INL/EXT-07-12535

Revision 1

Criticality Safety Basics for INL Emergency Responders

August 2012

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Criticality Safety Basics for INL Emergency Responders

August 2012

Idaho National Laboratory
Criticality Safety Engineering
Idaho Falls, Idaho 83415

http://www.inl.gov

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FOREWORD

This document is a modular self-study guide about criticality safety principles for Idaho National Laboratory emergency responders. This guide provides basic criticality safety information for people who, in response to an emergency, might enter an area that contains much fissionable (or fissile) material. The information should help responders understand unique factors that might be important in responding to a criticality accident or in preventing a criticality accident while responding to a different emergency.

This study guide specifically supplements web-based training for firefighters (0INL1226) and includes information for other Idaho National Laboratory first responders such as radiological control personnel.

For interested readers, this guide includes clearly marked additional information that will not be included on tests. The additional information includes historical examples (*Been there. Done that.*), as well as facts and more in-depth information (*Did you know …*).

INL criticality safety personnel revise this guide as needed to reflect program changes, user requests, and better information. Revision 0, issued May 2007, established the basic text. Revision 1 incorporates operation, program, and training changes implemented since 2007. Revision 1 increases focus on first responders because later responders are more likely to have assistance and guidance from facility personnel and subject matter experts. Revision 1 changes are not marked because the revision also completely reorganized the training to better emphasize information identified by firefighter trainers as most important. The changes are based on and consistent with changes made to course 0INL1226.

CONTENTS

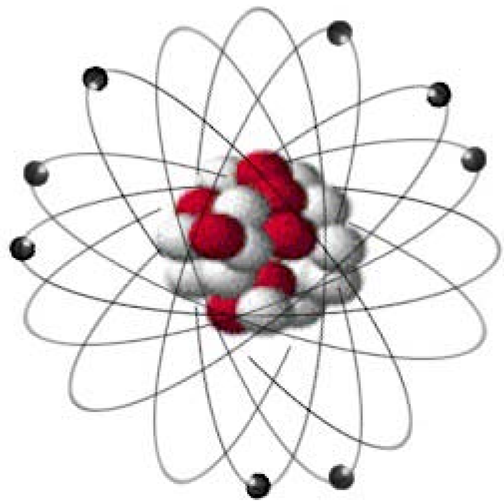
ACRONYMS

ANS	American Nuclear Society, La Grange Park, Illinois, USA
ANSI	American National Standards Institute
ATR	Advanced Test Reactor at the ATR Complex
ATRC	ATR Critical Facility at the ATR Complex
BEA	Battelle Energy Alliance, LLC
CAS	criticality (accident) alarm system
CCA	criticality control area (INL/BEA nomenclature)
CSO	criticality safety officer
CWI	CH2M-WG Idaho, LLFC (or CH2M Hill, Washing Group International, and Premier Technology), Idaho Falls and Scoville, Idaho
DOE	United States Department of Energy, Washington D. C.
EDMS	electronic document management system (http://edms.inel.gov/inl_index.html)
hr	hour
ICPP	Idaho Chemical Processing Plant. Currently Idaho Nuclear Technology and Engineering Center (INTEC)
INL	Idaho National Laboratory, Idaho Falls and Scoville, Idaho, USA (the DOE site and a DOE contract)
JCO	JCO Fuel Fabrication Plant, Tokaimura, Ibarakiken, Japan (*JCO* is a name, not an acronym)
LRD	laboratory requirements document (INL/BEA nomenclature)
LWP	lab-wide procedure
MFC	Materials & Fuels Complex at the INL. Formerly Argonne National Laboratory – West (ANL-W)
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.
NRX	Nuclear Reactor Experimental at Chalk River Laboratories (CRL), Chalk River, Ontario, Canada
PRD	program requirements document (CWI nomenclature)
rad	radiation absorbed dose
rem	radiation equivalent man
rev	revision
RA-2	not identified (a critical facility at the Constituyentes Atomic Center [Centro Atómico Constituyentes or CAC], Constituyentes [near Buenos Aires], Argentina)

SF-3	not identified (a critical assembly/machine at the Kurchatov Institute, Moscow, Moscow Oblast, Russian Federation)
SL-1	Stationery Low-power reactor/plant number 1 at what is now INL
USA	United States of America
VENUS	Vulcain Experimental Nuclear Study at the Nuclear Research Center (NRC), Mol, Antwerp Province, Belgium
VNIIEF	Russian abbreviation for Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics, Sarov (formerly *Arzamas-16*), Nizhny Novgorod Oblast, Russian Federation
Y-12	Y-12 Plant, Oak Ridge, Tennessee, USA (*Y-12* started as a codename, not an abbreviation)
ZPR-1	Zero Power Reactor number 1 at Argonne National Laboratory – East (ANL-E), Argonne, Illinois, USA. The site is currently *Argonne National Laboratory (ANL)*

MODULE 1 REVIEW OF ATOMS, NEUTRONS AND FISSION

Introduction



Criticality safety is protection against nuclear criticality accidents, preferably by accident prevention, but also by accident mitigation. Understanding criticality safety begins with a little knowledge about atoms and neutrons. Such basic knowledge lays a foundation for understanding the fission process, which, in turn, provides a basis for understanding what could cause or prevent a criticality accident.

Module 1 reviews background information about atomic structure, neutrons, neutron interactions, nuclear fission, chain reactions, and fissionable material. Much of this information is also part of other training courses (for example, radiation and nuclear safety courses). Readers need not review topics that they remember well.

Objectives

Explain basic atomic structure.

Define isotope.

Identify two major ways a neutron can interact with an atomic nucleus -- neutron scatter and neutron absorption.

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

Identify nuclear fission as one possible result of a neutron absorption event.

Describe a nuclear fission and nuclear fission chain reaction.

Describe fissionable material.

Identify the fissionable isotopes of most concern at INL.

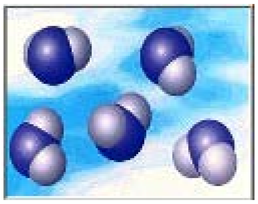
Describe subcritical in terms of a self-sustaining chain reaction.

Describe critical, and supercritical in terms of a self-sustained nuclear fission chain reaction.

My Notes:

Topic 1.1 Atomic Structure

1.1.1 Molecules and Atoms

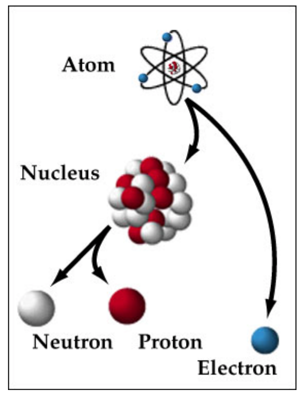


Depiction of water molecules

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*.



Depiction of an atom and its parts

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

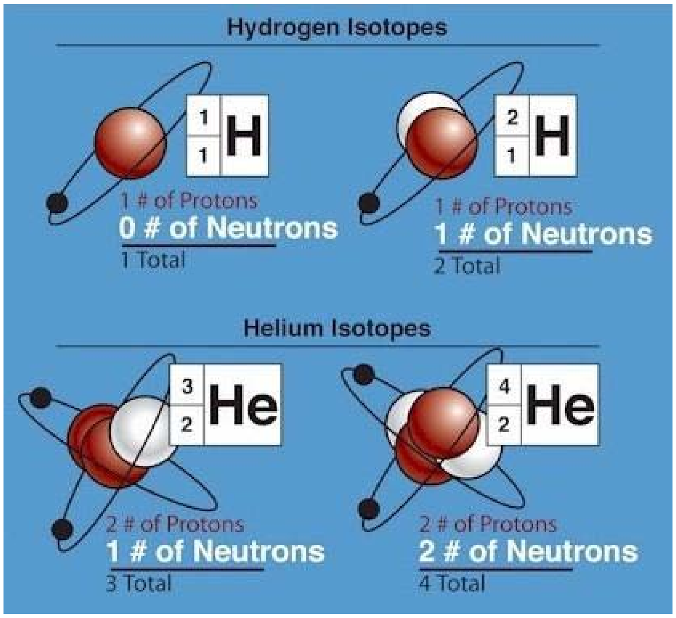
1.1.3 Outside an Atomic Nucleus: Electrons

Electrons orbit the nucleus. An electron is very small, and has very little mass, compared to a proton or neutron. Electrons are negatively charged particles. Electrons are very important in chemistry and other fields. But electrons are not important in causing or preventing criticality accidents.

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 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.

My Notes:

Review Questions

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

[ ]	Within an atom, electrons are located ____ the nucleus	A	molecules
[ ]	Within an atom, neutrons are located ____ the nucleus	B	atom
[ ]	Within an atom, protons are located ____ the nucleus	C	inside
[ ]	All uranium isotopes have the same number of ____.	D	outside
[ ]	____ have about the same mass and size as protons.	E	electrons
[ ]	____ have a positive electrical charge.	F	neutrons
[ ]	____ have a negative electrical charge.	G	protons
[ ]	_____ have no electrical charge; they are neutral.	H	isotopes
[ ]	U-233, U-235, and U-238 are _____ of uranium.		
[ ]	Plutonium isotopes Pu-238, Pu-239, Pu-240, and Pu-241 differ by their number of _____.		
[ ]	The chemical identity of an element is determined by the number of _____ in its nucleus		

Review Question Answers

D	Within an atom, electrons are located ____ the nucleus	A	molecules
C	Within an atom, neutrons are located ____ the nucleus	B	atom
C	Within an atom, protons are located ____ the nucleus	C	inside
G	All uranium isotopes have the same number of ____.	D	outside
F	____ have about the same mass and size as protons.	E	electrons
G	____ have a positive electrical charge.	F	neutrons
E	____ have a negative electrical charge.	G	protons
F	_____ have no electrical charge; they are neutral.	H	isotopes
H	U-233, U-235, and U-238 are _____ of uranium.		
F	Plutonium isotopes Pu-238, Pu-239, Pu-240, and Pu-241 differ by their number of _____.		
G	The chemical identity of an element is determined by the number of _____ in its nucleus		

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.

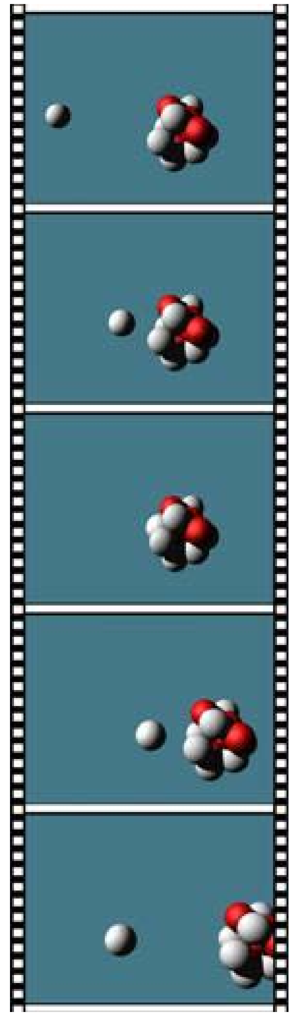
To help understand what might happen to a neutron in whatever system interests us, think of the neutron as a bullet that is fired in a random direction and the system as a large room in which there are many well-spaced objects, including boxes that contain more bullets. The room's objects represent nuclei 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:

Some things that might happen to a fired bullet are similar to things that might happen to a free 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***.

My Notes:

1.2.1 Neutron Scattering



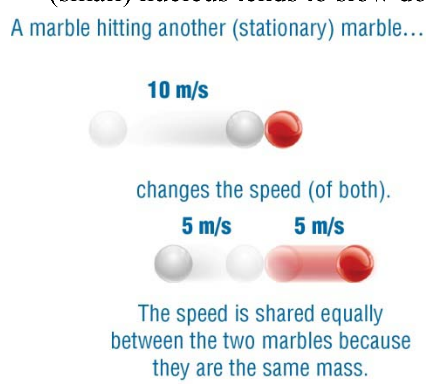
Above, a depiction of a neutron scatter event with a light nucleus.

Just as our bullet might ricochet off an object or wall, a neutron might "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 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 phenomena can be very important for reasons described in a later module.

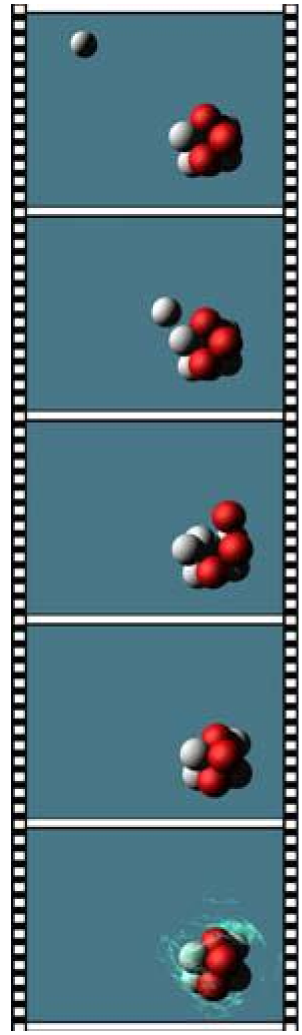


Did you know …

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.

