MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

Introduction

Welcome to Module 7.0 of the Fuel Cycle Processes Directed Self-Study Course! This is the seventh of nine modules available in this directed self-study course. The purpose of this module is to assist you in describing fundamental concepts of health and safety, and identifying hazards associated with nuclear fuel cycle processes. The processes are described in detail in Module 2.0, section 2.1.5. This self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. There are six learning objectives in this module. The module has self-check questions to help you assess your understanding of the concepts presented in the module.

Before you Begin

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

- ◙ Trainee Guide
- ◙ 10 CFR Part 20.1902 through Title 10 CFR Part 20.1905

Complete the following prerequisite(s):

- ◙ Module 1.0: Overview of the Nuclear Fuel Cycle

How to Complete this Module

1. Review the learning objectives.
2. Read each section within the module in sequential order.
3. Complete the self-check questions and activities within this module
4. Check off the tracking form as you complete the self-check questions and/or activity within the module.
5. Contact your administrator as prompted for a progress review meeting.
6. Contact your administrator as prompted for any additional materials and/or specific assignments.
7. Complete all assignments related to this module. If no other materials or assignments are given to you by your administrator, you have completed this module.
8. Ensure that you and your administrator have dated and initialed your progress on the tracking form.
9. Go to the next assigned module.

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

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MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

LEARNING OBJECTIVES

7.1 Upon completion of this module, the trainee will be able to describe fundamental concepts of health and safety and abnormal occurrences, and selected engineering controls and preventive measures.

7.1.1 Describe fundamental concepts of health and safety in fuel cycle facilities, including:

- Hazard classifications
- Radiation
- Toxicity and its effect
- Routes of exposure
- Carcinogens
- ALARA
- Risk
- Controls
- Resources and guidelines
- Quality assurance

7.1.2 Identify hazards associated with uranium and selected by-products in the nuclear fuel cycle.

7.1.3 Identify selected abnormal occurrences at fuel cycle facilities.

7.1.4 Identify selected engineering controls and preventive measures used in the nuclear fuel cycle.

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Learning Objective

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

7.1.1 Describe fundamental concepts of health and safety in fuel cycle facilities, including:
  - Hazard classifications
  - Radiation
  - Toxicity and its effect
  - Routes of exposure
  - Carcinogens
  - ALARA
  - Risk
  - Controls
  - Resources and guidelines
  - Quality assurance

HAZARD

Hazard refers to the potential that a chemical or physical characteristic of a material, system, process, or plant will cause harm or produce adverse consequences.

To identify the potential for harm or adverse consequences, it is necessary to determine the following:

- Specific adverse results or consequences of interest
- Material, system, process, and plant characteristics that would produce those results

Hazard Classification

Traditionally, hazards that can cause sickness, impair health, or cause significant discomfort in workers are classified as chemical, physical, biological, or ergonomic. For the purposes of this directed self-study, hazards in the nuclear fuel cycle will be classified as chemical, physical, or radiological. Physical hazards include ionizing radiation; however, because of the importance of radiological hazards in the nuclear fuel cycle, they will be listed separately.

- **Chemical** hazards are due to excessive airborne concentrations of mists, vapors, gases, or solids in the form of dusts or fumes. The majority of these hazards are due to the inhalation of chemicals, or skin contact with these chemicals. In the nuclear fuel cycle, chemical hazards can also involve liquids, such as acid spills.
- **Physical** hazards include excessive levels of electromagnetic radiation, noise, vibration, and extremes of temperature and pressure. Mechanical hazards, which will be considered a subclassification of physical hazards, are those caused by breakdown in the mechanical systems themselves. Mechanical failures may be gradual, such as corrosion, or sudden, such as a collision. Physical hazards can also relate to ergonomic and/or housekeeping hazards. For example, injuries may occur due to lifting heavy objects, the awkwardness of working in glove boxes, or slipping on wet floors that have been polished and mopped to reduce the amount of smearable contamination.
- **Radiological** hazards result from the emission of energy during spontaneous decay in the form of alpha, beta, or gamma radiation from the nucleus of an atom.

Note: Each of these hazards is covered in 10 CFR Part 70.

Memorandum of Understanding: NRC and OSHA

A Memorandum of Understanding (MOU) between the U.S. Nuclear Regulatory Commission (NRC) and the Occupational Safety and Health Administration (OSHA) states that "four kinds of hazards may be associated with NRC-licensed nuclear facilities." These four kinds of hazards are:

1. Radiation risk produced by radioactive materials
2. Chemical risk produced by radioactive materials
3. Plant conditions that affect the safety of radioactive materials and thus present an increased radiation risk to workers
4. Plant conditions that result in occupational risk but do not affect the safety of licensed radioactive materials

The MOU between NRC and OSHA was codified in 10 CFR Part 70 Subpart H and became effective September 2000. Generally, the NRC provides guidance and regulations for the first three hazards. A copy of the MOU between the NRC and OSHA is included at the end of this module. A memorandum was issued in March 2003 that reinforces the NRC's responsibility regarding chemicals that NRC regulates. A copy of Subpart H and the March 2003 memo are included at the end of this module. Plant conditions that result in an occupational hazard but do not directly affect the safety of licensed radioactive materials may have indirect effects. For instance, plant conditions might produce a fire and/or explosion that would cause a break in containment and result in a release of radioactive materials.

Hazard Identification

Adverse results are broadly classified by the American Institute of Chemical Engineers as human impacts, environmental impacts, or economic impacts. Identifying the potential consequences of the hazard will help define the scope of the hazard identification required. The hazard identification should be complete enough to identify all important hazards and provide some means for prioritization of these hazards. Common methods of hazard identification include analysis of the process material properties and conditions, review of organization and industry process experience, development of interaction matrixes, and application of hazard evaluation techniques.

The degree of hazard from exposure depends on the:

- Nature of the material or energy involved
- Intensity of exposure
- Duration of exposure
- Susceptibility of the biological system or subject

The recognition of hazards involves knowledge and understanding of the several types of workplace environmental stresses and the effect(s) of these stresses on the health and safety of the worker and the general public.

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RADIATION

Radiation refers to particles and/or energy capable of producing ionization (charged particles). Certain nuclides undergo spontaneous disintegration with the release of energy and generally result in the formation of new nuclides. Common examples of radiation include alpha radiation, beta radiation, gamma rays, X rays, and neutrons.

The distance penetrated by radiation emitted from radioactive material varies with the type of radiation emitted. Radiation may present a hazard both when it is external to the body and when it is internal. Table 7-1 illustrates the characteristics of ionizing radiation.

Alpha particles are the most massive and most highly charged of the types of radiation. Each particle is made up of two protons and two neutrons, giving it a charge of +2 and a mass about four times that of a neutron. This relatively high charge and mass cause the alpha particle to interact more readily with matter than other types of radiation; therefore, the alpha particle has very low penetrating ability. It cannot penetrate the outer layer of dead skin and is therefore not considered an external exposure hazard. However, if it enters the body, it can do sufficient damage to the surrounding sensitive tissue such as lungs and intestines. Alpha radiation is therefore considered an internal exposure hazard.

Beta particles are high-energy electrons that originate from within the nucleus. Beta particles interact with matter by three different mechanisms: ionization and excitation, just as with alpha particles, and by the emission of "bremsstrahlung." The probability of the beta particle giving up its energy in the form of bremsstrahlung is higher in material with a high atomic number. Beta particles will travel a few millimeters in tissue and will reach few internal organs (one important exception is the eyes). The effects of large external doses of beta radiation are like those of severe burns to the skin.

Table 7-1. Characteristics of Ionizing Radiation

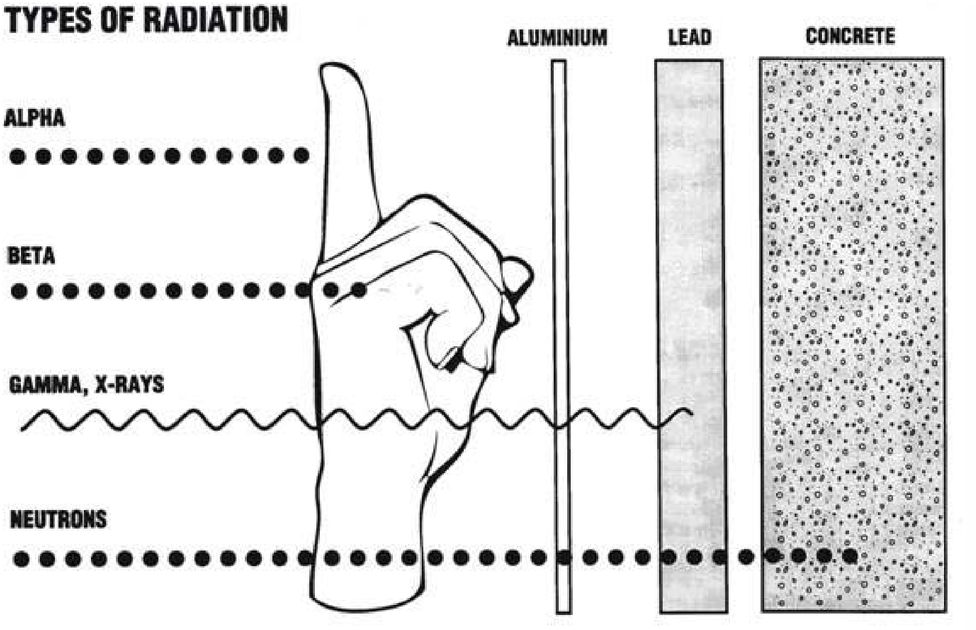
Type	Symbol	Composition	Mass (amu)	Charge	Typical Energies	Range (Air)	Range (Tissue)	Primary Hazard	Examples
Alpha Particle	α	2p + 2n	4	+2	4-8 MeV	A few centimeters	50 to 70 micrometers	Internal (high)	uranium, radon, plutonium
Beta Particle	β	Electron	0.00055	+1	.018-3	Up to a few meters	A few millimeters	External (some) and internal (high)	strontium-90, carbon-14, tritium
Gamma Ray	γ	Electro-magnetic ray	0	0	0.1-2 MeV	Indefinite	Indefinite	External (high) and internal (high)	colbalt-60, cesium-137
X Ray	x	Electro-magnetic ray	0	0	.01-150 KeV	Indefinite	Indefinite	External and internal	X-ray machines
Neutron	n	Neutron	1	0	.025 eV-5 Me	Indefinite	Indefinite	External (high) and internal (rare)	reactors, AmBe sources

Gamma rays and X rays are chargeless and essentially consist of massless waves of electromagnetic energy (photons). When high-speed electrons are suddenly slowed down on striking a target, they lose energy in the form of X radiation. The energy of the electrons principally determines the wavelength and penetrating quality of the resulting X rays. Gamma rays are identical to X radiation except for their source, which is the nucleus of the atom. Primarily because they are chargeless, gamma radiation and neutron radiation are highly penetrating in tissue and are termed "penetrating radiation;" they will pass through the whole body, causing biological damage to living cells due to ion pairs created in the path of the radiation. Gamma rays and neutrons are high external hazards. Gamma rays are also high internal hazards.

Neutrons carry no charge and can travel great distances in air. Neutrons lose all of their energy through collisions with nuclei, which may result in the immediate remission of the neutron as well as a gamma ray. The low-energy neutrons are eventually absorbed by another nucleus, and the resulting isotope may be radioactive. Neutrons are rarely internal hazards.

Figure 7-1 illustrates the penetration of the body by the different types of radiation.

Figure 7-1. Types of Ionizing Radiation



TOXICITY

Toxicity is the ability of a substance to produce an unwanted effect on a living organism (once it reaches a susceptible site on the body) by other than mechanical means. A toxic effect is any undesirable disturbance of a physiological function caused by a poison. The effect on the body can be reversible or irreversible; local or systemic; benign or malignant; and mutagenic, teratogenic, or terminal.

Toxicity Versus Hazard

In evaluating a hazard, toxicity is but one factor. Others are chemical and physical properties, including warning properties such as odor.

- ◙ The toxicity of a substance describes the nature, degree, and extent of its undesirable effects. It is a basic biological property of a material and reflects its inherent capacity to produce injury.

- The phrase "workplace hazard" describes the likelihood that this toxicity will have its effect within an occupational setting.

TOXIC EFFECT

A toxin could be defined as any agent capable of producing an unwanted effect in a biological system. This is not a useful working definition, since virtually every known chemical has the potential to produce injury or death if present in a sufficient amount. Many chemicals essential for health in small quantities are toxic in large quantities (e.g., zinc, copper, molybdenum, chromium, and nickel). Paracelsus (1493-1541) noted, "All substances are poisons; there is none which is not a poison. The right dose differentiates a poison from a remedy." In the workplace, the critical factor is not the inherent toxicity of a substance, but the risk or hazard associated with its use.

The harmfulness or toxic effect of a material depends on the:

- Chemical composition
- Type and rate of exposure
- Fate of the material inside the body (biotransformation)
- Dose

Types of Exposure

The toxic action of a substance can be divided into acute and chronic effects.

It should not be assumed that chronic effects are less serious simply because they result from exposure to a lower concentration of toxic materials. The ultimate effect can be quite serious and irreversible. See Table 7-2, Types and Rates of Exposure.

Table 7-2. Types and Rates of Exposure

Type	Time	Concentration of Toxin	Example
Acute	Short-term Sudden	High	Accident
Chronic	Long-term Repetitive and continuous	Low	Workplace exposure

Rate of Exposure Dose-Response Relationship

All toxicological effects are based on the dose-response relationship. This dose-response relationship is the basis for all exposure guidelines and regulations. Unusual exposures and times (e.g., extended shifts or stressful environments) may influence this relationship and make direct application of exposure guidelines inaccurate. The dose-response relationship can be expressed as the product of a concentration (C) multiplied by the time (T) of exposure. The product is proportional to a constant (K); C x T = K. The two variables, concentration and duration of exposure, can be combined to provide a hypothetical approximation of the effects to the chemical at different times and concentrations.

The terms "LD50" and "ED50" are used to describe dose.

- LD50 - Median lethal dose. It is a statistical estimate of the dose required to kill 50% of the test animal population.
- ED50 - Median effective dose. It is an estimate of the dose that will produce some effect on 50% of the test animals.

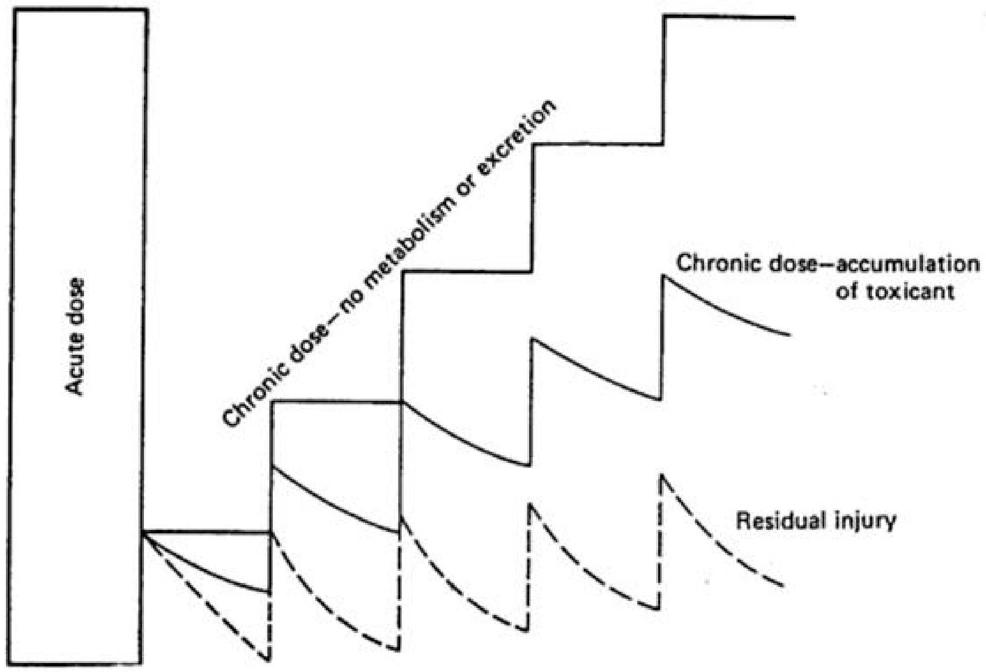
Fate in the Body

Once the chemical is inside the body, the effect will be determined by how the body handles the toxin. A single large dose can be expected to produce a greater response than the same total dose administered in small amounts over a long period of time. See Figure 7-2, Dose-Response Relationship Curve.

A small amount may be detoxified by the body, which is an important bodily defense. After absorption into the blood, the toxic substance goes to the liver, which can alter, degrade, or detoxify many substances. The simplified steps in detoxification are:

- Deposition in the liver
- Conversion to a nontoxic compound
- Transportation to the kidney via the bloodstream
- Excretion through the kidney and urinary tract

Figure 7-2. Dose-Response Relationship Curve



ROUTES OF EXPOSURE

Chemical compounds in the form of liquids, gases, mists, dusts, fumes, and vapors cause harm to the body by ingestion (eating or drinking), injection, skin absorption (direct contact), and inhalation (breathing). The method of entry will depend on the physical and chemical states of the agent and may occur by more than one route. The route of entry into the body will influence the extent of the hazard, as well as controls required for the hazard.

Ingestion

Ingestion is the entry of a substance into the body through the mouth and on to the intestine, where it may be absorbed into the blood and has the potential to harm the body. Oral toxicity is generally lower due to the relatively poor absorption of materials from the intestines into the bloodstream. Ingestion of materials may occur when workers eat lunch in contaminated work areas or when a worker with contaminated fingers and hands eats or smokes.

Injection

Injection is the deposition of a material into the skin or muscle, or directly into the bloodstream, pleural cavity, or peritoneal cavity of the body. Injection bypasses the protective mechanisms of the body and is a convenient and effective method for laboratory studies. The effects of injection are not an important route of worker exposure, although accidents may result in injection.

Skin Absorption

Skin absorption occurs through intact or nonintact skin and is an important route of entry for occupational exposure. This may cause irritation (the substance reacts with the skin), skin sensitization, or penetration of blood vessels under the skin and entry to the bloodstream. Factors that determine whether a substance will be absorbed through the skin are listed below:

- Physicochemical properties of a material
  (aqueous and lipid solubilities, and molecular size)
- Temperature
  (skin absorption increases due to increased vasodilation)

Therefore the absorption will be influenced by climate, season, and worker physical activity.

Inhalation

Inhalation is the most important route of entry for occupational exposure. The respiratory system is a quick and direct route for toxic materials because of its direct link to the body's circulatory system and the body's constant need for oxygen. Humans can survive for weeks without food and days without water—but only a few minutes without air.

Physical State of Contaminants

The physical state of an air contaminant is an important factor when determining effects on the body, the regulatory requirements, and the appropriate application of controls and protective equipment. Airborne contaminants that can be inhaled directly are classified as gases, vapors, or particulates (dusts, fumes, and mists) and are defined in Table 7-3, Forms of Air Contaminants.

Harmful substances that are inhaled can cause:

- Tissue reaction
- Tissue damage
- Disease
- Physical obstruction

For example, hydrogen fluoride is a gas that directly affects the lungtissue by acting as an irritant which will produce chemical burns. The inhalation of this gas causes pulmonary edema and directly interferes with the gas transfer mechanism of the alveoli lining.

