allowed some ejected solution to drain back into the holding vessel. This caused a series of four weaker excursions that ended at approximately 08:00. At 15:00, personnel remotely injected cadmium nitrate solution, anticipating that it would mix well with the aqueous solution thought to be in the vessel, assuring subcriticality. Instead, the cadmium lessened the system's subcritical margin by displacing organic solution from the rounded bottom of the vessel. A hose was then inserted to siphon solution from the vessel bottom. By removing the cadmium solution first and allowing organic solution back into the bottom, a sixteenth and final excursion occurred when remote siphoning began. However, personnel continued siphoning.

Total yield is now estimated at 6e16 fissions over 16 hours. The accident did not damage equipment or result in radioactive contamination. The process design was changed. After renovation, nearly all vessels had safe-by-geometry designs for all enrichments.

Since the area's criticality alarm system activated due to the first burst and personnel evacuated safely, the largest dose to any individual was less than 5 rem.

---

[e] Apparently, system safety analysis addressed inadvertent overflows, but the size and/or number of overflows were not necessarily anticipated.

## A.1.14 July 24, 1964, UNC, USA

Controlled factors: geometry

Other factors: concentration

Excursion(s): two separate bursts with second due to stabilization/recovery action

Criticality/radiation alarms: both

Radioactive contamination: ejected, possibly tracked, solution

Radiation exposure(s) (rad): 10,000, 100, 60 and minor

Medical consequences: one fatality, no other consequences reported

Equipment/facility damage: none

Lessons-learned topics: human factors (convenience [design/procedure], material segregation, labels, available vessels), conduct of operations (procedure compliance, communication, material segregation, labels), emergency planning (CAS, evacuation, multiple bursts, stabilization/recovery can cause additional excursions, material removal)

The United Nuclear Corporation Wood River Junction plant in Charlestown, Rhode Island, had scrap facilities designed to recover enriched uranium from reactor-fuel-fabrication scrap. Operations started in March and were still preliminary in July, when the accident occurred. Operators were trained on procedures and limits, but had little understanding of criticality safety and little or no nuclear experience. Supervisors had a little more training and experience.

Because of startup difficulties, there was an unusual accumulation of uranium-contaminated trichloromethane. There were also very concentrated U-235 solutions, from evaporator clean-out. Bottles of concentrated solutions were stored on individual bird-cage carts in a roped off area. But contaminated trichloromethane was stored in the same kind of 11-liter, 5-inch-diameter, 4-foot-long bottles, in the same general area.

Per procedure, operators recovered uranium from contaminated trichloromethane by adding sodium-carbonate solution to the bottles and then shaking the heavy bottles by hand. Operators eventually improvised to make this very tedious and tiring process easier. They put the contaminated trichloromethane and sodium-carbonate solution in a stirrer-equipped, bottom draining, 18-inch-diameter tank. Located on the third floor, the tank was supposed to be used only to make up sodium-carbonate solution. Two of three shift supervisors were aware of the improvisation, but had not intervened. The plant superintendent was unaware of the improvisation. This not-safe-by-geometry tank was the excursion site.

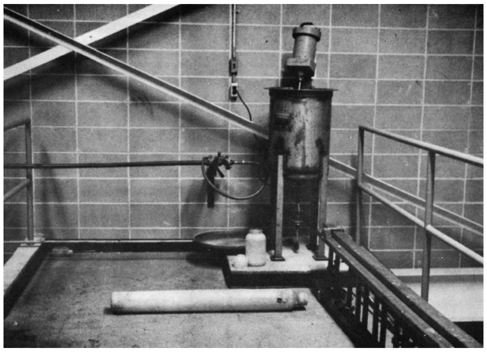
Reconstructed position of operator just before UNC criticality accident.

Although it was labeled and segregated, the operator apparently mistook a bottle of concentrated solution for trichloromethane and poured it into the sodium-carbonate-makeup tank.

From the most plausible event reconstruction, two excursions occurred about two hours apart. The first, a single burst of about 1e17 fissions, occurred after the operator poured most of the concentrated solution into the tank. He observed a blue flash. The shock of the excursion splashed about one-fifth of the solution out of the tank and knocked the operator onto the floor, causing him to drop the bottle into the tank.

Radiation alarms activated. The victim ran down stairs, out of the building and to an emergency center (guard shack) about 200 yards from the plant. He received a dose of about 10,000 rad and died 49 hours later. The supervisor and other workers in the building were at least 40 feet away from the vessel. They evacuated immediately by the nearest exit and received minor exposures.

The first excursion apparently ejected enough solution that the vortex from a tank stirrer maintained a subcritical state. Almost two hours after the first excursion, however, the superintendent and supervisor entered the area. The superintendent eventually approached the tank, moved the 11 liter bottle from the tank to the floor, turned off the stirrer, and proceeded downstairs. An attempt to drain the tank was unsuccessful. They returned to the tank, turned on the stirrer, proceeded downstairs, and successfully drained the tank.



After-accident scene with tank and stirrer, pan, one gallon bottle, 11 liter bottle, and ladder. These items helped investigators identify the operator's position. The splash/spill is barely visible.

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 men did not know about this excursion because radiation alarms were still sounding from the first excursion, they were not looking at their portable meters at that time, there was no light flash and they were too far away to feel any heat the excursion generated. The supervisor and superintendent received radiation doses of 60 and 100 rad, respectively.

Altogether, the excursions produced about 1.3e17 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. The tank was removed and safe-by-geometry equipment was put into operation for recovering uranium from trichloromethane.

## A.1.15 November 3, 1965 MPB, USSR

Controlled factors: mass or concentration (prevent most material from entering)

Other factors: enrichment, geometry, moderation

Excursion(s): one burst

Criticality/radiation alarms: CAS (unknown regarding radiation alarms)

Radioactive contamination: trays used in stabilization

Radiation exposure(s): one with maximum 3.4 rem

Medical consequences: none

Equipment/facility damage: gauge broken for stabilization

Lessons-learned topics: design (geometry, filter defects), conduct of operations (procedure compliance, equipment condition, perhaps configuration control), inadvertent transfer (in some sense), emergency planning (possibility of accident with low enriched uranium, CAS, evacuation, material removal)

This accident involves low-enriched (less than 10%) uranium powder. The process converted uranium hexafluoride gas, $UF_6$, into uranium dioxide powder, $UO_2$. For approximately a year, the process converted 2% enriched uranium. It was then shut down, completely cleaned, and restarted to convert 6.5% enriched uranium. The accident occurred 12 days after this restart, in a not-safe-by-geometry water-supply vessel for the vacuum pump.

$UF_6$ gas was burned in a conversion hopper to produce uranium-oxide solids, which were then transferred by a vacuum system to an accumulation hopper. The vacuum was then turned off and the oxide fed, by gravity, into a safe-by-geometry vessel that could be removed and transferred to another system.

A primary filter on the accumulation hopper and a secondary filter between the hopper and the rest of the system prevented oxides from entering the rest of the vacuum system. Procedures required the secondary filter be checked once each six-hour shift (four shifts per day). If the secondary filter had a defect, or was opaque due to oxide accumulation, procedures required it be replaced and the primary filter be inspected. Procedures also required that a sample of water from the supply vessel be analyzed for uranium each shift. There was no non-destructive assay equipment in place or routinely used to detect uranium accumulation.

On November 3, 1965 at 11:10, the building CAS activated, but the CAS in an adjacent building did not activate. All personnel evacuated per procedure. About 50 minutes later, the facility's chief physicist reentered the building and, using a portable gamma-ray detector, determined a criticality accident had occurred in the water supply vessel. Planned to avoid more excursions, stabilization involved breaking a gauge on the vessel's side to allow some liquid to drain into carefully positioned, safe-by-geometry trays.

Subsequent analysis, investigation, and cleanup revealed that the water supply vessel contained approximately 3.65 kg U-235. An additional nearly 1 kg U-235 was found in the vacuum system's heat exchanger. However, the entire vacuum system should have had no more than trace amounts of uranium anywhere past the filters.

The vacuum system restarted the previous month (October), with no uranium in it, but the filtering system was not properly maintained after restart. The primary filter was missing at the time of the accident, but investigators could not determine how long the facility had operated without it. The secondary filter was not completely secured in place. In addition, the water had not been sampled since restart. Further, a third filter was not installed before restart, although it was recommended (but apparently not required) to improve criticality safety for the higher enrichment.

The one-burst accident produced an estimated 1e16 total fissions. The excursion was probably initiated by slowly accumulating oxides that settled to the bottom of the water supply vessel after the vacuum system was turned off. Continued settling, or expulsion into interconnecting lines, could have shutdown the critical system. There was no damage, and contamination was limited to the aforementioned trays. One worker, who was approximately 4½ m (~4.9 yards) from the vessel when alarms sounded, could have received a maximum estimated 3.4 rem.

### A.1.16 December 16 1965, MPA, USSR

Controlled factors: concentration, mass

Other factors: geometry, absorption

Excursion(s): 11 separate bursts over 7 hours

Criticality/radiation alarms: CASs (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): 17 received maximum 1 rem, seven received 0.1-0.2 rem, two received 0.2-0.27 rem, and three responders received maximum 0.3 rem.

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry), conduct of operations (procedure compliance, communication, material accountability, schedule/production priority), human factors (operator expectation), emergency planning (CAS, evacuation, multiple bursts, remote readouts, absorber)

This accident at a Mayak Enterprise's facility for dissolving uranium scrap also involved highly enriched uranium. This accident occurred in a not-safe-by-geometry dissolver vessel in one of three identical dissolution-precipitation-reduction lines in one glovebox. The subject system recovered uranium from process residues generated at another facility. Subject residues typically contained less than 1 wt% uranium. However, the facility that generated these residues also produced more concentrated residues that were, by procedure, directed to other handling areas subject to special requirements.

On December 15, 1965, a shift supervisor directed that batch 1726 be calcined, prior to dissolution, in a system intended only for processing material that was less than 1 wt% uranium. This direction violated established criticality safety rules because the batch had greater than 1 wt% material. Batch 1726 was calcined, sampled, and, before sample results were available, transferred to a glovebox with other batches awaiting dissolution. The analytical laboratory determined the batch contained 44 wt% uranium, and recorded these results in its own records, but did not transmit these results to the facility for inclusion on batch 1726's accountability card. Later in the day, an operator noticed the lack of information on the card and contacted the laboratory. Due to poor communication, results from a different batch, with 0.32 wt% uranium, were provided, and the operator recorded this erroneous information on batch 1726's card.

On December 16, 1965, an operator put some of batch 1726's material into dissolver #1 using this erroneous information. At that point, the dissolver contained more than 700% of its mass limit. At the same time and in accordance with procedures, dissolution of other material proceeded in dissolvers #2 and #3 in the same glovebox.

Procedures required that material be dissolved at 100°C for at least 90 minutes with constant mixing. However, to accommodate a regularly scheduled cleaning on the next shift, dissolver #1's equipment was turned off after 40 minutes. Approximately 10 minutes later, the nearest criticality alarm sounded for a short time. Per procedure for a single alarm, the operator evacuated the area, reporting to a control room to determine alarm cause. As the operator arrived, that alarm again sounded. Within seconds, at approximately 22:10, other alarms activated. Eventually, several dozen alarms, located in different parts of the building, sounded. Personnel promptly evacuated to an underground tunnel per procedures.

From another building about 50 m (54½ yards) away, four more excursions, about 15 to 20 minutes apart, were observed using remote readout, neutron- and gamma-ray-sensitive equipment. Based on the readouts and other information, further response actions were safely moved to the subject facility’s control room, where additional excursions were observed through radiation instrumentation. Responders determined the excursions were occurring in either dissolver #1 or its associated holding vessel based on interviews, accountability records, system schematics, and radiation readings. After the ninth excursion, responders remotely added cadmium solution to the holding vessel. A tenth excursion approximately 20 minutes later proved the excursions were occurring in dissolver vessel #1. Removing vessel #1’s contents and/or adding cadmium solution to it were judged too dangerous due to the recurring excursions and the time-intensive manipulations required near the vessel. Therefore, responders decided to (1) remove two gloves and (2) through their ports, open the dissolver’s feed hopper and (3) insert a crumpled-up cadmium-foil ball into the dissolver through the hopper. The first two steps were completed. Then operations halted as instruments indicated an 11th excursion was under way. When radiation levels decreased, the third step was completed, and the foil immediately began to dissolve. The cadmium terminated the excursions. The following day, solution was transferred from the dissolver to safe-by-geometry vessels using temporary piping.

The 11 excursions produced an estimated 5.5e17 total fissions over seven hours. No equipment was damaged and no contamination resulted. Of the personnel in the area at the time of the first excursion, 17 received doses of 0.1 rem or less, seven received doses of 0.1 to 0.2 rem, and 3 received doses between 0.2 and 0.27 rem. Due to careful planning, special briefings, minimizing time in the area (30, 60, and 20 seconds respectively), and ensuring they did nothing to cause more excursions, the three operators who terminated the reaction each received no more than 0.3 rem.

Normal operations resumed within several days. During the following three years, about 94% of the process equipment was replaced with safe-by-geometry equipment.

### A.1.17 December 10, 1968, MPA, USSR

Controlled factors: concentration

Other factors: geometry

Excursion(s): three excursions, third caused by apparent “recovery” action

Criticality/radiation alarms: CASs (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): 2450 rem, 700 rem, 19 at less than 0.1 rem, four with 0.1 to 0.15 rem, one at 1.64 rem, one at 2 rem.

Medical consequences: one fatality, one radiation sickness with amputation (legs, one hand), no other consequences reported

Equipment/facility damage: none

Lessons-learned topics: design (geometry, connections between vessels), inadvertent transfers, change analysis, conduct of operations (material segregation, equipment condition, procedure compliance, limit violation stabilization/recovery, improvisation, ), emergency planning (CAS, evacuation, multiple bursts, re-entry authorization, stabilization/recovery can cause additional excursions, material removal)

A criticality accident occurred December 10, 1968, while testing a new technology for plutonium extraction at the Mayak Enterprise.