1.2.2 Neutron Absorption

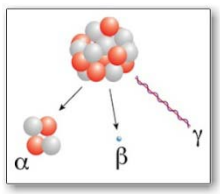
Neutron absorption occurs when a neutron collides with a nucleus and becomes part of that nucleus. To picture the process, imagine our bullet penetrating, but not passing through, an object. The object is small or light enough that, as it absorbs the bullet's energy, the object becomes momentarily unstable.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



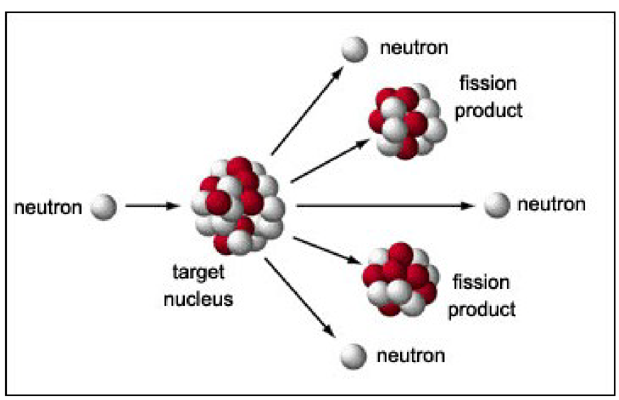
Above, a depiction of neutron capture in a B-10 nucleus (depiction ends before radioactive decay)

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 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 releasing 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 topic.



To the left, a depiction of nuclear fission (the target nucleus absorbs a neutron and splits into two fission products, releasing more neutrons

Did you know …

- You can find more information about radiation by consulting 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

- Neutron absorption creates an unstable nucleus, even if the unstable nucleus has a naturally occurring, stable counterpart. The compound nucleus has excess energy because it has a *mass defect*. The compound nucleus has more mass than its stable counterpart.

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

Topic 1.3 Nuclear Fission

1.3.1 One 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).

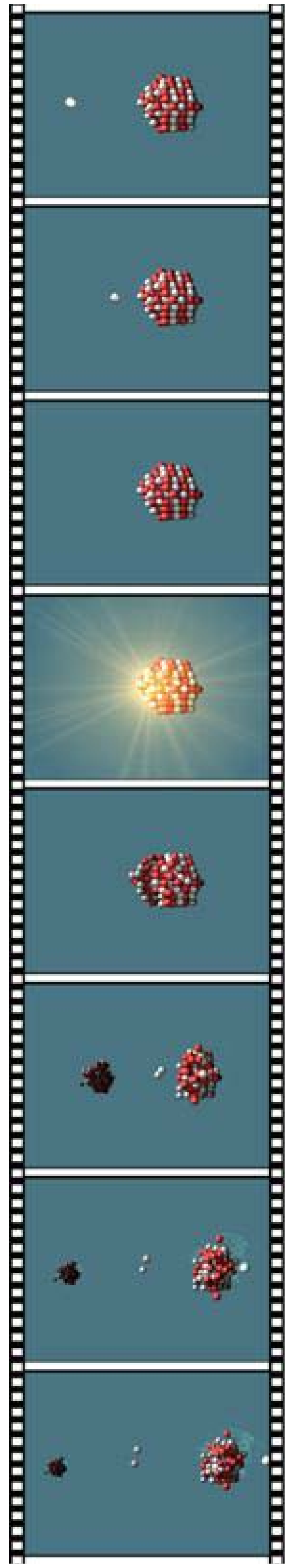
Fission fragments are more stable than the original nucleus, but they are still unstable. They are radioactive. They become more stable through radioactive decay. Fission fragments and their radioactive decay can be a health hazard if enough nuclei fission. This hazard will be discussed more in a later module. 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 also important because they are a form of radiation. This radiation can be a health hazard if enough nuclei fission. Radiological Worker Training and later modules of this training provide more information about the radiation hazards associated with nuclear 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

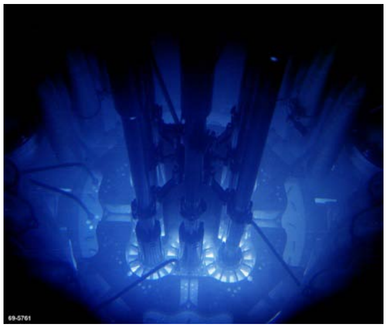
My Notes:

1.3.2 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.

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 the INL these days.

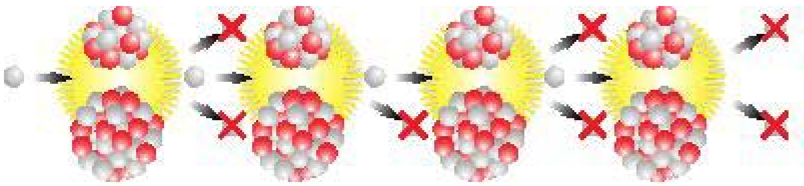


Critical condition in ATR

Critical condition in NRAD

1.3.3 Subcritical Fission Chain Reactions or Conditions

A *subcritical* material or system is one in which fission chain reactions ***are not*** self-sustaining. Any nuclear fission chain reaction is very brief.



A depiction of a subcritical nuclear fission chain reaction. Crossed out neutrons are neutrons that do not cause additional fissions. Within a few fissions, there are no free neutrons to continue the chain.

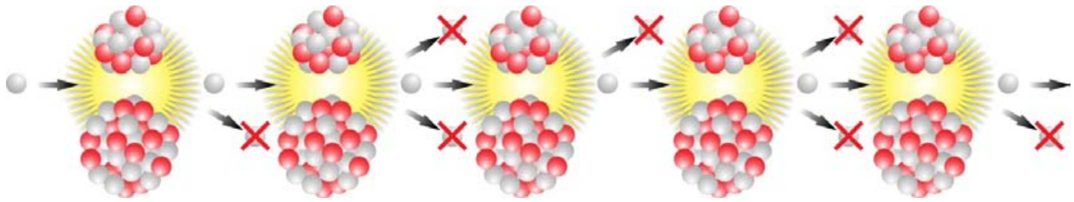
Except for ATR, ATRC, and NRAD, all systems and fissionable materials at INL must be kept subcritical. Even ATR, ATRC, and NRAD must be kept subcritical at times.

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

1.3.4 Critical Fission Chain Reactions or Conditions

A *critical* material or system is one in which fission chain reactions ***are*** self-sustaining.

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.

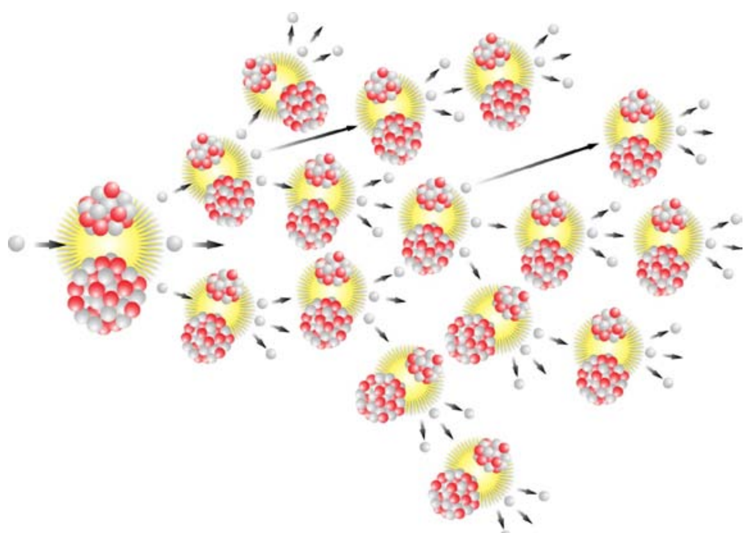


A depiction of a critical nuclear fission chain reaction. Each fission produces one free neutron that continues the chain.

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 the INL, a critical condition is undesirable unless the condition intentionally occurs in the ATR, ATRC, or NRAD.

1.3.5 Supercritical Fission Chain Reactions or Conditions

A *supercritical* material or system is one in which fission chain reactions ***are*** self-sustaining and the number of chain reactions is increasing.



A depiction of a supercritical nuclear fission chain reaction. Each fission produces more than one free neutron that continues the chain.

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 the 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 …

- 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 solid material in a storage system or with buried radiological waste (non-fuel) materials, but such accidents may be considered credible in some non-INL facilities.

- A supercritical condition normally does not last long. Out-of-reactor accidents usually release enough energy to displace or boil or melt material into a subcritical configuration within seconds.

My Notes:

Topic 1.4 Fissionable Material and Fissionable Isotopes

Nuclear fuels are examples of fissionable material. The uranium-aluminum fuels above have a large quantity of U-235.

Materials that can sustain a nuclear fission chain reaction are called *fissionable materia*l (at BEA facilities) or *fissile materials* (at CWI and most other facilities). Nuclear fuels are examples of fissionable material. Plutonium used in radioisotope thermal generators can also be fissionable material.

Fissionable materials contain a significant quantity 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 the INL in the forms, purities, and quantities that pose a criticality hazard.

The fissionable nuclides that could pose a criticality hazard at INL are specific isotopes of uranium (U), plutonium (Pu), neptunium (Np), and americium (Am). However, due to the type of information that is readily available, criticality safety may track all isotopes of plutonium neptunium, and americium:

U-233 **U-235** **Pu**

Np **Am**

We call these isotopes the *fissionable nuclides of concern*. The first three, in red, are the fissionable isotopes of **most** concern at the INL site. The specific isotope(s) of most concern at a specific facility varies. For example, U-235 is the primary criticality safety concern at the ATR Complex; plutonium is the primary concern in some MFC facilities.

A fissionable material that contains a large quantity of one or more of these isotopes is a criticality concern at the INL. If you encounter fissionable material during emergency response, avoid moving or handling it unless absolutely necessary.

Did you know …

You might sometimes hear the word *fissile*, instead of *fissionable*. Many popular, nontechnical dictionaries define the terms synonymously to mean *capable of undergoing nuclear fission*. Other definitions for the terms introduce subtle differences that do not truly help or hinder communications or work at the INL site. Therefore, INL emergency responders need not worry about other definitions here, even if some people use the terms as if they are not synonymous.

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	A	fission chain reactions are self-sustaining
☐	fissionable material	B	one or more neutrons from one nuclear fission cause one or more additional nuclear fissions
☐	fissionable isotopes of most concern	C	material capable of sustaining fission chain reactions
☐	subcritical	D	fission chain reactions are not self-sustaining
☐	critical or supercritical	E	the splitting of an atomic nucleus into two fragments, releasing energy and free neutrons
☐	fission chain reaction	F	U-233, U-235, Pu

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	A	safe
☐	critical	B	unsafe or undesirable
☐	supercritical		

Review-Question Answers

Description/definition match

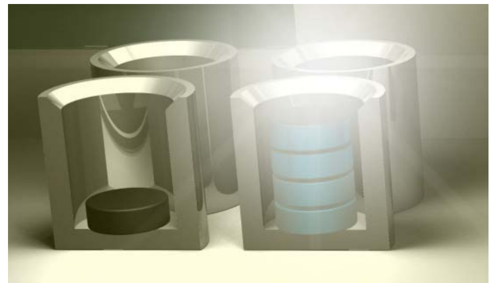
Answer	Term		Definition
E	nuclear fission	A	fission chain reactions are self-sustaining
C	fissionable material	B	one or more neutrons from one nuclear fission cause one or more additional nuclear fissions
F	fissionable isotopes of most concern	C	material capable of sustaining fission chain reactions
D	subcritical	D	fission chain reactions are not self-sustaining
A	critical or supercritical	E	the splitting of an atomic nucleus into two fragments, releasing energy and free neutrons
B	fission chain reaction	F	U-233, U-235, Pu

Description match for INL operations outside of ATR, ATRC, and NRAD

Answer	Term		Description
A	very subcritical	A	safe
B	critical	B	unsafe or undesirable
B	supercritical		

MODULE 2 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.

Personnel who respond to a criticality accident or who might adversely affect criticality safety while responding to a different kind of accident need to understand a few criticality accident characteristics to protect themselves.

Objectives

Define criticality accident.

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

Identify some characteristics of a criticality accident that are relevant to emergency response.

Identify initial symptoms of radiation sickness that might be observable in the first few hours.

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

My Notes:

Topic 2.1 Criticality Accidents

2.1.1 What is a Criticality Accident?

A criticality accident is an inadvertent or uncontrolled critical or supercritical nuclear fission chain reaction. 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.

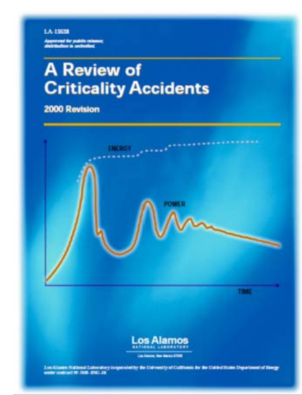
Criticality accidents are most serious when they occur in locations that do not have sufficient shielding to protect personnel. However, any criticality accident represents a loss of control(s) that has a potential for significant adverse consequences.

A criticality accident can occur without an easily recognized warning. There might be no sound, vibration, flash, significant heat, or anything else to warn you that an accident has, is, or will occur. 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.

2.1.2 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 ("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).



Report describing 60 criticality accidents.

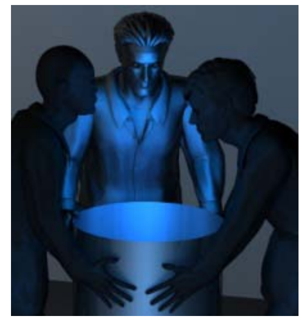
At the INL, we incorporate the information into our criticality safety programs to help accomplish our purpose of preventing and mitigating criticality accidents. We also incorporate information about criticality accident characteristics and accident-response experiences into INL emergency planning to help mitigate criticality accidents.