The amount of a substance absorbed via the respiratory tract depends on its form, its concentration in the air, the duration of exposure, and the pulmonary ventilation rate of the worker. Individual susceptibility to respiratory toxins varies and causes difficulty in assessment. In a work setting, workers may exhibit different degrees of pulmonary complication. This variation can be due to the following:

- Variation of the rate of clearance from the lung
- The effect of cigarette smoking
- A coexistent pulmonary disease
- Genetic factors

Table 7-3. Forms of Air Contaminants

Form	Explanation	Example
Particulates		
Dust	Formed from solid material by mechanical processes such as grinding, blasting, and drilling	Silica, talc, asbestos, and lead dusts
Fume	Small, solid particles formed by vaporization and subsequent condensation	Welding
Mist	Liquid particulates formed by direct atomization from a liquid or condensation from the gaseous state	Oil mist, painting, and spraying
Gases	Formless fluids that occupy the entire space of the enclosure and can be changed to a liquid or solid state only under increased pressure or decreased temperature	Hydrogen sulfide, carbon monoxide, and chlorine
Vapors	Evaporation products of substances normally liquid or solid at normal temperature and pressure	Carbon disulfide and trichloroethylene

CARCINOGENS

A carcinogen is a substance that will induce a malignant tumor in a human or animal following a reasonable exposure. New and abnormal tissue growth may be classified as a neoplasm; this term frequently refers to cancerous or potentially cancerous tissue and indicates that the cells are, to some extent, out of control. If neoplastic cells invade tissues or spread to new locations in the body (metastasize), the neoplasm has become cancerous or malignant. It is an established fact that exposure to some chemicals can produce cancer in laboratory animals and in humans.

Cancer is induced by mechanisms that are not clearly understood. There are a number of factors that relate to the incidence of cancer. These factors may include the genetic pattern of the host; viruses present; external radiation, including sunshine; hormonal imbalance; and exposure to certain chemicals. It is also possible that some combination of factors must be present to induce cancer.

ALARA

"As low as reasonably achievable" (ALARA) is the term used to describe a radiation protection approach that controls or manages exposures (both individual and collective, to the workforce and the general public) and releases of radioactive material to the environment as low as social, technical, economic, practical, and public policy considerations permit. As mandated in Title 10 CFR Part 20, ALARA is not a dose limit, but a process that seeks to attain dose levels as far below applicable levels as is practical.

RISK

Risk is the possibility of a hazard having adverse consequences under a defined set of conditions. Safety, the inverse of risk, is the probability that harm will not occur under specified conditions. Substances that are extremely toxic can be used safely if the environment is controlled to prevent the absorption of the toxic substance. The overall safety consideration is that possible risks to plant workers and the general public must be kept at levels in accordance with national regulations and the ALARA principle.

Risk/Safety Factors

The NRC lists specific topics that should be considered in the overall safety principles for granting a license to a facility. By general acceptance, factors that should be considered in any discussion of risk/safety assessment include the following:

- Effects of natural phenomena
- Building and process ventilation and off-gas
- Criticality prevention
- Fire prevention

- Radiation protection
- Radioactive waste management
- Maintenance
- Environmental protection
- Packaging and transportation of nuclear materials
- Accident analysis
- Chemical safety
- Sharing of facilities, structures, systems, and components
- Utilities essential to radiological safety
- Operations

Process Safety Requirements

OSHA has issued a performance standard, Title 29 CFR Part 1910.119, entitled "Process Safety Management of Highly Hazardous Chemicals (PSM)," effective August 26, 1992. This performance standard enhances licensees' abilities in fulfilling their responsibilities. This section provides a synopsis of the OSHA standard and a comparison to the risk management program (RMP) of the EPA (Title 40 CFR Part 68), which is similar to the OSHA regulation. OSHA and the EPA have similar process safety requirements with the following emphasis:

- OSHA process safety management (PSM) requirements address the workers.
- EPA risk management program requirements consider the public and the environment.

The following are additional regulations:

- OSHA related Performance Standard, 29.
- CFR Part 1910.119
- CFR Part 1926.64
- OSHA Hazard Communication Standard, 29 CFR Part 1910.1200.

EPA RMP and OSHA PSM require a process safety management program for any facility that manufactures, processes, handles, or stores highly hazardous chemicals in significant quantities (threshold quantities). The OSHA and EPA listings of chemicals differ in some respects:

- Each list is drawn from a consensus of relevant sources.
- The OSHA list reflects threshold quantities that would be reasonably anticipated to cause death or serious, irreparable health effects in the workplace.
- The EPA list is intended to be protective of the public offsite.

The PSM program has 12 elements:

- Process Safety Information
- Process Hazard Analysis
- Operating Procedures
- Training
- Contractors
- Pre-Startup Safety Review
- Mechanical Integrity
- Hot Work Permits
- Management of Change
- Incident Investigation
- Emergency Planning and Response
- Compliance Safety Audit

A compilation of chemicals found on both the OSHA and EPA lists is located at the end of this module. In addition, the National Fire Protection Association health, flammability, and reactivity ratings are included.

Risk Assessment

The goal of a risk assessment is to identify potential hazards and prioritize their respective impacts on the workplace and determine the likelihood. Once the risks have been identified and assessed, risk management may proceed. See Figure 7-3 for elements of research, risk assessment, and risk management.

Risk assessment includes the following:

- Workplace characterization
    - Process/operation description

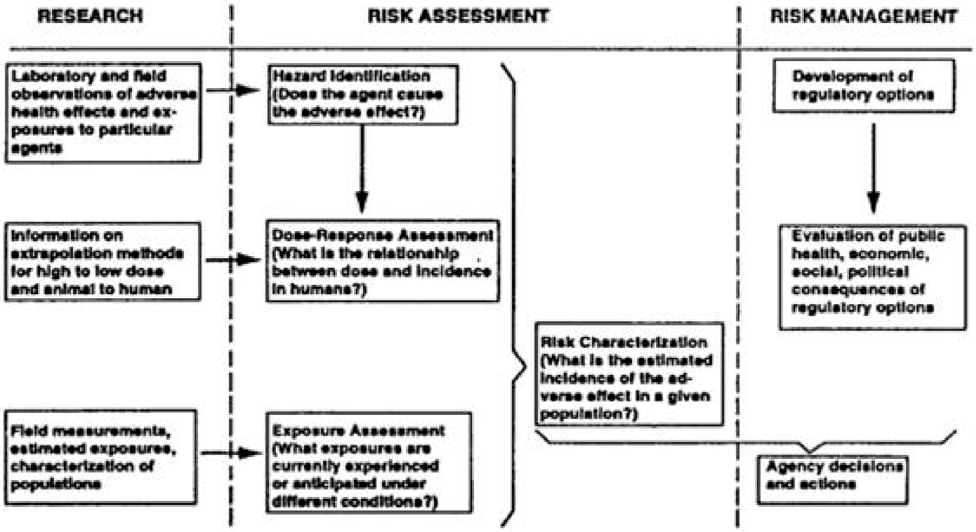
      Schematic diagrams:

        - potential emission and control points
        - flow of process and material
        - location of material handling tasks
        - material transfer and disposition of all process streams

  - Written description:
    - type of operation
    - location of potential exposures
    - chemical and physical process information
    - work practice procedures
    - use and type of control(s)
    - use of personal protective equipment
    - auxiliary operations
    - inventory of chemical, physical, radiological, and
    - biological agents and locations
- Work force characterization
  - Job titles/descriptions
  - Task analysis
  - Number of workers
- Characterization of agents
  - Health effects data
  - Regulations
  - Exposure limits and guidelines
  - Inventory of chemical, physical, radiological, and biological agents

The basic high standards for safety in the nuclear fuel cycle require that assessments for safety consider not only the need for safety and reliability during normal and abnormal operations, but also potential malfunctions due to internal and external hazards.

Figure 7-3. Elements of Research, Risk Assessment, and Risk Management



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CONTROLS

The control of hazards requires that exposure to harmful chemical stresses and physical agents does not exceed permissible limits. The controls can be classified as follows:

- Engineering controls are designed to eliminate the hazards, either by initial design specification or by applying the methods of substitution, isolation, or ventilation.
- Administrative controls control employees' exposures by limiting work times in contaminated areas, and/or other work rules.
- Personal protective equipment (PPE) protects the employees from exposures, but should be the last resort used when engineering or administrative controls do not sufficiently limit the effects of the hazard.

Protection built into the design of a process utilizing several levels is preferred over a method that depends on continual human implementation or intervention. To control the hazard, it is necessary to determine the source of the hazard, the path it travels to the worker, and the employee's work pattern and any use of protective equipment. Methods of control are presented in Table 7-4. One, or a combination, of these methods may be necessary to control a hazard. Hazards change with time, so controls require continuous review and revision.

Table 7-4. Methods of Control

Item	Method Control
Source/Hazard	◙ Substitution with a less harmful material ◙ Change of process ◙ Enclosure of process ◙ Isolation of process (space or time) ◙ Wet methods ◙ Local exhaust ventilation (capture at source) ◙ Adequate maintenance program
Pathway	◙ Housekeeping ◙ General exhaust ventilation ◙ Dilution ventilation (supplied air) ◙ Increased distance between source and receiver (semiautomatic or remote control) ◙ Continuous air monitoring ◙ Adequate maintenance program
Receiver/Worker	◙ Training and education (most important) ◙ Rotation of workers ◙ Enclosure of workers ◙ Personal monitoring devices (dosimeters) ◙ Personal protective equipment ◙ Medical monitoring

HEALTH AND SAFETY INFORMATION

Resources

To identify the hazards in the workplace, the process must be understood and the various chemical and/or physical factors or stressors identified. There are many published sources to provide information on the identification and analysis of hazards. The NRC has developed guidance (NUREG-1520) for evaluating hazards and assessing likelihoods and consequences from identified accident sequences. The American Institute of Chemical Engineers published information in 1992 for analyzing process systems and identifying potential accidents.

Professional and industrial organizations can provide specific information on particular processes.

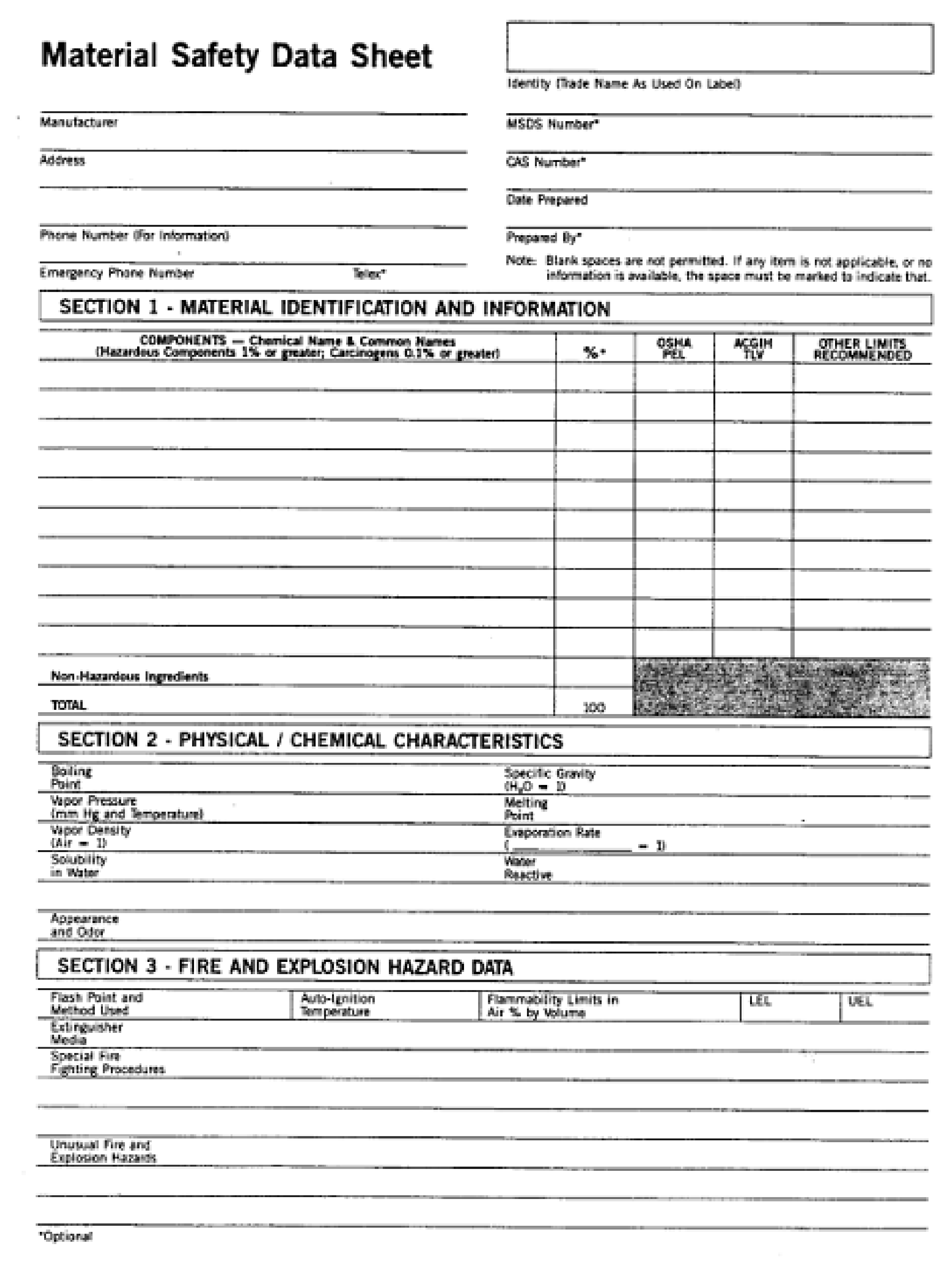
Some of the most useful resources of product information are the chemical manufacturers and/or suppliers. A summary of important health, safety, and toxicological information on a chemical or mixture may be obtained from a Material Safety Data Sheet (MSDS). A MSDS is designed to provide both workers and emergency personnel with the proper procedures for handling or working with a particular substance. It will include information such as physical data (melting point, boiling point, flash point, etc.), toxicity, health effects, first aid, reactivity, storage, disposal, protective equipment, and spill/leak procedures. The MSDS must be supplied by the chemical manufacturer to the purchaser for all hazardous materials under the Hazard Communication Standard (29 CFR Part 1910.1200). See Figure 7-4 for a copy of the OSHA MSDS form. The Hazard Communication Standard requires the following:

- Developing a written program
- Labeling containers
- Preparing and distributing MSDSs
- Training employees about hazards and protective measures

The labeling of hazardous chemicals, according to 29 CFR Part 1910.1200(f)(1), must include the following:

- The identity of the hazardous chemical(s)
- An appropriate hazardous warning
- The name and address of the chemical manufacturer, importer, or other responsible party

Figure 7-4. Material Safety Data Sheet (page 1)



Material Safety Data Sheet

Identity (Trade Name As Used On Label)

Manufacturer

Address

Phone Number (For Information)

Emergency Phone Number Telex*

MSDS Number*

CAS Number*

Date Prepared

Prepared By*

Note: Blank spaces are not permitted. If any item is not applicable, or no information is available, the space must be marked to indicate that.

SECTION 1 - MATERIAL IDENTIFICATION AND INFORMATION

COMPONENTS — Chemical Name & Common Names (Hazardous Components 1% or greater; Carcinogens 0.1% or greater)	%*	OSHA PEL	ACGIH TLV	OTHER LIMITS RECOMMENDED
Non-Hazardous Ingredients		▨	▨	▨
TOTAL	100	▨	▨	▨

SECTION 2 - PHYSICAL / CHEMICAL CHARACTERISTICS

Boiling Point	Specific Gravity (H_2O = 1)
Vapor Pressure (mm Hg and Temperature)	Melting Point
Vapor Density (Air = 1)	Evaporation Rate (________ = 1)
Solubility in Water	Water Reactive

Appearance and Odor

SECTION 3 - FIRE AND EXPLOSION HAZARD DATA

Flash Point and Method Used	Auto-Ignition Temperature	Flammability Limits in Air % by Volume	LEL	UEL

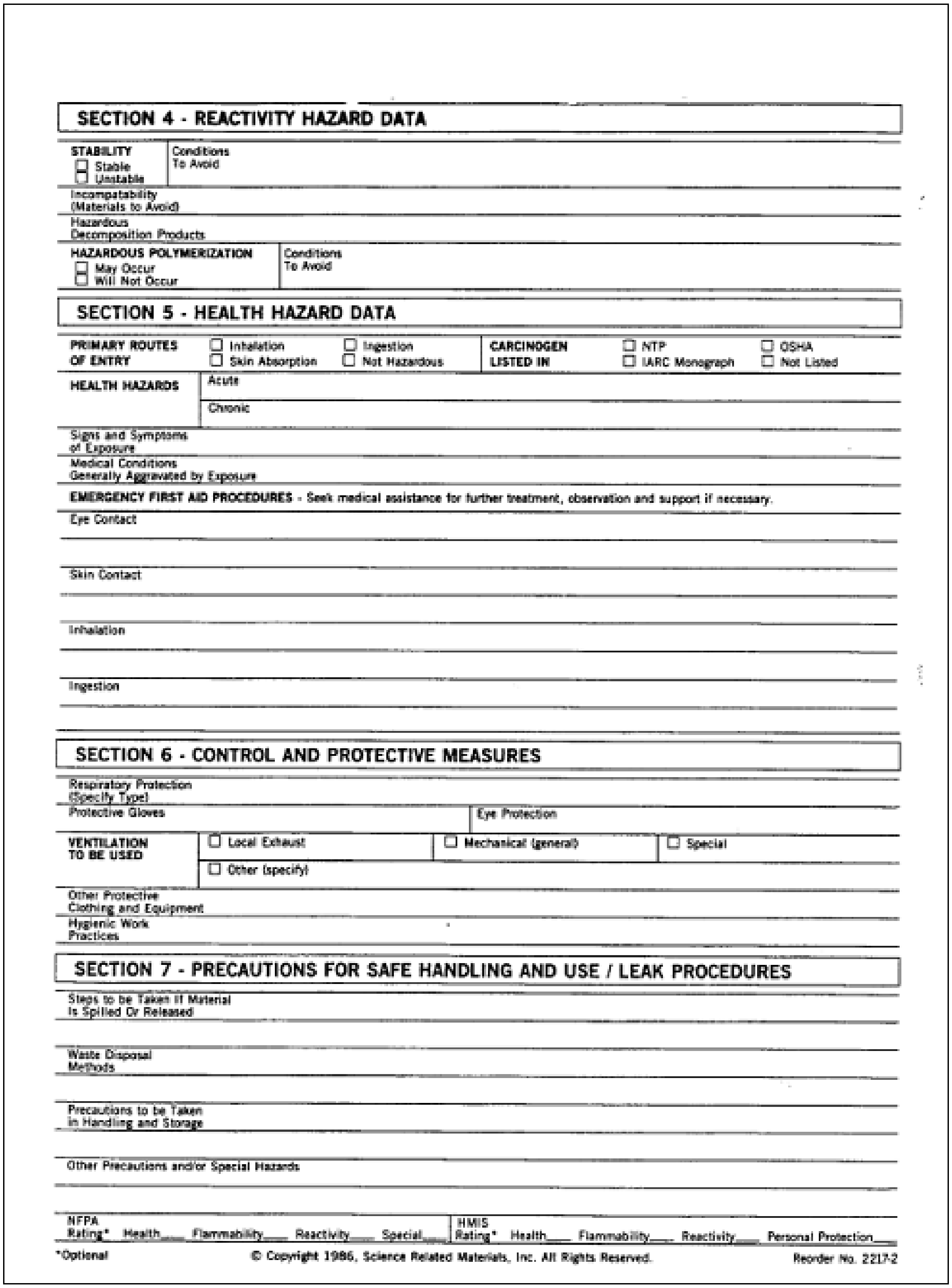
Extinguisher Media

Special Fire Fighting Procedures

Unusual Fire and Explosion Hazards

*Optional

Figure 7-4. Material Safety Data Sheet (page 2)



SECTION 4 - REACTIVITY HAZARD DATA

STABILITY
☐ Stable
☐ Unstable
Conditions To Avoid

Incompatability (Materials to Avoid)

Hazardous Decomposition Products

HAZARDOUS POLYMERIZATION
☐ May Occur
☐ Will Not Occur
Conditions To Avoid

SECTION 5 - HEALTH HAZARD DATA

PRIMARY ROUTES OF ENTRY ☐ Inhalation ☐ Ingestion ☐ Skin Absorption ☐ Not Hazardous

CARCINOGEN LISTED IN ☐ NTP ☐ OSHA ☐ IARC Monograph ☐ Not Listed

HEALTH HAZARDS
Acute
Chronic

Signs and Symptoms of Exposure

Medical Conditions Generally Aggravated by Exposure

EMERGENCY FIRST AID PROCEDURES - Seek medical assistance for further treatment, observation and support if necessary.