A small-scale research and development operation was set up to investigate purification properties of various organic extractants. As originally built, the piping and configuration prevented organic solution from entering tanks in a nearby area that were used for collecting very low concentration, aqueous, plutonium solutions. However, various changes allowed organic solution from two different extractants to migrate, undetected, to the tanks. Each of the tanks was equipped with neutron detectors to monitor plutonium concentration and sediment accumulation.

On December 10,1968 at 19:00, the shift supervisor directed an operator to sample tank 2 before transferring its contents to recovery operations. The operator sampled manually because the sampling device was out-of-order. Sample results indicated tank contents exceeded the tank's plutonium mass limit.

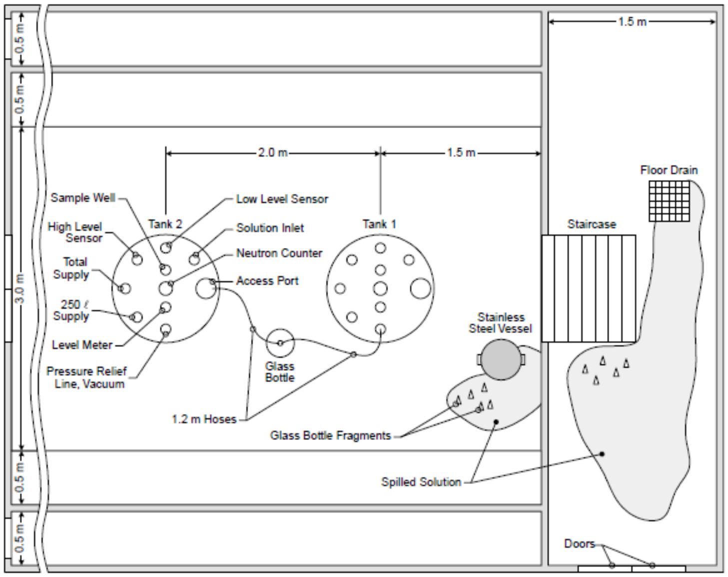
Per procedure, the supervisor ordered two additional samples. While taking these samples, personnel noticed there was organic material in the samples. The supervisor directed that the organic solution be decanted before sending these samples to the lab. Personnel confirmed the presence of an organic solution layer in tank 2 by viewing its contents through an access port. Before confirmatory sample analysis results were available, but knowing that downstream processes could not handle organic solution, the supervisor decided to remove the organic layer and transfer some of tank 2's aqueous solution to tank 1 so that tank 2 would comply with its limits.

Existing regulations prohibited temporary, improvised set-ups. However, organic solution removal was improvised using temporary hoses, a 20 L glass bottle normally used for chemical reagents, and a vacuum. Personnel decided that, if the glass bottle filled, its contents would be poured into a not-safe-by-geometry, 60 L, steel vessel typically used for low concentration wastes. As directed, two operators began decanting the dark-brown organic solution. (This color indicates high plutonium concentration.) After decanting approximately 17 L, they poured the decanted material into the steel vessel and began decanting more into the 20 L glass bottle. They stopped decanting because aqueous solution was also entering the glass bottle. One operator then went on to other duties while the second operator consulted with the shift supervisor. Adjusting the process as directed by the supervisor, the second operator resumed decanting, almost filling the 20 L glass bottle.

After pouring most of the bottle's contents into the 60 L steel vessel, the operator saw a flash of light and felt a heat pulse. Startled, he dropped the bottle, shattering it and spilling its remaining organic liquid around the steel vessel. At that instant (22:35), the criticality alarm sounded in the room above these tanks. A criticality alarm system in a building approximately 50 m (54½ yards) away also sounded briefly. Per procedure, all personnel evacuated to an underground tunnel. The radiation control officer notified plant managers of the accident, sent the operator to a decontamination and medical facility, collected dosimeter badges, and ordered personnel to stay out of the building in which the accident occurred.

Nearby neutron detectors recorded a second excursion at 23:50, while personnel were in the tunnel. This excursion might have resulted from solution cooling, which would increase solution density, or by a gas release due to a chemical reaction.

The shift supervisor reentered the work area, against the radiation control officer's orders. There is evidence he attempted to remove the 60 L vessel or pour its contents down stairs into a floor drain. A third, larger excursion occurred that set off criticality alarms in both buildings. Covered in plutonium organic solution, the supervisor returned to the tunnel and was then sent to a decontamination and medical facility.



Plan view sketch of the scene after the 1968 criticality accident.

Stabilization actions included draining solution from the steel vessel into safe-by-geometry containers using a long handled, large radius of curvature, hose and a portable vacuum pump. The volume and mass of organic solution in the steel vessel at the time of the first two excursions can only be estimated at about 35 L and about 1.6 kg Pu.

Yields are respectively estimated at 3e16 and 1e17 fissions for the first and third excursions. Only the glass bottle was damaged, when it dropped. Contamination was more significant than in most other criticality accidents because of the dropped bottle and supervisor's actions.

The shift supervisor received an estimated 2450 rem and died about a month later. The operator received an estimated 700 rem with extremity exposures that necessitated amputating both legs and one hand. Of the other 27 people who evacuated, 19 received no more than 0.1 rem, four received less than 0.15 rem, one received an estimated 1.64 rem, and one received an estimated 2 rem.

Investigation identified several contributing factors: (1) supervisor's decisions to take improvised, unauthorized actions to recover from a limit violation in tank 2, (2) piping changes that defeated provisions to prevent organic solution entering the tanks, (3) valve misalignments that resulted in advertent transfers from the research vessels to the tank and from the extraction facility to the tank, (4) a transfer from tank 1 to tank 2 on Dec. 10, 1968, which included an unknown amount of plutonium, and (5) supervisor's unauthorized actions between the second and third excursions.

### A.1.18 August 24, 1970, WW, UK

Controlled factors: not specified in summary here

Other factors: geometry, concentration

Excursion(s): one burst over less than 10 seconds

Criticality/radiation alarms: CASs (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): one at 2 rad, one at less than 1 rad

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry), change/system analysis (subtle effects, fully analyze safety features, very slow buildup), conduct of operations (material accountability)

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

The accident occurred in a solvent extraction portion of a plutonium recovery plant with well-established controls. A 25-foot deep-trap, or lute, installed as a safety feature for contamination control between a transfer tank and constant-volume feeder, contributed directly to the accident. Personnel did not realize that design and material characteristics caused any solvent in the tank to be trapped until a particular 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 10 g) from each batch. Presumably periodic plant cleanout sharply reduced the plutonium concentration without completely removing the solvent and plutonium, which delayed, but did not prevent, the critical excursion. The loss of plutonium in each transfer and, possibly, the gain of plutonium with each cleanout was probably so small that they were un-noticed or possibly even undetected.

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

Investigation indicated 39 L solvent, containing 2.15 kg Pu, was present in the tank and tank leg of the trap. Solvent degradation indicated this solvent had been trapped for at least several months and possibly up to two years as its fissionable concentration increased very slowly. The excursion, which produced about 1e15 fissions, apparently initiated and shut down due to very subtle differences in aqueous and organic phase geometries as that last transfer ended.

## A.1.19 October 17, 1978, INEL (ICPP), USA

Controlled factors: concentration

Other factors: geometry

Excursion(s): probably multiple bursts over an extended time

Criticality/radiation alarms: constant air monitors, no CAS (shielded facility; CAS installation not yet complete)

Radioactive contamination: none

Radiation exposure(s): none significant

Medical consequences: none

Equipment/facility damage: none, but plant shutdown for two years

Lessons-learned topics: human factors (operator experience, training), system analysis, conduct of operations (procedure compliance, instrument/alarm operability, questioning/observant attitude, configuration control, document control, adequate controls, response to non-normal conditions), design (geometry, process monitoring, valves leak, shielding), emergency planning (radiation alarms, evacuation)

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 excursions occurred in the lower head of a scrub column. The column had a relatively small-diameter main body and, above and below, rather large-diameter disengaging heads. The aluminum-nitrate scrubbing-agent was slowly diluted, by more than a factor of 10, because water leaked through a valve to a makeup tank. Dilution went unnoticed because a low-density solution alarm was inoperable, the dilution was so slow it would require analyzing several days of chart recordings to discover from the chart, the chart recorder had been out of paper for about 18 days, and the feed tank's 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. 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, by about a factor of 100, in aqueous solution that was in the column's lower head region. At the time of the accident, the lower disengaging head had an estimated 10 kg uranium, compared to its normal inventory of slightly less than 1 kg.

On Tuesday, October 17, 1978 at approximately 20:00, an operator had trouble controlling the associated extraction column. He therefore adjusted system pressure. This adjustment increased aqueous flow to the scrub column. At approximately 20:40, the plant-stack-radiation-monitor alarmed, probably due to fission products in plant-stack gasses. Shortly thereafter, many radiation alarms around the plant sounded and the stack monitor showed a full-scale reading. The shift supervisor ordered area evacuation at 21:03 based on measured radiation (100 mrem/hr) outside the building. Plant personnel relocated to a guard-gate more than 50 yards away; other personnel assembled in an area approximately 3½ miles away. Prior to evacuating, an operator shut off feed to the columns, but did not stop column pulsation.

This concentration and configuration apparently was slightly *delayed supercritical* over an extended time.[f] Increasing temperature would normally make the system subcritical (negative reactivity feedback effect), but higher temperatures enhanced uranium extraction, maintaining the supercritical condition. The excursion probably terminated due to the effects of operator action, temperature feedback, or both.

The accident produced 2.7 e18 fissions over about 25 minutes without any solution release or equipment damage. Shielding prevented any substantial radiation exposure to personnel.

Investigators identified several contributing factors, in addition to the previously described reasons that aluminum-nitrate dilution was not identified: (1) personnel did not notice that significantly more solution was transferred to the make-up tank than should have been available, (2) the density recorder and alarm for the aluminum nitrate tank had not been installed although it appeared on controlled plant-drawings, (3) procedures used

---

[f] The reaction was sustained by neutrons released up to 1½ minutes after each fission event. In a reactor, delayed neutrons allow a more stable power level.

on the floor were out-of-date, although they included the sampling instructions that had not been followed, (4) the level of operator experience declined dramatically in the two years preceding the accident, (5) a four year old safety analysis had identified the criticality risk of dilute aluminum nitrate, but had not developed controls to assure dilute solution was not used and did not define recovery actions if dilute solution was found.

As a result, the plant was shut down for two years. During that time, safety analysis, operating procedures, maintenance procedures, and operator training were intensively reviewed and, as necessary, revised. In addition, an extensive, highly instrumented plant protection system, with redundant sensors and automatic safety controls, was installed.

## A.1.20 December 13, 1978, SCC, USSR

Controlled factors: mass

Other factors: geometry

Excursion(s): one burst

Criticality/radiation alarms: CASs (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): one with 250 rad whole body and 20000 rad to hands, seven with 5 to 60 rad

Medical consequences: one case of severe radiation sickness with amputation (lower arms) and eventual sight impairment, no other permanent consequences reported

Equipment/facility damage: none

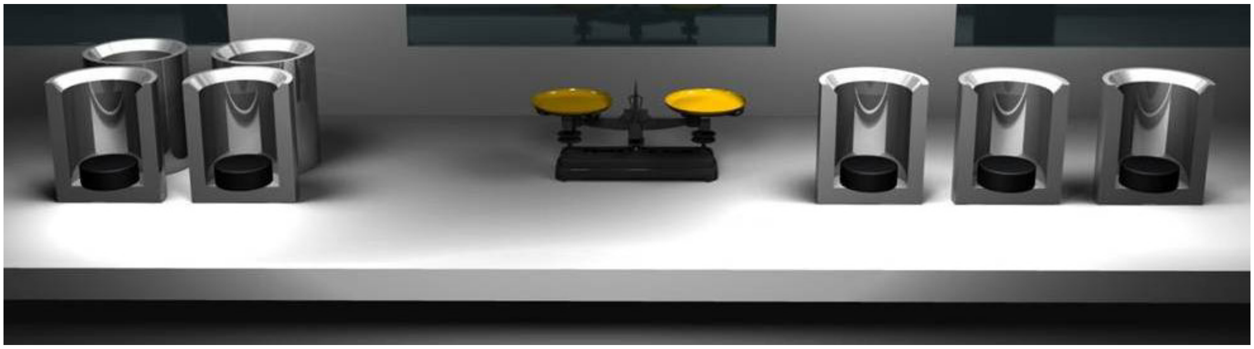
Lessons-learned topics: design (geometry, process monitoring), conduct of operations (procedure compliance, communication, perhaps different limits for one out of many glove boxes, material accountability, defined responsibilities), perhaps human factors (different limits for one out of many glove boxes), emergency planning (CAS, evacuation, material removal)

This fourth Siberian Chemical Combine accident is unique because it involves metallic fissionable material in a configuration not intentionally designed to be critical.

Plutonium ingots were transferred through partially shielded glove boxes where they could be temporarily stored in containers. Ingots were made elsewhere, and contained a maximum 4 kg of pure plutonium oxide, or maximum 2 kg of plutonium from other sources.

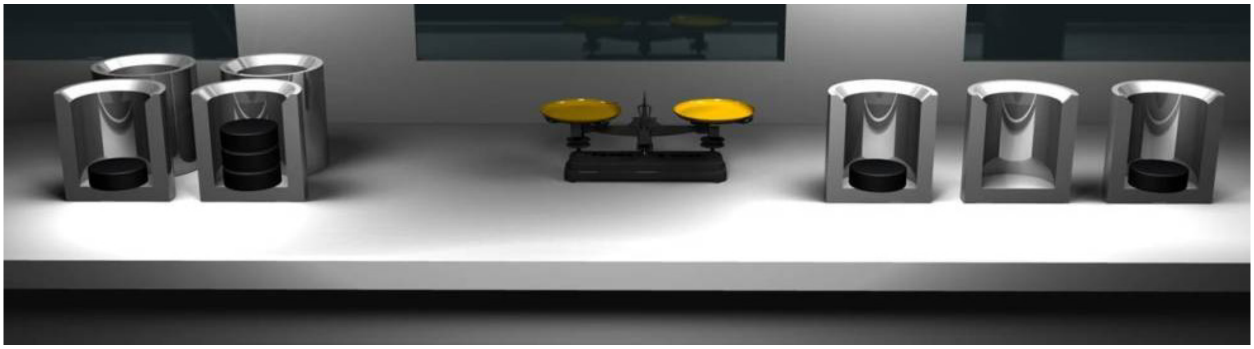
Ingot containers were lined with polyethylene and cadmium to reduce neutron interaction. The lining ensured that a planar array of containers was subcritical if each container was subcritical, regardless of the number or arrangement of containers. In most of the area, each container was limited to no more than two ingots that, together, did not exceed 4 kg. However, in glovebox 13 where the accident occurred, containers were limited to one ingot each.