Did you know …

Three criticality accidents occurred in recent years. The 1997 accidents at the Novosibirsk Chemical Concentrates Plant and VNIIEF in Russia and the 1999 accident at the JCO Plant in Japan remind us that criticality safety controls, standards, and vigilance must be maintained.

2.1.3 Causes

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.



Human error was a major factor in most criticality accidents

None of these historical accidents involved unpredictable or inexplicable nuclear phenomena.

Some accidents involve one or more problems with equipment. But, in most cases, human error is a major factor.

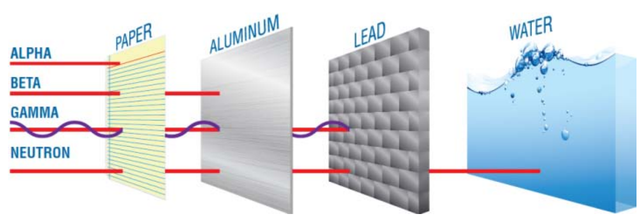
None of these historical accidents included bursts caused by firefighters, radiological control technicians, or security personnel. However, there is a very small risk that such first responders could commit actions that contribute to such bursts.

Did you know …

Most process (out of reactor) criticality accidents occurred with similar materials. Most of these excursions occurred in moderated fluids (solutions, powders, gases, 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.

2.1.4 Radiation

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



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

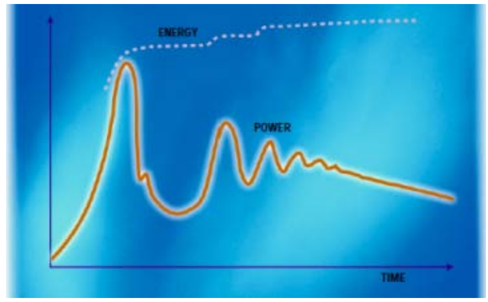
The amount of radiation generated in a local area due to a criticality accident is large, even for a small accident. A criticality accident can generate higher levels of neutron and gamma radiation in a shorter time than almost any other radiological accident.

Radiological shielding is very important in protecting emergency responders. But the use of such shielding must consider the neutron reflection properties of shielding materials and of the human body. Such effects are described in Module 4 (Topic 4.3).

2.1.5 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.

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 burst, multiple bursts, or burst(s). 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.



A criticality accident power history might include multiple bursts, a special hazard for responders.

Criticality accidents with multiple bursts and/or quasi-steady state power can be especially dangerous to rescuers and other emergency responders.

A single-burst criticality accident might last no more than a small fraction of a second. The elapsed time of an accident with multiple bursts or a quasi-steady state power might be several minutes to days or longer. Some accidents require human intervention to terminate.

Radiation levels tend to follow power levels. The amount of radiation emitted is proportional to the number of fissionable isotopes that fission.

Been there. Done that.

Some 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. 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 Sarov, Russia on June 17, 1997. 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 2.2 Criticality Accident Consequences

2.2.1 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.

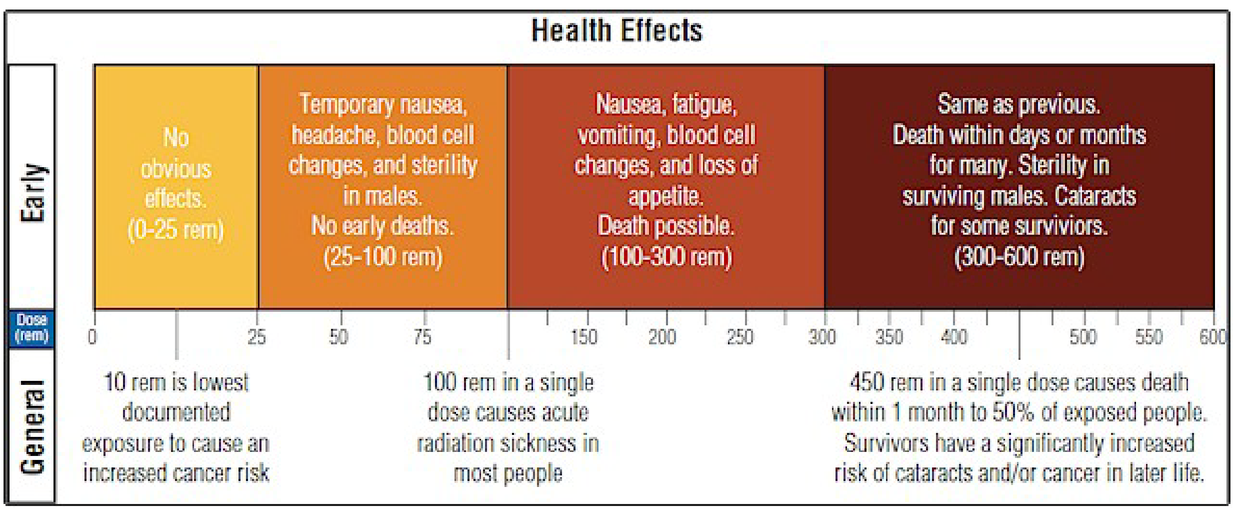
For example, consider the 60 reported criticality accidents that occurred since the 1945. Collectively these accidents resulted in 21 fatalities and 29 other people with acute radiation injury. All seriously exposed individuals suffered acute radiation sickness. At least seven people suffered permanent 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.

However, predictions based on distance alone are only generalities.

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

Did you know …

You can learn more about the health effects of radiation exposure from one or more of the following:

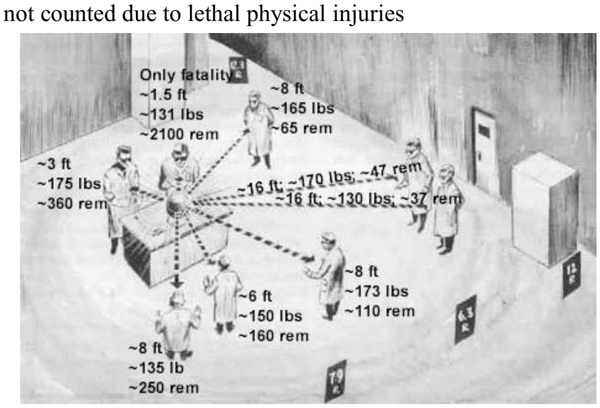
- The Radiological Worker Training Study Guide
- Course 000TRN74, General Employee Radiological Training (GERT)
- Course 00TRN213, Radiological Worker I
- Course00TRN211, Radiological Worker II
- Instruction EPI-76, Emergency Radiation Exposure Control, Appendix A

Been there. Done that.

- The human body is a reasonable dosimeter for severe radiation exposures. In general, the higher the radiation dose, the more severe the symptoms and the earlier they manifest.

number of people with			***(from 23 accidents in which at least one person's exposure ≥ 100 rad)***
lethal exposures	**non-lethal exposures ≥ 100 rad**	**non-lethal exposures < 100 rad**	**time of symptom onset**
3	0	0	immediate (5 minutes or less)
5	2	0	rapid (5 to 30 minutes)
2	1	0	moderate (30 minutes to few hours)
	12	0	slow (few hours to one day)
	2		very slow (more than one day)
		7	no symptoms
8	12	43	not identified in readily available documents
3			not counted due to lethal physical injuries

- Health effects can vary considerably even for similar sources, distances from the source, and exposure times. 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. 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.



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

The similarly energetic, single burst, 1978 Siberian Chemical Combine criticality accident occurred with unmoderated, reflected, plutonium bricks. 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.

2.2.2 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 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 scattered radioactive debris locally, but no contamination was detected outside the respective facility fence line. With the exception of I-131, contamination from the 1961 Stationery Low-Power Reactor 1 (SL-1) explosion was confined to three acres within the complex boundaries. Even in the case of the 1999 JCO accident in Japan, 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.

2.2.3 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.

- 48 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 in Japan. However, sometimes the accident itself caused a little damage. For example, a 1958 criticality accident in Los Alamos displaced the tank in which the accident occurred by about 3/8 inches at its supports.
- Several in-reactor criticalities caused significant, but still localized damage. For example, the 1954 destructive test of the Boiling Water Research Reactor number 1, the 1961 Stationery Low-power reactor number 1 accident, and the 1962 destructive Special Power Excursion Reactor Test ID test 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.

	Statement		Phrase
☐	The health effects of radiation exposure due to a criticality accident _____	A	time, distance and shielding
☐	Short term health effects might include _______.	B	radiological contamination
☐	If the exposure is not lethal, long term health effects might include _____.	C	can vary greatly
☐	_______ might occur as the result of an accident, but it was very local in historical accidents.	D	nausea, diarrhea, vomiting, loss of consciousness, and convulsions
☐	Most criticality accidents result in _____.	E	little or no equipment damage
☐	_______ are the three major factors influencing the radiological dose a person might receive as the result of a criticality accident.	F	eye cataracts and cancer

Review-Question Answers

C	The health effects of radiation exposure due to a criticality accident _____	A	time, distance and shielding
D	Short term health effects might include _______.	B	radiological contamination
F	If the exposure is not lethal, long term health effects might include _____.	C	can vary greatly
B	_______ might occur as the result of an accident, but it was very local in historical accidents.	D	nausea, diarrhea, vomiting, loss of consciousness, and convulsions
E	Most criticality accidents result in _____.	E	little or no equipment damage
A	_______ are the three major factors influencing the radiological dose a person might receive as the result of a criticality accident.	F	eye cataracts and cancer

MODULE 3 INL CRITICALITY SAFETY PROGRAMS

Introduction

INL contractors develop criticality safety programs to prevent and mitigate criticality accidents. These programs are part of the basis for criticality safety information and response actions identified in emergency response and pre-incident planning.

To comply with the programs, contractors must identify areas that require criticality controls. Knowing a little about such areas could help firefighters and other responders during initial emergency response.

Objectives

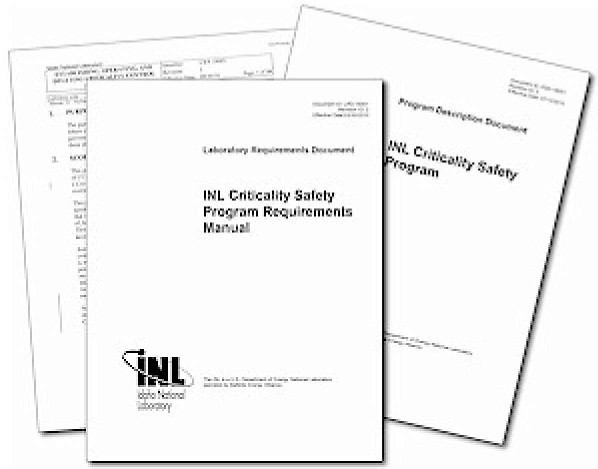
Describe the purpose of a criticality safety program and how it is related to emergency response.

Describe how areas requiring criticality control might be posted.

My Notes:

Topic 3.1 INL Criticality Safety Programs

3.1.1 Program Purpose

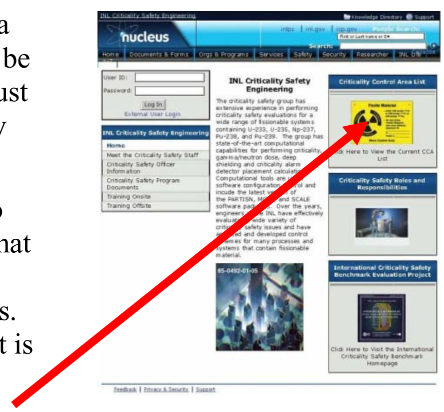


INL contractors that have areas requiring criticality controls also have criticality safety programs. The purpose of each program is to protect people and the environment by preventing and mitigating criticality accidents. The programs are important in preventing injurious, or even lethal, radiation exposures.

The programs implement all relevant national, federal, and DOE requirements. The programs also incorporate relevant recommendations and best management practices. In addition, the programs are based on the core functions and guiding principles of integrated safety management systems.

Where applicable, these criticality safety programs are consistent with the contractor's emergency planning requirements.

3.1.2 BEA Criticality Control Areas



At BEA contractor facilities, a criticality control area (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 CCA has a criticality safety officer (CSO) who represents facility management. The CSO ensures that relevant criticality safety information for the area is incorporated in documents such as pre-incident plans. Such information includes any criticality control that is important to emergency response.

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

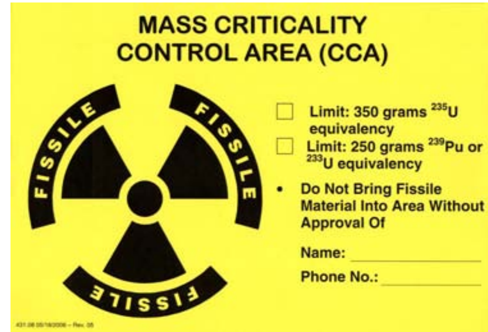
3.1.3 BEA CCA Postings

The CSO posts CCA entrances when it is determined to be useful to people who work in or near a CCA, might pass through a CCA while transferring fissionable material, and/or might respond to an emergency in or near the CCA.

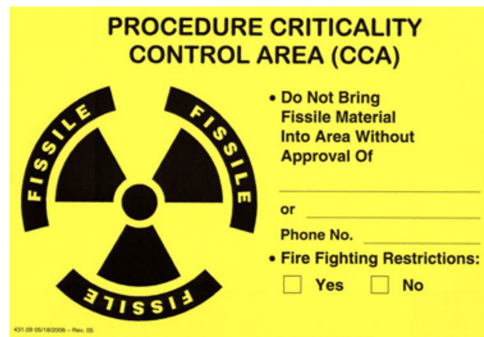
In addition, any relevant fire-fighting restrictions that are necessary for criticality safety are posted if such posting would help remind firefighters of the restrictions.