Eye Contact

Skin Contact

Inhalation

Ingestion

SECTION 6 - CONTROL AND PROTECTIVE MEASURES

Respiratory Protection (Specify Type)

Protective Gloves

Eye Protection

VENTILATION TO BE USED ☐ Local Exhaust ☐ Mechanical (general) ☐ Special ☐ Other (specify)

Other Protective Clothing and Equipment

Hygienic Work Practices

SECTION 7 - PRECAUTIONS FOR SAFE HANDLING AND USE / LEAK PROCEDURES

Steps to be Taken if Material Is Spilled Or Released

Waste Disposal Methods

Precautions to be Taken in Handling and Storage

Other Precautions and/or Special Hazards

NFPA Rating* Health___ Flammability___ Reactivity___ Special___

HMIS Rating* Health___ Flammability___ Reactivity___ Personal Protection___

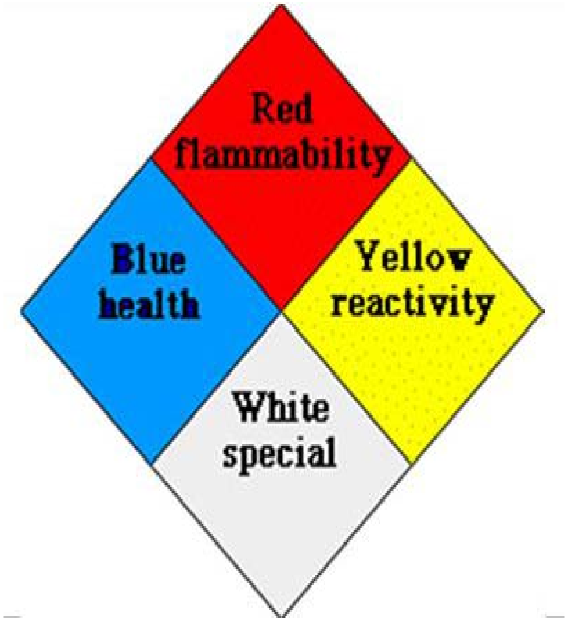
*Optional

Reorder No. 2217-2

Hazardous materials should always be properly labeled. One common type of chemical label is from the U.S. National Fire Protection Association (NFPA) system. See Figure 7-5 Standard Chemical Label.

Each color on the standard chemical label represents a different type of hazard. The white section on the bottom of the diamond represents a special hazard such as an oxidizer, acid, alkali, corrosive, use no water, or radioactive hazard. Information in this area is conveyed by use of symbols which represent the special hazard. For example, a radioactive hazard may be indicated by use of the radiation symbol in the white section of the diamond. Each facility may have its own method of entering this information. The blue section on the left side of the diamond represents a health hazard. The red section on the top of the diamond represents a flammability or fire hazard. The yellow section on the right side of the diamond represents a reactivity hazard. There are also numbers from zero to four inside each of these blue, red, and yellow sections. The numbers indicate the degree of a particular hazard: 0 = minimal hazard; 1 = slight hazard; 2 = moderate hazard; 3 = serious hazard; and 4 = severe hazard. Regardless of the numbers on the label, even if they carry ones or zeros, be cautious. All chemicals should be handled in accordance with approved methods or procedures.

Figure 7-5. Standard Chemical Label



When visiting a fuel cycle facility, you need to be aware of chemical hazard labels. You should also be familiar with specific posting and labeling requirements for radiological hazards as outlined in Title 10 CFR Part 20.1902 through Title 10 CFR Part 20.1905.

Additional sources of health and safety information are listed in the References of the Trainee Self-Study Course Guide.

Hazard Guidelines

After the presence and extent of specific hazards have been identified, the risk associated with the hazards must be determined. This is done by referring to standard reference sources for data and guidelines.

OSHA uses the term permissible exposure limit (PEL). The original PELs were taken from the threshold limit values (TLVs), which are published by the American Conference of Governmental Industrial Hygienists. At the time they were converted, the TLVs and PELs were identical in value, although the meanings were slightly different. Since that time, the differences have become more pronounced. Although both refer to the eight-hour time-weighted average concentration to which an individual should not be exposed, the primary difference is that PEL is a legal term and the TLV is intended as a guideline for exposure. The PEL is the level above which it would be illegal to expose an employee, although OSHA does not state or imply that exposures below the PEL are safe. The intent of the TLVs is to provide guidelines for airborne concentrations below which it is believed that nearly all workers can be exposed without adverse health effects.

QUALITY ASSURANCE

The NRC regulates nuclear fuel facilities under the authority of the Atomic Energy Act of 1954 and Title 11 of the Energy Reorganization Act of 1974. The NRC has a commitment to ensure safe operations at its licensed facilities. The NRC staff help licensees recognize potential problems with the operations and ensure that licensees implement solutions to safety issues.

Quality assurance includes all those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service. These actions should include the calibration, maintenance, and performance of all systems employed for safety, radiation safety, process safety, and confinement of radioactive or other hazardous materials.

After a risk has been identified, an assessment is made to prioritize the risk. The management of the risk is determined by the safety assessment and includes the controls necessary to ensure that appropriate protective measures are taken to prevent their occurrence or mitigate their consequences.

- ◙ To ensure that the fuel cycle facilities are operated in a safe manner, Guidance on Management Control/Quality Assurance, Requirements for Operation, Chemical Safety, and Fire Protection for Fuel Cycle Facilities (March 21, 1989) provides steps that should be taken by the licensees:

- Establish an organization responsible for developing, implementing, and assessing the management control program.
- Establish a plant safety committee(s) to monitor and oversee important plant activities and changes.
- Develop written administrative and general plant procedures, including procedures for evaluating changes to equipment, tests, and procedures. These must be approved and documented in a manner endorsed by management.
- Establish and implement a surveillance, testing, and inspection program to ensure safety.
- Provide and document periodic, independent audits to determine the effectiveness of the management control program.
- Establish and implement training programs to provide the employees with skills and knowledge to perform their jobs safely. The effectiveness of these programs must be evaluated against predetermined objectives and criteria.

In September 2000, the NRC published a revised regulation for fuel facilities based on assessing and addressing risk.

In 2002, the NRC published guidance in NUREG-1520, Standard Review Plan (SRP) for the Review of License Application for a Fuel Cycle Facility, to be used for evaluating the risk associated with fuel facilities. The SRP contains the following sections:

1. General Information
2. Organization and Administration
3. Integrated Safety Analysis (ISA) and ISA Summary
4. Radiation Protection
5. Nuclear Criticality Safety
6. Chemical Process Safety
7. Fire Safety
8. Emergency Management
9. Environmental Protection
10. Decommissioning

11. Management Measures

Each SRP section addresses:

- Reviewer responsibilities
- Regulations on technical matters
- Acceptance criteria
- Process and procedures
- Appropriate conclusions to summarize the review

Self-Check Questions 7-1

INSTRUCTIONS: Fill in the missing word(s) in each statement. Answers are located in the answer key section of the Trainee Guide. Choose from the following words:

assessment
carcinogen
concentration
dose-response
extent
hazard
kidney
material
particulates
physical activity
quality assurance
susceptibility

beta
chemical
contaminated
emission
form
intensity
last
MSDS
penetrating
pressure
rate
time

body
chemical burns
continuous
energy
fumes
internal
limiting
neutrons
permissible
process
skin absorption
toxic

bremsstrahlung
composition
deposition
engineering
gamma
ionization
living cells
nontoxic
physical
occupational
source
unwanted

1. Hazard refers to the potential that a____________________or physical characteristic of a material, system, process, or plant, will cause harm or produce adverse consequences.

2. Chemical hazards are due to excessive airborne concentrations of mists, vapors, gases, or solids in the form of dusts or__________________.

3. Physical hazards include excessive levels of electromagnetic radiation, noise, vibration, and extremes of temperature and__________________.

4. Radiological hazards result from the________________of energy during spontaneous decay in the form of alpha, beta, or___________________radiation from the nucleus of an atom.

5. Common methods of hazard identification include analysis of the process _____________properties and conditions, review of organization and industry process experience, development of interaction matrixes, and application of hazard evaluation techniques.

6. The degree of hazard from exposure depends on the:

   - ◙ Nature of the material or__________________ involved
   - ◙ ___________________of exposure
   - ◙ Duration of exposure
   - ◙ ___________________ of the biological system or subject

7. Radiation refers to particles and/or energy capable of producing _____________ (charged particles).

8. Common examples of radiation include alpha radiation, beta radiation, gamma rays, X rays, and _______________.

9. Alpha radiation is considered an_________________exposure hazard.

10. Beta particles interact with matter by three different mechanisms: ionization and excitation, and by the emission of__________________.

11. The effects of large external doses of_________________radiation are like those of severe burns to the skin.

12. Primarily because they are chargeless, gamma radiation and neutron radiation are highly _________________in tissue; they will pass through the whole body, causing biological damage to _______________ due to ion pairs created in the path of the radiation.

13. Toxicity is the ability of a substance to produce an_________________ effect on a living organism (once it reaches a susceptible site on the body) by other than mechanical means.

14. A ___________________effect is any undesirable disturbance of a physiological function caused by a poison.

15. The toxicity of a substance describes the nature, degree, and___________________of its undesirable effects. It is a basic biological property of a material and reflects its inherent capacity to produce injury.

16. The harmfulness or toxic effect of a material depends on the:

    - ◙ Chemical ________________
    - ◙ Type and_________________ of exposure
    - ◙ Fate of the material inside the _______________(biotransformation)
    - ◙ Dose

17. All toxicological effects are based on the_________________relationship.

18. The dose-response relationship can be expressed as the product of a multiplied by the__________________ of exposure.

19. The simplified steps in detoxification are:

    - ◙ __________________in the liver
    - ◙ Conversion to a________________compound
    - ◙ Transportation to the________________via the bloodstream
    - ◙ Excretion through the kidney and urinary tract

20. Chemical compounds in the form of liquids, gases, mists, dusts, fumes, and vapors cause harm to the body by ingestion, injection,___________________, and inhalation.

21. Ingestion of materials may occur when workers eat lunch in contaminated work areas or when a worker with____________________fingers and hands eats or smokes.

22. Skin absorption will be influenced by climate, season, and worker_________________.

23. Inhalation is the most important route of entry for_____________________exposure.

24. The___________________state of an air contaminant is an important factor when determining effects on the body, the regulatory requirements, and the appropriate application of controls and protective equipment.

25. Airborne contaminants that can be inhaled directly are classified as gases, vapors, or _____________________.

26. Hydrogen fluoride is a gas that directly affects the lung tissue by acting as an irritant which will produce___________________.

27. The amount of a substance absorbed via the respiratory tract depends on its _____________ , its concentration in the air, the duration of exposure, and the pulmonary ventilation rate of the worker.

28. A ___________________is a substance that will induce a malignant tumor in a human or animal following a reasonable exposure.

29. As mandated in 10 CFR Part 20, ALARA is not a dose limit, but a _________________that seeks to attain dose levels as far below applicable levels as is practical.

30. Risk is the possibility of a __________________having adverse consequences under a defined set of conditions.

31. The goal of a risk____________________is to identify potential hazards and prioritize their respective impacts on the workplace.

32. The control of hazards requires that exposure to harmful chemical stresses and physical agents does not exceed__________________limits.

33. ___________________controls are designed to eliminate the hazards, either by initial design specification or by applying the methods of substitution, isolation, or ventilation.

34. Administrative controls control employees' exposures by__________________work times in contaminated areas, and/or other work rules.

35. Personal protective equipment (PPE) protects the employees from exposures, but should be the__________________resort used when engineering or administrative controls do not sufficiently limit the effects of the hazard.

36. To control a hazard, it is necessary to determine the__________________of the hazard, the path it travels to the worker, and the employee's work pattern and any use of protective equipment.

37. Hazards change with time, so controls require___________________review and revision.

38. A summary of important health, safety, and toxicological information on a chemical or mixture may be obtained from the_____________________.

39. _________________includes all those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

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

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

Learning Objective

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

7.1.2 Identify hazards associated with uranium and selected by-products in the nuclear fuel cycle.

HAZARDS OF URANIUM AND SELECTED BYPRODUCTS

Atoms that are unstable (radioactive) undergo spontaneous decay and emit one or more types of radiation until they reach a stable form. Uranium-235 is the only fissile nuclide that exists in nature to any significant extent and can be used to sustain a nuclear chain reaction in the presence of moderated ("slow") neutrons.

Uranium Radioactivity

Naturally occurring uranium consists of three primary isotopes: U-238, U-235, and U-234. In nature, about 99.3% of the uranium is U-238, about 0.711% is U-235, and approximately 0.006% is U-234. The primary isotopes of uranium are all long-lived alpha emitters. However, several other radionuclides can be significant at uranium facilities, depending on the uranium materials and the processing.

The concentration of radioactivity, or the relationship between the mass of radioactive material and the activity, is called the specific activity. It is expressed as the number of becquerels (or curies) per unit mass or volume. The specific activity depends on its degree of enrichment, and normally describes only alpha activity. The beta activity from associated decay products can be expressed separately. Therefore, two specific activities (one for alpha and one for beta) might be calculated for uranium-bearing materials. Since the activity of the decay products can vary with time, the beta specific activity can also vary. The specific activity will influence the particular hazard and the control(s) needed for each stage of the fuel cycle.

Specific activity increases with enrichment, primarily because of the increase in the amount of U-234 present. Gaseous diffusion, the current method of enriching uranium, causes a greater increase in the number of U-234 atoms than U-235 atoms during the enrichment process. For example, when U-235 content is increased from 0.711% (natural) to 2.96% (a fourfold increase), the U-234 increases from 0.006% to 0.03% (a fivefold increase). Typical values of specific activity are shown in Table 7-5, categorized by the percentage of U-235 present.

The decay products of uranium isotopes are also radioactive and form "decay chains." U-238 and U-234 belong to the uranium series, while the U-235 isotope belongs to the actinium series. The type of radiation emitted and the half-life will vary according to the isotope that is present in each step of a process of the nuclear fuel cycle. Any hazard assessment must include specific information on the isotopes present to allow for proper calculation of potential exposure.

Table 7-5. Specific Activity

Type	% U-235	Specific Activity (Ci/g)
Natural	0.711	7×10^{-7}
Depleted	0.20	4×10^{-7}
Enriched	2.0	1×10^{-6}
Enriched	20	6×10^{-6}

Uranium Toxicity

The chemical toxicity of uranium has generally been the primary concern in the establishment of control limits and procedures. Uranium, a heavy metal, is toxic to the kidneys, and high exposure to soluble (transportable) compounds can cause renal injury. A concentration of 3 µg of uranium per gram of kidney tissue has been used as the guideline for limiting the chemical toxicity of uranium. Standard man (a scientific model of an average man based on the International Commission on Radiological Protection [ICRP] 30 model for metabolism) has a kidney mass of 310, so this would translate as a total kidney burden of 1 mg. Table 7-6 lists airborne concentrations of transportable (soluble) uranium published by various organizations.

Table 7-6. Toxicological Limits on Airborne Concentrations of Transportable (Soluble) Uranium

Agency	Chronic Occupational Exposure (mg/m3)	Reference
Nuclear Regulatory Commission (NRC)*	0.2	Footnote to Appendix B, Title 10 CFR Part 20
American Conference of Governmental Industrial Hygienists (ACGIH)	0.2	Threshold limit values (TLVs) and biological exposure indices, ACGIH
Occupational Safety and Health Administration (OSHA) [preferred/ recommended limit]	0.05	Title 29 CFR Part 1910.1000

* Title 10 CFR Part 20.1201(e) limits soluble uranium intake to 10 mg per week, based on chemical toxicity.

Transportability

The transportability of an inhaled or ingested material determines its fate within the body and, therefore, the resulting dose or chemical effect. All materials are classified by the ICRP into three inhalation classes:

- **Class D** is the most soluble (lung retention time in days).
- **Class W** is moderately soluble (lung retention time in weeks).
- **Class Y** is the least soluble (lung retention time in years).

The OSHA limit is recommended for exposures to soluble/ transportable (Class D) uranium unless enrichment dictates more stringent controls based on radiological concerns. Table 7-7 lists inhalation classification of some uranium compounds.

Table 7-7. Inhalation Classification for Some Uranium Compounds

Uranium hexafluoride	UF_6	Class "D"
Uranyl fluoride	UO_2F_2	Class "D"
Uranyl nitrate	$UO_2(NO_3)_2$	Class "D"
Uranyl acetate	$UO_2(C_2H_3O_2)_2$	Class "D"
Uranyl chloride	UO_2Cl_2	Class "D"
Uranyl sulfate	UO_2SO_4	Class "D"
Uranium trioxide	UO_3	Class "D"
Uranium tetrafluoride	UF_4	Class "W"
Uranium oxide	U_3O_8	Class "W"
Uranium dioxide	UO_2	Class "W"
Uranium tetraoxide	UO_4	Class "W"
Ammonium diuranate	$(NH_4)_2 + U_2O_7$	Class "W"
Uranium aluminide	UAl_x	Class "Y"
Uranium carbide	UC_2	Class "Y"
Uranium-zirconium alloy	UZr	Class "Y"
High-fired uranium dioxide	UO_2	Class "Y"

Biological Effects of Uranium

Most data on human response to uranium have come from accidental exposures (generally UF_6 releases). Accidental exposures to UF_6 have resulted in at least three fatalities, caused primarily by the hydrogen fluoride/hydrofluoric acid (HF) that was formed by hydrolysis of UF_6 as opposed to the UF_6 itself. Accidental high, nonfatal doses have produced pulmonary edema, nausea, vomiting, abdominal cramps, and chemical burns on the skin due to HF formed by the hydrolysis of UF_6. Once absorbed into the blood, uranium is primarily distributed to the bones and kidneys. Urinary and blood abnormalities indicate kidney damage due to inhibited resorption in the tubules. For inhaled uranium, the amount of time spent in the lungs will depend on the solubility of the material.