These ingot containers could physically hold more than the minimum critical mass of ingots. It was assumed that operating personnel were proficient and disciplined enough to avoid gross errors when loading ingot containers. This assumption was also supported by procedures. First, procedures required that ingots be removed from, and inserted into, containers one at a time. Second, by procedure, each operator was assigned specific tasks when the shift started, and was not allowed to deviate from those assigned tasks even to help another operator with other assigned tasks.

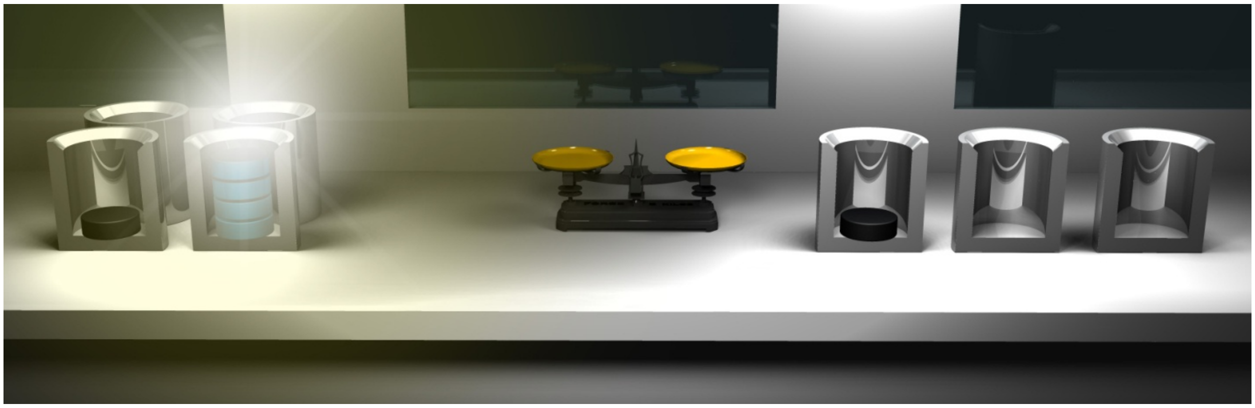


Before first loading error on Dec. 13 1978. No more than one ingot per container.

After first loading error (operator B) on Dec. 13 1978. Two ingots in one container.



After second loading error (operator A) on Dec. 13 1978. Three ingots in one container.



With third loading error (operator A) on Dec. 13 1978. Four ingots in one container.

On December 13, 1978, each of the seven containers in glovebox 13 contained one ingot. Operator A was assigned to transfer six ingots out of the glovebox, and transfer another six ingots into the glovebox. Operator A completed transferring two ingots out and another two ingots in following the shift instructions. Then, motivated by production pressure to complete the assigned transfers as quickly as possible, Operator A asked Operator B to help, without authorization and in violation of procedures. Working from oral rather than written instructions during Operator A's absence, Operator B mistakenly transferred one ingot into a container already holding an ingot, violating the container's limit. Operator A soon thereafter transferred a third and fourth ingot to the container that Operator B had already double batched.

While placing the fourth ingot into the container, Operator A felt a sharp temperature increase near his hands and saw a light flash. The excursion was immediately terminated by thermal expansion and either removal or ejection of the fourth ingot. At the same time, the criticality alarm sounded in the subject building and in an adjacent building. Personnel evacuated per procedure, except Operator A, who delayed long enough to transfer two of the remaining three ingots to containers in other gloveboxes.

Investigators determined that, during the final overbatch, the container had 267% of its mass limit, as well as 400% of its ingot-number limit. The single excursion produced an estimated 3e15 fissions. No equipment was damaged, and no contamination resulted from the excursion.

Operator A received 250 rad whole body, with up to 2000 rad to his hands. His hands and lower arms were amputated to save his life. Later his eyesight became impaired. Seven other persons in the general area received doses from 5 to 60 rad, apparently without permanent adverse affects.

Initial summary reports in English identified the following contributing factors: (1) procedure violations, (2) container physical capacity, (3) lack of instrumentation to monitor plutonium mass in containers, and (4) lack of clearly defined responsibilities for material accountability.

### A.1.21 May 15, 1997, NCCP, RF

Controlled factors: geometry, mass (number of rods)

Other factors: density (precipitate vs. dilute solution), enrichment, absorption

Excursion(s): 6 bursts over 26 hours, with quasi-static system after the fifth burst

Criticality/radiation alarms: CASs (unknown regarding radiation alarms)

Radioactive contamination: none

Radiation exposure(s): insignificant

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: design (geometry), change analysis (enrichment, precipitation, geometry), conduct of operations (material accountability, process monitoring, configuration control, equipment integrity, questioning/observant attitude, change approval), emergency planning (CAS, evacuation, quasi-static system, neutron absorber)

The last Russian 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 that collected solution from a uranium-fuel-rod etching process. For its 13 years of operation, the etching process controls had been (a) number of fuel rods etched per batch, (b) solution temperature, (c) reagent concentration, and (d) etching duration. There were no requirements or provisions to monitor or measure uranium content in the solutions, or precipitation in the vessels. There were also no criticality safety requirements to monitor or remove uranium accumulation(s) in this process. This was because, by original design and according to records, the entire system used safe-by-geometry equipment with exception of the vessels in which rods would be immersed.

In 1996, a large solid uranium deposit was discovered in one of the process vessels during an inspection. Analysis indicated the deposit included 36% enriched uranium from fuel etched more than ten years before, as well as 90% enriched uranium from fuel etched since 1986. This deposit was dissolved, but no further actions were taken to determine if other equipment held such deposits because neither criticality safety nor material accountability required such actions. (Material accountability was based on mass balances for the entire building. The small fraction of material lost by precipitation in these vessels went unnoticed compared to the large amount of material in a fuel rod batch.)

The two, large (3.5 × 2 × 0.10 m [138 ×79 × 3.9 in.]), parallel slab tanks were designed to be safe-by-geometry for uranium enriched to 36% or less. Each tank included interior tie rods to ensure the tanks maintained their geometry. In addition, steel sheets were placed parallel to, and about 14 cm (5.5 in.) from the tanks to preclude close reflection. These tanks were licensed for 36% or less enriched fuel, but the regulatory authority had not been consulted when the fuel was changed to 90% enriched.

On May 15, 1997 at 10:00, an operator completed etching a fuel-rod batch and began transferring solution. At 10:55, the criticality alarms in much of the subject building sounded, and personnel evacuated per procedure.

Based on exposure rates measured with portable instruments, responders determined the critical excursion occurred in one or both slab tanks. To terminate excursions and stabilize the tanks, responders pumped borated solution through the system to the slab tanks, after which the tanks contained about 95% of their capacity.

Despite this action, four more excursions were detected at 18:50, 22:05, and, on May 16, at 02:27 and 07:10. Responders decided to circulate solution and introduce lithium chloride, a neutron absorber that is much more soluble than boron. To ensure personnel safety, this further action was delayed until after the sixth and final excursion at 13:00. At 14:00, lithium chloride injection began, and the system was safely shutdown.

Investigation and analysis revealed that the bottom of the tanks contained precipitated uranium in the form of slurry and a solidified crust. Approximately 24.4 kg uranium, with an average 70% enrichment, was recovered from the tanks. In addition, the tanks had bulged near their bottoms, apparently slowly deforming over their lifetime. The maximum and average deformations were approximately 132% and 117% of the design thickness, respectively. Investigation also revealed that, after the fifth excursion, the accident entered a quasi-static phase that required intervention to terminate.

The six excursions over approximately 26 hours produced an estimated 5.5e15 total fissions. No equipment was damaged and no contamination resulted. Radiation exposures were negligible; the combined dose of the 20 closest people was a maximum

0.4 rem. Although the fire department responded when evacuation alarms sounded, the accident did *not* involve any fires or injuries

The facility remained shut down for about three months. In that time, personnel replaced tanks, cleaned out the process, and instituted programs to regularly monitor vessel integrity and uranium accumulation.

## A.1.22 September 30, 1999, JCO, Japan

Controlled factors: mass, enrichment

Other factors: geometry, reflection

Excursion(s): one burst followed by a quasi-static system over about 19¾ hours

Criticality/radiation alarms: gamma-sensitive constant air monitor, no CAS (criticality accident deemed *not credible*)

Radioactive contamination: small quantity of spilled solution

Radiation exposure(s): 16-20 GyEq, 6-10 GyEq, 1-5.4 GyEq, responders at maximum 1 mrem, many off-site people with less than 0.05 mrem, a few off-site people with up to 0.25 mrem.

Medical consequences: two fatalities, one other case of radiation sickness, some claims of what appear to be psychosomatic conditions

Equipment/facility damage: none

Lessons-learned topics: human factors (mind-set, training [limits, reasons for limits], convenience, availability of equipment), conduct of operations (procedure compliance, change approval and control, oversight, perception of controls, review, perceived schedule/production pressure), design (convenience, geometry, facility/plant location with respect to public), emergency planning (radiation alarm/CAS, evacuation, quasi-static system, material removal, public protective actions, public information, public education, internet, available resources), regional and global consequences, criminal investigation

The most recent out-of-reactor criticality accident occurred in a uranium fuel fabrication facility of the JCO Company in Tokaimura, Japan. The accident is unique because of the facility's inner-city location. Members of the public (off-site people) received measurable radiation doses, albeit well below allowable worker annual doses.

JCO had three production facilities. Two were large-scale facilities with enrichments up to 5%. The third, the Fuel Conversion Test Facility, was a small-scale facility used occasionally for processing material with higher enrichments. The accident occurred in this small-scale facility while preparing 18.8% enriched uranyl nitrate solution, a process that was last performed more than a year previous.

Criticality safety was implemented by batch mass-limits that were enrichment-specific. A criticality accident was deemed incredible based on these limits and assumed procedure compliance. Workers were therefore trained on procedures and applicable limits, but were not trained on general criticality safety. JCO had a few gamma-sensitive radiation alarms, but no criticality alarm system. Similarly, they had an emergency plan, but it did not address major radiological accidents, let alone criticality accidents.

The license-approved written procedure for this particular job required (1) adding one batch of uranium oxide and nitric acid to a dissolver vessel, (2) transferring that batch's uranyl nitrate solution to one or more of four safe-by-geometry vessels, (3) homogenizing accumulated solution by circulating solution between, and bubbling nitrogen gas through, the safe-by-geometry vessels, and (4) draining the homogenized solution into small containers.[g]

However, workers used a different procedure that included two significant deviations from the licensed procedure. To save about an hour of time per batch, the JCO-approved procedure allowed workers to dissolve each batch separately in 10-L stainless steel buckets. Although this deviation from the license-approved procedure increases worker risk, any effect on criticality safety is limited to safety-culture issues.

The second deviation is much more significant to criticality safety: operators poured dissolved batches into a not-safe-by-geometry precipitation tank that was also part of the facility's versatile system (similar to operator decisions in the UNC accident, Subtopic A.1.14). Compared to the four safe-by-geometry vessels, this large diameter tank had

- about the same volume as the four vessels combined,
- a mechanical stirrer that could homogenize solution more quickly,
- a drain-cock that was much more conveniently located for filling the small containers, and
- a coolant (water) jacket that would reflect neutrons when it contained water. This jacket contained water at the time of the accident.

The JCO accident tank. The larger diameter portion is a water jacket around the tank.

On Wednesday, September 29, 1999, three operators dissolved four batches, separately pouring solution into the precipitation tank. The next day, these same three operators followed the same procedure with three more batches to complete the job. Each of the seven batches was close to its individual mass limit. They began pouring the seventh, and last, batch into the tank at about 10:35 as shown to the right. When they were nearly finished, all JCO's radiation alarms activated. (At this time, the tank contained more than 650% of its applicable mass limit.)

Approximate, initial location of operators O and S during the JCO excursion.

Everybody on-site evacuated per procedures. Personnel then relocated because portable instrumentation indicated an unusually high gamma radiation field in the original assembly area. About 4½ hours after the start of the accident, radiation readings indicated a combined neutron and gamma dose rate of about 5 mSv/hr (0.05 mrem/hr) at the plant boundary. Tokaimura's mayor therefore recommended that people living or working within 350 m (383 yards) of the JCO plant evacuate to more remote locations. The order affected approximately 200 people. About 12 hours after the start of the accident, local, prefecture, and government officials

---

[g] This license approval does not indicate that regulators reviewed every line of a procedure. This license-approved procedure included a significantly more efficient solution-homogenization method than regulators later indicated they understood was approved.

recommended people within 10 km (6.2 miles) of the plant remain indoors because of measurable airborne fission product activity. This recommendation affected approximately 310,000 people in all of Tokaimura and parts of eight other municipalities. The order effectively closed many businesses, several important roads, and part of the commuter train system.

JCO personnel initially used radiation readings at the first personnel assembly area to determine that a criticality accident had occurred and was ongoing. However, JCO was not prepared to respond to a criticality accident because such accidents had been deemed incredible. Response therefore included obtaining expertise and neutron-sensitive instruments from nearby nuclear facilities operated by different organizations.[h]

After the initial burst, the critical condition continued with a quasi-stable power level for about 17 hours. Responders were then able to partially drain the tank's water jacket by breaking a pipe. The critical condition continued at a reduced quasi-stable power level for about 2-1/2 hours. Responders then forced water from the jacket by injecting argon gas through the piping. Later, responders added soluble neutron absorber to the tank to ensure that the system remained subcritical during investigation, recovery, and cleanup. The accident produced an estimated 2.5e18 fissions total in its approximate 19-3/4 hours at power, burning an estimated 0.001 g U-235.