BEA defines two CCA types and has similar, but different postings for each type:

- A mass limit CCA is an area in which criticality safety is ensured by limiting fissionable material to a very small amount. It is extremely improbable that an emergency responder will respond to a criticality accident in such an area. It is also extremely improbable that an emergency responder could do anything that would cause a criticality accident in one of these areas.



- 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. Criticality safety controls are typically unique to the area. A procedure CCA might have a firefighting restriction for criticality safety purposes. Criticality accidents in such areas are very improbable; but, in general, there is a higher risk of a criticality accident in a procedure CCA than in a mass limit CCA. In addition, it is conceivable, but very rare, that emergency responders might affect criticality safety in such an area even if the emergency is not a criticality accident.



3.1.4 CWI Areas Requiring Criticality Control

CWI does not specifically name or categorize areas that require criticality control.

However, like BEA, each CWI area that requires such controls has a CSO. The CSO ensures that any criticality controls important to firefighters are identified in the area pre-incident plan.

You can access a list of CWI CSOs and their areas that require criticality controls from the CWI Nuclear Safety home page. The specific URL in August 2012 was http://icpportal/eshq/ESHQ/NuclearSafety/CSOList.aspx.

3.1.5 Postings for CWI Areas Requiring Criticality Control

CWI does not require posting entrances to areas that require criticality control. Instead, CWI relies on documents such as pre-incident plans to identify the locations and boundaries of such areas for emergency response.

However, CWI requires posting criticality safety limits ***if*** such posting is determined useful. In some sense, emergency responders can confirm they are in an area that requires criticality controls if they see such a posting.

Three typical examples of blank, generic postings are described below.

- CWI examples 1 and 2, with *Fissile Mass Limited Area* in their headings, are used for areas that are much like BEA mass limit CCAs. Criticality safety is ensured by limiting the amount of fissionable material to a fairly small amount. Such a CCA does not have a fire fighting restriction for criticality safety purposes. It is extremely improbable that an emergency responder will respond to a criticality accident in such an area. It is also extremely improbable that an emergency responder could do anything that would cause a criticality accident in such a CCA.

CWI example 1

CWI example 2

- CWI example 3 is used in typical areas in which nuclear waste containers are handled and/or stored. Each container may have a small quantity of fissionable material, but an area with many such containers could have a relatively large quantity of fissionable material. However, due to the nature of waste material, the probability of a criticality accident with such containers is comparable to the probability of such an accident in a CCA posted with a *Fissile Mass Limit Area* sign.

CWI example 3

CWI also has other areas that require criticality control. These areas are somewhat analogous to BEA's procedure CCAs. For example, each area has criticality controls that are determined specifically for the area, its material, and its activities. Criticality safety controls are typically unique to the area. Such an area might have a firefighting restriction for criticality safety purposes. Criticality accidents in such areas are very improbable; but, in general, there is a higher risk of a criticality accident in these areas than in fissile mass limited areas. In addition, it is conceivable, but very rare, that emergency responders might affect criticality safety in such an area even if the emergency is not a criticality accident.

3.1.6 Other INL Criticality Safety Programs

There might be other INL areas operated by other organizations that require criticality controls. Possible examples include areas within the Naval Reactor Facilities Complex or the Advanced Mixed Waste Treatment Project.

Names and postings for such areas may differ from BEA and CWI postings, but criticality safety principles, control factors, and precautions would be similar.

Facility or complex management provides separate emergency-responder training for such areas when needed.

3.1.7 Recognizing the Fissile Material Label

BEA's CCA identification signs include the fissile material symbol, shown to the right. Depending on the symbol's size, it might or might not include the word *fissile*.

Fissionable/fissile material symbol

In addition to CCA signs, you might find this symbol on labels for containers and objects in a CCA. The symbol doesn't always appear on fissionable material labels. But if you see it on a label, treat the container or object as fissionable material.

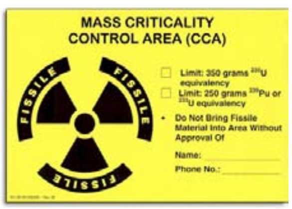
Try to avoid moving or handling the material unless you have specific training for handling such material in the CCA or, as an emergency responder, you have authorization and directions developed as part of a specific emergency's response.

My Notes:

Review Questions

Fill in the blanks.

1. A criticality safety program's purpose is to protect people by ______________________ and __________________criticality accidents.
2. A criticality safety program is important in preventing injurious, or even lethal, ______________________ ______________________.
3. A/an _________________ is a BEA area in which fissionable material must be controlled to ensure criticality safety.
4. A ____________________ ____ ______________________is one type of CWI area that requires criticality control. Other areas requiring criticality control do not have have special names.
5. Any one of the following postings indicates you are near or in a BEA or CWI area requiring ______________ ______________________.



6. BEA CCA signs include the fissile material symbol. If that symbol appears on a container label, it indicates the container may have ____________ ____________ inside.
7. When needed, ______________ or ________________ _____________________ provides separate firefighter training for non-BEA, non-CWI areas that require criticality control.

Review-Question Answers

1. preventative, mitigative
2. radiation exposure
3. CCA (or criticality control area)
4. fissile material limited area
5. criticality control(s)
6. fissionable (or fissile) material
7. facility, complex management

MODULE 4 CRITICALITY ACCIDENT PREVENTION DURING EMERGENCY RESPONSE

Introduction

A facility that has a large amount of fissionable material might have controls and precautions to prevent a criticality accident during emergency response to some other kind of accident.

To perform their tasks safely, first responders need some understanding of certain criticality controls and of how such controls affect their emergency response.

Idaho National Laboratory

Form # FD-121
Rev: 1

Pre-Incident Plan Fire Department	COMPLEX ABBREVIATION BUILDING NUMBER BUILDING NAME	Identifier: Periodicity: Page:	COMPLEX 3 Years 1 of N
Document Control Center: 526-5262	Document Owner: Fire Department Manager	Effective Date:	Month Year

1. ADDRESS
Street:
Street address if applicable

Objectives

Identify the document(s) that specify area-specific criticality safety requirements and precautions or that activate criticality safety consultation for responders. (The documents may differ for different types of emergency responders.)

Describe precautions first responders might take in an area with moderation, reflection, geometry, or interaction controls.

For radiological first responders: Describe the affects fissionable mass might have on emergency response.

Identify common neutron moderators and reflectors responders might use or encounter.

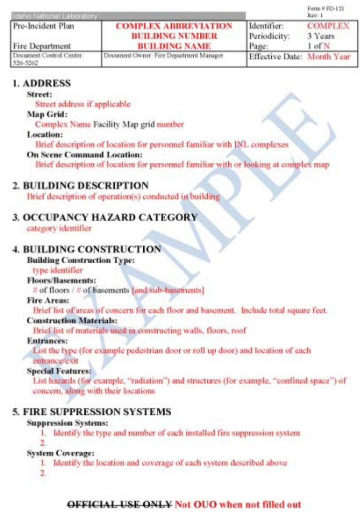
My Notes:

Topic 4.1 Criticality Accident Prevention During Emergency Response

4.1.1 Pre-planned Emergency Response

To maintain subcriticality, safety personnel and management establish very reliable criticality controls. These controls are designed to ensure that no single, credible failure will result in a criticality accident. However, in some cases there is no guarantee of criticality safety after two or more failures.

Although very unlikely, emergency responders who do not have sufficient information could conceivably cause one or more failures in the criticality controls of an area. Facility-specific emergency response planning provides information to protect responders who do not regularly work in facilities where such failures are a concern.



Idaho National Laboratory

Form # FD-121
Rev: 1

Pre-Incident Plan Fire Department	COMPLEX ABBREVIATION BUILDING NUMBER BUILDING NAME	Identifier: Periodicity: Page:	COMPLEX 3 Years 1 of N
Document Control Center: 526-5262	Document Owner: Fire Department Manager	Effective Date:	Month Year

1. ADDRESS
   - Street:
     Street address if applicable
   - Map Grid:
     Complex Name Facility Map grid number
   - Location:
     Brief description of location for personnel familiar with INL complexes
   - On Scene Command Location:
     Brief description of location for personnel familiar with or looking at complex map

2. BUILDING DESCRIPTION
   Brief description of operation(s) conducted in building

3. OCCUPANCY HAZARD CATEGORY
   category identifier

4. BUILDING CONSTRUCTION
   - Building Construction Type:
     type identifier
   - Floors/Basements:
     # of floors / # of basements [and sub-basements]
   - Fire Areas:
     Brief list of areas of concern for each floor and basement. Include total square feet.
   - Construction Materials:
     Brief list of materials used in constructing walls, floors, roof
   - Entrances:
     List the type (for example pedestrian door or roll up door) and location of each entrance/exit
   - Special Features:
     List hazards (for example, "radiation") and structures (for example, "confined space") of concern, along with their locations

5. FIRE SUPPRESSION SYSTEMS
   - Suppression Systems:
     1. Identify the type and number of each installed fire suppression system
     2.
   - System Coverage:
     1. Identify the location and coverage of each system described above
     2.

~~OFFICIAL USE ONLY~~ Not OUO when not filled out

Blank pre-incident plan.

The INL Emergency Plan/RCRA Contingency Plan provides an overall framework for emergency response, but does not contain much specific criticality safety information.

If an area has criticality controls important to response by firefighters, the controls are included in pre-incident plans. Otherwise, firefighters do not have unescorted emergency access to such areas. INL firefighters can access pre-incident plans on the fire department server.

Other responders typically use other response plans or procedures that are specific to a facility, a complex, and/or an aspect of emergency response (for example, EPI-92, "MFC Operational Emergency Categorization/Classification and Protective Actions," specifies MFC emergency protective actions; EPI-47, "Criticality at MFC" identifies initial MFC response to criticality alarms and accidents; other emergency plan implementing procedures for a facility; or the emergency medical response plan). Such documents would include appropriate instructions if initial response actions could present a criticality hazard to responders. If criticality safety is a concern for the emergency response beyond the initial response, the procedures activate criticality safety personnel and appropriately qualified facility personnel to consult with and assist responders.

To date, no criticality accident was actually initiated by emergency response, but the possibility must be considered. In addition, unplanned actions taken during emergency response have caused additional, supercritical pulses. Therefore, it is important that emergency responders understand criticality controls that might affect their own safety during emergency response.

Been there. Done that.

This module describes, in additional information paragraphs, a variety of criticality accidents and challenges to criticality safety that did not involve emergency response personnel. If you read such paragraphs, think about actions that an emergency responder might take that could contribute to similar criticality accidents. Consider for example:

- The 1958 criticality accident at the Mayak Production Association, in which three experimenters picked up and tilted a vessel of uranium solution. The change in solution geometry and the additional reflection by three experimenters resulted in a criticality accident.   Could emergency responders do something similar if they find a large vessel, partially filled with liquid, obstructing their response?
- The 1970s event at the Idaho Chemical Processing Plant in which a janitor used a mop bucket to catch leaking uranyl nitrate solution. Could an emergency responder similarly challenge criticality safety by putting a container under a solution leak while responding to a hazardous chemical release?
- The 1980s event at the Idaho Chemical Processing Plant in which a worker removed samples from a storage system specifically designed for those samples. Could an emergency responder similarly challenge criticality safety by removing fuel or other fissionable material from a storage rack in a search for hot spots or other problem areas?
- The 1997 criticality accident in Sarov, Russia, in which an experimenter dropped a copper reflector shell onto a uranium metal sphere. Could a similar criticality accident occur if, during a similar experiment, a non-radiological emergency occurred and a responder bumped or collided with the reflector shell?

Did you know …

Definitions for terms 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.

My Notes:

Topic 4.2 Precautions if Criticality Controls involve Neutron Moderators

4.2.1 What are neutron moderators?

Neutron moderators are substances that contain light (small) nuclei that are mixed well with fissionable material.

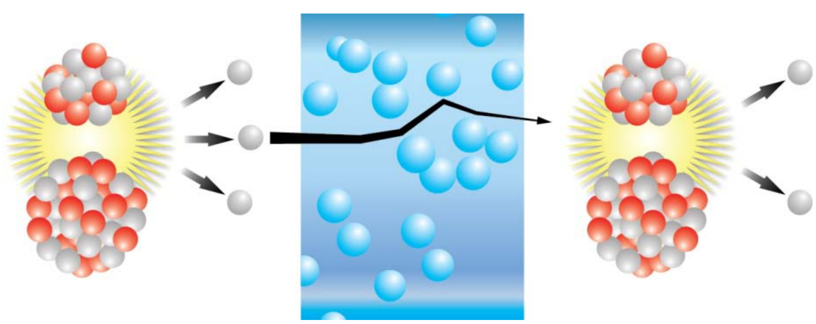
All materials containing much hydrogen and many materials containing carbon can be good moderators. Examples include water, paraffin, plastic, and graphite. Also, a large percentage of many fire suppressants consist of these elements (for example, water, foam, and CO_2). However, foams and CO_2 are rarely dense enough to be effective moderators.

Many fire suppressant materials could be effective moderators ***if*** there is enough of the suppressant distributed well enough through fissionable material.