Soluble uranium compounds attack the respiratory system, blood, liver, lymphatics, kidneys, skin, and bone marrow. The insoluble uranium compounds attack the skin, bone marrow, and lymphatics. The following uranium salts are reported to be capable of penetrating intact skin:

- Uranyl nitrate
- Uranyl fluoride
- Uranium pentachloride
- Uranium trioxide
- Sodium diuranate
- Ammonium diuranate
- Uranium hexafluoride

Radiological Versus Toxic Limits

Inhalation can result in both radiological and toxic hazards. When radiological hazards are the most important health and safety factor, chemical hazards can generally be neglected, except in overexposure situations. When chemical hazards are the most important health and safety factor, radiological hazards can be neglected only if the radiation doses are below regulatory limits. The determination of the hazard (chemical or radiological) that is most significant depends on the following:

- Transportability (solubility in body fluids)
- Enrichment
- Duration of exposure (chronic or acute)

For low enrichment, the chemical toxicity is the limiting hazard; for high enrichment, radiological effects are the limiting hazards. The radiological impact should be considered for all intakes, even when chemical toxicity is the limiting hazard.

URANIUM COMPOUNDS AND BY-PRODUCTS

Hydrogen Fluoride

Hydrogen fluoride is an extremely corrosive acid that is relatively volatile in its anhydrous form. It is a by-product of the production of UF_4 from UF_6 and is generated whenever UF_6 is released to the atmosphere (H_2O in air + UF_6 ---> UO_2F_2 and HF). External contact with HF causes chemical burns and irritation of the skin; airborne exposure causes chemical burns and irritation to the eyes, nose, and throat. Generally, the irritation and olfactory senses will provide warnings; individuals can smell HF at levels of 0.02-0.2 mg/m^3. The TLV of 2.5 mg/m^3 is based primarily on the irritation of the eyes and mucous passages, which would occur before any permanent damage to the body. According to the National Institute for Occupational Safety and Health Guide to Chemical Hazards, the "immediately dangerous to life or health" concentration limit is 30 parts per million (ppm). This represents the maximum concentration from which, in the event of respirator failure, one could escape within 30 minutes without experiencing impairing or irreversible health effects. Proper protective equipment, including respirators, should be worn in areas where HF presents a hazard.

There have been several incidents associated with HF release at the Paducah, Oak Ridge Y-12, and Portsmouth facilities. In November 1990, workers at Paducah were cleaning a valve when a high-efficiency particulate air (HEPA) filter failed, releasing HF and uranium reaction products into the area. The HF, generated by the cleaning activities, can cause deterioration of the borosilicate glass filtering material and failure of the HEPA filter. In a separate incident, a leak was detected in an HF tank car awaiting delivery to the plant. It is estimated that a total of about 250 lb of HF was lost over a period of more than one hour; emergency procedures were instituted to prevent the spread of the material, and no off-site impact was observed. In January 1992, at the Oak Ridge Y-12 Plant, a rupture disk installed in an HF vaporizer opened, releasing approximately 600 pounds of liquid and gaseous anhydrous hydrogen fluoride into a work area. Nine employees were transferred to the medical facility, and a total of 18 sought medical attention. In October 1992, two Portsmouth maintenance workers conducting postmaintenance testing on a compressor were exposed to HF. The instrument line was not properly reconnected to a process seal system.

Uranium Hexafluoride

Uranium hexafluoride (UF_6) is produced on a large scale at conversion plants for use as a fuel for uranium enrichment by gaseous diffusion or gas centrifugation. It is a white, somewhat volatile, solid at room temperature and pressure. Uranium hexafluoride reacts with almost all metals to form metal fluorides and reacts, often explosively, with organic material to form fluorinated compounds and hydrogen fluoride. The radioactivity of the UF_6 will vary according to the U-235 enrichment.

With water or almost any level of water vapor, uranium hexafluoride forms highly corrosive and toxic hydrogen fluoride gas, and particulate uranyl fluoride (UO_2F_2), which tends to settle on surfaces. The UO_2F_2 and HF, which form quickly during a release to the atmosphere, are readily visible as a white cloud. A concentration of 1 mg of UO_2F_2 per cubic meter of air is visible, and the cloud produced by large releases may obscure vision.

Containment of UF_6 is a prime safety concern throughout the enrichment process. Typical containment materials, such as stainless steel and copper, retain their integrity by forming a protective fluoride layer when the UF_6 first comes in contact with the surface to prevent further corrosion. A primary concern for UF_6 is the potential environmental hazard; therefore, a leak detection and an alarm system are important safety features.

Nitric Compounds

Nitric acid is used to digest uranium metal and for "pickling" metal products to inhibit oxidation. Concentrated nitric acid gives off fumes that cause irritation to the eyes, mucous membranes, and skin. When uranium materials, especially metal, are dissolved in nitric acid, oxides of nitrogen (NOx) are given off. The symbol "NOx" refers to mixtures of nitric oxide (NO) and nitrogen dioxide (NO_2), which are the most common forms. Exposures can cause eye irritation, shortness of breath, chest pain, pulmonary edema, and rapid heartbeat.

Hydrogen Gas

Hydrogen gas (H_2) is often generated by dissociating ammonia; thus, ammonia, rather than hydrogen, is frequently identified as the reactant in the processes. Hydrogen is used as a reactant in the production of UF_4 from UF_6 and in the reduction of UO_3 to UO_2, an intermediate step in the production of UF_4 from UO_3. Another use of hydrogen is in the reduction process for the conversion of U_3O_8 to UO_2 prior to pellet pressing. Any facility where H_2 is used as a reactant should include design features to ensure that hydrogen is not allowed to accumulate (e.g., monitors, roof vents, forced ventilation, designated storage areas). Hydrogen can also be generated when moisture contacts uranium (e.g., chips produced during the machining of uranium) and in battery charging rooms. Hydrogen has the highest burning velocity of all gases and a wide flammability range. In addition, it may be an explosion hazard in containers where mixtures of hydrogen and an oxidizer may form. The lower explosive limit is 4 and the upper explosive limit is 74.5.

Ammonia

Anhydrous ammonia is used as source material for the production of hydrogen for use in reduction processes, such as the hydrofluor process of UF_6 production. During fabrication, using the dry conversion fluid bed process, the solid uranyl fluoride is pyrohydrolyzed in a reducing atmosphere of hydrogen (from "cracked" ammonia) to remove the residual fluoride and reduce the UO_2F_2. Ammonia is a flammable gas that may also be an explosion hazard if ignited in a confined space. Its lower explosive limit is 15 and its upper explosive limit is 28. Ammonia is covered under both OSHA and EPA regulations.

Ammonia is a colorless, strongly alkaline, and extremely soluble gas with a characteristic pungent odor. Contact with anhydrous ammonia or aqueous solutions is intensely irritating to the mucous membranes, eyes, and skin and may cause corrosive skin burns or blister formation. Mild to moderate exposure to the gas can produce headache, salivation, nausea, vomiting, and chest pain. If a victim does not escape, there may be severe irritation of the respiratory tract or pulmonary edema, or respiratory arrest. In areas where ammonia hazards exist in concentrations above the standard, respiratory, eye, and skin protection must be provided. Emergency showers and eyewash stations must be provided if liquids containing greater than 10% ammonia are used. The federal standard for ammonia is an eight-hour time-weighted average (TWA) of 50 ppm (35 mg/m^3); the ACGIH recommends a TWA of 25 ppm (18 mg/m^3).

Chlorine Trifluoride

Chlorine trifluoride (CIF_3) is used as a barrier treatment gas in the cascade for uranium enrichment. Chlorine trifluoride is a powerful oxidizing agent, igniting many organic compounds on contact and reacting violently with water. Its reactivity has led to its use as a fluorinating agent. At room temperature and pressure, ClF_3 is a colorless gas, with a density 3.14 times that of air. It is highly irritating, even at low concentrations, and will cause eye and respiratory irritation. Its odor is sweet and suffocating, and it is highly corrosive to animal tissue; any contact with the skin or eyes will result in severe damage. The OSHA eight-hour permissible exposure limit (PEL), and the ACGIH TLV is 0.1 ppm (0.4 mg/m^3).

Self-Check Questions 7-2

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

1. What is specific activity and how is it expressed?

2. Why does specific activity increase with enrichment?

3. Besides the half-life varying according to the isotope that is present in each step of a process of the nuclear fuel cycle, what else will vary?

4. What has generally been the primary concern in the establishment of control limits and procedures for uranium?

5. In Title 10 CFR Part 20.1201(e) what is the chemical toxicity based on soluble uranium intake?

6. The transportability of an inhaled or ingested material determines ___________________.

7. Name three uranium salts that are capable of penetrating intact skin.

8. For low and high enrichments what are the limiting hazards?

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

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

Learning Objective

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

7.1.3 Identify selected abnormal occurrences at fuel facilities.

CHEMICAL PROCESS SAFETY AT FUEL CYCLE FACILITIES

NUREG-1601, Chemical Process Safety at Fuel Cycle Facilities (August 1997), provides broad guidance on chemical safety issues relevant to fuel cycle facilities. It describes an approach acceptable to the NRC staff, with examples that are not exhaustive, for addressing chemical process safety in the safe storage, handling, and processing of licensed nuclear material. It expounds to license holders and applicants a general philosophy of the role of chemical process safety with respect to NRC-licensed materials; sets forth the basic information needed to properly evaluate chemical process safety; and describes plausible methods of identifying and evaluating chemical hazards and assessing the adequacy of the chemical safety of the proposed equipment and facilities. Examples of equipment and methods commonly used to prevent and/or mitigate the consequences of chemical incidents are discussed in NUREG-1601.

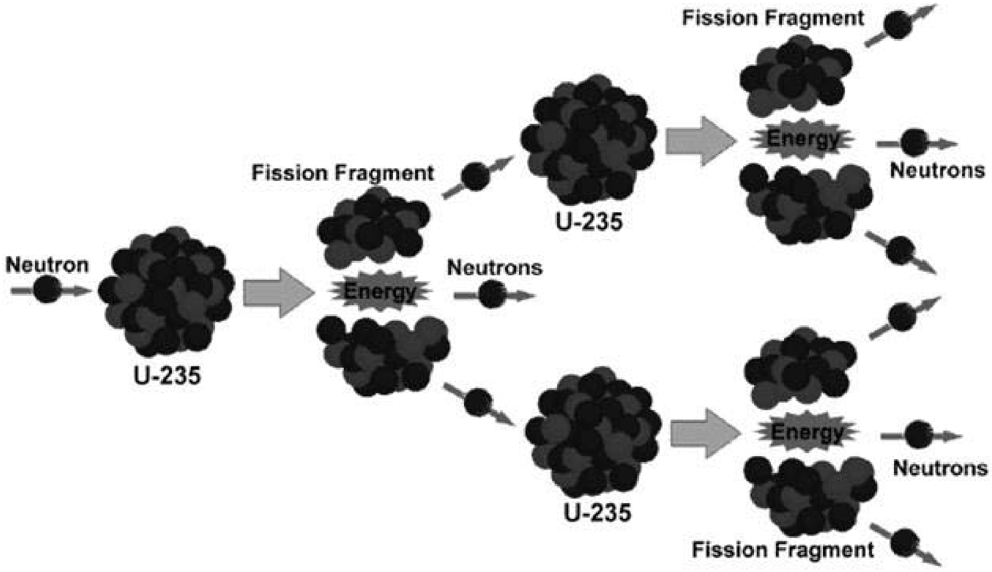
CRITICALITY SAFETY

A criticality accident is an uncontrolled nuclear chain reaction that occurs where it is not intended (usually outside a nuclear reactor). All operations with fissionable materials outside reactors are controlled to prevent criticality accidents and the sudden release of heat, neutrons, and gamma radiation, which may be lethal to nearby personnel (within approximately 15 feet of the reacting material). In addition, depending on the circumstances of the incident, measurable, but non-life-threatening offsite doses are possible from the release of volatile fission products, such as radioactive isotopes of krypton and xenon. Outside the immediate area surrounding the source material, a criticality accident becomes primarily a contamination and environmental hazard. Because of the potential for lethal doses to workers, all fuel cycle licensees consider criticality to be a high-consequence event under 10 CFR 70.61.

Neutron Physics

Nuclear power reactors represent nearly optimized arrangements of fissionable materials, in order to make efficient use of the awesome energy in the atomic nucleus. Outside reactors, conditions are usually not favorable for criticality because nuclear processes are designed to handle fissionable materials in safe quantities, forms, and arrangements. Whenever sufficient quantities of material are available, positive control must be maintained to prevent the inadvertent occurrence of criticality. The basic fission process is shown in Figure 7-6.

Figure 7-6. Basic Fission Process



A neutron impacts a fissionable nucleus such as ^{235}U, which causes it to become unstable and split into two (generally unequal) fission products, along with the emission of 2 or 3 neutrons. For ^{235}U fission by *thermal neutrons*, the average number of neutrons emitted ($\bar{\nu}$, or “nu-bar”) per fission is around 2.4, whereas for ^{239}Pu fission, it is around 2.9. Once neutrons are emitted, there are several possible things that can happen to them. A neutron can:

- Escape from the fissionable material.
- Be absorbed. Materials that are good absorbers have a large absorption cross section.
- Be absorbed and result in a nuclear fission.
- Be scattered, with or without a change in neutron direction and kinetic energy.

Criticality and Neutron Multiplication

The parameter usually used to describe a specified system relative to criticality is referred to as the *neutron multiplication factor*, k-effective (symbol k_{eff}):

$$k_{eff} = \text{(neutrons produced)} / \text{(neutrons absorbed + neutrons leaked)}$$

We define a *critical system* as one in which the total number of neutrons produced just exactly balances the number of neutrons which are absorbed or escape—where $k_{eff} = 1$.

$k_{eff} = 1$	*Critical*—neutron population remains steady over time (desirable in a reactor)
$k_{eff} < 1$	*Subcritical*—the desired condition for fissionable materials outside reactors. The neutron population decreases exponentially with time, with no net build-up.
$k_{eff} > 1$	*Supercritical*—to be avoided except in nuclear weapons. The neutron population increases exponentially with time, with a dramatic release of energy.

Sometimes we refer to a system that is actually supercritical as being critical. The suddenness of the neutron chain reaction makes criticality inherently different from chemical safety, where there is the possibility to protect personnel through a "see and flee" approach. There is a possibility to outrun a chemical cloud, but there is no possibility of outrunning gamma rays or neutrons. The only possible mitigation is fixed shielding in place before an accident.

Calculations, Subcritical Margin, and Safety Margin

The various techniques available to demonstrate that a system is subcritical have limited accuracy. Because of this, these techniques have varying amounts of *margin* to ensure, with high confidence, that systems determined to be subcritical actually are subcritical, and remain that way.

Some of the techniques that can be used to demonstrate subcriticality are, in decreasing order of preference:

- Experiments
- Industry-accepted handbooks and industry consensus standards (ANSI, ISO)
- Computer Calculations (may be deterministic or statistical)
- Hand Calculations (solid angle method, surface density method, etc)

Computer methods have limited accuracy, and so an *upper subcritical limit* (USL) is typically determined. The USL is the maximum k_{eff} that can be safety considered to be subcritical for a given calculational method. The USL is calculated as follows:

$$k_{eff} + 2\sigma \leq USL = k_{calc} - \Delta k_{calc} - \Delta k_m$$

where k_{eff} = value as determined by the calculational method, σ = uncertainty in the calculated value of k_{eff}, k_{calc} = the average value of k_{eff} for a set of known *critical benchmarks*, Δk_{calc} is the uncertainty in k_{calc}, and Δk_m is the *minimum margin of subcriticality* (aka the *administrative margin* or *arbitrary margin*).

WARNING! The terms *safety margin* and *subcritical margin* are often confused. The subcritical margin is a measure of how far a nuclear system is from criticality (i.e., difference between the USL and the calculated k_{eff}). The greater the subcritical margin, the more assurance there is that the system is subcritical. This does *not* mean that a system with a lower k_{eff} is necessarily more safe. The only thing that k_{eff} tells you is whether the systems is critical or subcritical. The *safety margin* usually refers to the change in a parameter that is needed to make the system critical. For example, if the normal mass in a glovebox operation is 5 kg UO_2, but it takes 50kg UO_2 before criticality is possible, there is a very large safety margin in terms of mass. Safety depends not on the subcritical margin, but on the margin that exists in system parameters such as mass.

Criticality Parameters

The various macroscopic physical parameters that affect the value of k_{eff} are listed below (from NUREG-1520 and -1718):

mass
geometry
density
enrichment[1]
reflection
moderation
concentration
interaction[2]
neutron absorber[3]

volume
heterogeneity[4]

and sometimes:
process variables
physicochemical form

[1] also called *isotopics* (because it may include plutonium or other isotopes besides ^{235}U)
[2] also called *spacing*
[3] also called neutron *poison*
[4] may actually be ensuring *homogeneity*

The choice of parameters is a convention. Lists may include as few as 9 and as many as 13 parameters, and may differ from facility to facility or country to country. Licensees have the option as to which criticality parameters they want to control. A given process may involve as few as one controlled parameter, or it may involve nearly all of them. Most of us have heard about critical mass (which will be discussed below), but in criticality safety, mass is just one of the parameters that affects k_{eff}.

Licensees generally choose those parameters that are (1) more convenient, given the nature of the process, (2) easier to control, or (3) more reliable, or some combination thereof. We will consider each of these criteria in turn.

Considered generally reliable

- geometry/volume: most preferable; generally passively controlled
- absorber (fixed): often combined with geometry; generally passively controlled
- enrichment: will not change (except in an enrichment process)
- mass: mass is conserved, though may need to be administratively controlled
- moderation: in bulk powder processes may be only feasible means of control; often passively controlled
- interaction: may be administratively or passively controlled
- density: of solid materials, often relatively stable, controlled by the process

Considered inherently unreliable

- concentration: concentration of solution particularly difficult to control against such upsets at overbatching, precipitation, and chemical transformation
- heterogeneity: size and distribution of inhomogeneity in bulk material often difficult to control, and requires active means such as blending, stirring, and screening
- reflection: transient reflectors may include human beings, water, solutions, plastics, etc, and are difficult to exclude or quantify their effects on k_{eff}

Mass

Mass is how much fissionable material is available. The more fissionable material, the more likely it is that neutrons will collide with other fissionable atoms and lead to a self-sustaining criticality. Care must be taken when talking about mass to use the proper units—sometimes, the total mass of material (e.g., UO_2 and water) is used, sometimes total uranium mass, and sometimes fissile isotope mass (^{235}U). There is a different critical value for each.

A *critical mass* is present when there is enough material present to sustain criticality. The mass required in a given fissionable system depends on the size, shape, chemical and physical form, enrichment, reflection, moderation, etc., of the material. The term *minimum critical mass* is therefore used to indicate the smallest amount of material needed to sustain criticality, and therefore implies that all other parameters are at their worst-credible values. The minimum critical mass is generally the mass required for criticality for spherical geometry, full reflection, and optimum moderation.