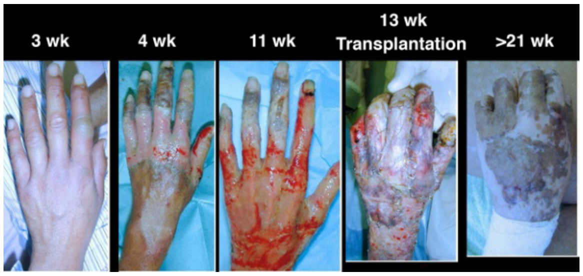
In addition to the stated procedure violations, the following contributing factors can be concluded from investigation reports:

- Most or all JCO personnel had a weak understanding of criticality control factors in a general sense. Production personnel specifically did not understand geometry effects. These people also did not recognize that a water jacket could be a critical factor.
- Human factor considerations and company pressures to operate more efficiently motivated workers to develop shortcuts that were not imagined when system safety was analyzed.
- The mind-set at all JCO and regulatory levels was that a criticality accident was not credible at JCO. This conviction resulted in inadequate review of procedures, equipment, human factors, emergency plans, etc. In turn, inadequate review resulted in inadequate training, procedures, ergonomic designs, plans, oversight, etc.

---

[h] At the time, Tokaimura was home to 15 nuclear facilities including commercial power reactors, processing facilities, reprocessing facilities, research facilities, and laboratories. Adjacent municipalities also had nuclear facilities.

Of interest to emergency planners and public educators, the overall response effort also included much more media interest, and a much larger internet-communication component, than had ever been considered during emergency planning. These factors complicated efforts to provide appropriate information and explanations, minimize misinformation, minimize public panic, protect individual's privacy, and protect information needed for accident and criminal investigations.



Clinical course of radiation burns (Operator S)

Radiation exposures ranged from severe to negligible. Operator O, who held the funnel, received 16-20 GyEq (~1600-2000 rem),[i] was hospitalized, and died 82 days after the accident. Operator S, who poured solution into the funnel, received 6-10 GyEq (~600-1000 rem), was hospitalized, and died 210 days after the accident. Operator Y, who was at a desk a few meters from the tank, received 1-4.5 GyEq (~100-450 rem), was hospitalized, and was released from the hospital 81 days after the accident. Of offsite people within the 350 m radius, 90% received less than 5 mSv (0.05 mrem), and none received more than 25 mSv (0.25 mrem). Responders were administratively limited to a maximum 0.1 Sv (0.001 rem) each.

The accident had many far-reaching consequences:

- the site was shutdown with associated loss of jobs and JCO lost its license(s),
- six JCO employees (including the head of the plant and the surviving operator) were convicted, in criminal court, of professional negligence,
- JCO and its parent company were expected to pay compensations to area residents and businesses,
- associated bad publicity cost the region many tourist dollars,
- fissionable material operations throughout much of the world were systematically reviewed in light of this accident's lessons learned, and
- an English company that contracted to provide JCO's facility upgrades lost significant money for much already-built equipment.

---

[i] *GyEq* means *Gray-equivalent*, where 1 Gy = 100 rad. This is the unit specified in Japanese and IAEA reports. A *GyEq* is somewhat analogous to *rem*, but is adjusted for very severe, very acute exposures.

## Topic.A.2 Non-Process Criticality Accidents

Thirty-eight criticality accidents have occurred in reactors and other systems that were designed to be critical or supercritical under particular conditions (Table A2). It should be no surprise that such a system will be critical under those conditions, regardless of how the conditions were approached. It should also be no surprise that an inadvertent criticality can be achieved with maloperation of an experiment or assembly designed to operate under conditions that are just barely subcritical.

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 fourteen accident histories are included here to illustrate certain lessons. Due to local interest, all criticality accidents in Idaho and/or Argonne reactor facilities are included.

Facilities described in these accidents do not have criticality alarm systems. Reactor and critical-assembly instrumentation generally provide adequate, alternative monitoring for those specific locations. The need for alarm systems to cover surrounding areas is specifically addressed for each facility considering credible activities in those areas.

### A.2.1 August 21, 1945, *Dirty Gerty*, LASL, USA

Relevant controlled factors: reflection

Relevant other factors: none

Excursion(s): one burst

Radioactive contamination: none

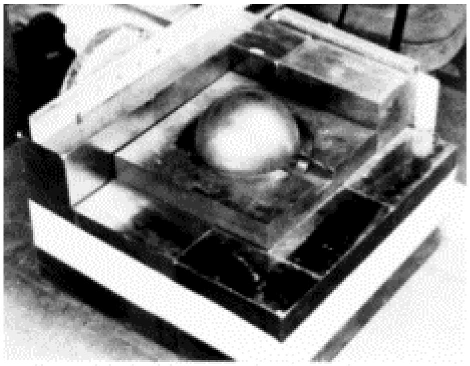
Radiation exposure(s): 510 rem, 50 rem.

Medical consequences: one fatality, one with mild radiation sickness

Equipment/facility damage: none

Lessons-learned topics: design (remote vs. hands-on), effects of small changes, conduct of operations (written procedures, formal review), emergency planning (evacuation)

The first reported criticality accident with a system designed to be critical occurred at 11:55 p.m., Tuesday, August 21, 1945. It occurred during a hand-stacking critical experiment with a plutonium metal sphere that is coated with nickel. The total sphere mass is 6.2 kg, with a density of about 15.7 g/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.


Reconstructed 1945 experiment without the last tungsten carbide brick.

## Table A2. Reactor and Critical Experiment Accidents

| start date | site | material | geometry | power history ~ duration | ~ no. of exposures[a] | | | total fissions |
|---|---|---|---|---|---|---|---|---|
| | | | | | ≥ 1 rem | ≥ 12 rad | fatal | |
| **FISSIONABLE SOLUTION SYSTEMS** | | | | | | | | |
| Dec. 1949 | LASL, USA | ~1 kg $^{235}$U as uranyl nitrate | Water Boiler Reactor: sphere, C reflected | unk | 1 | 0 | 0 | ~3e16 |
| Nov. 16, 1951 | HW, USA | 1.15 kg Pu as nitrate | Hanford Homogenous Reactor: bare sphere, 93% filled | 0.5 sec | 0 | 0 | 0 | 8e16 |
| May 26, 1954 | Y-12, USA | 18.3 kg $^{235}$U as uranyl fluoride | cylindrical annulus, bare | 40 sec. | 0 | 0 | 0 | 1e17 |
| Feb. 1, 1956 | Y-12, USA | 27.7 kg $^{235}$U as uranyl fluoride | cylindrical bare | short (1 burst) | 0 | 0 | 0 | 1.6e17 |
| Jan. 30, 1968 | Y-12, USA | 0.95 kg $^{233}$U as nitrate | sphere, water reflected | short (1 burst) | 0 | 0 | 0 | 1.1e16 |
| **BARE AND REFLECTED METAL SYSTEMS** | | | | | | | | |
| Aug. 21, 1945 | LASL, USA | 6.2 kg δ-phase Pu | "Dirty Gerty": sphere, Wc reflector | < 1 sec | 2 | 2 | 1 | ~1e16 |
| May 21, 1946 | LASL, USA | 6.2 kg δ -phase Pu | "Dirty Gerty": sphere, Be reflector | < 1 sec | 8 | 8 | 1 | ~3e15 |
| Feb. 1, 1951 | LASL, USA | 62.9 kg U(93) metal | cylinder and annulus in water | short[b] | 0 | 0 | 0 | ~1e17 |
| Apr. 18, 1952 | LASL, USA | 92.4 kg U(93) metal | Jemima: bare cylinder | 0.3 sec | 0 | 0 | 0 | 1.5e16 |
| Apr. 9, 1953 | VNIIEF, USSR | ~8 kg δ-phase Pu | FKBN machine: sphere, natural U reflector | short (1 burst)[c] | 1 | 0 | 0 | ~1e16 |
| Feb. 3, 1954 | LASL, USA | 53 kg U(93) metal | Godiva: bare sphere | short (1 burst) | 0 | 0 | 0 | 5.6e16 |
| Feb. 12, 1957 | LASL, USA | 54 kg U(93) metal | Godiva: bare sphere | short (1 burst) | 0 | 0 | 0 | 1.2e17 |
| June 17, 1960 | LASL, USA | ~51 kg U(93) metal | cylinder, C reflector | short (1 burst) | 0 | 0 | 0 | 6e16 |
| Nov. 10, 1961 | Y-12, USA | ~75 kg U(93) metal | paraffin reflector | short (1 burst) | 0 | 0 | 0 | ~1e16 |
| Mar. 11, 1963 | VNIIEF, USSR | ~17.35 kg δ-phase Pu | MSKS machine: sphere, LiD reflector | short[c] | 5 | 2 | 0 | ~5e15 |
| Mar. 26, 1963 | LRL, USA | 47 kg U(93) metal | Kukla: cylinder, Be reflector | < 1 min. | 0 | 0 | 0 | 3.7e17 |
| May 28, 1965 | WSMR, USA | 96 kg U(93)-Mo alloy | fast burst reactor: bare cylinder | short (1 burst) | 0 | 0 | 0 | 1.5e17 |
| Apr. 5, 1968 | VNIITF, USSR | 47.7 kg U(90) metal | FKBN machine: sphere, natural U reflector | short (1 burst) | 2 | 2 | 2 | 6e16 |
| Sep. 6, 1968 | APRF, USA | 123 kg U(93)-Mo alloy | APRF reactor: bare cylinder | short (1 burst) | 0 | 0 | 0 | 6.09e17 |
| June 17, 1997 | VNIIEF, RF | ~44 kg U(90) | FKBN-2M machine: sphere, Cu reflector | 6 days, 13 hr, 55 min.[c],[d] | 1 | 1 | 1 | ~1e19 |

(a) Exposures to workers in the accident vicinity, not including responders and investigators. No member of the public was exposed in any of these accidents. Accident reports that include responder data indicate responder exposures were within responder guidelines in-effect at the time and, in most cases, were negligible. However, several reports about the SL-1 accident indicate that the highest exposure to any rescuer, responder, or cleanup worker was 27 roentgens.

(b) Multiple unplanned bursts during a planned scram of the solution assembly.

(c) Terminated by human intervention.

(d) The power history consisted of multiple bursts followed by an equilibrium power. The first burst yielded about $2 \times 10^{17}$ fissions.

## Table A2. Reactor and Critical Experiment Accidents (continued)

| start date | site | material | geometry | power history ~ duration | ~ no. of exposures(a) | | | total fissions |
|---|---|---|---|---|---|---|---|---|
| | | | | | ≥ 1 rem | ≥ 12 rad | fatal | |
| **MODERATED METAL AND OXIDE SYSTEMS** | | | | | | | | |
| June 6, 1945 | LASL, USA | 35.4 kg U(79.2) as ½-inch cubes | pseudosphere, water reflector | short (1 burst) | 3 | 2 | 0 | ~4e16 |
| ~1950 | CRL, Canada | natural U, Al clad | ZEEP assembly: rods in heavy water | short (1 burst) | 3 | 1 to 3 | 0 | unknown |
| June 2, 1952 | ANL-E, USA | U(93) oxide in plastic | ZPR-1 assembly: elements in water | < 1 sec | 4 | 3 | 0 | 1.22e17 |
| Dec. 12, 1952 | CRL, Canada | natural U fuel rods | NRX reactor: heavy water moderator | < 3 min.(c) | not reported | 0 | 0 | 1.20e20 |
| July 22, 1954(d) | NRTS, USA. | 4.16 kg U(93) as U/Al alloy | BORAX-1 reactor: fuel elements in water | short (1 burst) | 0 | 0 | 0 | 4.68e18 |
| Oct. 15, 1958 | BKI, Yugo-slavia | natural U rods | RB reactor: rods in heavy water | up to several min.(c),(e) | 6 | 6 | 1 | ~2.6e18 |
| Mar. 15, 1960 | CENS, France | 2.2 tons U(1.5) as oxide | Alize assembly: rods in water | unk. | 1 | 0 | 0 | 3e18 |
| Jan. 3, 1961 | NRTS, USA. | U(93), Al clad | SL-1 reactor: rods in water | short (1 burst) | 3 | 3 | 3(f) | 4.4e18 |
| Nov. 5, 1962(g) | NRTS, USA. | U(93)/Al alloy plates, Al clad | SPERT-1D reactor: elements in water | short (1 burst) | 0 | 0 | 0 | ~1e18 |
| Dec. 30, 1965 | NRC, Belgium | U(7) oxide | VENUS assembly: $H_2O/D_2O$ moderator | short (1 burst)(c) | 1 | 1 | 0 | ~4e17 |
| Feb. 15, 1971 | KI, USSR | U(20)$O_2$ fuel rods | SF-7 assembly: Be reflector | 7 min.(c) | ≥ 2 | ≥ 2 | 0 | 2e19 |
| May 26, 1971 | KI, USSR | U(90)$O_2$ fuel rods | SF-3 assembly: water reflector | short (1 burst) | 4 | 4 | 2 | 2e18 |
| Sep. 23, 1983 | CAC, Argentina | U/Al alloy plates, Al clad | RA-2 reactor: pool type reactor | short (1 burst) | 9 | 3 to 8 | 1 | ~4e17 |
| **MISCELLANEOUS SYSTEMS** | | | | | | | | |
| Feb. 11, 1945 | LASL, USA | U hydride in styrex | Dragon assembly | short (1 burst) | 0 | 0 | 0 | ~6e15 |
| Nov. 29, 1955 | ANL-W, USA | enriched U in NaK | EBR-I reactor | short (1 burst) | 0 | 0 | 0 | ~4e17 |
| July 3, 1956 | LASL, USA | U(93) foils in graphite | Honeycomb assembly | short (1 burst) | 0 | 0 | 0 | 3.2e16 |
| Nov. 18, 1958 | NRTS, USA | U oxide in Ni-Cr | HTRE-3: aircraft engine prototype | short (1 burst) | 0 | 0 | 0 | 2.5e19 |
| Dec. 11, 1962 | LASL, USA | large U(93)-C cylinder | Zepo assembly: cylinder plus annular reflector | short (1 burst) | 0 | 0 | 0 | ~3e16 |

(a) Exposures to workers in the accident vicinity, not including responders and investigators. No member of the public was exposed in any of these accidents. Accident reports that include responder data indicate responder exposures were within responder guidelines in-effect at the time and, in most cases, were negligible. However, several reports about the SL-1 accident indicate that the highest exposure to any rescuer, responder, or cleanup worker was 27 roentgens.