4.2.2 Why might neutron moderators be a criticality concern?

Fission neutrons are born fast, but slow neutrons are more likely than fast neutrons to cause fissions in some fissionable isotopes (U-233, U-235, Pu-239, and/or Pu-241), but not all. Therefore, a critical condition is more likely with these isotopes 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 with U-233, U-235, Pu-239, and Pu-241 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 absorbed in a fissionable isotope, causing another fission.

So, mixing water or another moderator with certain fissionable isotopes might cause a criticality accident by slowing neutrons and increasing the number of fissions that occur.

However, just adding a moderator to U-233, U-235, Pu-239, and/or Pu-241 is not necessarily unsafe. To be effective, there must be enough moderator and it must be adequately mixed with fissionable material. 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.

Been there. Done that.

Many historical criticality accidents involved well moderated fissionable material. As of August 2012, all but one of the criticality accidents that occurred outside of reactors involved fissionable solutions or slurries; 18 of the 38 reported in-reactor criticality accidents also involved well-moderated fissionable material. In most of these cases, the presence of moderated fissionable material was normal. In some cases, the fissionable material should have been unmoderated. In these latter cases, either workers did not remove water when required or normally dry material accumulated in a vessel that contained moderator. For example:

- Three single burst criticality accidents occurred in 1952, 1965, and 1983 respectively in the ZPR-1, VENUS, and RA-2 reactors. In each case, personnel were rearranging core components. In each case, they also violated procedures by not completely draining moderator from the reactor vessel before moving those components.
- In 1961, a two-burst criticality accident occurred at the Siberian Chemical Combine with a slurry of uranium and oil or water. Over time, dry, gaseous uranium hexafluoride leaked from its process system into a pump's reservoir, where the uranium precipitated. Workers identified and accepted such accumulation, changing the fluid as necessary to improve pump operation. However, in the weeks before the accident, various plant upsets resulted in a much higher leak rate, and faster uranium accumulation, than personnel realized.

None of the historical criticality accidents directly involved the addition of water or other moderator. However, similar critical configurations can occur by adding moderator to fissionable material, as opposed to (1) adding fissionable material to moderator or (2) moving fissionable material in a moderator. Using some fire suppressants can at least hypothetically result in similar configurations.

A loss of moderator can also terminate a critical excursion. For example, the nuclear excursion might produce enough energy to boil off water, terminating the excursion. This mechanism terminated an inadvertent excursion in a very large tank at the ICPP after 20 or 30 minutes in 1959. As another example, draining water might terminate an excursion. This mechanism terminated inadvertent excursions with a Los Alamos experiment in 1945, a Y-12 critical experiment in 1954, the NRX reactor in 1952, an SF-3 critical assembly in 1971, and the RA-2 reactor in 1983.

4.2.3 What precautions might apply when neutron moderators are a concern?

Sometimes a fire fighting restriction is necessary as part of

Facility management and criticality safety personnel carefully consider fire suppression before limiting moderators to prevent a criticality accident. They do their best to ensure that firefighting restrictions are not necessary, even when moderator limits are established.

a moderator control.

However, sometimes it is necessary to impose a firefighting restriction as part of an area or operation moderator limit. In such a case, the pre-incident plan will identify which fire suppressants are restricted, which are allowed, and, sometimes, recommendations associated with fire-suppressant use. For example, water might be restricted, but foam might be allowed. In rare cases, all hydrogenous and/or carbon-based suppressants are restricted because even a little water might contribute to a criticality accident. In these rare cases, the pre-incident plan might instruct firefighters to let the fire burn until a facility representative can advise emergency responders.

Did you know …

Fire-suppression water might be restricted for reasons other than criticality safety. Water could be restricted for a variety of reasons: for example, economic considerations, chemical safety, criticality safety, and/or electrical safety.

Consider the National Fire Protection Association (NFPA) diamond symbol to identify the possible presence of materials, such as sodium, that can react violently when water contacts them. The symbol in this case is a "W" with a line through it because this reaction must be considered before deciding to use water as a fire suppressant.

Example of the NFPA diamond identifying chemical hazards.

My Notes:

Topic 4.3 Precautions if Criticality Controls involve Neutron Reflectors

4.3.1 What are neutron reflectors?

All materials are neutron reflectors.

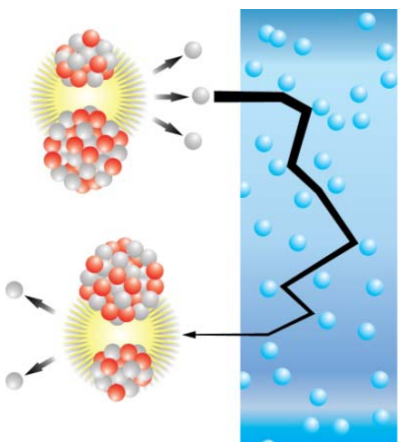
But some materials are much better than others as neutron reflectors. Hydrogenous materials and carbon compounds can be excellent neutron reflectors. Water and people are examples of such reflectors.

Radiation shielding materials can also be excellent neutron reflectors when located very close to fissionable material. Lead, steel, concrete, water, and polyethylene are examples of such reflectors.

Note that some materials, such as water, can be good moderators and good reflectors. In such cases, the controls might only be referred to as moderator controls.

Radiation shielding materials such as lead and concrete, as well as hydrogenous materials such as water and people can be effective neutron reflectors.

4.3.2 Why might neutron reflectors be a concern?



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. By returning a neutron to the material, a reflector provides additional opportunities for the neutron to cause fission.

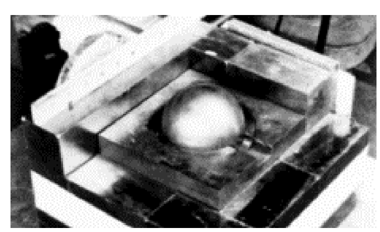
So, adding or increasing a neutron reflector around a fissionable material could contribute to a criticality accident.

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

Been there. Done that.

Neutron reflection played a significant role in some criticality accidents. For example:

- In 1945, a Los Alamos experimenter inadvertently dropped a tungsten brick onto an already reflected plutonium metal sphere. The additional reflection initiated a single supercritical burst that resulted in his lethal radiation exposure. The excursion terminated because the experimenter removed the additional brick and/or the reaction created enough energy to eject it.



Assembly involved in 1945 criticality accident without the full tungsten brick reflector.

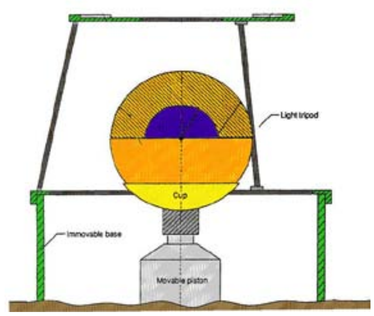
- In 1946, another Los Alamos experimenter dropped a hemispherical shell reflector of beryllium into place around the same sphere, initiating a single supercritical burst that resulted in his lethal radiation exposure. The excursion terminated because the experimenter removed the shell and/or the reaction created enough energy to eject it. Page 24 includes an illustration of personnel locations around the sphere.

Reconstruction of 1946 criticality accident with beryllium reflectors

- In 1958, three Russian experimenters manually moved a vessel of uranyl nitrate solution, violating safety requirements. Their bodies acted as neutron reflectors, significantly contributing to a single, supercritical burst that resulted in their lethal radiation exposures and the severe radiation exposure of a fourth experimenter. In this case, a change in the reflector did not terminate the reaction. Instead, the excursion terminated because the burst generated enough energy to eject solution.

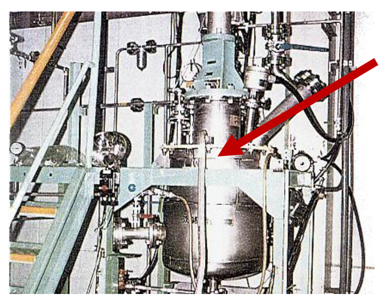
Reconstruction of 1958 criticality accident with human reflectors.

- In 1997, a Russian experimenter dropped a copper shell onto a roughly spherical assembly containing a uranium metal core. The additional reflection initiated a criticality accident that resulted in his lethal exposure. The excursion(s) included a series of supercritical bursts and a quasi-steady-state reaction that responders terminated after about 6½ days. (After evacuation, the room's shielding protected people. Responders were able to take as much time as they wanted to develop, test, and rehearse a remote means for removing parts of the assembly from the reflector.)



Reconstruction of 1997 criticality accident with dropped copper shell reflector.

- In 1999, two Japanese workers added the last batch of fissionable material to a large tank, violating safety requirements. A water-filled jacket that surrounded the tank cooled the tank and its contents. The combination of fissionable material quantity, tank diameter, and water reflection caused a criticality accident that resulted in their lethal exposures. The accident excursion included a series of supercritical bursts and a quasi-steady-state reaction. Responders terminated the excursion after about 19 hours by blowing water out of the coolant system. Then responders were careful not to reflect the tank with their bodies while stabilizing the system.



Tank of the 1999 criticality accident with red arrow pointing to water jacket reflector.

4.3.3 What precautions might apply when neutron reflectors are a concern?

In most cases, criticality safety controls do not affect emergency actions that would increase neutron reflection. But on rare occasions it might be physically possible for something to happen that has an unanticipated impact on an area with fissionable material. Therefore, neutron reflection should be considered before emergency responders:

- Closely approach large quantities of fissionable material
- Move something massive close to such material
- Add a very large amount of water around such material

My Notes:

Topic 4.4 Precautions when Criticality Controls involve Geometry (shape)

4.4.1 Why might fissionable material geometry be a criticality concern?

The geometry of a fissionable material is characterized by its shape. Changing the shape of a fissionable material affects the chances for a criticality accident.

Compare units of fissionable material that differ only by shape. More free neutrons will escape from the unit with the most surface area than from the unit with the least surface area.

The chances for a criticality accident decrease as the number of escaping neutrons increase. So the chances for a criticality accident are less for a unit with a large surface area compared to a unit with a small surface area. Some shapes are therefore safer or better than other shapes.

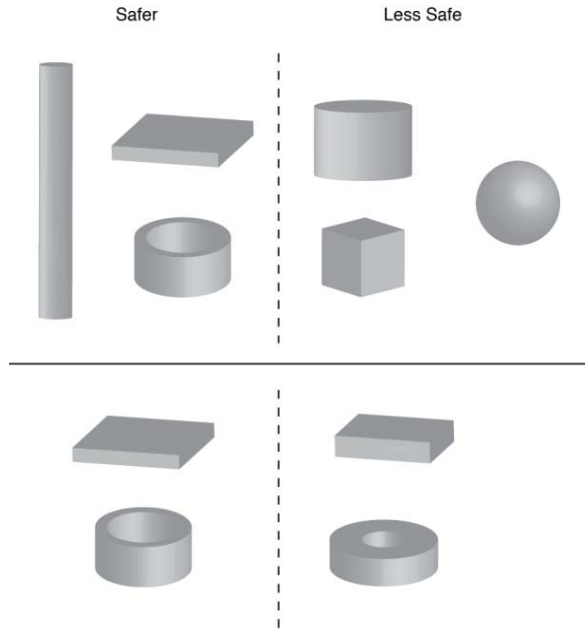
4.4.2 Which fissionable material geometries (shapes) are better?

Consider a variety of simple shapes. Assume that, except for shape, the units are identical. All of them have the same volume, material, density and mass.

A sphere has the least surface area and is therefore 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 (ring) 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.

Been there. Done that.

Geometry (shape and size) played a significant role in some criticality accidents. In many accidents with solutions, the container in which fissionable material accumulated was not designed for the amount and/or kind of fissionable material involved. In a few accidents, the container had a significantly larger capacity than necessary for the allowed contents. In a couple of accidents, the container lost its shape, or inadvertent transfers moved fissionable material to containers with the wrong shape. For example:

- In the 1958 criticality accident at the Mayak Production Association, three Russian experimenters manually moved a vessel of uranyl nitrate solution, violating safety requirements. They tipped the vessel, changing the solution geometry from a flat slab to the geometry illustrated on page 41. The change in geometry plus the neutron reflection by three adult humans caused a single, supercritical burst that resulted in the lethal radiation exposures of the three experimenters and the severe radiation exposure of a fourth experimenter.
- The non-lethal criticality accident at the Y-12 Plant in 1958 occurred in a 55-gallon (large-diameter) drum that was used as a wash-solution catch tank in accordance with instructions. Unfortunately, uranium solution leaked from favorable geometry equipment elsewhere into equipment that, at the time, was only supposed to contain wash solution. Not knowing about the leak, a worker transferred solution to a large diameter drum. The accident occurred when enough uranium solution entered the drum. The excursion lasted about 13 minutes. Investigators believed that the excursion terminated because the excursion's energy caused boiling, which vaporized water, which removed moderator from the solution.

- The criticality accident at the United Nuclear Corporation Plant in 1964 occurred in a large-diameter mixing tank that was more convenient for workers to use than the required tall, skinny, heavy cylinders. A single, supercritical burst resulted from the combination of the tank's geometry, mistaken solution identity, and shapes that different solutions took while mixing. Similar factors resulted in a second supercritical burst when a responder turned the tank's mixing mechanism off and then on again.
- The non-lethal criticality accident at the Russian Novosibirsk Chemical Concentrates Plant in 1997 occurred in slab tanks that had bulged in a few areas. In those areas, the tanks lost the shape needed to maintain subcriticality for the solution that they contained. This change, together with a few other changes, resulted in a series of supercritical bursts and a quasi-steady-state chain reaction that lasted about 26 hours until responders terminated the reaction.