Geometry

Geometry control consists of limiting dimensions of equipment containing fissionable materials. Often in the past, single-parameter limits from standards or widely-accepted handbooks were used for the dimensions of systems which could be represented by simple geometric shapes—typically cylinders, slabs, and spheres. When a cylinder, slab, or sphere can be circumscribed around a more complicated piece of equipment, the corresponding limits may be used.
A geometry-limited system is one where dimensions must be no greater than those specified in a criticality model. Geometry may be combined with control of other parameters to ensure the system is subcritical. A favorable/safe geometry system is one in which maintaining equipment dimensions to less than controlled limits is sufficient to ensure subcriticality. All other system parameters are assumed to be at their worst-credible values.

Some licensees make distinctions between the terms *favorable geometry* and *safe geometry*, whereas others use the terms interchangeably. Care should be taken to understand how the particular licensee uses these terms. Among those who make a distinction, *favorable geometry* is often taken to mean geometry control in conjunction with other parameters, whereas *safe geometry* is often taken to mean geometry control alone as the basis for subcriticality.

Density

Density control consists of limiting the amount of fissionable material per unit volume. The less dense the fissionable material is, the fewer fissions and absorptions per unit volume, and the greater the mean free path (the greater the leakage). When density is not credited, *full theoretical density* is assumed. This is the maximum density of a solid material—we do not speak of density when dealing with solutions—assuming there are no void spaces in the material. This may be realized in uranium metal or a perfect sintered oxide, but in real oxides is impossible to achieve. Most finished fuel has a density of ~95% of theoretical density. Powders tend to be even less dense, with *green* pellets (pressed but not yet sintered) having densities of ~ 7 g/cc and bulk powder having densities of ~3-4 g/cc. This can result in a significant reduction in $k_{eff.}$

Enrichment

Enrichment control consists of limiting the amount of ^{235}U in the total amount of uranium present. It is expressed in terms of *weight percent* of $^{235}U/U$, or wt% ^{235}U. Because chemical reactions do not distinguish between different isotopes of an element, the enrichment cannot be changed by chemical means. It can only be changed by physical processes that have some dependence on isotopic mass (e.g., diffusion, centrifugation, curvature in a magnetic field). Because there is such a small mass difference between the major isotopes of uranium, ^{235}U and ^{238}U, the isotopic separation of uranium can be safely assumed to not occur accidentally (these isotopes differ by only ~1%). Enrichment can be thought of as an amalgamation of several other parameters. As enrichment increases, not only the proportion but also the density of ^{235}U atoms increases, which increases fission and decreases leakage. In addition, the density of

^{238}U atoms increases, which serves to primarily increase absorption. (Perhaps a few percent of the fissions occur from ^{238}U, but these occur mostly at high energies.) As enrichment increases, the subcritical dimensions and masses will decrease.

Reflection

Reflection control consists of limiting the presence of certain materials surrounding fissionable material. Materials that make good reflectors have large scattering cross sections, because the phenomenon of reflection consists of backscattering neutrons back into the system where they can cause more fissions. Increasing reflection decreases neutron leakage. Reflectors with low mass numbers may also be good moderators. Examples of reflectors that are also moderators include: water, hydrocarbons such as oil and plastics, concrete, graphite, and beryllium. Their presence increases k_{eff} both by reflecting neutrons of all energies back into the fissionable material, reducing leakage, and by thermalizing the neutron spectrum. Besides these, examples of materials that are good reflectors but not effective moderators include such heavy materials as lead and steel. Depleted uranium also reflects neutrons, but due to its large ^{238}U absorption cross section, only reflects a small fraction of the neutrons that impinge on it. The best reflector has a large scattering cross section, a low absorption cross section, and a low mass number (i.e., it is a poor absorber and a good moderator). The best generally available reflectors are materials containing a lot of hydrogen, such as water.

Moderation

Moderation consists of the slowing down of neutrons through collisions between neutrons and nuclei with low mass numbers. The closer the masses of the projectile (neutron) and the target (moderator nucleus), the more kinetic energy will be transferred between the particles and the more slowing down of neutrons will occur. This is the reason the lightest nuclei make the best moderators. Good moderators also have large scattering cross sections and small absorption cross sections. Hydrogen (including both light hydrogen and deuterium), beryllium, carbon, and materials containing these elements, are the best commonly encountered moderators.

The same material may be considered a moderator or a reflector, depending on where it is in the system. As stated above in the section on reflection, many reflectors are also moderators. Thus, water is chiefly considered a reflector if it completely surrounds the fissionable material, and a moderator if it is mixed in with the fissionable material, or if it is between clumps of fissionable material. Moderators that are between clumps of fissionable material are referred to as *interstitial moderators*. A common example is water that is presumed to exist between the elements of any array of fissionable units, such as an array of waste drums or storage cans on shelves in a vault.

Concentration

Concentration refers to the amount of fissionable material per unit volume of solution. Both moderation and concentration involve the relative proportion of fissionable and moderating material. The term *moderation control* is usually used for powders or other solid materials, and the term *concentration control* is reserved for solution systems. We are normally accustomed of speaking of moderation control when control is exerted over the amount of liquid present, and of concentration control when control is exerted over the amount of fissionable material present. However, the underlying physical phenomena and concerns are the same. The units of concentration are normally expressed in terms of fissionable material per unit volume (g ^{235}U/l, g U/l, kg Pu/l, etc; g/cc is usually used for density of solid materials).

Interaction

Interaction control, also known as *spacing* control, is ensured by limiting the distance between fissionable material units by engineered or administrative means. This includes both horizontal spacing, as in a drum storage array on the floor, and vertical spacing, as in rack storage. When units are spaced closer together, there is more neutron interaction between them (the extent to which neutrons leaving one unit can enter another). The amount of neutron interaction depends on several factors, most importantly the solid angle between the two units (the basis of the “solid angle” hand calculation technique). It also depends on any intervening materials, whether absorbers or moderators, and so interaction control is often used in conjunction with neutron absorber control or moderator control. Units are considered *neutronically isolated* when the neutron interaction between them has a negligible effect on k_{eff}.

Absorber

Neutron absorber control consists of placing materials with large neutron absorption cross sections in the vicinity of fissionable materials. There are two kinds of neutron absorbers—fixed neutron absorbers and soluble neutron absorbers. *Fixed absorbers* are solid materials that are incorporated into either the fissionable material (such as absorbers that are integral to the fuel) or equipment containing or surrounding the fissionable material. Soluble absorbers are added to liquids (the most common example being borated water). Besides these two categories, *Raschig Rings* are a special type of fixed neutron absorber. They are made from borosilicate glass and resemble small transparent napkin rings. Raschig Rings are added to unfavorable geometry tanks to permit them to store solutions with higher concentrations than would be otherwise possible.

Materials commonly used as neutron absorbers include **boron, nitrogen, chlorine, and depleted uranium**. The transition metals can also be used as absorbers. These include: **gadolinium**, **cadmium**, **erbium**, **hafnium**, and **samarium**. The thermal neutron absorption cross section of boron is ~775 barns, whereas the cross section of cadmium is ~20,000 barns, for example.

Volume

Volume control consists of limiting the size of single units. Unlike geometry control, this is not established by maintaining limits on dimensions, but rather by limiting the overall volume of a container or piece of equipment. If a licensee is relying on the shape of a container or piece of equipment, that is *geometry* control. If a licensee doesn't care what shape it is, but only what the total volume is, that is *volume* control. A *safe volume* is the volume of a particular material that is safely subcritical regardless of its dimensions or shape. Because of this, the worst-case shape for a given volume is assumed when deriving volume limits. The worst-case shape is the shape that has the minimum leakage, and therefore the minimum surface area, for a given volume—a sphere.

Heterogeneity

More efficient use can be made of nuclear fuel if it is divided into discrete or heterogeneous lumps with moderator in between (this also has the advantage of efficient heat transfer from fuel to cooling water). This is why modern light-water reactor fuel consists of heterogeneous rods of fuel placed in water or some other coolant. Subcritical limits—mass, volume, and dimensions—are lower for heterogeneous nuclear material than for homogeneous nuclear material. The reason for this has to do with what we call *resonance self-shielding*. Fission is more likely at lower (thermal) neutron energies, but the highly energetic neutrons produced in nuclear fission need to be moderated from fast to thermal energies. As the neutrons are slowed down, they must pass first through the ^{238}U resonance region, where the cross section is very large. Because of this, these neutrons stand a very high likelihood of being absorbed before they can be thermalized. When the fuel is homogeneous and there is a lot of ^{238}U around (for fuel enriched to 5wt% ^{235}U, there are 20 atoms of ^{238}U for every atom of ^{235}U), the likelihood of their being absorbed before reaching thermal energy is very high. However, if the fuel is lumped, at least some of the fissions will occur near the boundaries of the fuel, and many of the neutrons will enter the moderator and rapidly be moderated before they can enter another fuel lump or be reflected back. Then their energy is too low to be absorbed by the high absorption resonances.

The following table provides a summary of what parameters tend to be used where in the fuel cycle:

Table 7-8. Parameters in the Fuel Cycle

Process Area	Typical Controlled Parameters	Corresponding Controls
Enrichment Facility		
UF_6 Cylinder Handling & Feed	Enrichment, Moderation	Maximum limits on enrichment in UF_6 cylinders and natural/depleted uranium used in feed. Moderation control ensured by cylinder integrity and fluorinating environment created by UF_6/HF gas.
Gaseous Diffusion or Gas Centrifuge Cascade	Enrichment, Mass, Moderation	Enrichment controlled by monitoring the process. Mass in any given area is very small as a result of UF_6 being in a gaseous form. Moderation ensured by process equipment integrity, fluorinating environment, and lack of liquids used in the process.
Blending/Product Withdrawal	Enrichment, Moderation	Enrichment ensured to be less than cylinder limits before withdrawal. Moderation limited as above.
Fuel Manufacturing Facility		
Wet Chemistry: ADU Process & Uranium Recovery	Geometry (and possibly Absorbers), Interaction, Physicochemical form	Solutions contained within favorable geometry columns, annular and slab tanks, etc. Backflow prevention provided by overflows and siphon breaks. Drains and dikes prevent accumulation in the event of leaks or rupture of favorable geometry equipment. Depending on throughput needs, equipment may include fixed absorbers (e.g., cadmium sheets). Spacing between favorable geometry equipment is fixed. Chemical form of solution is controlled by monitoring process parameters (acidity, temperature, etc.) and by means such as in-line filters.
Oxide Conversion	Geometry, Mass, Moderation	Geometry of boats entering calciner limited to a single layer. Mass per boat/oxide container limited by procedure. Moderation in product limited by ensuring minimum calciner temperature and residence time, thereafter by sampling and keeping containers closed.
Powder Handling and Pelletizing	Mass, Density, Moderation	Mass per oxide container limited by procedure (bulk powder processing does not typically rely on mass). Density of powder prior to sintering may be credited

Table 7-8. Parameters in the Fuel Cycle

Process Area	Typical Controlled Parameters	Corresponding Controls
		(verified by sampling/measurement). Moderation of material in containers and bulk powder blending limited by procedure, by defining areas as Moderator Control Areas, and by equipment integrity (verified by sampling/measurement).
Fuel Fabrication	Geometry, Absorber, Moderation	Geometry of fixed fuel limited by design. Geometry of loose pellets and rods limited to less than a safe slab. Absorber materials that are integral to the fuel may be credited (but not usually). Moderation limited inside gloveboxes and Moderator Control Areas; generally not limited for finished fuel.
Waste Handling & Uranium Recovery	Mass, Moderator, Interaction, Concentration	Mass and moderator in waste drums limited. Drums may be spaced apart by procedure or birdcages, or may be prohibited from being stacked. In large geometry tanks (e.g., aqueous raffinate and wastewater), concentration by in-line monitoring and sampling is generally the main control.
Laboratories	Mass, Interaction, Concentration	Mass and concentration of individual samples may be limited. Only small quantities are generally needed for analysis. Spacing between mass-limited workstations controlled by procedure.

Other controlled parameters may be used in these areas, but these are the major parameters that tend to be used in these areas. To summarize, wet processes typically rely on geometry control and dry processes typically rely on a combination of mass and moderator control.

Process Variables

Often the 11 parameters discussed above depend on other process parameters—these may include pressure, temperature, acidity, etc. In the Hazard and Operability (HazOp) method of hazard evaluation, the change in each physical parameter that defines the state of a system is considered in turn, and its effect on the system safety considered. HazOp studies may consider such upsets as “high temperature” or “more pressure” or “less acid.” If these conditions result in scenarios that can lead to criticality, they need to be controlled. If the reliability of controls on the other parameters depend on them, they need to be controlled.

Physicochemical Form

The subcritical limits—mass limits, dimensional limits, volumetric limits, concentration limits—are usually defined for a particular reference medium. When we say that single-parameter limits (mass limits, dimensional limits, etc.) are derived assuming that all other parameters are at their worst credible values, we mean that this is the worst case for a particular reference medium. Unless the most reactive possible physical and chemical form of material is assumed, conditions needed to ensure that the material remains in that form need to be controlled—and especially when there are different forms of fissionable material present in a facility. Wherever there is a transition from a more reactive to a less reactive physical or chemical form (as from UO_2-and-water to uranyl nitrate), controls will generally be in place to preclude the more reactive material from moving downstream. Wherever there is a transition from a less reactive to a more reactive form (as from uranyl nitrate back to an oxide), there may need to be controls to prevent backflow.

Double Contingency Principle (DCP)

The “Double Contingency Principle” is a time-honored rule that has probably accounted for, along with the traditionally very conservative technical practices (and the large safety margin resulting from them), the very low historical incidence of criticality accidents. Even in this time of risk-informed regulation, double contingency continues to be an important part of the fuel industry’s safety strategy.

The DCP is usually stated as follows (from ANSI/ANS-8.1-1998):

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

NRC believes that this means, in practical terms, that no single upset condition should lead to criticality. This is more, however, than just an expression of defense-in-depth. Not only should no single event lead to criticality, but the two (or more) events necessary for criticality must each be unlikely and they must be independent. The various parts of the DCP are summarized below (we’re assuming there are only two events involved, for simplicity):

independent: There must be at least two independent events before criticality is possible. Not only can one event not cause the other, but the occurrence of one event must not increase the likelihood of occurrence of the other event.

unlikely: There is no quantitative definition of what ”unlikely” means, but in general the events will be considered sufficiently unlikely if there are controls to prevent them. (The presence of two independent administrative controls is generally enough to meet the DCP, but may not be sufficient to meet the “highly unlikely” requirement of 10 CFR 70.61. See FCSS-ISG-03.)

concurrent: The two events have to occur *concurrently,* meaning that the second event occurs while the system is still under the effects of the first event. This does not mean the two events have to occur *simultaneously*, just that the system is suffering from both failures at the same time. There is an implicit assumption here that there are means to detect failures promptly so that the process is not allowed to run with only one control for an extended duration.

changes in process conditions: This phrase has been subject to much debate. Some hold that only a change in a controlled parameter constitutes a change in process conditions, whereas others think that any abnormal event, whether or not it causes a change in a parameter, is a change in process conditions. The practical effect of this is that some believe the DCP requires control over two *different* parameters (dual-parameter control), while others believe that two controls on a single parameter meets the DCP (single-parameter control). The NRC historically has accepted both single- and dual-parameter control, but holds that dual-parameter control is preferable. The reason for this is that it can be difficult to be convinced that all possible failure mechanisms have been identified (that there is no unanticipated common-mode failure over a single controlled parameter). A common example is dual moderation control, such as occurs in the enrichment cascade at the gaseous diffusion plants. Although there are multiple controls on moderation, it may not be obvious that all events that can lead to loss of moderation control have been thought of. On the other hand, if controls are established on mass and moderation, it is much harder to postulate a single event that can wipe out both.

Lastly, it says “before a criticality accident is possible” rather than “before a criticality accident occurs.” This is an implicit acknowledgment that, even if all controls are lost, a criticality will probably not occur. This is because we assume worst-case conditions when a parameter has failed, but the likelihood that the worst case will be realized is probably very low. The large margin that exists because of the conservative way that criticality safety is done is probably responsible for why there have been so few accidents, even when all criticality controls have been lost.

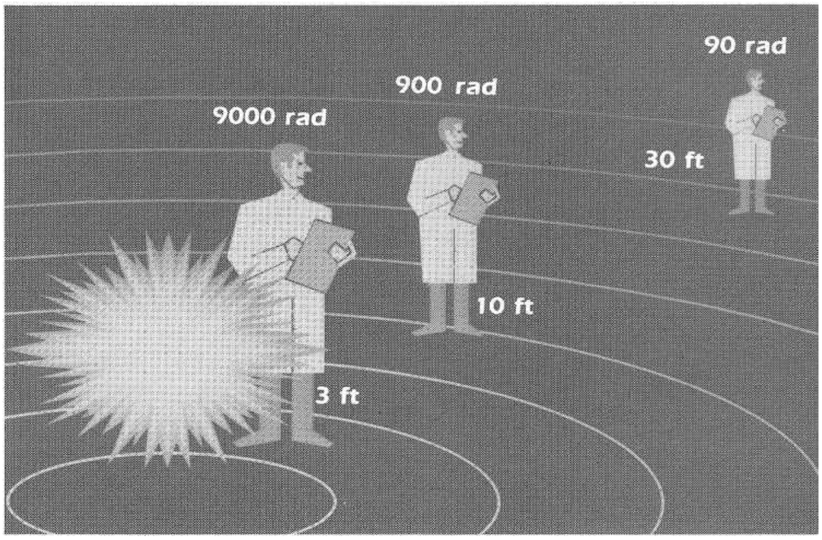
It’s a common misconception that the DCP requires two controls. In reality, sometimes less than two controls are needed, and sometimes more are needed. Sometimes the events that have to occur for criticality are sufficiently unlikely that controls do not need to be established.

More controls may be needed when not all the controls are independent, or when there are many different ways to get to criticality. There may be several dozen scenarios leading to criticality in a given process, and each of them may need one or more controls to meet the DCP. The entire process may therefore have to control most, if not all, of the parameters discussed above.

Consequences of Criticality

At larger distances, significant doses capable of causing acute radiation effects or latent cancer risk (see Site Access Training course) are likely from a criticality accident. Beyond about 200 feet, depending on the thickness of intervening shielding, less significant doses still in excess of 10 CFR Part 20 dose limits are possible. Measurable but non-life- threatening offsite doses are possible from the release of volatile fission products, such as radioactive isotopes of krypton, xenon, and iodine. The figure below shows the approximate ranges of concern (without taking shielding into account):

Figure 7-7. Radiation Range



A criticality accident would have a similar effect to other localized industrial accidents. The recent Los Alamos report LA-13638, “A Review of Criticality Accidents,” 2000, summarizes the 60 known worldwide criticality accidents that have occurred since 1945. The incidence of these accidents has decreased significantly over time, due in large measure to increased reliance on engineered controls (geometry control in particular) and other criticality safety practices.