(c) Terminated by human intervention.

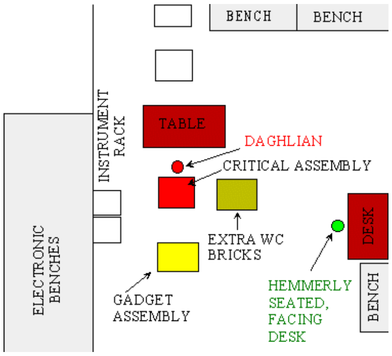
(d) This event qualifies as an accident only because the energy release was much larger than expected. However, the event was a test intentionally designed to destroy the reactor.

(e) The power history consisted of a steadily rising power level until operators scrammed the reactor. The entire experiment was supposed to be subcritical, but the reactor was supercritical between one and eight minutes.

(f) These fatalities were directly due to physical injuries. However, these three workers also received lethal radiation exposures.

(g) This event occurred as part of a series of tests intentionally designed to damage, and eventually destroy, the reactor. It qualifies as an accident because total destruction occurred due to an unexpected pressure pulse.

The experimenter hand-stacked tungsten-carbide bricks to build a 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 pulled back, this final brick slipped. It fell on the assembly. The assembly became supercritical on prompt neutrons. The experimenter quickly pushed the final brick off the sphere and then un-stacked his assembly.



Room layout and personnel locations during 1945 criticality accident

The experimenter's exposure was about 510 rem. He died 28 days later. An army guard who was in the same room, but not helping with the experiment, received a dose of about 50 rem.[j] Contemporary literature does not report health effects for the guard, but more than 40 years later a variety of mostly anti-nuclear sites report the guard suffered radiation sickness and blamed his exposure for other symptoms that developed later in life.

The one burst accident produced about 1e16 total fissions. The burst did not damage any equipment, and it did not cause any radiological contamination.

At the time, safety practices were based on experimenter knowledge, skill, and experience rather than on formal analyses. Safety practices were implemented by oral instructions and discussions. They were not necessarily part of written instructions. The experiment seemed safe enough beforehand, but it lacked many readily identifiable safety measures.

**Did you know …**

**That the experimenter and guard did *NOT* describe the light flash they saw as blue?** Descriptions that include the blue color did not appear for decades, and did not come directly from either the experimenter or the guard. The lack of color makes sense because there was no significant hydrogenous matter near the core for bremstrahlung radiation.

## A.2.2 May 21, 1946, *Dirty Gerty*, LASL, USA

Relevant controlled factors: reflection

Relevant other factors: none

Excursion(s): one burst

Radioactive contamination: none

Radiation exposure(s): 2100, 360, 250, 160, 110, 65, 47, and 37 rem.

Medical consequences: one fatality, at least four cases of radiation sickness, possible additional ailments for at least two survivors many years later

Equipment/facility damage: none

Lessons-learned topics: design (remote vs. hands-on), effects of small changes, conduct of operations (written procedures, formal review), emergency planning (evacuation)

---

[j]. The worker location graphic is from: Arnold Dion, "Harry Daghlian: Americas first peacetime atom bomb fatality," http://arnold_dion.tripod.com/Daghlian/, accessed Feb. 15, 2006. This website includes much useful information, but its listed doses are not consistent with the doses listed in medical and scientific literature. The radiological doses listed on the website are expressed in terms of roentgens due to soft x-rays and gamma radiation, and the source for the values is not identified.

On Tuesday afternoon, May 21, 1946, an experienced scientist was demonstrating neutron reflection principles with a plutonium sphere to other scientists. It was the same sphere as the one used during the criticality accident nine months earlier (Subtopic A.2.1).

Reconstruction of 1946 criticality accident.

This time, the reflector was composed 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 screwdriver.

At about 3:20 p.m., the screwdriver slipped and the upper beryllium hemisphere fell into place around the plutonium sphere. The assembly immediately became prompt critical. Either the scientist or the burst's k**inetic energ**y threw the upper beryllium hemisphere to the floor, which terminated the reaction.

Everybody immediately evacuated the room. The scientist received about 2100 rem and died nine days later. The other seven people in the room received doses of about 360, 250, 160, 110, 65, 47, and 37 rem. (See the illustration on page 50.) Apparently two additional people were further away in an adjacent loft area, but their doses are not reported. Health consequences for the survivors are not well reported in non-medical literature, but radiation exposures due to this accident was blamed for medical ailments that at least two of the survivors suffered many years later.

This one burst accident produced about 3e15 total fissions. The burst did not damage any equipment, and it did not cause any radiological contamination.

Safety practices at this time were almost the same as practices in-effect during the first accident (Subtopic A.2.1). Because 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.

**Did you know …**

- **The now popular name for the sphere, *demon core*, is comparatively recent?** In interviews within several decades of the accident, survivors and area workers called the sphere *Dirty Gerty*. Personnel who stored and worked with the sphere during the 1980s referred to it as *the plutonium sphere* or by its nuclear material tracking identifier.
- **That many people call this accident the *tickling the dragon's tail accident,* but neither this accident nor its equipment were part of critical experiments known as *dragon's tail experiments*?** However, both names are based on the same concept (a very small change initiates a supercritical or critical condition).

## A.2.3 June 2, 1952, ZPR-I, ANL-E, USA

Relevant controlled factors: moderation, absorption

Relevant other factors:

Excursion(s): one burst

Radioactive contamination: minor

Radiation exposure(s): 136, 127, 60, and 9 rep (roentgen equivalent physical)

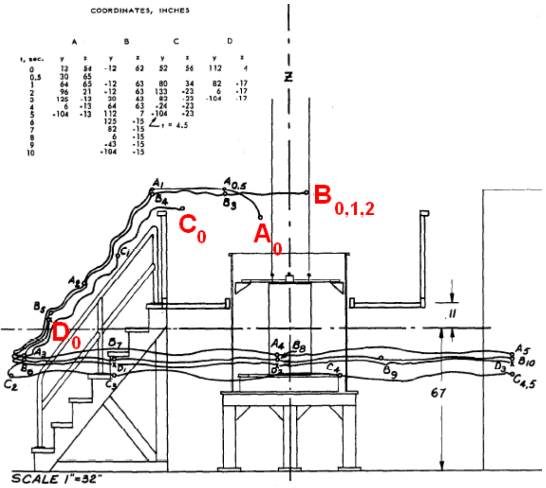
Medical consequences: none

Equipment/facility damage: severe

Lessons-learned topics: conduct of operations (obtain and follow procedures, number of people in room), emergency planning (evacuation)

This accident with the ZPR-I reactor occurred at approximately 3:52 on a Monday afternoon. Experimenters were comparing central control rod worths. After establishing a critical condition with three configurations, they inserted all control rods. However, contrary to procedures, they did not drain water from the reactor tank before making further changes to the core.

At the time of the accident, three experimenters were standing on a platform around the reactor tank and a fourth experimenter was on the steps leading to the platform. One experimenter (B) unclamped the central control rod and began to remove it from the tank. By the time the rod had been withdrawn about a foot, experimenters heard a dull thud characterized as an underwater shock. They also observed a blue light emanating from the top, persisting for a fraction of a second. At the same time end caps on dummy elements buckled, allowing outward lateral displacements of the tops of the core elements. The water displaced from the core rose suddenly, as a bubble, with some gas evolution to a height of about 20 cm before spreading to the sides of the tank. Within seconds, the experimenter dropped the control rod back down its guide tube and rapidly exited the room with the other two experimenters (A and C) from the platform. The fourth experimenter (D) exited the room at about the same time.



COORDINATES, INCHES

| | A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| t, sec. | y | z | y | z | y | z | y | z |
| 0 | 12 | 54 | -12 | 62 | 52 | 56 | 112 | 4 |
| 0.5 | 30 | 65 | | | | | | |
| 1 | 64 | 65 | -12 | 63 | 80 | 34 | 82 | -17 |
| 2 | 96 | 21 | -12 | 63 | 133 | -23 | 6 | -17 |
| 3 | 125 | -13 | 30 | 63 | 82 | -23 | -104 | -17 |
| 4 | 6 | -13 | 64 | 63 | -24 | -23 | | |
| 5 | -104 | -13 | 112 | 7 | -104 | -23 | | |
| 6 | | | 125 | -15 | | | | |
| 7 | | | 82 | -15 | | | | |
| 8 | | | 6 | -15 | | | | |
| 9 | | | -43 | -15 | | | | |
| 10 | | | -104 | -15 | | | | |

Elevation view of equipment layout and personnel locations during the 1952 criticality accident.

The prompt critical reaction was actually terminated by the thermal expansion and by voids caused with bubble generation, resulting in some severely damaged fuel elements. Reactor safety features also activated, draining the reactor tank very shortly after the burst, making ZPR-I even more subcritical. The reactor room and some adjacent areas in the building were slightly contaminated, but it was easily removed when cleanup began eight days after the accident.

None of the four experimenters experienced more than very mild radiation sickness or became clinically ill during their 16-day observation in a nearby hospital. The experimenter who started to remove the control rod received a 136 rep radiation dose. With exception of some nausea and vomiting several hours after exposure, he was asymptomatic. The experimenter who received a 60 rep dose also experienced nausea and vomiting on the third day of hospitalization, but the symptoms appeared to be due to stress and anxiety. She was otherwise asymptomatic. The experimenters who received 127 and 9 rep doses were asymptomatic.

### A.2.4 July 22, 1954, BORAX-I, NRTS (ANL-W), USA

Relevant controlled factors: absorption (control rods)

Relevant other factors: moderation

Excursion(s): one burst

Radioactive contamination: major, but did not reach public areas

Radiation exposure(s): negligible

Medical consequences: none

Equipment/facility damage: severe

Lessons-learned topics: nuclear excursions can initiate more destructive phenomena

BORAX-I was a research reactor built partially underground and operated remotely from a considerable distance. Conducted Thursday, July 22, 1954, the final BORAX-I experiment was the last of a series of destructive reactor tests. This last experiment involved rapid ejection of a high worth control rod. The test was expected to severely damage the core, melting fuel, releasing about 80 megajoules of energy, and producing a relatively large steam explosion.

The last BORAX-I destructive test.

This test is categorized as an accident because it released much more energy (about 135 megajoules) and was much more destructive than expected.

Extensive fuel melting and damage occurred as a direct result of the nuclear excursion. But more followed. Initiated as a result of damage caused by the criticality, the subsequent steam explosion caused much additional damage. For example, some fuel pieces remained in the reactor, but some small pieces were ejected, landing up to 200 feet away. The explosion was forceful enough to toss the 2200 pound control rod mechanism about 30 feet up into the air. However, damage was limited to the reactor.

### A.2.5 November 29, 1955, EBR-I, NRTS (ANL-W), USA

Relevant controlled factors: absorption (control rods)

Relevant other factors: not identified

Excursion(s): one burst

Radioactive contamination: minor

Radiation exposure(s): none reported

Medical consequences: none

Equipment/facility damage: half of the fuel melted, some vaporized NaK forced into reflector

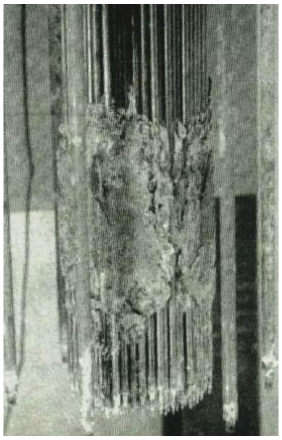
Lessons-learned topics: conduct of operations (communication, safety feature changes), design (defeating automatic safety measures)

EBR-I's second core exhibited a prompt-positive power coefficient of reactivity under some abnormal operating conditions. Several experiments were conducted to investigate the resultant instabilities. Conducted on Tuesday, November 29, 1955, the last experiment included a disabled reactor cooling system. Since the reactor's automatic shutdown mechanisms would have prevented the experiment from being conducted, some instrument trip points were set at unusually high levels and at least one mechanism was disconnected. For this experiment, shutdown relied primarily on human action.

At the appropriate moment, the scientist in charge told the reactor operator to press the "reactor off" button, which would have shut the reactor down quickly enough. Due to a misunderstanding, the operator initiated the scram with slow moving control rods rather than using the fast scram method. This slower shutdown was too slow to prevent overheating and a reactivity addition as fuel rods bowed. Within two seconds, the operator and instruments actuated the fast scram method.

Radiation levels rose in the building shortly after the experiment. Personnel evacuated for a short while. There were no personnel injuries or reportable radiation exposures. There was no appreciable contamination of the NaK coolant remaining in the system and no contamination outside of the core and coolant system.

However, it was later determined that about half the core had melted. Some fuel rods adhered to the core's bottom plate and required special methods to remove. In addition, some of the NaK coolant had vaporized and was forced into the reflector.


Melted fuel from the EBR-I criticality accident.

The excursion produced close to 4.6e17 fissions total, reaching a maximum power of 9 to 10 megawatts. Analysis indicated that, if the excursion had continued until the core shut itself down, the energy release could have been nearly 2½ times greater. However, contrary to writings by various inexperienced persons, such a continued reaction would not have violently disassembled the core. For example, with NaK coolant, there was no chance for a steam explosion.

## A.2.6 July 3, 1956, Honeycomb Critical Assembly, LASL, USA

Relevant controlled factors: interaction

Relevant other factors: reflection

Excursion(s): one burst

Radioactive contamination: none

Radiation exposure(s): none

Medical consequences: none

Equipment/facility damage: none

Lessons-learned topics: effects of small changes, design (remote operation)

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 Zero Power Physics Reactor assemblies that were operated at ANL-W.[k] Each array of the LASL split assembly consisted of a square matrix of 576 aluminum tubes, 3 in. × 3 in. × 3 feet. One array was stationery. The second array was aligned with the first and could be moved on a cart along tracks.