Reconstructed position of worker in 1964 criticality accident, showing the safe-by-geometry cylinder and not-safe-by-geometry tank.

- The criticality accident at the Japanese JCO Plant in 1999 occurred in a large diameter precipitation tank that was more convenient for workers to use than the required, tall, small diameter, buffer/mixing/storage tanks. The tank is shown in an after-accident photo on page 41. The precipitation tank's geometry, in combination with the afore-mentioned water jacket, resulted in a criticality accident and lethal radiation exposures to two workers. The nuclear excursions consisted of a series of supercritical bursts and a quasi-steady-state chain reaction that lasted about 19 hours until responders terminated the reaction.
- An event apparently occurred during the 1970s at the Idaho Chemical Processing Plant when a janitor noticed solution leaking from a pipe. The janitor decided to catch the solution in a mop bucket, without understanding that the bucket was not-safe-by-geometry for the uranyl nitrate solution that was leaking. A health physics technician saw the situation and kicked over the bucket, understanding that contamination from the solution was safer than a criticality accident.

4.4.3 What precautions might apply when geometry is a concern?

Emergency responders rarely affect the geometry of a fissionable item. But it has happened. As an example, imagine that a solution leaks onto a floor during an emergency. If there is a chance the solution is fissionable material, it is probably better to let it leak until possible solution containers are adequately evaluated for criticality safety.

A thin layer of solution on the floor has much more surface area than the same amount of solution in a mop bucket. A contaminated floor is less dangerous than a criticality accident.

If fissionable solution is leaking, it is probably safer to let the leak continue until possible solution containers are evaluated for criticality safety

Also be wary of picking up a large container partially filled with fissionable solution. Tipping the container changes the solution geometry. It might not be safe in the tipped geometry.

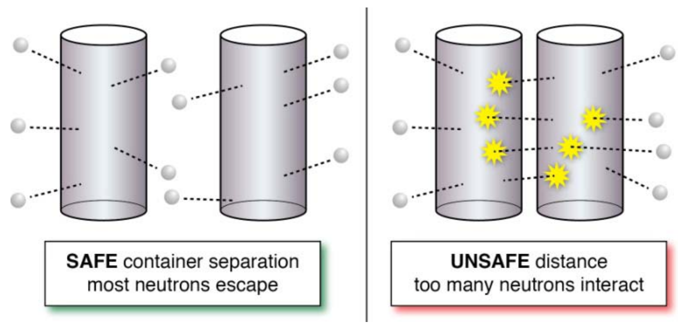
As another example, fissionable material or its container might deform during an emergency. Be wary if such deformation causes a large decrease in the surface area of the material or container.

My Notes:

Topic 4.5 Precautions when Criticality Controls involve Neutron Interaction

4.5.1 What is neutron interaction and why might it be a concern?

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



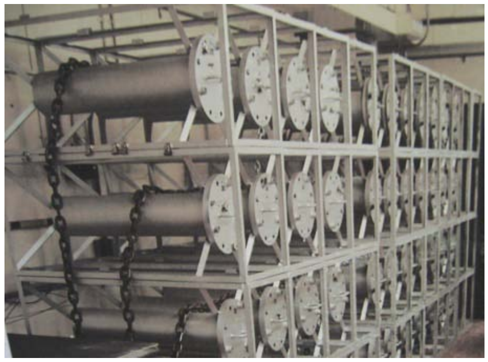
4.5.2 Why might neutron interaction be a criticality concern?

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

4.5.3 What is safer if neutron interaction is a criticality concern?

Neutron interaction is usually controlled by separating units. Decreasing the distance between units increases the chances for a criticality accident. Increasing the distance between units decreases the chances for a criticality accident.

Controls limit the minimum distance between units. Fissionable material shipping, transfer, and storage equipment usually reduce neutron interaction by including structures that separate units of fissionable material. In some cases, administrative controls require a minimum separation distance.



“Birdcage” packages include structure to separate package contents.

ATR Fuel Transfer Racks include broad base structures and tilted positions.

- INDIVIDUAL ARRAYS **MUST** BE SEPARATED BY A **MINIMUM 2 FEET**

Other examples of interaction control include some spent nuclear fuel storage racks, dry fresh fuel storage racks and administrative controls that specify a minimum spacing between arrays of fissionable material units.

Been there. Done that.

- A small amount of interaction can contribute significantly to a criticality accident. For example, the criticality accident at the Novosibirsk Chemical Concentrates Plant in 1997 occurred in two slab tanks. Interaction between the tanks did not initiate the accident. However, it appears that, once one tank became critical, neutron interaction between the tanks contributed to additional bursts and a quasi-static reaction with both tanks. Investigators concluded that, without neutron interaction between the tanks, the excursions might have terminated sooner and would have occurred in only one tank.
- In the early 1980s at the Idaho Chemical Processing Plant, a worker removed fissionable material samples from specifically sized compartments lined with solid neutron absorber. He stacked inspected samples on a table nearby during a nuclear material accountability inventory. The worker apparently did not consider that moving samples from compartments to table changed the interaction between samples. The criticality safety manager saw and corrected the situation before anything occurred that might add a large amount of water to and around the stacked samples.

4.5.4 What precautions apply when neutron interaction is a concern?

Emergency responders should be wary of fissionable material in structures that have deformed badly or collapsed because such damage changes the amount of neutron interaction in the structure.

It probably is NOT a good idea to add water to such a damaged structure unless/until possible consequences are reviewed for criticality safety considering the structure’s damaged configuration.

There are many reasons that fissionable material might be moved during emergency response. However, care might be needed to ensure that the move does not cause a criticality accident by increasing neutron interaction. The pre-incident plan will include precautions if a responder might make such moves before facility personnel are available for consultation. In the case of moving a container, the plan might direct firefighters to move items apart, or to use a particular path during the move. Or the plan might recommend, if high pressure water streams could move fissionable material, that firefighters use the streams to separate items and avoid gathering items together.

The plan might not include precautions or might not include further precautions. In some cases, there are no such precautions. In other cases, facility personnel should be available to advise responders within a very short time of the initial response.

My Notes:

Topic 4.6 Precautions when Criticality Controls involve Mass

NOTE: This topic is primarily intended as a review for radiological control personnel. Other personnel may read this topic if they are interested.

4.6.1 What is fissionable material mass?

Mass is the quantity of matter contained by a body, regardless of location. Mass is constant. It 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.

Criticality mass controls often limit the maximum amount of grams or kilograms of fissionable nuclides. But sometimes a mass control limits the number of units such as the number of ATR fuel elements.

4.6.2 Why might fissionable material mass be a criticality concern?

A small mass has fewer fissionable isotopes than a large mass. The fewer fissionable isotopes, the less chance a free neutron will cause a nuclear fission. Increasing fissionable mass increases the chance of a criticality accident; decreasing the mass decreases the chances.

However, radiological control personnel have another interest in the mass of fissionable material. The radiation emitted from a critical source is proportional to the quantity (or mass) of fissionable isotopes involved in the chain reactions. The more fissionable isotopes involved, the more radiation is emitted.

Been there. Done that.

Most process (out-of-reactor, out-of-critical-assembly-machine) criticality accidents involve too much fissionable material that accumulated or was placed in a particular area or container. For example:

- The 55-gallon drum in which the 1958 Y-12 criticality accident occurred was intended to contain no more than residual amounts of U-235 (a small amount of uranium diluted by a large amount of water). However, the accident occurred when a large amount of U-235 (kg quantities of uranium in a relatively small amount of water) leaked into the drum from elsewhere.
- In the 1964 United Nuclear Corporation criticality accident, a worker poured a relatively large amount of U-235, in the form of high-concentration solution, into a tank that was not meant to contain any U-235 (see the illustration on page 44). The tank was subcritical with the small amount of U-235, in the form of very-low-concentration solution, workers had previously poured into the tank; it was supercritical with the large amount. The excursion generated enough energy to expel some of the solution, which terminated the first burst.
- In the 1978 Siberian Chemical Combine accident involved a severely overbatched container in a glovebox. The relevant mass limit was implemented by limiting the container to no more than one plutonium metal ingot. However, two workers working at separate times placed a total of four ingots in the container. The chain reaction ended because either the worker who added the fourth ingot removed it, or the supercritical reaction generated enough energy to eject the fourth ingot. Page 18 includes a graphic depicting the critical burst of this accident.
- Workers involved in the 1999 Japanese criticality accident overbatched the mass limit for the relevant tank by approximately 650%. (Page 41 includes a photo of the tank.) This mass would have been safe in the equipment workers were supposed to use; it was critical in the not-safe-by-geometry tank, with filled water jacket, that they did use.

4.6.3 What precautions might apply when mass is a concern?

Generally, emergency responders do not affect the amount of fissionable material in an area. It is rare that fissionable material, or containers of fissionable material, must be moved from one area to a second area during emergency response, especially during initial response. In such a rare event, responders should consult with a facility representative to ensure that placing the fissionable material in the second area will not cause a criticality accident in the second area.

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.

☐ Moderation	A A physical characteristic important to criticality safety because increasing the surface area allows more neutrons to escape.
☐ Reflection	B A process in which a neutron slows down through one or more neutron-scatter events.
☐ Interaction	C A process in which an escaped neutron returns to a fissionable material through one or more neutron-scatter events.
☐ Shape (geometry)	D A process in which neutrons from one fissionable unit enter another fissionable unit.

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

☐ Adding an effective neutron reflector around fissionable material tends to …	A move the fissionable material closer to critical, increasing chances for a criticality accident
☐ Up to a point, mixing a moderator such as water with U-233, U-235, Pu-239, and/or Pu-241 tends to …	B move the fissionable material away from critical, decreasing chances for a criticality accident
☐ Increasing the distance between two units of fissionable material tends to …	C have no effect on criticality safety
☐ Increasing the surface area of a fissionable material tends to …	

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

	Material		Type
☐	concrete	A	neutron moderator and reflector
☐	graphite	B	mostly a neutron moderator
☐	humans	C	mostly a neutron reflector
☐	thick lead		
☐	plastic		
☐	thick steel		
☐	water		

Select the best answer option.

1. What document identifies criticality safety information relative to a firefighter's emergency response at a particular building?
   a. The INL emergency plan
   b. The facility safety analysis report
   c. The facility pre-incident plan
   d. The INL book of secrets

2. A firefighter is searching for hot spots in an area where lots of fissionable material is stored in compartments in racks. What does it mean if the pre-incident plan has no precautions about this work?
   a. There are never any concerns with fissionable material in rack compartments
   b. Firefighter training covers the hazards so well that written precautions are unnecessary
   c. Somebody forgot to include the precautions
   d. There are no concerns in this case or, by that stage of the emergency, facility personnel will be available and will be consulted

3. Which of the following precautions would **NOT** appear in a pre-incident plan if neutron reflectors are a serious concern?
   a. Immediately build thick lead brick walls around fissionable material to provide a radiation shield.
   b. Avoid moving lots of fissionable material closer to the thick concrete wall.
   c. Consult facility personnel before adding lots of water around the fissionable material.
   d. Avoid approaching large quantities of fissionable material to the extent practical.

For radiological control personnel: *Select the best answer option.*

4. Which statement describes a characteristic of the criticality control factor *mass*?
   a. In criticality safety, mass is the quantity of fissionable material or of fissionable isotopes, typically expressed in grams or kilograms.
   b. Increasing the mass of fissionable material tends to increase the chance of a criticality accident.
   c. Increasing the quantity of fissionable isotopes in a source tends to increase the amount of radiation emitted by the source.
   d. All of the above.

Complete each sentence in the left column by entering the letter for the appropriate phrase in the right column in the box before the sentence. Some phrases are used more than once.

☐	A building or facility _____ identifies area-specific criticality controls or precautions that are important to firefighters.
☐	An example of a/an _____ might read, “Do not use water for fire suppression, but foam is allowed.”
☐	An example of a/an _____ might read, “Do not move containers closer to each other.”
☐	An example of a/an _____ might read, “Do not use water or foam for fire suppression. Let the material burn until a facility representative provides guidance.”
☐	An example of a/an _____ might read, “Do not collect/catch solution leaking from these containers until a facility representative provides guidance.”
☐	An example of a/an _____ might read, “Do not move these containers against the concrete wall.”
☐	An example of a/an _____ might read, “Do not closely approach the fissionable material storage rack.”
☐	An example of a/an _____ might read, “Do not remove containers or fuel elements from the rack without guidance from a facility representative.”
☐	A facility that has criticality controls a firefighter might affect will either have appropriate information incorporated in the facility _____ or will prevent firefighter access until a facility representative is available to provide guidance.

A	moderator control or precaution
B	reflector control or precaution
C	geometry control or precaution
D	interaction control or precaution
E	pre-incident plan

Review-Question Answers

Definition match

B	c	A	A physical characteristic important to criticality safety because increasing the surface area allows more neutrons to escape.
C	Reflection	B	A process in which a neutron slows down through one or more neutron-scatter events.
D	Interaction	C	A process in which an escaped neutron returns to a fissionable material through one or more neutron-scatter events.
A	Shape (geometry)	D	A process in which neutrons from one fissionable unit enter another fissionable unit.