The default criticality accident used in most licensee accident analyses is the one described in NUREG/CR-6410, “Accident Analysis Handbook,” Section 3.4.2, which assumes an initial burst of 10^{18} fissions, followed by 47 subsequent bursts of 1.92×10^{17} fissions each over eight hours, for a total of 10^{19} fissions. While several accidents took place over longer durations (or may have if they were not terminated by human intervention), this total number of fissions bounds all but a single accident; the 1959 accident at the Idaho Chemical Processing Plant (ICPP). This accident was unique in that it involved an unusually large quantity of solution, some 25 times the minimum critical mass in a 5,000 gallon tank (the material involved was 30.9 kg ^{235}U in 800 liter of fissile solution). The default criticality model above is therefore expected to bound nearly all critical excursions expected in fuel facilities, especially those involving solutions. However, it should be recognized that the actual fission yield from a criticality accident can vary widely, over several orders of magnitude (from a minimum of 10^{15} to a maximum of $4x10^{19}$). Factors that determine the actual consequence include the following:

- The amount of fissile material present
- The form of fissile material (metal, oxide, solution)
- The excess reactivity (e.g., delayed or prompt critical, supercritical)
- The reactivity insertion rate (e.g., rate of solution addition)
- Shutdown mechanisms (e.g., whether the tank is vented, heat needed to evaporate till a subcritical concentration achieved)
- Whether the excursion is terminated by human intervention

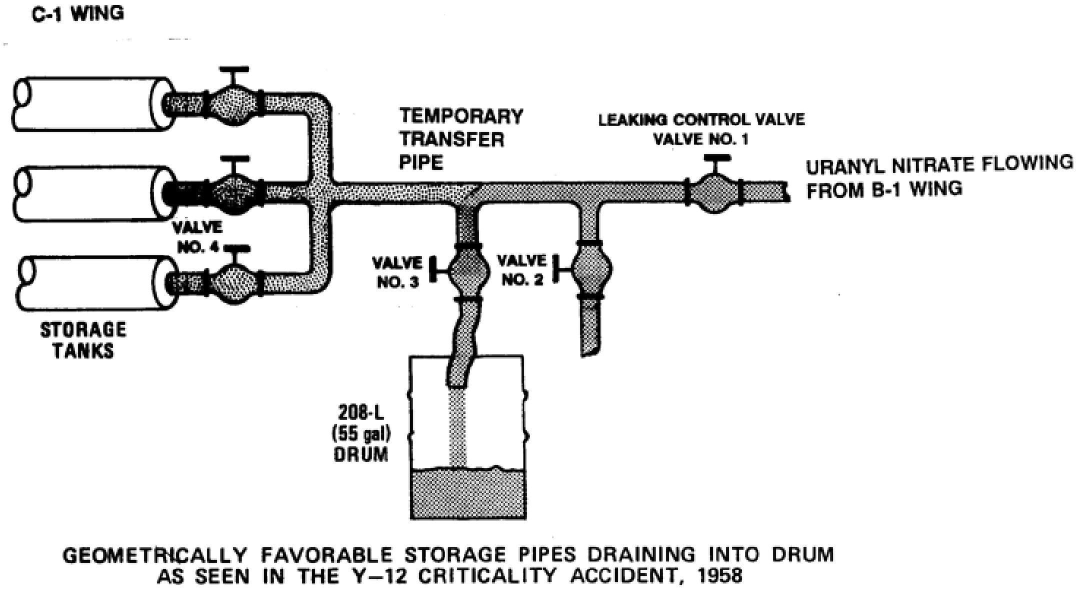
HISTORICAL ACCIDENTS AND SIGNIFICANT EVENTS

The best source of information on criticality accidents worldwide is LA-13638, “A Review of Criticality Accidents: 2000 Revision.” There have been 22 process facility criticality accidents worldwide since 1953, 7 occurred in the United States, 13 in the Soviet Union/Russian Federation, 1 in the United Kingdom, and 1 in Japan. The following is a *very brief* summary of the 7 US Criticality accidents. Refer to LA-13638 and the Nuclear Criticality Safety Self-Study Course for more information.

Y-12 Chemical Processing Plant, TN (June 16, 1958)

A criticality accident occurred in a high-enriched (93wt% ^{235}U) uranium recovery operation in which solid waste was dissolved in nitric acid and converted to uranium tetrafluoride (UF_4). In the days leading up to the accident, the facility had been shut down for inventory, during which time three five-inch diameter tanks in the C-1 wing were being leak tested by being filled with water, which was then drained to a 55-gallon drum. Meanwhile, the B-1 wing had been placed back in service, and was producing uranyl nitrate. Unknown to operators, the single isolation valve #1 between the C-1 and B-1 wings began to leak, allowing concentrated solution to flow out of the B-1 (see figure 7-8).

Figure 7-8. Geometrically Favorable Storage Pipes Draining into Drum



GEOMETRICALLY FAVORABLE STORAGE PIPES DRAINING INTO DRUM AS SEEN IN THE Y–12 CRITICALITY ACCIDENT, 1958

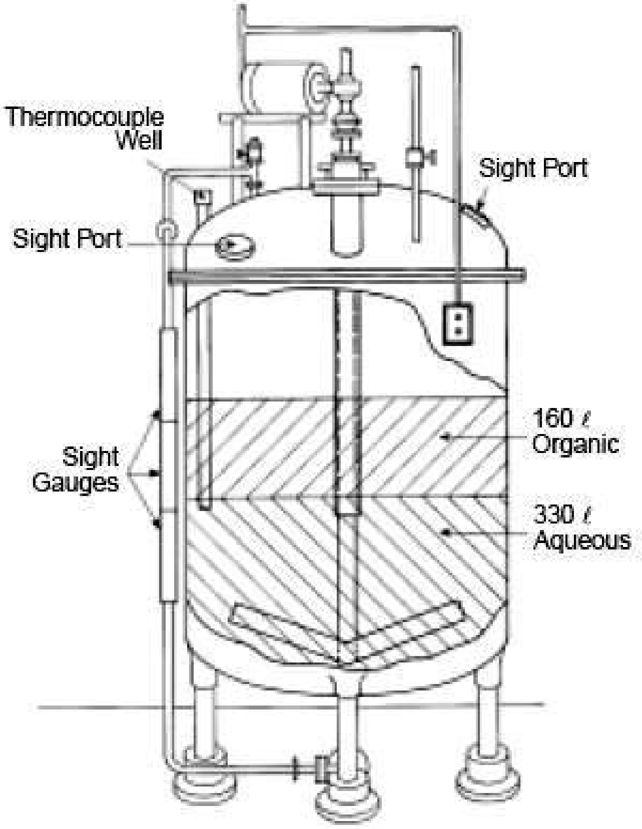
Workers discovered the leak and closed valve #2, allowing the solution to flow into the storage tanks in the C-1 wing. There is conflicting testimony as to whether these workers passed word of the leak on to the following shift, but on the next shift, workers filled the tanks with water and drained them to the 55-gallon drum, unaware that they contained fissile solution. Because the drum was not favorable geometry, when enough solution had accumulated in the drum, it went critical. The criticality was terminated when enough water entered the drum to dilute the solution.

Approximately 56 liters of uranyl nitrate solution at 37.5 g^{235}U/l drained was drained into the drum when it went critical, resulting in ~1.3×10^{18} fissions. Several bursts were reported. Even though the criticality alarms sounded, eight individuals received doses of between 28.8 and 461 rem. The facility returned to operation three days later.

Los Alamos Scientific Laboratory, NM (December 30, 1958)

A criticality accident occurred in a plutonium recovery operation in which wash solution from contaminated equipment was mixed with an organic solvent in a large-geometry tank. Similar to what occurs in a solvent extraction process, the plutonium would be transferred from the aqueous to the organic phase and then transferred for further processing. As with the Y-12 accident above, a material inventory was underway at the time of the accident. Normally the aqueous solution only contained trace amounts of plutonium (less than ~0.1 gPu/l), but on this occasion plutonium rich solids that had accumulated over several years were transferred to the tank, in violation of concentration limits. Initially the organic and aqueous layers in the tank were separate, but when the stirrer was started the two layers started to mix and the solution went critical. The tank involved in the accident is shown below.

Figure 7-9. Los Alamos tank involved in the accident



The criticality was terminated when the two layers were sufficiently mixed that the plutonium concentration dropped. Approximately 160 liters of plutonium nitrate solution at 18.4 gPu/l was involved in the accident, resulting in a single burst of ~1.5×10^{17} fissions. An operator who was standing on a ladder and watching the process through the sight glass received a fatal dose of ~12,000 rad. Two other operators—including one who ran to assist the mortally wounded operator—also received significant doses. There was no criticality alarm, even though some distant radiation detectors registered a dose, and it was not immediately apparent what had incapacitated the operator. The facility returned to operation after six weeks.

Idaho Chemical Processing Plant, ID (October 16, 1959)

A criticality accident occurred in a process involving the processing of high-enriched (91 wt% ^{235}U) spent nuclear fuel, in which fuel was dissolved in sulfuric acid and then purified in three pulsed columns. After the first pass extraction, the fissile solution was held in two banks of favorable geometry "pencil tanks." A 5,000-gallon waste tank (unfavorable geometry) was connected to the pencil tanks through an elevated transfer line so that material could not be inadvertently gravity fed to the tank. Operators initiated an air sparge to circulate solution in the pencil tanks to ensure drawing a representative sample, but one of the pressure gauges was broken and an operator turned on the air supply so forcefully that it caused fissile solution to be siphoned from the pencil tanks into the 5000-gallon tank. There were multiple excursions, which were ultimately terminated by evaporating much of the water; when the tank was later opened, most of the water had evaporated and the uranyl nitrate has crystallized on the tank walls.

This is the largest process criticality accident on record. Approximately 800 liters of uranyl nitrate at 38.6 g^{235}U/l were involved, resulting in a total of ~4x10^{19} fissions. Despite the large number of fissions, there were no significant direct radiation exposures due to the remoteness of operations and the presence of thick shielding. Two individuals received substantial doses from airborne fission products during evacuation, however. No general evacuation alarm was sounded, although local radiation alarms did actuate.

<u>Idaho Chemical Processing Plant, ID</u> (January 25, 1961)

A criticality accident occurred in an evaporator involved in concentrating uranyl nitrate solution at 90wt% ^{235}U, produced in the dissolution of spent nuclear fuel. The accident occurred just a few days after a year-long shutdown. Concentrated uranyl nitrate solution was rapidly ejected from the favorable geometry evaporator into a 60-cm diameter disengagement head located above the evaporator. While an overflow was installed below the disengagement head to prevent this, apparently the violence of the transfer cause the overflow to be ineffective. The exact cause of the transfer is not known, though the most probable cause is thought to have been high-pressure air from an earlier line unplugging operation.

The excursion was of short duration, and the exact excursion mechanism and total number of fissions is not accurately known. It is thought that about 40 liters of concentrated solution at 180 g^{235}U/l was involved, with a total of ~6x10^{17} fissions (±25%). Radiation alarms sounded throughout the facility, but there were no significant exposures.

<u>Hanford Works, WA</u> (April 7, 1962)

A criticality accident occurred in an unfavorable geometry transfer tank connected to a solvent extraction hood processing plutonium nitrate solution. A product receiving tank connected to the hood overflowed into the hood, contaminating the floor of the hood and a nearby sump with plutonium solution. Contrary to procedures, an operator opened a valve to transfer the solution to the unfavorable geometry transfer tank. Criticality did not occur immediately; it only occurred following the subsequent addition of low-concentrated aqueous solution and mixing.

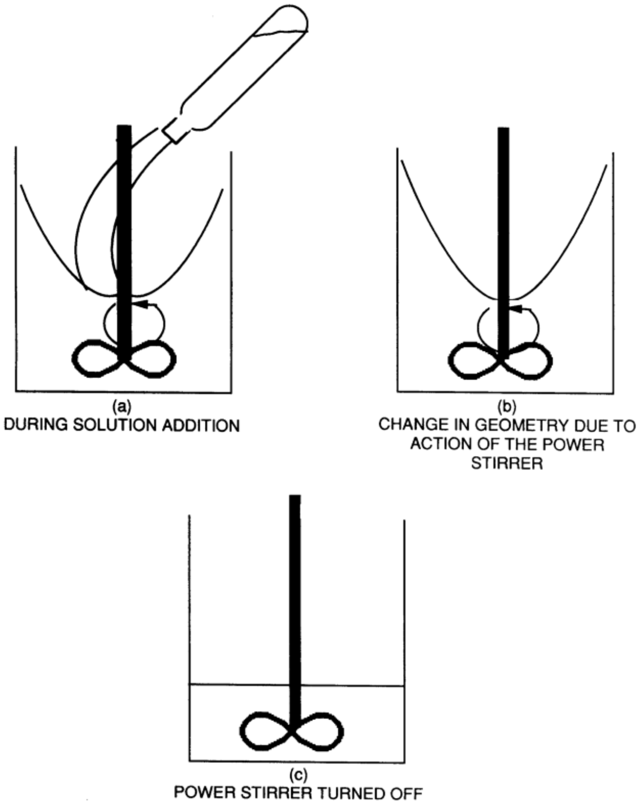
This was the longest duration process criticality accident, lasting for a total of 37.5 hours. The shutdown mechanism is not known, but it may have been due to radiolytic decomposition of tributyl phosphate to dibutyl phosphate, and the subsequent settling of the plutonium-rich organic into a pipe at the bottom of the tank. Approximately 45 liters of 28.7 gPu/l solution was involved, leading to ~$8x10^{17}$ total fissions. The evacuation alarms were sounded and the facility was promptly evacuated, but three operators received significant radiation doses. The facility never recovered.

Wood River Junction, RI (July 24, 1964)

A criticality accident occurred in a process involved in the recovery of high enriched uranium left over from un-irradiated reactor fuel. This was the only criticality accident to occur in a US commercial fuel facility. Uranyl nitrate solution, purified by solvent extraction, was bubbled through a trichloroethane (TCE) column to remove any residual organic. This was a new process (having only operated for four months at the time of the accident), and larger volumes of TCE than anticipated were being used. To recover the uranium from the TCE prior to discard, it was washed with a sodium carbonate solution by manually swirling it in 11-liter polybottles. Due to a large backlog of accumulated TCE awaiting washing, operators sought and received permission to deviate from the normal process and instead perform the wash in the 18-inch diameter sodium carbonate makeup tank.

While several bottles of low-concentration solution were being washed in the makeup tank, operators discovered a plug of uranyl nitrate crystals in an evaporator line. The crystals were dissolved with steam and stored in 11-liter polybottles. Although labeled to indicate they had high-concentration solution, the bottles were otherwise identical to those being used for the sodium carbonate wash. The accident occurred when operators mistook a bottle with the high concentration solution for one containing TCE and added it to the makeup tank. Almost the entire bottle was added to the makeup tank, which was being stirred and already contained 41 liters of sodium carbonate solution, before it went critical. The criticality alarm immediately sounded and the operator fell to the floor as ~20% of the tank contents spilled out, and the critical excursion ceased. About 1½ hours later, the plant superintendent and shift supervisor entered the building to drain the tank and turned off the stirrer preliminary to draining the tank. The change in geometry resulting from turning off the stirrer was enough the cause a second excursion, but since the alarm was still sounding this was not known for some time. This situation is illustrated below.

Figure 7-10. Change in geometry resulting from turning off the stirrer

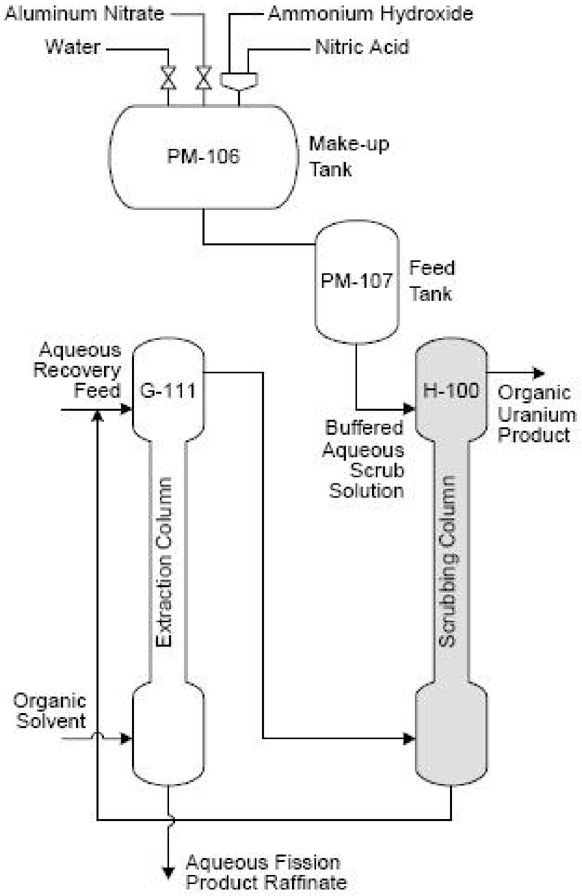


Approximately 41 liters of 50.5 g^{235}U/l solution was involved in the criticality. The first of the two excursion resulted in ~1.1x10^{17} fissions; the second excursion resulted in ~2-3x10^{16} fissions. The operator who initially poured the high-concentration solution into the makeup tank was killed, and the two operators who reentered the building received 60 and 100 rad.

<u>Idaho Chemical Processing Plant, ID</u> (October 17, 1978)

A criticality accident occurred in the lower disengagement section of a scrubbing column, part of a solvent extraction process purifying uranium at 82wt% ^{235}U recovered from spent nuclear fuel. In the scrubbing column, organic product from the extraction column is scrubbed with 0.75 M nitric acid to remove residual fission products that made it into the organic stream. However, during continuous operation of the uranium recovery process, the water inlet valve to the nitric acid makeup tank leaked, causing the gradual dilution of nitric acid to 0.08 M. The density alarm on the makeup tank had failed so that operators were not alerted to the low acid level. The situation is illustrated in Figure 7-11.