On that Tuesday, the assembly was loaded with highly enriched uranium in the form of thin foils arranged between graphite slabs, with a beryllium reflector surrounding the core. 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 a quarter mile 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 0.2 in./sec., 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 3.2e16 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.

## A.2.7 October 15, 1958, RB Reactor, BKI, Yugoslavia

Relevant controlled factors: moderation

Relevant other factors: absorption

Excursion(s): steadily rising power level until 'scrammed'

Radioactive contamination: none

Radiation exposure(s): 205, 320, 410, 415, 422, and 433 rem

Medical consequences: one fatality, five cases of severe radiation sickness, no further consequences reported

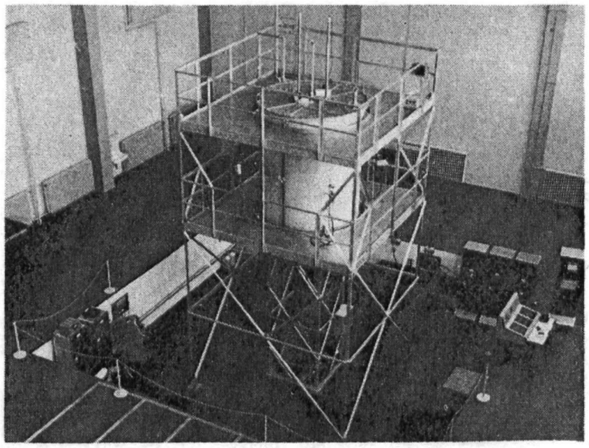
Equipment/facility damage: none

Lessons-learned topics: conduct of operations (equipment condition, questioning attitude), design (shielding)

At the time, the six month old 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. Water pumped from a cell below the reactor was normally used to control system reactivity. Two cadmium safety rods were installed, but not interlocked with the assembly's flux recorder.

---

[k] Somewhat like the Zero Power Physics Reactor. Picture two post-office-box arrays facing each other, but, instead of boxes, each array has deep, identical square tubes. Trays with pieces of solid nuclear fuel, reflectors, moderators, and/or experiments are placed in each tube. The assembly is made critical by decreasing the distance between the arrays. Trays and tubes are typically filled by hand, but the arrays are brought together using remotely operated equipment.



The RA-2 reactor in 1958. The operating console is near the bottom right. The dosimetry panel is behind and slightly to the left of the operating console. The controls for the water pump are on or under the lowest reactor platform. Personnel were located at each of these locations during the accident.

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. The instruments did not register the expected radiation level increase when the lead experimenter announced the water level was high enough. The experiment leader climbed to the reactor top to ensure the neutron starter source had not stuck. Two of the $BF_3$ chambers performed as before (leveling off at a higher signal level). Third chamber behaved erratically and was therefore disconnected. Within minutes, a technician arrived and replaced the third chamber, but the replacement also failed. The reactor was critical, but the staff did not yet know it.

After the assembly operated for five to eight minutes, an experimenter smelled ozone and realized the system must be supercritical at some unknown power level. They shut down the reactor and evacuated to the Institute's medical dispensary. Radiation safety personnel were already cautiously approaching the reactor building because GM counters up to half a mile away had saturated.

Investigators though the chambers worked properly, but had saturated. They read a constant maximum value although assembly power level was increasing steadily.

The person who climbed to the reactor top received the highest dose, the person operating the water pump received the second highest dose, and the person who arrived to replace the radiation instrument received the lowest dose. Depending on the report, personnel exposures for the six people in the room were estimated as 205, 320, 410, 415, 422, and 433 rem or as 400, 700, 850, 850, and 1100 rad. One died and the others recovered after suffering severe radiation sickness and aggressive medical treatment. The critical assembly withstood an energy release of 80 megajoules (about 2.6e18 fissions) with no reported damage and no resultant contamination.

## A.2.8 November 8, 1958, HTRE-3, NRTS, USA

HTRE-3 Engine without nuclear components after 1988

Relevant controlled factors: absorption (control rods)

Relevant other factors: not identified

Excursion(s): one burst

Radioactive contamination: minor

Radiation exposure(s): none significant

Medical consequences: none

Equipment/facility damage: severe to core, none outside reactor

Lessons-learned topics: design (ensure instrument/wiring behavior will not exacerbate abnormal conditions, review changes)

HTRE-3 was an experimental power plant assembly for nuclear aircraft. On Tuesday, November 18, 1958, workers conducted two tests. The second low-power test was to raise the power to 120 kilowatts, 80% of the fuel range and twice the power achieved earlier in the day. At the time of the event the reactor was on automatic servo control. However, some added wiring designed to reduce electronic noise caused a problem in other instrumentation while the control rods were being withdrawn. This accident is unique in that it seems to have been due solely to instrumentation.

In a nonviolent power excursion producing about 2.5e19 fissions, all core fuel elements experienced some melting. A few zirconium hydride moderator pieces were also ruined. Some fission product activity was released and traveled outside the facility fence line, but none of the activity dispersed across NRTS boundaries. Personnel exposures were, apparently, negligible.

## A.2.9 January 3, 1961, SL-1 reactor, NRTS, USA

Relevant controlled factors: absorption, moderation

Relevant other factors: excess fissionable mass

Excursion(s): one burst

Radioactive contamination: major inside reactor building, minor or negligible elsewhere, contained within 3-acre plot except for I-131.

Radiation exposure(s): not reported

Medical consequences: three fatalities, no further consequences reported

Equipment/facility damage: reactor core destruction, severe damage to the reactor vessel

Lessons-learned topics: design and maintenance, conduct of operations, nuclear excursions can initiate more destructive phenomena

Tuesday, January 3, 1961 was very cold when three crew men were carrying out their assignment to reassemble the SL-1 reactor's control rod drives and prepare the reactor for a startup the following day. By current standards, the reactor core was in poor condition, but the accident was probably independent of this condition.

One of the crew men manually pulled the central control rod out of the reactor as rapidly as he could at about 9:00 p.m., for an unknown reason. The reactor became supercritical as the rapid increase of reactivity caused a rapid increase in power. Thermal expansion and steam void formation terminated the excursion, but not in time to prevent a steam explosion.

Post-accident SL-1 core

The steam explosion destroyed the reactor, seriously contaminating the reactor room and building. Special measures were needed to ensure cleanup workers did not track contamination elsewhere. The reactor building was not designed to be air tight, but, in spite of the large radioactive release from the core, very little contamination escaped the building and, except for I-131, all was contained within a 3-acre plot. Effluent deposits (I-131) above background were detected outside NRTS, but the levels detected were well within the applicable limits.

Investigation and rescue were delayed by high radiation levels detected in the reactor room (500 to 1000 R/hr). The three crew men received lethal radiation doses. However, they died of physical injuries caused by the explosion (two instantly, the third within two hours). Three rescuers received doses between 25 and 27 roentgen. Nineteen other people who participated in the first week of response, investigation, and victim recovery received doses between 3 and 25 roentgen. Of the hundreds of other people involved in the response, investigation, recovery, and cleanup, nobody received more than their quarterly limit of 2.5 roentgens.

### A.2.10 November 5, 1962, SPERT-1D, NRTS, USA

Relevant controlled factors: absorption, moderation

Relevant other factors:

Excursion(s): one burst

Radioactive contamination: within facility fence

Radiation exposure(s): within plans and limits

Medical consequences: none

Equipment/facility damage: reactor core destruction,

Lessons-learned topics: emergency planning, nuclear excursions can initiate more destructive phenomena

In light of the destructive steam pressure pulses from events such as the final test of BORAX-I final test (Subtopic A.2.4) and the SL-1 accident (Subtopic A.2.9), an experiment series of non-destructive to increasingly destructive tests was conducted in the SPERT-I reactor. In addition to fuel damage, steam explosions were anticipated but could not be truly predicted for the destructive tests. The non-destructive tests and two destructive tests had been successfully completed with predicted results and no steam explosions.

The roofing and some side panels were removed from the reactor building and additional cameras and instruments were installed to better record the next test. Special procedures for the test therefore required specific weather conditions, evacuation of non-essential personnel, and a specific readiness status of safety support people at the NRTS. Special testing and reentry procedures were also prepared.

The final test was initiated at 12:25 on Monday, November 5, 1962. The nuclear excursion proceeded very much as predicted, including transient rod ejection and partial melting of all fuel plates. The excursion terminated.

About 15 milliseconds later, a violent pressure surge completely destroyed the core. It caused some damage to structural members of the reactor building and released contaminated water and gaseous fission products. The explosion did not eject solid contaminants into the air.

The first re-entry team approached the reactor about four hours later, detecting negligible airborne activity, about 2 mr/hr at floor level 50 feet in front of the reactor and about 25 r/hr about 10 feet above the normal core center over the open reactor vessel.

The steam explosion is attributed to rapid energy transfer between the molten fuel and the water moderator. Experimenters had anticipated a steam explosion, but they did not predict it and they were surprised by its magnitude. Further, the delay between nuclear excursion termination and non-nuclear pressure pulse were not fully anticipated. These unexpected, criticality-induced results are the reason this test is categorized as a criticality accident.

### A.2.11 December 30, 1965, VENUS Critical Facility, NRC, Belgium

Relevant controlled factors: absorption, moderation

Relevant other factors: none

Excursion(s): one burst

Radioactive contamination: none

Radiation exposure(s): one person with about 300-400 rem to his head, 500 rem to his chest, and 1750 rem to his left ankle

Medical consequences: no fatalities, one case of severe radiation sickness with amputation (foot), no further consequences reported

Equipment/facility damage: none

Lessons-learned topics: conduct of operations (procedure compliance [safety prerequisites, step sequence], human factors [speed]), self-shielding

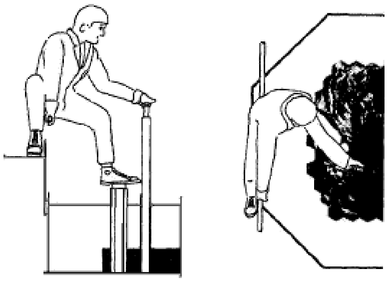
At the time, VENUS was a tank-type, water-moderated, critical assembly machine. Its heavy water ($D_2O$) moderator could be diluted with light water ($H_2O$) to soften the neutron energy spectrum and maintain reactivity as fissionable material was consumed. For experiments in progress, moderator and reflector were composed of 70% $H_2O$ and 30% $D_2O$. The reflector extended 30 cm (~1 foot) above the core. The fuel was $UO_2$ with a total $1.2 \times 10^6$ 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.

A reactor operator devised a plan to achieve the new rod pattern desired for an 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: empty water from the reactor vessel before manually manipulating rods.

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



Reconstructed operator position during VENUS criticality accident.

The reactor became critical as the technician extracted the manual rod. His left foot projected over the tank edge, resting on a grid about 5 cm (2 in.) 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 energy release was about 13 megajoules (4.3e17 fissions). The excursion apparently terminated due to the dropped manual rod. However, vessel water was automatically dumped, an action that might have accelerated 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, but his left foot had to be amputated.

### A.2.12 May 26, 1971, SF-3 assembly, KI, USSR

Relevant controlled factors: absorption

Relevant other factors: interaction, moderation, mass

Excursion(s): one burst

Radioactive contamination: limited to room

Radiation exposure(s): 600, 2000, 700-800, 700-800 rad

Medical consequences: two fatalities, two severe cases of radiation sickness followed by adverse long term health effects

Equipment/facility damage: destroyed fuel rods

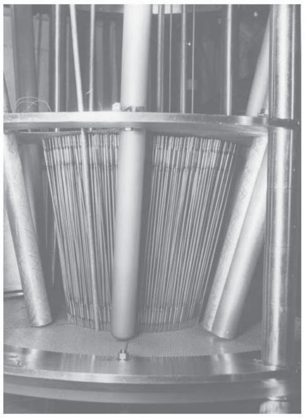
Lessons-learned topics: design (structural integrity, spacing, absorbers), conduct of operations (equipment/system testing)

This accident occurred in an experimental facility to measure critical masses for arrays of highly enriched uranium fuel rods. Each assembly primarily consisted of a flooded hexagonal array of identical rods, supported by a Plexiglas base plate in a tank. In each case, rods were held in place with thin, perforated aluminum plates. Control for various steps in the experiment process was maintained with control rods, emergency protection rods, the number of loaded fuel rods, and/or water level. The tank had a slow dumping valve and a fast dumping valve for draining water. The material and dimensions of nonfuel items were carefully selected to avoid perturbing measurements, which resulted in relatively fragile systems.

For each lattice pitch, personnel loaded the dry tank with considerably less than the estimated critical number of rods. Measuring reactivity throughout, they then flooded the tank until water was at least 20 cm (7.9 in.) above the rods. In a classic step-by-step procedure, personnel added a few rods, measured 1/M, and plotted and extrapolated the critical number of rods. In the range of lattice pitches measured, the critical number of rods increased dramatically as the pitch decreased. The final experiment involved the smallest pitch, for which the critical number of rods was at least seven times as many as the number of rods needed at the optimal pitch.

Measurements were completed on the final experiment. All control rods and emergency protection rods were fully inserted. Four staff member, including the supervisor, entered the shielded experiment compartment. The supervisor ordered personnel to drain water using the fast dumping valve, which had not been used for draining the previous experiments.

Due to the system's materials, dimensions and weight, rapid draining caused the Plexiglas support plate to sag. Fuel rods fell out of the upper lattice plate. These rods separated into a fan-shaped array. The resultant pitch was nearly optimal. The system was suddenly supercritical.



1971 after-accident fuel rod configuration, reconstructed without water

The single burst excursion destroyed two peripheral rows of fuel rods, splashed water out of the tank, and produced about 5e18 total fissions. Radioactive contamination outside the tank was minimal, and there was no contamination of the facility's outer premises. These results are typical for uranium-water systems in open tanks with rapid reactivity insertions.

Other consequences were severe. One technician received about 6000 rem and died five days after the accident. The supervisor received about 2000 rem and died 15 days after the accident. The other two staff members each received 700 to 800 rem. Medical intervention saved these two people, but they suffered long term health effects.