Action effect match

A	Adding an effective neutron reflector around fissionable material tends to …	A	move the fissionable material closer to critical, increasing chances for a criticality accident
A	Up to a point, mixing a moderator such as water with U-233, U-235, Pu-239, and/or Pu-241 tends to …	B	move the fissionable material away from critical, decreasing chances for a criticality accident
B	Increasing the distance between two units of fissionable material tends to …	C	have no effect on criticality safety
B	Increasing the surface area of a fissionable material tends to …		

Material type match

C	concrete	A	neutron moderator and reflector
A	graphite	B	mostly a neutron moderator
C	humans	C	mostly a neutron reflector
C	thick lead		
A	plastic		
B	thick steel		
A	water		

Multiple choice questions

1. What document identifies criticality safety information relative to a firefighter's emergency response at a particular building?
   a. The INL emergency plan
   b. The facility safety analysis report
   c. The facility pre-incident plan
   d. The INL book of secrets

2. A firefighter is searching for hot spots in an area where lots of fissionable material is stored in compartments in racks. What does it mean if the pre-incident plan has no precautions about this work?
   a. There are never any concerns with fissionable material in rack compartments
   b. Firefighter training covers the hazards so well that written precautions are unnecessary
   c. Somebody forgot to include the precautions
   d. There are no concerns in this case or, by that stage of the emergency, facility personnel will be available and will be consulted

3. Which of the following precautions would **NOT** appear in a pre-incident plan if neutron reflectors are a serious concern?
   a. Immediately build thick lead brick walls around fissionable material to provide a radiation shield.
   b. Avoid moving lots of fissionable material closer to the thick concrete wall.
   c. Consult facility personnel before adding lots of water around the fissionable material.
   d. Avoid approaching large quantities of fissionable material to the extent practical.

Multiple choice questions for radiological control personnel:

4. Which statement describes a characteristic of the criticality control factor *mass*?
   a. In criticality safety, mass is the quantity of fissionable material or of fissionable isotopes, typically expressed in grams or kilograms.
   b. Increasing the mass of fissionable material tends to increase the chance of a criticality accident.
   c. Increasing the quantity of fissionable isotopes in a source tends to increase the amount of radiation emitted by the source.
   d. All of the above.

Sentence completion match

E	A building or facility _____ identifies area-specific criticality controls or precautions that are important to firefighters.	A	moderator control or precaution
A	An example of a/an _____ might read, “Do not use water for fire suppression, but foam is allowed.”	B	reflector control or precaution
D	An example of a/an _____ might read, “Do not move containers closer to each other.”	C	geometry control or precaution
A	An example of a/an _____ might read, “Do not use water or foam for fire suppression. Let the material burn until a facility representative provides guidance.”	D	interaction control or precaution
C	An example of a/an _____ might read, “Do not collect/catch solution leaking from these containers until a facility representative provides guidance.”	E	pre-incident plan
B	An example of a/an _____ might read, “Do not move these containers against the concrete wall.”		
B	An example of a/an _____ might read, “Do not closely approach the fissionable material storage rack.”		
D	An example of a/an _____ might read, “Do not remove containers or fuel elements from the rack without guidance from a facility representative.”		
E	A facility that has criticality controls a firefighter might affect will either have appropriate information incorporated in the facility _____ or will prevent firefighter access until a facility representative is available to provide guidance.		

MODULE 5 CRITICALITY ACCIDENT MITIGATION

Introduction

Emergency response to a criticality accident involves protecting people who would otherwise be exposed to the accident's radiation, terminating the critical or supercritical excursion(s), stabilizing the system in which the accident occurred, and monitoring the area.

To perform their tasks safely in these cases, responders need some understanding of some criticality accident features (see Module 2), methods of detecting critical excursions, alarm responses, and reentry precautions.

Objectives

State how a criticality accident is detected in an area that is not well shielded.

Describe INL criticality alarm signals and the proper response to them.

Radiological control personnel: Describe the process for assessing the validity of a criticality alarm.

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

Describe general precautions to take when reentering the scene of a possible criticality accident.

Identify the emergency response group most often responsible for assessing the validity of a criticality alarm.

Radiological control personnel: Describe the method(s) used to quickly identify exposed individuals.

My Notes:

Topic 5.1 Criticality Accident Mitigation

5.1.1 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) and facility features to help facility management and emergency planners identify designs, alarm systems, and response actions that would mitigate the accident.

Criticality safety personnel evaluate accident scenario(s) and facility features to help facility management and emergency planners.

5.1.2 Shielding

Some facilities have significant shielding. If the shielding is insufficient to adequately protect workers from a criticality accident, facility management may add more shielding, install a criticality alarm system, or both.

Radiological protection personnel and emergency planners consider the shielding as well as any alarm systems in use when developing emergency response instructions and information for criticality accidents.

The Fuel Conditioning Facility and Hot Fuel Examination Facility cells have enough shielding to protect personnel in the event of a criticality accident

5.1.3 Criticality Alarm Systems

A CAS is one way to mitigate a criticality accident if such an accident were to occur in an area with insufficient shielding. A CAS is necessary because your senses cannot detect a criticality accident until it is too late. In many cases, your senses cannot detect a criticality accident even after it is too late.

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

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

important if the accident is ongoing, to additional radiation from the accident. **The underlying reason for having a CAS is to avoid lethal 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.

It is important to know criticality alarm sounds might vary between complexes at the 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 August 2012, other INL complexes do not have facilities that require a criticality alarm system.

If an area has a CAS, the area criticality safety officer or facility management ensures responders are familiar with the sound of that area's criticality alarm. Course 0INL1226, *Criticality Safety for Firefighters*, includes a demonstration of criticality alarm sound(s).

Did you know …

You might hear radiation alarms as well as criticality alarms in the event of a criticality accident. Typically, nearby radiation area monitors (RAMs) and constant air monitors (CAMs) will also alarm.

5.1.4 Responding to a Criticality Alarm

A criticality alarm 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.

- Quickly evacuate the immediate area without running. Running increases your chances of falling, which can increase your exposure by delaying or disabling your evacuation.

  Evacuation routes necessarily vary due to building, facility, and complex layout. Before entering an area with a CAS, emergency responders should be aware of exit routes and facility features that could help shield them during evacuation. Emergency responders become familiar with such information through maps, inspections, and/or tours. Pre-incident plans also include maps for firefighter use. Facility or complex management informs responder organizations of construction and other activities that would affect evacuation.

Evacuation routes vary from facility to facility.

- Take advantage of shielding materials near your route as you evacuate.
- Assemble at your on-scene command post or other designated assembly area.

Your response to a nearby criticality alarm is also important. If a criticality alarm sounds near but not in your area:

- *Stay* away *from a building or area in which a criticality alarm is activated*.
- Do not enter or approach buildings in which a criticality alarm is sounding without planning that considers the possibility of a criticality accident in the buildings.

In most cases, radiological control personnel and facility management assess the validity of a criticality alarm. They usually base their assessment on the very high radiation levels and dramatic changes in radiation levels that are typical of criticality accidents. The assessment might also use information from criticality safety personnel, facility workers, and instrument technicians. Radiological control personnel receive separate training for their emergency response methods.

Been there. Done that.

- Immediate evacuation was an important factor in protecting nearby workers during most unshielded criticality accidents. 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. This additional dose can be very damaging.

5.1.5 Time and Radiation Dose

Radiation dose increases with exposure time. The less time you are near a source (the body in which the criticality accident occurred), the lower your dose will be. This is one reason for evacuating workers, evacuating responders if conditions worsen, and limiting the amount of time a responder is allowed within an accident scene.

5.1.6 Distance and Radiation Dose

Radiation dose decreases as distance from the source increases. The farther you are from a source, the lower your dose will be. This is another reason for evacuating workers and for staging emergency responders away from the source.

5.1.7 Time, Distance, and Radiation Dose

Effective evacuation decreases your time near a critical source and increases your distance from the source. This combination is very effective in limiting the dose you receive from the source.

Let's assume a criticality accident produces a steady 5000 rem in one hour at one foot from the source. The next page illustrates the variation in dose based on time near and distance from the source. The firefighter receives 5000 rem if he is one foot away for an entire 60 minutes; but no more than 0.21 rem if he is 20 feet away for only one minute.

5.1.8 Shielding and Radiation Dose

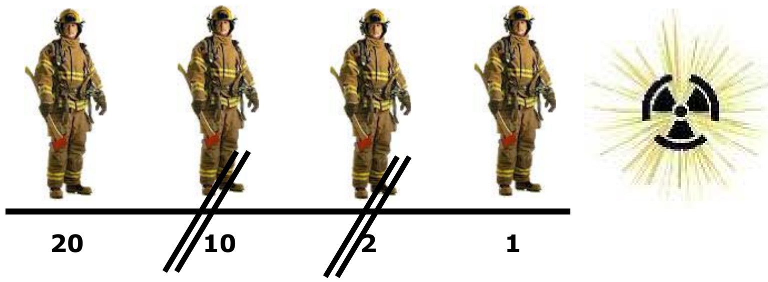
Radiation dose decreases as the amount of shielding increases. The more shielding between you and a source, the lower your absorbed dose will be. This is one reason evacuation and reentry paths might be planned to take advantage of existing concrete walls and earth berms.

Although even a little shielding might help reduce dose, many typical, lightweight and/or thin radiation shielding materials are not very effective against the high-energy gamma rays and neutrons produced during a criticality accident. Instead, thick, dense materials are needed to effectively shield people from gamma rays. Hydrogenous materials and/or very, very thick, dense materials are needed to effectively shield people from neutrons.

In addition, materials that are effective for shielding gamma rays and/or neutrons can also be effective neutron reflectors. This reflection effect must be considered carefully before responders are directed to put portable shielding made from such materials very close to a critical or barely subcritical source.

Been there. Done that.

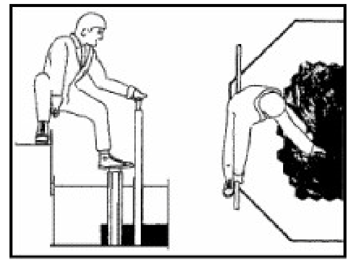
- A little bit of shielding can help, even if it isn't very effective. Consider the 1946 and 1978 accidents discussed on page 24. The accidents with plutonium metal produced a single burst of similar duration and magnitude. The primary victims were in similar postures about the same distance from the source. But the primary victim in the 1946 accident had little or no shielding between his vital organs and the source; he received a lethal dose. The 1978 accident occurred in a plastic lined container in a glovebox. That little bit of shielding is a major reason the primary victim of the 1978 accident survived, although doctors eventually had to amputate his forearms to save his life.



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

Your potential radiological dose decreases if you increase your distance 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 at one foot from the source.

- For a person within a few feet of a critical source, posture can cause differences in distance and shielding that result in a large radiation exposure variation across the person's body. Consider, for example, the worst-exposed person from the 1965 criticality accident with the VENUS reactor in Mol, Belgium. At the time of the single-burst accident, the victim was located above the water moderated and reflected reactor, as indicated in the illustration to the right. His left foot was closest to the critical source, and much of his torso was between the source and the back of his right shoulder. He received an estimated dose of about 4000 rem to the toes on his left foot, 1750 rem to his left ankle, 500 rem to his chest, and 300 to 400 rem to his head.



5.1.9 Reentering a Criticality Accident Scene, Possible Reasons

There are various reasons that some responders might be required or asked to reenter the scene of a criticality accident while emergency response is in progress. They include:

There might be a good reason to re-enter a criticality accident scene

- **Victim rescue**. It seems improbable that victim rescue would be necessary, but the possibility cannot be dismissed. Victims of historical criticality accidents have all left the immediate scene, on their own or with coworker help, before official first responders arrived, with one exception. The exception is the SL-1 accident on what is now the INL site. Three men received lethal physical injuries from a steam explosion as well as lethal radiation doses from a single-burst supercritical excursion. Historically, no responder has rescued a criticality accident victim that would have died without rescue.
- **Measuring or assessing conditions**. It is conceivable that first responders might need to reenter the scene of an accident to assess the accident. However, responders need as much protection as practical when attempting such reentries. Once people are protected, it is appropriate to take all the time needed to plan actions that might involve scene reentry.
- **Excursion termination**. Currently considered highly improbable at the INL, some inadvertently self-sustaining chain reactions require human intervention to terminate. Timely termination is typically considered prudent and desirable. However, identifying specific actions to terminate a criticality accident typically requires information about the critical system itself and about on-scene conditions. The termination activities themselves are typically conducted by facility personnel with support from radiological control personnel. Termination activities therefore are typically not part of initial response. Such activities occur after careful planning involving consultations with criticality safety and facility personnel.
- **System stabilization**. A system in which a criticality accident was terminated might be barely subcritical. A minor disturbance might cause another critical or supercritical excursion. Reentry might be needed to stabilize the system and/or confirm that the system is stable before emergency response ends. However,

stabilization occurs with or after terminating a critical excursion. First response activities do not include actions that require reentry to ensure the system in question is both subcritical and stable.

Based on experience, there is absolutely no reason to allow reentry without careful planning for the specific emergency in progress. Further, reentry planning must include input from radiological control personnel, even for rescue operations.

Been there. Done that.

A major reason that some criticality accidents lasted for hours or days is that, once people are protected, responders and facility personnel could take time to plan actions for terminating the excursions and stabilizing the system.