Figure 7-11. Situation Illustration #1



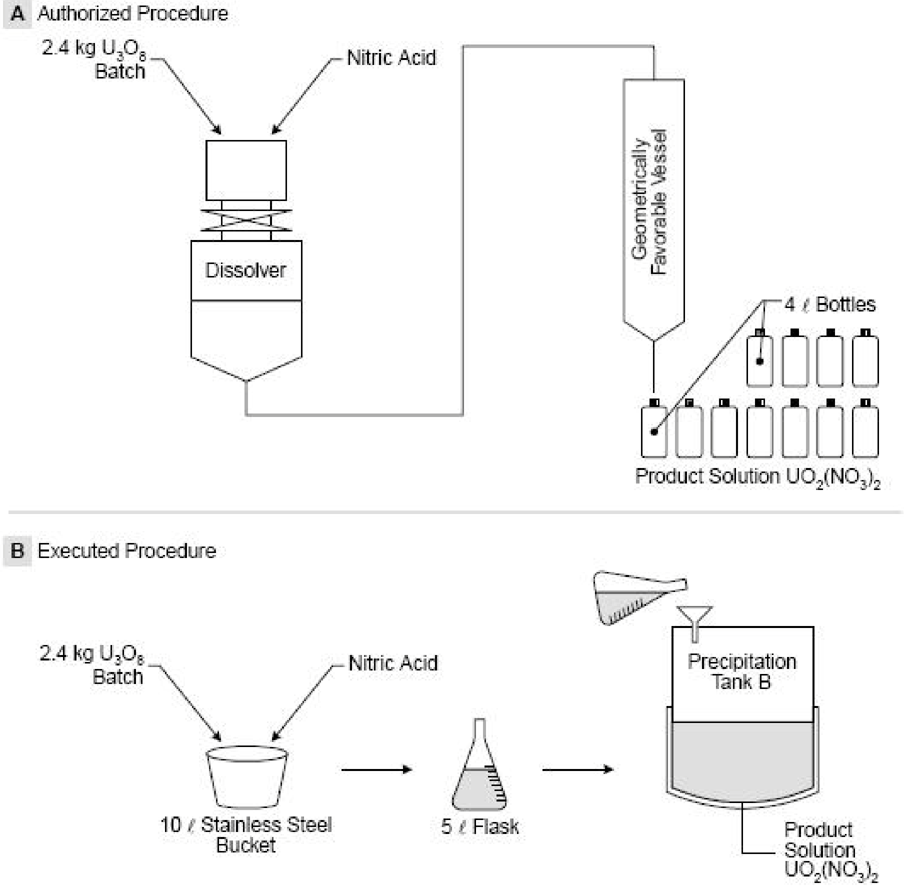
The low acid level caused the stripping of uranium from organic back into the aqueous phase, which was then fed back into the extraction column. This caused the uranium inventory in the two columns to steadily rise. The uranium eventually built up until it sank to the unfavorable geometry section of the scrubbing column, where it went critical.

The plant stack radiation monitors alarmed following the excursion, most likely due to venting of the fission product gases. Approximately 316 liters of 19.3 g^{235}U/l solution was involved in the excursion. It is unknown how long the excursion lasted or whether there were additional pulses. There were no significant exposures, and the facility experienced a long shutdown.

We will include one foreign event, the most recent criticality accident at Tokai-mura, Japan, as well as three near-miss criticality events:

This criticality accident is very similar to the accident at Wood River Junction in 1964. Both of these accidents involved the unapproved manual addition of high-enrichment or concentration solution to an unfavorable geometry tank. The accident at Tokai-mura involved the dissolution of U_3O_8 in nitric acid to form uranyl nitrate product for experimental breeder reactor fuel. The facility was approved for up to 20wt% ^{235}U, with different mass limits applicable over different enrichment ranges. At the time of the accident, the facility had just recently begun processing higher enrichment (18.8wt% ^{235}U) material. Operators were supposed to dissolve the oxide in safe mass batches (2.4 kgU for this enrichment) in a dissolver vessel, then transfer solution to a series of favorable geometry columns, per authorized procedure (see figure below).

Figure 7-12. Situation Illustration #2



But this procedure was cumbersome, and so the company had authorized the dissolution to take place in 10-liter buckets, unbeknownst to the regulator. Operators further deviated from the authorized procedure by manually transferring the solution into an unfavorable geometry precipitation tank instead of the favorable geometry columns. This resulted in a much more efficient process, but significantly degraded the safety margin—a fact that was not realized until the switch to higher enrichment led to the accident.

Over two days, operators dissolved a number of batches in the buckets in accordance with the unofficial procedure. While pouring the seventh safe mass batch into the precipitation tank, the resulting solution, which had now lost both geometry and mass control, went critical. The radiation alarms sounded and the workers evacuated immediately, but two workers ultimately received a fatal dose, and the other worker present received a very significant dose. Radiation monitors indicated a small but measurable radiation reading off-site, but there was a long delay in notifying and evacuating members of the public. This is the only process criticality accident known to have resulted in measurable exposures to the public. The JCO facility is in the center of Tokai city; it is separated only by a low stone wall from nearby houses and industrial plants. The critical excursion continued at a gradually decreasing level after a single supercritical spike, and was only terminated by draining all the water from the cooling water jacket surrounding the tank. Several more operators received small doses while attempting the drain the water jacket.

Approximately 45 liters of 69.3 $g^{235}U/l$ uranyl nitrate solution at 18.8wt% ^{235}U was involved in the excursion, which resulted in ~2.5×10^{18} total fissions. There were two fatalities, one major exposure, numerous small exposures, criminal prosecutions, and JCO's license was revoked by the Japanese government.

Near Misses and Significant Upsets

The loss of criticality controls is a fact of life. Licensees have been required to report certain losses of criticality controls ever since the GE-1991 event (see below), and hundreds of such "91-01 Reports"—named after NRC's Bulletin 91-01—have been reported. There are many reasons why there has not been a criticality accident in the United States since 1978. Among the reasons is reliance on double contingency, so we do not rely on a single control, and even more significantly the existence of very large safety margins.

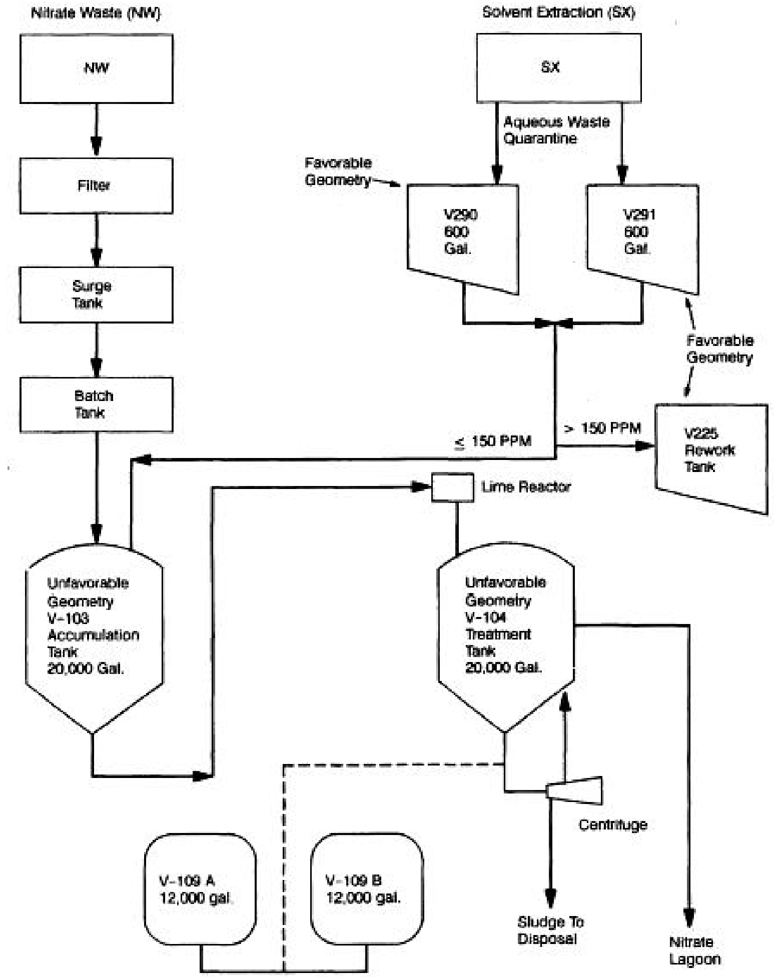
Despite these factors, there have been several "near miss" events and significant upsets that provide opportunities to learn about safety vulnerabilities before they lead to an accident. There is no set of criteria for what constitutes a "near miss," but generally they are all characterized by a loss of all controls and very significant degradation of the safety margin. The NRC does not give licensees credit for random factors that may have prevented a criticality from occurring—such as the fact that only a small amount of mass was actually present at the time of an incident.

Some of the more significant events that did *not* lead to criticality are summarized below:

GE-Wilmington, NC (May 29, 1991)

General Electric performed solvent extraction as part of its uranium recovery operation. Scrap from the fuel manufacturing process was purified using solvent extraction; the purified uranyl nitrate product would be recycled to make new nuclear fuel, and the low-level aqueous waste ultimately transferred to unfavorable geometry collection tanks prior to discharge. Equipment involved in the incident is illustrated below.

Figure 7-13. Situation Illustration #3



During routine operation of uranium recovery, operators experienced difficulty maintaining the interface between the aqueous and organic phases, due to a control valve malfunction. Instead of shutting down the process to correct the problem, operators instead attempted to control the process by manually throttling a valve. After several hours and a shift change, maintenance staff forced the malfunctioning valve open with instrument air. Doing so also had the undesired effect of allowing the concentrated uranium solution to enter two favorable geometry aqueous waste quarantine tanks. During the next several hours, uranyl nitrate continued to be fed into the solvent extraction process, and nine transfers from the quarantine tanks to an unfavorable geometry waste accumulation tank were made. Several of these transfers were made without prior sampling; of the remainder, the samples appear to have been faulty. The system was only shut down when a sample from the quarantine tank finally indicated a concentration of ~7000 ppm (the limit was 150 ppm). While the licensee was investigating, an operator transferred the entire contents of the 20,000 gallon waste accumulation tank to a second large accumulation tank.

The licensee did not initially consider the situation an emergency and did not notify the NRC until late in the afternoon of May 29. The actual time the licensee discovered that it had lost concentration control over the unfavorable geometry tanks is uncertain. The licensee did not declare an alert, at NRC's urging, until nearly 7:00 the morning of May 30. The licensee began to use a centrifuge to remove solution from the accumulation tank the evening of May 29, and continued recovery activities until June 3. In all, the licensee recovered approximately 150 kg of uranium from the tank, well in excess of a minimum critical mass.

This event is highly significant for several reasons. First, the incident involved the transfer of greater than a minimum critical mass of solution to an unfavorable geometry tank. Geometry, mass, and concentration control were lost, such that no controls remained to prevent criticality. Only the arrangement of fissile material in the tank, which was not being controlled, prevented the contents from going critical. In addition, there were several programmatic weaknesses that contributed to the incident. The licensee did not adequately stress the need for compliance with procedures or audit operations to ensure compliance. Employee training contributed to a lax safety culture by stressing that no criticality had ever occurred at a low-enriched fuel facility. Operators routinely worked around problems and deviated from authorized procedure, as they did in this case. Controls that would have prevented such an unauthorized transfer had been downgraded over time, until sampling was the only control remaining.

This was the event that led to NRC requiring licensees to report events involving the loss of double contingency (Bulletin 91-01). It also led, together with the 1986 Sequoyah Fuels UF_6 chemical accident, to revision of 10 CFR Part 70. As a result of this event, licensees now must obtain prior NRC approval to make certain changes to their facilities and operations, perform ISAs that identify credible hazards, identify applicable controls relied on for safety, and report events with significant safety implications to the NRC.

This incident is documented in NUREG-1450, "Potential Criticality Accident at the General Electric Nuclear Fuel and Component Manufacturing Facility, May 29, 1991."

AREVA-Richland, WA (April 2-3, 2002)

AREVA handles low-enriched UO_2 powder used to manufacture light-water reactor fuel in 45-gallon drums. Criticality controls consisted of limiting the moderation of the powder and only using drums containing neutron-absorbing “spiders,” or arrangements of several steel rods containing boron. At the time of the incident, employees were using a utility hood to transfer powder from 5-gallon safe batch containers into 45-gallon drums. A newly trained temporary employee, who was performing the transfer alone for the first time, needed a 45-gallon drum to receive the powder. Unfortunately, the drum that the operator selected had been set aside for destruction, and had had the spider assembly removed. Licensee personnel later said that they believed operators would realize they were using the wrong drum due to the large weight difference between an empty drum and a spider-containing drum. The operator nevertheless placed the drum under the hood and began filling it with powder. The procedure required the operator to inspect the opened drum to ensure the spider was present, but the space between the top of the drum and the filling funnel was very small. Some operators pulled the drum out of the hood, violating the radiation work permit, to inspect the drum. Other operators used a hand-held mirror to see inside the drum. Inspecting the drum was difficult, and the operator did not realize that the drum did not have a spider assembly.

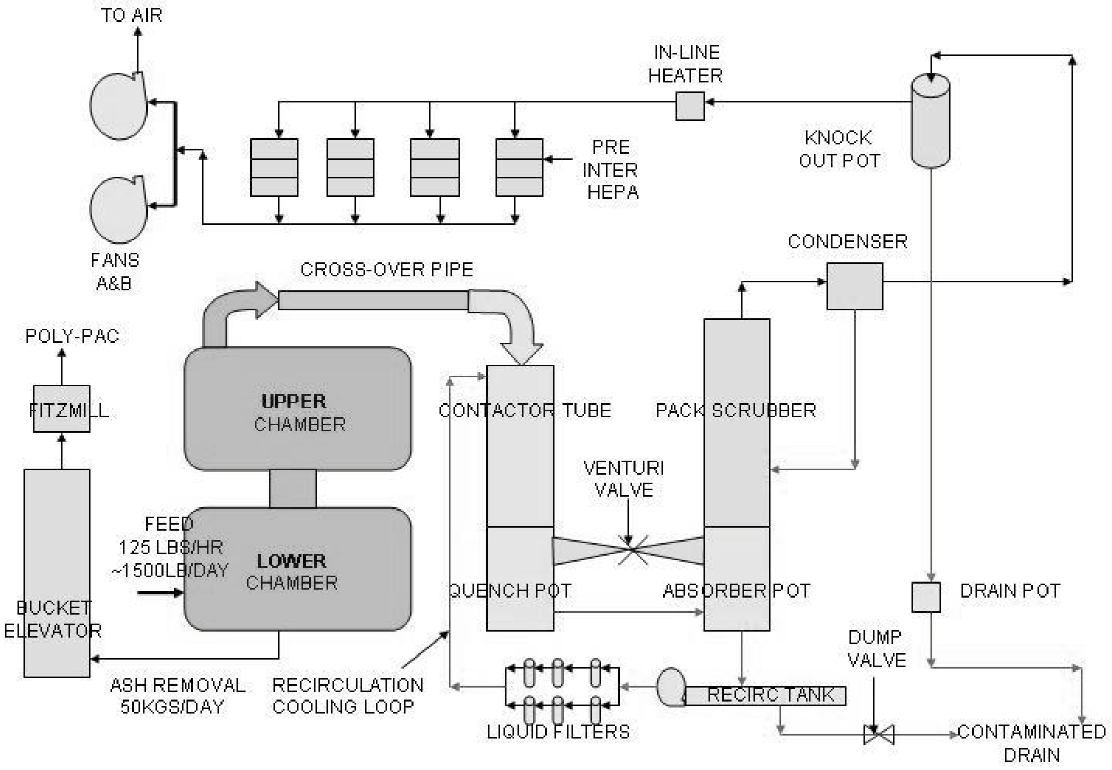
This event is significant because no controls were present to prevent criticality. The drum is an unfavorable geometry container containing significantly more than a minimum critical mass. No significant moderation was found in the powder, but there were no moderator controls in place while the drum was open, and there were solutions processed in the area, including on the mezzanine above the utility hood. In addition, NRC’s special inspection found that required moisture samples had not been performed on some material received from off-site. Two such containers (not transferred into the drum) were found to have moisture levels exceeding the limit. The only event needed for criticality was the introduction of sufficient moderator.

This incident is documented in Inspection Report 70-1257/2002-03.

Westinghouse Electric, SC (March 5, 2004)

The Westinghouse incinerator is a large furnace devoted to the burning of contaminated low-level waste such as paper and plastic incidental to the manufacture of nuclear fuel. Burning allows for a significant reduction in waste volume. The incinerator, and especially its off-gas system, are expected to contain only relatively low concentrations of uranium. The licensee had assumed that the incinerator’s upper chamber, whence the off-gas from burned waste eventually travels to the scrubber prior to being filtered and discharged through the stack, could credibly contain less than a critical mass of uranium. Over the course of several years, since at least 1996, higher than normal stack readings indicated there was more carryover to the incinerator’s upper chamber than thought possible. Nuclear Criticality Safety either was not made aware of these indicators or did not recognize their significance. Finally, in March 2004, a criticality engineer evaluating a procedure change realized that there may be more material in the upper chamber than evaluated. When the upper chamber was cleaned out, the licensee discovered that 271.1 kg of material had accumulated in the upper chamber, and 54.4 kg had accumulated in the cross-over pipe leading to the scrubber. The material was later determined to exceed both the mass and uranium content (grams uranium per gram of waste) limits in the upper chamber and cross-over pipe. The equipment involved is shown below.

Figure 7-14. Situation Illustration #4



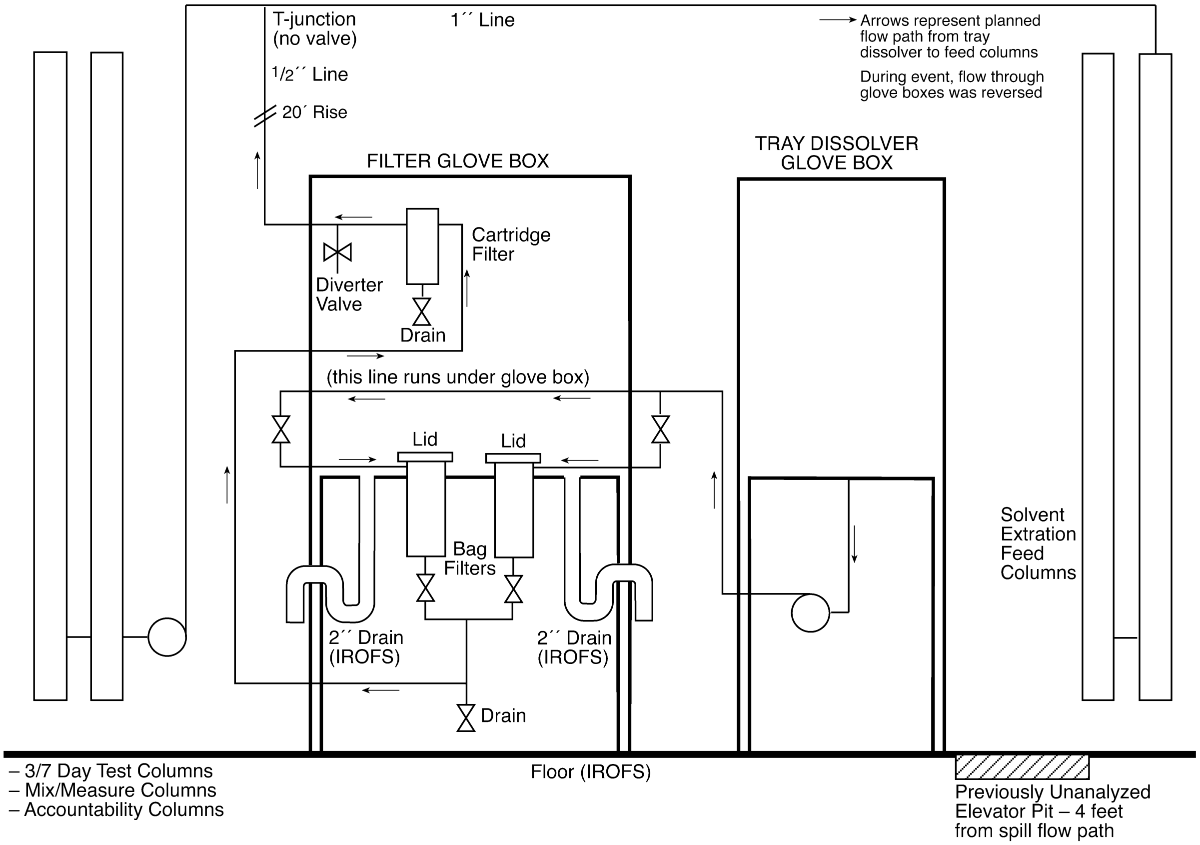
In addition to exceeding mass and uranium content limits, the amount of material in the upper chamber exceeded the minimum critical mass (established at 212 kg for material with 30wt% uranium). As a result of the higher-than-expected uranium mass and content, as well as the unfavorable geometry of the upper chamber, no controls remained to prevent criticality. For criticality to occur, moderation would also have to be present. No moderator controls had been established because it was not considered credible to get a critical mass in the upper chamber. While there was no significant moderation present in the material recovered from the upper chamber or cross-over pipe, there was an unlimited supply of water available from the city water supply connected to the scrubber system. An overflow of water into the upper chamber could have moderated and rearranged the material and led to criticality.