## A.2.13 September 23, 1983, RA-2 Facility, CAC, Argentina

Relevant controlled factors: moderation, absorption

Relevant other factors: mass

Excursion(s): one burst

Radioactive contamination: none

Radiation exposure(s): one with about 2000 rad gamma and 1700 rad neutron; two with about 20 rad gamma and 15 rad neutron; six with lesser doses down to 1 rad; and nine with doses less than 1 rad.

Medical consequences: one fatality, no other consequences reported

Equipment/facility damage: none

Lessons-learned topics: conduct of operations (procedure compliance)

The RA-2 reactor was a pool reactor with MTR-type fuel elements, each made with 19 fuel plates. Its control rods were like its fuel elements, except two of the 19 plates were made of cadmium. 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.

On that Friday, a qualified operator with 14 years experience was alone in the reactor room making a fuel configuration change. Accident investigators believe the operator intended to place two control elements, without cadmium plates, into the reactor core. They also found two significant operator errors. The moderator had not been drained as required by procedures. Also contrary to safe practices, two fuel elements were placed just outside the graphite instead of being removed from the tank.

Apparently, the reactor went critical as the second control element was inserted at about 4:10 p.m. The excursion consisted of a single burst yielding about 3 to 4.5e17 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 about 15 rad neutron and 20 rad gamma. Six others received lesser exposures down to 1 rad, and nine received less than 1 rad.

### A.2.14 June 17, 1997, FKBN-2M machine, VNIIEF, RF

Relevant controlled factors: mass, reflection

Relevant other factors: interaction

Excursion(s): one initial sharp burst, a second burst of 3 to 5 minutes, power oscillations separated by 40 minute intervals, and finally an equilibrium power level (overall the accident lasted 6 days, 14 hours, and 5 minutes.)

Radioactive contamination: none, but activated some materials inside bunker

Radiation exposure(s): one case with 4500 rad neutron and 350 rad gamma

Medical consequences: one fatality

Equipment/facility damage: copper-nickel coating on fissionable pieces

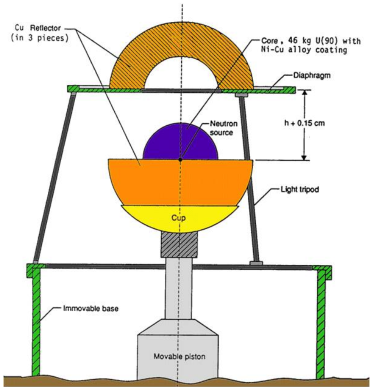
Lessons-learned topics: conduct of operations (procedure compliance, calculation review, proper use of equipment), human factors (confidence), design (shielding, assembly design)

This Russian accident occurred in a well-shielded experiment room in an underground bunker in Sarov Russia, while a scientist built a spherical, metallic, critical assembly with a highly enriched uranium core and a copper reflector. 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. He built the critical experiment on a vertical split machine, which is designed to hold the fissionable sphere and lower half of the reflector on a table, and the upper half of the reflector on a ring. Similar to the previously described split table experiment (Subtopic A.2.3), each part of the experiment should have been assembled separately by hand, and then the parts should have been brought together remotely.

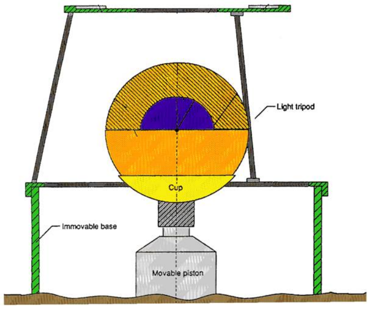
The accident resulted from a chain of mistakes and violations of established practice. The scientist was confident he was recreating an experiment that had been successfully performed in 1971, but he miscopied some information. He had a significantly thicker reflector than was used in 1971. He was working alone, without having completed the proper paperwork, violating two important safety requirements. The scientist acted as both senior supervisor and senior control engineer, which was permitted although these assignments were supposed to provide independent checks on actions and decisions. Some reports indicate that the scientist did not use a startup source that was needed to ensure that certain instruments could adequately detect and signal an approach to the critical condition.


Reconstructed position of scientist just before 1997 Sarov accident.

On June 17, 1997, the scientist assembled this critical experiment. At 10:40, he tried to position a copper shell, before leaving to add the last shell remotely. His position was something like the one shown at the right. The configuration he planned to build is illustrated below left. The shell dropped onto the upper hemisphere, causing the upper hemisphere to drop onto the lower part or the assembly, making it prompt critical, and causing the machine to scram.[1] The scrammed configuration is illustrated below right. This scram lowered the assembly to the table-down position, but did not otherwise affect the experiment. With the entire assembly on the lower part, the scram could not separate the experiment into upper and lower parts.



Desired assembly configuration on June 17, 1997



After-scam assembly configuration on June 17, 1997

Technical response included immediately evacuating the general area near the bunker and suspending a variety of activities to ensure there was no danger to anybody outside the bunker. Responders took time developing and testing further response actions because the assembly was well shielded. They used a robot for reconnaissance, measurements, removing other fissionable 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.

Estimates indicate the scientist's 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 might not have been involved in the experiment. This person exited the area minutes before the accident. He apparently received some radiation exposure and was treated on-site.

---

[1] Reports at the time of the accident occasionally focused on "slippery gloves." The scientist might have dropped the reflector shell because of such gloves.

# Appendix B
# Bibliography

10 CFR 71, “Packaging and Transportation of Radioactive Material.”

49 CFR 173 Subpart I, “Class 7 (Radioactive) Materials,” (49 CFR 173.401 through 49 CFR 173.476).

ANSI/ANS-8.1-1998 (R2007), *Nuclear Criticality Safety in Operations with Fissionable Material Outside Reactors, An American National Standard*, ANS, approved Sept. 9, 1998.

ANSI/ANS-8.3-1997 (R2003), *Criticality Accident Alarm System, An American National Standard*, ANS, approved May 28, 1997.

ANSI/ANS-8.19-2005, *Criticality Accident Alarm System, An American National Standard*, ANS, approved May 16, 2006.

ANSI/ANS-8.20-1991 (R1999, R2005), *Nuclear Criticality Safety Education and Training Standard*, LaGrange, Illinois: American Nuclear Society, 1991.

ANSI/ANS-8.23-2007, *Nuclear Criticality Accident Emergency Planning and Response, An American National Standard*, ANS, approved March 23, 2007.

DOE O 426.2, *Personnel Selection, Qualification, and Certification Requirements for DOE Nuclear Facilities*, Sept. 20, 2011.

DOE O 420.1B, *Facility Safety*, approved Dec. 22, 2005. Especially, Chapter 3, “Nuclear Criticality Safety.”

Frolov, V[ladimir] V., B[oris] G. Ryazanov, and V[ictor] I. Sviridov, “A Review of Criticality Accidents which Occurred in the Russian Industry,” in *ICNC'95 Proceedings of the Fifth International Conference on Nuclear Criticality Safety, Albuquerque, New Mexico USA, Sept. 1995*, Vol. I, University of New Mexico: Albuquerque, Sept. 1995, pp. P·23-P·30.

Knief, Ronald A[llen], *Nuclear Criticality Safety, Theory and Practice*, La Grange Park, Illinois: American Nuclear Society, 1985.

Kovach, Bela J., John A. Auxier, and Fred W. Sanders, “Memories of an Early Nuclear Accident. 15 October 1958, Vinca, Yugoslavia,” in *Radiation Protection Management*, Vol. 14, No. 4, July/August 1997.

LRD-18001, “INL Criticality Safety Program Requirements Manual.”

LWP-14002, “Timeout and Stop Work Authority.”

LWP-18003, “Establishing, Operating, and Deleting Criticality Control Areas.”

McLaughlin, Thomas P., et. al., “A Review of Criticality Accidents, 2000 Revision,” LA-13638, Los Alamos, New Mexico: Los Alamos National Laboratory, May 2000.

Pruvost, Norman L., and Hugh C. Paxton (editors), *Nuclear Criticality Safety Guide*, LA-12808, Los Alamos, New Mexico: Los Alamos National Laboratory, Sept. 1996.

Putman, Valerie L., "30 Sept. 1999 Criticality Accident, Summary to Date," INL/MIS-1999-1139, last updated Nov. 30, 1999.

"The Report of the Uranium Processing Plant Criticality Accident Investigation Committee," Nuclear Safety Commission: Japan, Dec. 24, 1999 (provisional translation, May 29, 2000).

United Nuclear Corporation, Compliance Investigation Report, Volumes 1 and 3, Aug. 14 and Sept. 16, 1964.

# Appendix C
# Glossary

*In most cases non-technical or simplified technical definitions are listed. If both non-technical and technical definitions are often used for criticality safety purposes at INL, both are listed. Definitions listed here are adequate for basic criticality safety training. However some non-technical definitions are not appropriate for criticality safety analyses. Some criticality-safety definitions are not appropriate for non-criticality-safety purposes.*

*Absorber, neutron*. See *neutron absorber*.

*Absorption, neutron*. See *neutron absorber*.

*Administrative control*. A control that relies on human actions for its implementation. (Subtopic 5.2.3)

*Atomic mass unit (amu)*. One-twelfth the mass of a C-12 atom, which has six protons, six neutrons, and six electrons. One amu is equal to $1.66053873e^{-27}$ kg.

*Atom*. The smallest component of a chemical element having all chemical properties of the element. (Subtopic 1.1.1)

*Atomic mass*. The ratio of the mass of an atomic or subatomic particle to one-twelfth the mass of a C-12 isotope (see atomic mass unit). The atomic masses of a proton and neutron are each about one amu. The atomic weight of an electron is negligible (almost zero amu). Sometimes called *atomic weight*.

*Atomic mass number*. (Subtopic 1.1.6) (1) The total number of protons and neutrons in an atomic nucleus. For example, 233 is the mass number of U-233 because it has 92 protons and 141 neutrons. (2) Sometimes used interchangeably with the phrase, *atomic weight*, because the two quantities are nearly equal.

*Atomic nucleus*. The positively charged central portion of an atom that comprises most of the atom’s mass and that consists of protons and neutrons except in the case of H-1 in which the nucleus consists of one proton.

*Atomic number*. The number of protons in an atomic nucleus. (Subtopic 1.1.4)

*Atomic weight*. See *atomic mass*.

*Binding energy (or force)*. The force between neutrons and protons that holds an atomic nucleus together. This force must be overcome for nuclear fission to occur.

*Capture, neutron*. See *neutron capture*.

*Cask*. An approved, shielded container used to store, transfer, or transport radioactive material. The only radioactive material of concern in this document is fissionable material, which is often considered a form of radioactive material. See the *Radiological Worker Training Student Guide*, available through on-line training, for further information about radioactive material.

*Chain reaction*. See *nuclear [fission] chain reaction*.

*Concentration*. (Topic 3.7) (1) Technically, the ratio of the mass of a specific component of a material to the material’s volume. (2) Non-technically, synonymous with density.

*Contingency*. A criticality control or parameter (Module 3) that is controlled in a specific operation to prevent a criticality accident. The event(s) necessary to cause the factor to be outside of its limits are considered to be unlikely.

*Control*. See *criticality control*.

*Control factor*. See *criticality [control] factor*.

*Critical*. (1) A phenomenon characterized by a sustained nuclear fission chain reaction in which each fission produces, on the average, one neutron that causes an additional fission. (Subtopic 2.4.2) (2) Also used for a phenomenon characterized by a sustained nuclear fission chain reaction in which each fission produces, on the average, one or more neutrons that cause additional fissions. (Subtopic 2.4.3) Also see *subcritical* and *supercritical*.

*Critical mass*. (1) Any mass of fissionable material that will support a self-sustaining nuclear chain reaction. (Topic 3.1). (2) A minimum mass of a fissionable material that will support a self-sustaining nuclear chain reaction under specified conditions

*Criticality accident*. An inadvertent or uncontrolled critical or supercritical nuclear fission chain reaction. (Module 4)

*Criticality alarm system (CAS)*. A network of gamma- and/or neutron-sensitive detectors connected to audible alarms, designed to (1) detect a criticality accident within a specific area and (2) immediately alarm so that affected people know to take protective action (Subtopic 5.3.3). At INL, the protective action is immediate evacuation as described in the relevant emergency plan and in relevant INL, complex, and/or facility access training (Subtopic 5.3.4)

*Criticality control*. Method(s) and/or mechanism(s) devised to ensure that the value of one or more criticality control factors stays within acceptable limits to prevent a criticality accident. For example, a criticality control might be an upper limit on the mass of fissionable material allowed to accumulate in a specific location. Another criticality control might be the diameter of a container in which fissionable material is handled, stored, or transferred. (Topic 5.2)

*Criticality control area (CCA)*. An area that is allowed to contain fissionable material in quantities and forms that require criticality control. (Subtopic 5.1.3)

*Criticality [control] factor*. A parameter (physical characteristic) that can be controlled to prevent a criticality accident (Module 3).

*Criticality hazard*. A possible source for a criticality accident.

*Criticality safety*. Protection against the consequences of a criticality accident, preferably by preventing the accident but also by mitigating the consequences if an accident were to occur. Protection includes controls, limits, physical protection, training, procedures, emergency response, and other precautions.

*Criticality safety officer (CSO)*. A person assigned by management, approved by the Criticality Safety Engineering, and qualified through training, education, and/or experience for a specific CCA to (1) provide on-the-floor criticality safety expertise for routine operations, (2) request and review criticality safety related documentation for the CCA, and (3) be liaison between CCA management, FMHs who work in the CCA, and the INL criticality safety group.

*Delayed neutron*. A neutron released by radioactive decay of fission products. A delayed neutron might be released up to one and a half minutes after a fission event. In a nuclear reactor, delayed neutrons can be used to provide a more stable power level.

*Density*. (Topic 3.7) (1) Ratio of a material's mass to its volume. (2) Sometimes used as a synonym for *concentration*.

*Depleted uranium*. Uranium byproduct that results from removing U-235 from some natural to enrich other uranium.

*Design feature*. See *engineering control*.

*Electron*. Subatomic particle having a single negative electrical charge, typically found orbiting an atomic nucleus. (Subtopic 1.1.3)

*Element*. A substance that cannot be decomposed into simpler substances by chemical means.

*Engineered control*. See *engineering control*.