- The SL-1 reactor experienced a critical excursion, quickly followed by a steam explosion that destroyed the reactor in January 1961. Firefighters and a health physics technician initially entered the facility in an attempt to determine the kind of accident that had occurred and to locate facility personnel. Several false emergency alarms had occurred that day, but these responders still cautiously approached the facility with radiation instruments and plans to retreat if radiation levels were too high. After the first retreat, health physics technicians mandated extremely short reentry times because radiation levels near the reactor room exceeded their instrument range. In addition, available protective equipment did not perform well in the subzero temperatures. Their initial response ceased with recovery of the one severely injured worker who was still alive when they located him.
- During the 1962 criticality accident at a Hanford Works facility, responders deployed a remote-controlled, camera-equipped robot to identify the accident location precisely, to place and read radiation meters, and to manipulate valves in accident-termination attempts. However, the accident terminated after 37 hours due to phenomena that apparently were not greatly affected by the responders.
- Russian facility personnel worked from a remote shift-supervisor office to terminate the 1962 criticality accident at the Mayak Production Association. They devised and attempted three different plans to terminate the accident and stabilize the system. Each of the first two attempts caused an additional supercritical burst, but personnel were protected by distance and materials between the critical system and the office.
- The 1997 criticality accident in Sarov, Russia, occurred with an experiment inside a well-shielded facility. Shielding protected everybody but the experimenter throughout the six day accident, providing time to plan, rehearse, and implement actions to terminate the excursion. Responders deployed remote controlled robots for scene reconnaissance, removing material in the room with the critical assembly, and, eventually, assistance in disassembling the inadvertently critical assembly. Responders rehearsed all reentry and robot-manipulation activities in a mockup built soon after the accident began.
- During the nearly 20 hour, 1999 Japanese criticality accident, reentry planning was required to approach and/or enter the building in which the accident occurred. More than 20 radiological control and facility personnel reentered at different times to gather information, attempt to terminate the accident, and, once terminated, to ensure the accident's tank was very subcritical and stable. Until the final reentry, planners protected personnel by limiting reentry times to mere minutes using specified routes for people with instructions to perform no more than one or two simple tasks. There was no true radiological shielding on scene at the time, although the walls of various buildings provided a little shielding along specific routes. They took advantage of equipment outside of the building in their attempts to first drain and then blow out water in the tank's water jacket. Stabilization required that personnel reenter the building, but they used long, curved hoses to maintain as much distance as practical from the tank while injecting a neutron absorber into it.

5.1.10 Reentering a Criticality Accident Scene, General Precautions

Reentry requires planning.

Like many emergencies, event-specific reentry planning is necessary to protect responders who enter the scene of a criticality accident. Procedure EPI-77, "Reentry," establishes a framework for reentry planning that includes identify suitable precautions. Many such precautions are based on general precautions either for the type of emergency or for emergencies in general.

The following general precautions seem to be unique to criticality-accident-scene reentry:

- Responders and response planners need to know that typical radiological personnel protective equipment does not shield a person well from the intense, direct radiation of a critical or supercritical excursion. However, such equipment might be very effective protection against other on-scene hazards.
- Responders need resources (for example, information, instruments, instructions, etc.) to recognize and protect against an ongoing excursion or additional excursions if such excursions are possible.
- Responders need resources to avoid causing additional excursions, except as planned and necessary to terminate the reaction and/or stabilize the scene.

The following general precautions are applicable to many radiological emergencies, including criticality accidents:

- Three factors for limiting radiological exposure apply to criticality accident scenes. Response methods should:
    - ➢ Limit exposure time.
    - ➢ Keep as much distance as practical between the source and any person.
    - ➢ Use radiological shielding, if effective materials are available.
- The number of people reentering a scene should be limited considering the possible need for assistance in case of injury or unexpected exposure, assigned task(s), the method(s) for accomplishing the task(s), and needs for assistance with the task(s).
- Responders need resources to recognize and avoid or mitigate other hazards that might exist inside the scene. (For example, do not overlook industrial hazards during criticality accident response.)

If personnel enter an accident scene as part of an emergency's recovery phase, precautions may also be identified using procedure EPI-80, "Recovery."

Been there. Done that.

- Typical industrial hazards can complicate criticality-accident-scene reentry planning. For example, in response to the 1997 criticality accident in Sarov, Russia, personnel used a facility mockup to rehearse actions to terminate the fission chain reactions. A tension cable snapped during one rehearsal, seriously injuring two workers as it whipped around before coming to rest on the floor.
- Unauthorized or poorly planned response actions can make a criticality accident worse. The 1964 United Nuclear Corporation accident and the 1968 Mayak Production Association accident 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 actions that were not well planned.

During response to the 1964 criticality accident, one of two people who re-entered the accident scene turned a stirring mechanism off and then on. The actions led to a second supercritical excursion as they left the area, resulting in an approximate 100 rad dose to the person closest to the source.

During response to the 1968 criticality accident, a supervisor reentered the scene against orders. Apparently, he caused one additional supercritical excursion while trying to dispose of fissionable solution. He received a lethal radiation dose from this excursion, but was able to exit the area.

5.1.11 Identifying an Exposed Person

People exposed to a criticality accident are among the objects that the accident source irradiates. This exposure makes their bodies slightly more radioactive than normal. The increase is detectable, but it does not constitute, in and of itself, a risk to responders who come in contact with exposed person(s).

In the event of a criticality accident, radiological control personnel are assigned to identify exposed personnel. They use methods identified in LWP-15015, *Response to Abnormal Radiological Situations*, to detect the extra radioactivity in such people.

However, these radiological control personnel are not necessarily the first responders to arrive near the scene. It is helpful if other first responders report their observations regarding persons who were or might have been at the accident scene and any readily observable medical conditions these persons exhibit. Such reports can help lessen the time needed to get such a person medical assistance.

Important Reminder for Emergency Medical Technicians (EMTs)

Radiation exposure never preempts treatment for trauma. *Always* treat significant trauma first.

Did you know …

Neutron absorption is the reason a person exposed to a criticality accident is slightly more radioactive than other people. Some isotopes in objects around the critical or supercritical source capture neutrons that escape the source. In a human, certain sodium isotopes in blood and potassium isotopes in hair readily capture neutrons.

Been there. Done that.

Readily observable behavior is not necessarily a good indicator of acute radiation exposure. Victim behavior varies widely whether or not medical symptoms manifest quickly. In most historical cases, individuals at the accident scene evacuated and immediately reported their involvement and/or sought help. However, sometimes a person with a lethal exposure competently ran the emergency response until leaving for a hospital or otherwise becoming very sick. Sometimes a person with a serious exposure left the scene and then attempted to deny his or her presence at the scene. In addition, sometimes a person with little or no exposure acted as if he or she received a very significant overexposure. A first responder might also encounter a person who was not exposed, but, nonetheless, is very worried that he or she might have received a serious exposure. The table on the next page summarizes the behaviors of victims who received a dose of 100 rad or more. The data are from reports of 23 criticality accidents. Other criticality accidents either did not involve such high exposures or the available reports do not include information about victim behavior.

Number	Some criticality accident victim behaviors with 100 rad or more exposure
1	Incoherent almost immediately, but left immediate scene with assistance
1	Incoherent almost immediately, but left immediate scene without assistance
45	Sufficiently coherent and ambulatory to evacuate and, if appropriate, shower
2	Collapsed completely within minutes
2	Denied presence at accident scene (anecdotal information)
8	Acted as responder or expert advisor (provided reports, estimated doses, etc.)
5	Altered evidence (attempt stabilization, hide guilt, etc.) before evacuation
1	Altered evidence during re-entry, leading to lethal exposure
1	Altered evidence during re-entry, leading to non-lethal, potentially injurious exposure

My Notes:

Review Questions

Complete each sentence in the left column by entering the letter for the appropriate phrase in the right column in the box before the sentence. Some phrases might be used more than once or might not be used at all.

☐ Management installs criticality alarm systems in some areas to warn you that a criticality accident has occurred or is in progress so that _____.	A. firefighters
☐ Even if you think a criticality alarm is false, you should _____.	B radiological control personnel
☐ Criticality alarms at different INL complexes _____.	C stay away from the building in which the alarm is sounding
☐ If a criticality alarm sounds in your area, you should _____.	D respond as if the alarm were real
☐ If a criticality alarm sounds near, but not in, your area, you should _____.	E accident-specific reentry planning
☐ _____ is required before reentering the scene of a criticality accident.	F find a radiological control person to determine if the alarm is real
☐ _____ might provide effective protection from some on-scene hazards, but will not sufficiently shield a person from the intense direct radiation of a criticality accident	G evacuate immediately without running
☐ In the event of a criticality accident, _____ are responsible for identifying exposed personnel.	H may sound different
☐ In the event of a criticality alarm, _____ are typically responsible for assessing the alarm's validity.	I all sound the same
	J standard radiological personal protective equipment
	K you can take action to avoid lethal radiation exposure from a criticality accident

Review-Question Answers

K	Management installs criticality alarm systems in some areas to warn you that a criticality accident has occurred or is in progress so that _____.
D	Even if you think a criticality alarm is false, you should _____.
H	Criticality alarms at different INL complexes _____.
G	If a criticality alarm sounds in your area, you should _____.
C	If a criticality alarm sounds near, but not in, your area, you should _____.
E	_____ is required before reentering the scene of a criticality accident.
J	_____ might provide effective protection from some on-scene hazards, but will not sufficiently shield a person from the intense direct radiation of a criticality accident
B	In the event of a criticality accident, _____ are responsible for identifying exposed personnel.
B	In the event of a criticality alarm, _____ are typically responsible for assessing the alarm's validity.

A. firefighters

B radiological control personnel

C stay away from the building in which the alarm is sounding

D respond as if the alarm were real

E accident-specific reentry planning

F find a radiological control person to determine if the alarm is real

G evacuate immediately without running

H may sound different

I all sound the same

J standard radiological personal protective equipment

K you can take action to avoid lethal radiation exposure from a criticality accident

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Appendix B
Glossary

In most cases non-technical or simplified technical definitions are listed. If both non-technical and technical definitions are often used 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.

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 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 weight. See *atomic mass*.

Chain reaction. See *nuclear [fission] chain reaction*.

Control. See *criticality control*.

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 1.3.4) (2) Also used for a phenomenon characterized by a sustained nuclear fission chain reaction in which each fission produces, on the average, more than one neutron that causes additional fissions. (Subtopic 1.3.5) Also see *subcritical* and *supercritical*.

Criticality accident. An inadvertent or uncontrolled critical or supercritical nuclear fission chain reaction. (Subtopic 2.1.1)

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 5.1.3). At the INL, the protective action is immediate evacuation as described in the relevant emergency plan and in relevant INL, complex, and/or facility access training

Criticality control. Method(s) and/or mechanism(s) devised to prevent a criticality accident.

Criticality control area (CCA). A BEA area that is allowed to contain fissionable material in quantities and forms that require criticality control. (Subtopic 3.1.2)

Criticality hazard. A possible source for or contributor to a criticality accident.

Criticality safety. Protection against the consequences of a criticality accident, preferably by preventing the accident but also by mitigating an accident if it occurred. 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 group, and qualified through training, education, and/or experience for a specific facility or are to (1) provide on-the-floor criticality safety expertise for routine operations, (2) request and review criticality-safety-related documentation for the area, (3) ensure necessary criticality safety information is included in the area's pre-incident plan and emergency procedures, and (4) be liaison between area management, personnel who work in the area, the criticality safety group, and cognizant safety analysts.

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.

Fast neutron. A free neutron with high energy. Such neutrons travel at very high velocities. Free neutrons produced by nuclear fission are almost always released as fast neutrons.

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 1.4), which definition is now used at the INL for some purposes.

Fissile mass limited area. A CWI area in which criticality safety is provided through generically determined limits on U-235 or Pu-239.

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 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). However, at BEA facilities of the 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 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 the INL, fissionable nuclides of concern are the isotopes U-233, U-235, Np-237, Pu-238, Pu-239, Pu-241, and Am-241. You may simplify matters by considering only the isotopes U-233 and U-235 and the elements Pu, Np, and Am.

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.

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). For our purposes, the geographical site now known as the Idaho National Laboratory, including programs, projects, and operations conducted on the site.

Interaction, neutron. See *neutron interaction*.

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 1.1.4) Isotope refers to the entire atom, including the atom's electrons. (2) Sometimes used interchangeably with nuclides.

Kinetic energy. Energy associated with motion. Particles with kinetic energy are capable of producing heat through friction with other particles.

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. (Subtopic 4.6.1.)

Mass limit CCA. A BEA area in which criticality safety is provided through generically determined limits on the mass of U-233, U-235, and plutonium. (Subtopic 3.1.3)

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 and typically found in an atomic nucleus. (Subtopic 1.1.2)

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.

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 4.5).

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 4.2.2).

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. (Subtopic 4.2.1)

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. (Subtopic 4.3.2)

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. (Subtopic 4.3.1)

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)

Nuclear Accident Dosimeter (NAD). Passive device specifically made of various materials 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. (Subtopic 1.3.2)

Nuclear fission. Splitting an atomic nucleus into lighter nuclei (fission fragments), releasing one or more neutrons (neutron radiation), gamma radiation, and kinetic energy. (Topic 1.3)

Nuclide. (1) An atomic species characterized by its number of protons, number of neutrons, and, sometimes, its energy. (2) Sometimes used as interchangeably with *isotope*.

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 3.1.3, 3.1.5, and 3.1.6 include information on such posting.

Procedure CCA. A BEA area that requires specific controls to ensure criticality safety and that is not designated a mass limit CCA. (Subtopic 3.1.2)

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

Reflection, neutron. See *neutron reflection*.

Reflector, neutron. See *neutron reflector*.

Scatter, neutron. See *neutron scatter*.

Subatomic particle. A discrete particle smaller than an atom. For example, a proton, neutron or electron.

Subcritical. 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. (Subtopic 1.3.3)

Supercritical. 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. (Subtopic 1.3.5)