*Engineering control*. (1) Usually, a design feature that reliably serves a criticality control (Subtopic 5.2.2). Also called an *engineered control*. (2) Rarely, a design feature that supports implementation of an administrative control (Subtopic 5.2.3).

*Enrichment*. (1) A process by which the amount of one isotope in an element is increased above the amount that occurs naturally. (2) For the isotope that has an increased amount, the percentage of the isotope in the element. Typically, enrichment refers to the amount of U-235 in the uranium if said quantity is more than the amount that occurs naturally (Topic 3.2). Enrichment is not typically used when referring to a plutonium isotope because plutonium does not occur naturally. It is also not typically used for the quantity of U-233 in uranium.

*Epithermal neutron*. (1) A free neutron with more energy than a technically defined thermal neutron and less energy than a fast neutron. (2) Sometimes, used interchangeably with intermediate neutron.

*Factor, criticality [control]*. See *criticality [control] factor*.

*Favorable geometry*. Deprecated at INL. Instead, see *safe-by-geometry*.

*Fast neutron*. A free neutron with high energy (typically defined as at least 0.1 MeV). Such neutrons travel at very high velocities. Free neutrons produced by nuclear fission are almost always released as fast neutrons. A few materials that can fission will only fission with fast neutrons (for example, U-238).

*Fertile nuclide*. A nuclide capable of absorbing a neutron and, through radioactive decay, becoming fissile (Did-you-know information of Topic 2.3).

*Fissile*. (1) Capable of undergoing nuclear fission with neutrons at any energy, but, most importantly, with slow neutrons. (2) Often used interchangeably with *fissionable* (Topic 2.3), which definition is now used at INL for some purposes.

*Fissile material*. (1) Material capable of sustaining a nuclear fission chain reaction with slow neutrons. Fissile material contains fissile nuclides. (2) Often used interchangeably with fissionable material.

*Fissile material shipping package*. A package approved by DOT or the NRC for transporting fissionable material (a) on or across public roads; (b) over waterways outside of NRC-licensee facilities and DOE complexes; and/or (c) by aircraft outside of NRC-licensee facilities and DOE complexes.

*Fissile nuclide*. A nuclide that is fissile. The primary fissile isotopes at INL are U-233, U-235, and Pu-239, but many other isotopes are also fissile (for example, Pu-241). At INL we are also concerned with Np-237, Pu-238, and Am-241, which are fissionable, but, depending on definitions, not fissile (see fissionable nuclides of concern).

*Fission*. See *nuclear fission*.

*Fission fragment*. An isotope or nuclide produced directly by nuclear fission.

*Fission product*. A fission fragment or an isotope into which a fission fragment radioactively decays.

*Fissionable*. (1) For criticality safety purposes, capable of undergoing nuclear fission. (2) Sometimes, capable of undergoing nuclear fission, but only with fast neutrons. (3) Often used interchangeably with fissile.

*Fissionable material*. A material that is capable of sustaining a nuclear fission chain reaction. Fissionable material contains fissionable nuclides of concern.

*Fissionable material handler (FMH)*. A person appointed by management and currently certified or qualified to handle, process, store, or otherwise manipulate more than 15 g of fissionable material. FMHs must periodically satisfy specific training requirements to maintain their qualification. (Subtopic 5.1.6)

*Fissionable nuclide*. A nuclide that is fissionable (specifically, capable of fissioning).

*Fissionable nuclide of concern*. A fissionable nuclide that could pose a credible criticality hazard. For INL, fissionable nuclides of concern are the isotopes U-233, U-235, Np-237, Pu-238, Pu-239, Pu-241, and Am-241. However, we do not count fissionable nuclides in natural or depleted uranium. Other fissionable nuclides (for example, Am-242, Am-243, Cm-243, Cm-244, Cm-245, Cm-247, Cf-249, and Cf-251) may be a criticality concern elsewhere, but there are no missions or processes at INL to introduce them in the quantities and isotopic purities that would cause a concern here. Similarly, some fissionable nuclides, such as U-238, are not a concern because, although they can fission, they are far more likely to capture neutrons.

*Free neutron*. A neutron that is not part of an atomic nucleus. A free neutron might be released from a nuclide through radioactive decay. However, neutrons freed as result of nuclear fission, often called fission neutrons, are a more significant criticality hazard.

*Fuel, nuclear*. See *nuclear fuel*.

*Fuel handler*. An FMH who primarily handles, processes, stores, or otherwise manipulates nuclear fuel.

*Gamma dose*. The quantitative of gamma radiation that is/was absorbed, usually for a specified time period or due to a specified incident. The radiological dose units rem and Sv are based on chronic exposure to gamma radiation. Consult the Radiological Worker Training Student Guide, available through INL on-line training courses, for further information.

*Gamma radiation*. Gamma rays, which are photons or radiation quanta emitted spontaneously by a radioactive substance or as a result of nuclear fission. Gamma rays exhibit both particle and wave characteristics. Gamma rays are a highly penetrating form of ionizing radiation. Consult the Radiological Worker Training Student Guide, available through INL on-line training courses, for further information.

*Idaho National Laboratory (INL)*. (1) For criticality safety program purposes, the INL consists of areas, programs, and projects that are administered under DOE's current contractor for the INL site, excluding the Idaho Cleanup Project and the Naval Reactor Facility. (2) For purposes of emergency response and locating facilities and complexes, the site now known as INL, including Idaho Cleanup Project and the Naval Reactor Facility areas.

*Interaction, neutron*. See *neutron interaction*.

*Intermediate neutron*. A neutron with an energy that is less than the energy of fast neutrons but more than the energy of slow neutrons (typically greater than 1 eV and not less than 0.1 MeV).

*Isotopes*. (1) Atoms having the same atomic number but different atomic masses or weights. For example, U-233, U-235 and U-238 are all uranium isotopes. (Subtopic 1.1.5) Isotope refers to the entire atom, including the atom's electrons. (2) Sometimes used interchangeably with nuclides.

*$k_{eff}$, k-eff, or k-effective*. The neutron multiplication factor. Mathematically, it is the ratio of the rate at which fission neutrons are produced to the rate at which neutrons are absorbed or escape. (Subtopic 2.4.4.)

*Kinetic energy*. Energy associated with motion. Particles with kinetic energy are capable of producing heat through friction with other particles.

*Limit*. An upper or lower bound placed on a controlled parameter (a criticality control factor). For example, a maximum 350 g U-235 (fissionable mass), minimum 10 g/L B-10 (soluble neutron absorber concentration), maximum 5.0 in. diameter (geometry), or minimum 8.25 in. separation (interaction).

*Mass*. The property of a body that is a measure of its inertia, that is commonly taken as a measure of the amount of material it contains, that causes a body to have weight in a gravitational field, that along with length and time constitutes one of the fundamental quantities on which all physical measurements are based, and that according to the theory of relativity increases with increasing velocity. Fissionable material mass is typically measured in grams or kilograms. (Topic 3.1.)

*Mass Limit CCA*. An area in which criticality safety is provided through generically determined limits on the mass of U-233, U-235, and plutonium. (Subtopic 5.1.4)

*Mass number*. See *atomic mass number*.

*Moderation, neutron*. See *neutron moderation*.

*Moderator, neutron*. See *neutron moderator*.

*Molecule*. The smallest component of a chemical compound having all the chemical and physical properties of that compound. (Subtopic 1.1.1)

*Natural uranium*. Uranium with the isotopic content found in nature.

*Neutron*. A subatomic particle having no electrical charge, typically found in an atomic nucleus. At $1.67492716e^{-27}$ kg, a neutron has an atomic mass of 1.00866 amu. (Subtopic 1.1.2 and Topic 1.2)

*Neutron absorber*. A material or object that readily captures neutrons (Topic 3.5). Also sometimes called a *neutron* or *nuclear poison*.

*Neutron absorption*. A phenomenon 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 1.2.2)

*Neutron capture*. See *neutron absorption*.

*Neutron dose*. The quantity of neutron radiation that is/was absorbed, usually for a specified time period or due to a specified incident. Consult the Radiological Worker Training Student Guide, available through INL on-line training courses, for further information. (NOTE: the rem and Sv dose units are based on chronic exposure to gamma radiation. Neutron dose must be multiplied by a weighting factor [or quality factor] to determine a total dose in rem or Sv. However, most published weighting factors are also based on chronic exposures and, therefore, inaccurate for use with a severe, acute exposure that can result from a criticality accident.)

*Neutron, fast*. See *fast neutron*.

*Neutron, free*. See *free neutron*.

*Neutron interaction*. (1) A phenomenon in which a free neutron interacts with an atomic nucleus (Topic 1.2). (2) A phenomenon in which neutrons escape one body and then interact with atomic nuclei in another body (Topic 3.6).

*Neutron leakage*. A phenomenon in which a free neutron leaves a body or system without undergoing neutron absorption. (Mentioned in Topic 1.2).

*Neutron moderation*. A neutron scattering phenomenon in which a free neutron both changes its travel direction and loses kinetic energy as a result of colliding with an atomic nucleus (Topic 3.4).

*Neutron moderator*. A material or object that causes neutron moderation. Specifically, the material reduces neutrons kinetic energy by neutron scattering collisions without appreciable neutron absorption. Good moderators include oil, carbon, and hydrogenous materials (for example, water and plastics) if the moderating material is well mixed with the fissionable material. (Topic 3.4) Also see *special moderator*.

*Neutron multiplication factor*. See *$k_{eff}$, k-eff, or k-effective*.

*Neutron poison*. See *neutron absorber*.

*Neutron radiation*. Free neutrons. Neutrons are a highly penetrating form of ionizing radiation. Consult the Radiological Worker Training Student Guide, available through INL on-line training courses, for further information.

*Neutron reflection*. A neutron scattering phenomena in which free neutrons that would otherwise escape return to a fissionable mass. (Topic 3.3)

*Neutron reflector*. A material or object that reflects incident free neutron back into a fissionable mass. Good reflectors include concrete, heavy metals, and good moderators. (Topic 3.3) Also see *special reflector*.

*Neutron scatter*. A phenomenon in which a free neutron collides with an atomic nucleus, changing the incident neutron's travel direction and possibly losing some energy. (Subtopic 1.2.1)

*Neutron, slow*. See *slow neutron*.

*Neutron, thermal*. See *thermal neutron*.

*Nuclear Accident Dosimeter (NAD)*. Passive device specifically made of various materials and located to provide, when analyzed, radiological dose information about a criticality accident. NADs are strategically placed in areas where criticality alarm systems are required.

*Nuclear [fission] chain reaction*. A reaction in which nuclear fission of one atomic nucleus leads to fission in one or more other atomic nuclei. (Topic 2.2)

*Nuclear fission*. Splitting an atomic nucleus into lighter nuclei (fission fragments), releasing one or more neutrons (neutron radiation), gamma radiation, and kinetic energy. (Topic 2.1)

*Nuclear fuel*. (1) (a) Fissionable material with a composition and form for use as fuel in a nuclear reactor or critical assembly or (b) pieces of such material. (2) Sometimes used interchangeably with fissionable material.

*Nucleon*. A proton or neutron (Subtopic 1.1.2).

*Nuclide*. (1) An atomic species characterized by the constitution of its nucleus, specifically the number of protons, the number of neutrons, and, sometimes, its energy. (For example, the different isotopes of an element are composed of nuclides having the same atomic number but different mass numbers.) (2) Sometimes used as interchangeably with *isotope*.

*Parameter, criticality [control]*. See *criticality [control] factor*.

*Poison, neutron*. See *neutron absorber*.

*Posting*. (1) For criticality safety purposes, the placement of signs to indicate the presence of fissionable material, to designate work and storage areas, or to provide instruction or warning to personnel. (2) Signs that have been posted. Subtopics 5.1.4 and 5.1.5 include information on CCA posting.

*Procedure CCA*. An area that requires specific controls to ensure criticality safety and that is not designated a Mass Limit CCA. The controls are determined by and identified in an approved criticality safety evaluation. (Subtopics 5.11and 5.12)

*Prompt critical*. A nuclear critical or supercritical condition achieved with prompt neutrons.

*Prompt neutron*. A neutron released directly by a nuclear fission event.

Proton. A subatomic particle having a single positive electrical charge, typically found in an atomic nucleus. At $1.67262158e^{-27}$ kg, one proton has an atomic mass of 1.00728 amu. (Subtopic 1.1.2)

*Reflection, neutron*. See *neutron reflection*.

*Reflector, neutron*. See *neutron reflector*.

*Safe-by-geometry*. An equipment or system characteristic that ensures subcriticality by virtue of neutron leakage under worst credible conditions (Topic 3.8). Also sometimes called *favorable geometry*.

*Scatter, neutron*. See *neutron scatter*.

*Shipping package*. See *fissile material shipping package*.

*Slow neutron*. A neutron with low energy (no more than 1 eV). Also see *thermal neutron*.

*Special moderator*. A material that is a significantly more effective neutron moderator than water. For example, heavy water, reactor-grade graphite, and extremely large quantities of beryllium.

*Special reflector*. A material that is a significantly more effective neutron reflector than water. For example, good moderators, lead, very thick steel, and concrete.

*Subatomic particle*. A discrete particle smaller than an atom. For example, a proton, neutron or electron.

*Subcritical*. (Subtopic 2.4.1) A phenomenon characterized by the lack of a self-sustained nuclear chain reaction. If nuclear fission occurs, then, on the average, each fission event results in less than one neutron that causes an additional fission event. This condition has a k-eff less than 1.0. (Subtopic 2.4.4)

*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 uncertainty and bias in the calculation methodology.

*Supercritical*. (Subtopic 2.4.3) A phenomenon characterized by a divergent nuclear chain reaction in which, on the average, each fission results in more than one neutron that causes an additional fission. This condition has a k-eff greater than 1.0. (Subtopic 2.4.4.)

*Thermal neutron*. (1) Technically, a slow neutron that is in thermal equilibrium with its ambient medium. Such a neutron's energy is probably about 0.025 eV and, therefore, the neutron is probably moving at a speed of about 2.2 km/s. Thermal neutrons are important because they are most likely to produce fission in $^{235}$U. (2) Nontechnically, interchangeable with *slow neutron*.