Nuclear Fuel Services, TN (March 6, 2006)

NFS's Blended Low Enriched Uranium (BLEU) process involves the dissolution of high-enriched uranium metal and oxides in nitric acid to form uranyl nitrate, which is ultimately downblended to form low-enriched light water reactor fuel. Following batch dissolution in tray and column dissolvers, the uranyl nitrate is filtered to remove undissolved solids before being processed downstream in favorable geometry equipment. To facilitate replacement of the filters, filter housings are placed inside gloveboxes. Such gloveboxes, or enclosures, are equipped with two isolation valves to prevent leaks from connected piping while the filters are being removed, and with two drains to prevent accumulation to greater than a safe depth in the event of a spill. The arrangement of equipment involved in the incident is shown below.
The enclosure involved in the incident had been newly installed and never formally placed into service. It was supposed to be isolated from fissile material processes until final approval, but it was left connected to the process without being properly isolated. At the time of the event, the licensee identified a small amount of yellow liquid (indicative of uranyl nitrate) in the enclosure. There was not supposed to be any fissile material in the enclosure, but operators did not realize the significance of the leak and merely made plans to relocate the enclosure. Operators then loosened the filter lids and drained the filters preparatory to the move. At about the same time, other operators decided to transfer 200 liters of 266 gU/l uranyl nitrate at 63wt% ^{235}U to another part of the process. The transfer was completed, but some of the liquid overflowed the filters and spilled into the enclosure, then through the drains and onto the floor. In total, ~34 liters of high-enriched solution was spilled, significantly in excess of a minimum critical mass.

This event is highly significant for several reasons. First, the enrichment and the amount of material would be sufficient to cause criticality, if it attained the right geometry. Second, no controls remained to prevent criticality. The enclosure drains functioned as required, but since the enclosure was not supposed to be in service or contain fissile material, the drains were not being inspected. Shortly beforehand, operators had found cheesecloth and yellow liquid in the enclosure. Cheesecloth could have clogged the drains and allowed a larger amount of liquid to exceed a critical depth. The solution spread out on the floor, but because the floor was sloped, it flowed out into the hallway. The licensee took credit for the flatness of the floor, but did not account for the presence of an elevator pit in the hallway. The solution flow path came within about four feet of the elevator pit. Both the enclosure—if the drains did not work—and the pit were unfavorable geometry and could have led to a criticality if they had accumulated enough solution. Third, while the spill was not large enough to cause criticality in either of these two locations, there was nothing to prevent larger or additional solution spills. A criticality analysis performed after the fact showed that 130 liters would be needed for criticality in the enclosure or 100 liters in the elevator pit. Several opportunities to investigate and correct the deficiencies were missed.

Figure 7-15. Situation Illustration #5



Lessons Learned from Accidents, Near Misses, and Significant Events

Many lessons can be learned from both the criticality accidents that have occurred, from near misses, and from the numerous other criticality incidents that have occurred. Refinements in the practice of criticality safety as a result thereof have led to a very good record of safety.

The history of criticality safety tells us that some operations are inherently more risky than others. The most vulnerable to criticality are those involving either high enriched uranium or plutonium; those involving solutions, especially in recovery operations; and those involving transfers from favorable to unfavorable geometry. Many of them have involved events that were either not thought of or considered to be incredible. Most accidents and incidents have involved multiple contributing causes, human error being especially predominant. It is possible nevertheless to identify some strong commonalities between them.

Some contributors to the accidents and incidents listed above (and others) include:

- A lax attitude towards safety—the idea that “criticality can’t happen” here. A good track record and large safety margin contributes to this erroneous idea.
- Lack of a questioning attitude and the dismissal of criticality scenarios as incredible.
- Procedures that are unclear, overly burdensome, or difficult to perform, leading to operator “work-arounds”
- Inadequate communication between departments and shifts
- Over-reliance on administrative control and hands-on operation
- A mindset of production over safety
- Failure to establish a strong corporate safety culture
- Workers inadequately trained in criticality safety
- The need for configuration and change control
- The presence of new, changed, or temporary operations
- The need for redundancy and defense-in-depth, especially in sampling

Some of the lessons learned from these accidents and incidents include:

- Reliance should be placed, to the extent practical, on passive or active engineered means rather than administrative controls
- Whenever possible, nuclear processes should be performed in favorable geometry equipment
- Extreme caution should be taken wherever there is a transition from favorable to unfavorable geometry; at a minimum, redundant sampling and in-line monitoring should be relied on to prevent such an event.
- Complex chemical operations, especially those involving mixtures of aqueous and organic phases (such as in scrap recovery) should be tightly controlled and closely monitored.
- Operating, maintenance, and emergency activities should be formalized in written procedures, supported as appropriate by operator aids such as checklists and postings.

- Programmatic and human factors have been major contributors to most accidents and incidents. The importance of requiring operator compliance, empowering employees to stop work, developing an effective problem reporting and corrective action program, training fissile material operators on criticality hazards and controls, and otherwise fostering a strong safety culture cannot be overstressed.
- Exerting control over the configuration of equipment and the conduct of operations is crucial. Knowing what is relied on for safety and having any changes reviewed by the criticality safety experts is crucial.
- Effective regulatory oversight to ensure good technical practices related to criticality safety is very important.
- Criticality alarms, timely evacuation, and well-thought out plans for responding to and recovering from a criticality accident save lives.

ABNORMAL OCCURRENCE HAZARDS

Fire

Fire is a hazard that must be considered throughout the fuel cycle due to the potential for release of radioactive material. Combustible material and oxygen are present at certain points during the fuel cycle; however, additional energy is needed to start combustion and continuity of combustibles is needed for fire growth. Prevention, detection, containment, and suppression by engineering design may be utilized to prevent and/or control fires.

Finely divided uranium metal and zirconium is able to ignite spontaneously (pyrophoric). This type of material should be handled and stored to minimize fire potential. Machining chips are stored under water or machining oil so that any H_2 that is generated does not accumulate.

There is a potential for fires involving UO_2 powder at various stages of transfer and conversion. There have been incidents, dating back to 1977, in which the oxidizing uranium powder was believed to be the source of ignition, and combustible materials, such as transfer hoses and boots, provided the fuel. It should be noted that unstable uranium oxide feed material (composed mostly of UO_2, with other oxide forms present) in granulated form and in contact with oxygen undergoes exothermic oxidation reactions. The heat generated by the reactions may ignite combustible elements of the transfer passages or other powder-handling equipment. The potential for the exothermic oxidation seems mainly dependent on the fineness of the powder and the temperature. Friction of the granulated material in motion may generate heat to raise the temperature.

In June 1992, an Oak Ridge employee was contaminated as a result of a U-235 metal fire. The uranium ignited as an employee opened a plastic bottle containing approximately 50 g of 93% enriched U-235 rolled foils being prepared for shipment. The foils had previously been rolled in air (in the same laboratory) and were stored in a screw-top plastic bottle in a sealed metal can. The metal burned slowly, causing oxide contamination of the general area and some melting of the plastic bottle.

The employee grabbed the bottle with tongs and placed it in a stainless steel sink. The drain was plugged with some toweling, and a small amount of water was applied to cool the reacted material. The event emphasized the need for proper procedural guidance and training on extinguishing metal fires. Sand or class D extinguishing powder, such as Met-L-X, should have been used when extinguishing the fire.

Zirconium is a structural material for atomic reactors and, when alloyed with aluminum, is a cladding material for fuel rods. The metal is very reactive and, as a powdered metal, is a fire and explosive hazard that may ignite spontaneously. Zirconium fires require quenching by smothering with some pulverized mineral carbonate, such as dolomite. Serious explosions have occurred from moist exposure of metal scrap containing zirconium as a contaminant. Zirconium has a minimal explosive concentration of 40 oz/1,000 ft2, and zirconium metal dust dispersed with U and UH_4 as a cloud ignites under certain conditions.

Table 7-9 lists various bulk chemicals associated with the fuel cycle that are potential fire hazards. Table 7-10 shows facilities where these hazards could occur.

Table 7-9. Bulk Chemicals That are Fire Hazards

Chemical	**Application in Fuel Cycle**	**Hazard Characteristic**
Nitric acid	◙ Yellowcake digestion ◙ Nitrate organic materials	Facilitates ignition
Solvents	◙ Extraction/purification of feed	Low flashpoint
Sulfuric acid	◙ High-sodium yellowcake digestion ◙ Charring organic material	Facilitates ignition
Anhydrous ammonia	◙ Material for production of hydrogen	Flammable gas
Hydrogen	◙ Reduction of feed	Flammable gas
Fluorine	◙ Fluorination of feed	Reacts violently with hydrogen and organic materials

Table 7-10. Summary Of Selected Chemical and Chemical Reaction Hazards

HAZARD DESCRIPTIONS	MINING		MILLING	CONVERSION	ENRICHMENT				FUEL FAB
	Open Pit	Underground			AVLIS	Electro-magnetic	Gas Centrifuge	Gaseous Diffusion	
Alcohol			X		X				
Ammonia (NH_3)			X						
Ammonium hydroxide (NH_4OH)									X
Ammonium sulfate [$(NH_4)_2SO_4$]				X					
Anhydrous ammonia (NH_3)									X
Calcium hydroxide ($Ca(OH)_2$)				X					
Chlorine trifluoride (ClF_3)								X	
Compressed gases				X	X				
Diesel and gasoline	X	X			X				X
Fluorine (F_2)				X			X	X	
Heavy metals	X	X			X				
Hydrogen fluoride (HF)				X			X	X	X
Hydrogen gas (H_2)					X		X	X	
Hydrogen sulfate (H_2SO_4)				X					
Kerosene			X						
Liquid nitrogen				X					
Manganese dioxide (MnO_2)			X						
Molten metal				X					
Molybdenumhexafluoride (MpF_6)				X					
Nitric acid (HNO_3)				X	X				X
Nitrogen oxide (NOx)									X

Table 7-10. Summary Of Selected Chemical and Chemical Reaction Hazards

HAZARD DESCRIPTIONS	MINING		MILLING	CONVERSION	ENRICHMENT				FUEL FAB
	Open Pit	Underground			AVLIS	Electro-magnetic	Gas Centrifuge	Gaseous Diffusion	
Propane (LPG)									X
Silica (SiO_2)	X	X							
Soda lime				X					
Sodium chlorate ($NaClO_3$)			X						
Sodium hydroxide (NaOH)									X
Sulfuric acid (H_2SO_4)			X						
Transuranics							X	X	
Technetium (Tc)					X		X	X	X
Uranium chloride (UCl_3,UCl_4)									
Uranium dioxide nitrate ($UO_2(NO_3)_2$)				X					
Uranium hexafluoride (UF_6)				X			X	X	X
Uranium metal					X	X			
Uranyl fluoride (UO_2F_2)				X			X	X	
Uranyl nitrate ($UO_2(NO_3)_2$)				X					
Uranium tetrachloride (UCl_4)						X			

Explosions

The potential for an explosion in some areas of the nuclear fuel cycle may occur due to the following:

- Production and use of hydrogen throughout the fuel cycle processes
- Chemical or corrosion reactions through finely divided, oxidizable dusts or pyrophoric materials
- Certain nitric acid/heavy metal/organic matter reactions

An explosion may cause physical damage, such as a breach of containment, a change in geometry, or system pressurization, causing an unplanned release of radioactive material. The use of an inert gas atmosphere or dilution system should be considered so that the containment system may be able to withstand possible explosions.

Prior incidents have resulted in warnings regarding the explosion potential associated with pumping solutions that contain ammonium nitrate in uranium fuel fabrication and conversion facilities. During these incidents, pumps were left on for long periods of time (e.g., 40 hours), the solutions were concentrated because the water partially boiled off, and a rapid thermal decomposition resulted. The concentrated solution of ammonium nitrate with the energy of the overheated pump was sufficient to produce an explosion.

It is important to identify potentially explosive compounds and mixtures, note their location and points where they may accumulate, and take preventive measures to ensure that conditions for explosion do not occur. For the incidents involving the pumping of solutions containing ammonium nitrate, appropriate corrective measures were included in NRC Information Notice No. 90-70, Pump Explosions Involving Ammonium Nitrate. Some suggestions include the following:

- Use of temperature sensor shutoff devices with pumps
- Use of "dead man" switches in automatic or semiautomatic operations to prevent personnel from overriding pump operations
- Use of a water rinse between operations involving nitric acid and ammonium hydroxide, to prevent the formation of ammonium nitrate
- Evaluation of vent and scrubber systems
- Interlocking pumps with tank-level indicators to shut off pumps at a low level
- Implementation of a valve-tagging system

Many dusts are combustible and, in certain concentration ranges, explosive. Dust collection equipment should be designed to reduce the risk of property damage and personal injury where explosive mixtures of dust and air are probable. Alternatives are to design the dust collector housing to contain the considerable pressure resulting from an explosion or to equip it with explosion vents. National Fire Protection Association 68-1978, Guide for Explosion Venting, is a commonly referenced work regarding dust collectors for potentially explosive dusts.

Criticality

A criticality accident is an uncontrolled nuclear chain reaction occurring in an assembly or facility containing fissile materials. All operations with fissile materials outside nuclear reactors are performed to prevent the establishment of nuclear chain reactions and the sudden release of energy. The energy released would be in the form of heat; the associated ionizing radiation might be lethal to nearby personnel. In addition, damage to equipment could possibly cause fission products generated by the incident to escape. Damaged equipment would result in the interruption of operation schedules and could lead to the release of sufficient material to provide a contamination problem or an environmental hazard.

The achievement of criticality depends on the following:

- The properties of the fissile material
- The mass of fissile material present and its distribution among the components of the system being assessed
- The mass and distribution of all other materials associated with fissile material

Criticality Control

Factors that must be controlled to prevent criticality include the following:

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

Criticality safety can be achieved through the following:

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

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

Equipment and Instrument Failure

In any facility, there is a possibility of equipment or instrument failure resulting in the potential interruption of an essential safety function, such as containment or cooling. Furthermore, fire or explosion may interconnect sections of a plant that are normally separated.

Malfunctions in mechanical systems may be due to breakdowns in the mechanical systems themselves, mainly caused by failures in such parts as sensors, connectors, or actuators. The operation and maintenance of these portions must be checked and properly maintained.

Facility production processes and supporting activities require a large amount of electrical power to operate. Since many of the chemical processes contain hazardous materials at elevated temperatures and pressures, these processes operate using many electrically or pneumatically operated safety features. Standby utilities must be maintained in order to provide a safe and orderly shutdown of the process during a complete power failure. In addition, a pressurized nitrogen system may be used. This would provide pressure for pneumatic instrumentation, as well as an inert gas for purging process piping and vessels during an electric power failure.

The corrosive nature of the chemicals used in the fuel cycle may be a potential cause for equipment failure. Corrosion has resulted in only minor incidents of radioactive material problems, although plant operation is usually impaired. Preventive measures against corrosion are implemented by careful quality assurance:

- Components are constructed from corrosion-resistant material under strict quality assurance.
- Evaporators operated under reduced pressure and at a lower boiling point will increase the equipment's lifetime and improve the overall safety of the operation.

The degree of automation throughout the fuel cycle is advanced; however, the possibility of human error still exists. Plants and processes are designed and operated in order to minimize this possibility. An important part of computer control system design software is the built-in redundant system to improve reliability, thus minimizing downtime and operational loss. Operators receive training to carry out routine tasks and respond to abnormal conditions.

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

Serious injuries can occur when personnel ignore or circumvent safety procedures, systems, or equipment. To prevent such an injury, it is important that personnel strictly adhere to procedures and operating parameters. When unsafe conditions are noted, corrective actions should be taken and the employees should be advised of the conditions and corrective actions that were instituted. Communication to the employees is important in order to emphasize overall safety awareness.

The importance of adherence to procedures is noted in NRC Information Notice No. 91-44, Improper Control of Chemicals in Nuclear Fuel Fabrication. This notice informs licensees who use chemicals in nuclear fuel production activities of the importance of establishing procedures to adequately identify, store, and handle incoming shipments of chemicals. Such actions include establishment of:

- Procedures to check and verify chemicals before they are introduced to production operations.
- Requirements for authorized personnel to review shipping manifests and directly supervise the off-loading of materials.
- Periodic inspections to ensure adequate marking and labeling of storage tanks and the availability of appropriate safety equipment.
- Emergency response procedures for chemical spills and the use of appropriate safety equipment.
- A hazard communication program, as required by Title 29 CFR Part 1910.1200.

The importance of adherence to procedures is also noted in NRC Information Notice No. 90-20, Personnel Injuries Resulting From Improper Operation of Radwaste Incinerators. Two uranium fuel fabrication facilities reported personnel injuries and noted that the accidents did not directly involve radiation safety hazards. "However, any serious injury in the vicinity of radioactive material has the potential to escalate to a situation which could result in a radiation hazard." The accidents involved the following:

- Unauthorized removal of a safety shield
- Failure to follow proper procedures
- Operator error
- Component failure
- Poor safety design
- Inadequate sorting of waste products

Self-Check Questions 7-3

INSTRUCTIONS: Complete the following questions. For multiple-choice Questions 1 and 17, circle the appropriate responses. For short-answer Questions 2, 4, 11 through 14, 16, and 18, write the appropriate responses in the spaces provided. For completion Questions 3 and 15, fill in the blanks. For matching Questions 5 through 10, select the appropriate responses. Answers are located in the answer key section of the Trainee Guide.

1. Examples of equipment and methods commonly used to prevent and/or mitigate the consequences of chemical incidents are discussed in:

   a. NUREG-1601, Chemical Process Safety at Fuel Cycle Facilities (August 1997).

   b. NRC Information Notice No. 90-20, Personal Injuries Resulting From Improper Operation of Radwaste Incinerators.

   c. NRC Information Notice No. 91-44, Improper Control of Chemicals in Nuclear Fuel Fabrication.

   d. NRC Regulatory Guide 3.32, General Design Guide for Ventilation Systems for Fuel Reprocessing Plants (September 1975).

2. Due to the potential for release of radioactive material, what hazard must be considered throughout the fuel cycle?

3. The potential for the exothermic oxidation seems mainly dependent on the ___________________and __________________.

4. What method is used to extinguish a zirconium fire?

Match each bulk chemical in Column A with its fire hazard characteristic in Column B. Responses may be used more than once.

	Column A **Chemical**	**Column B** **Hazard Characteristic**
5. ___	Anhydrous ammonia	A. Low flashpoint
6. ___	Fluorine	B. Facilitates ignition
7. ___	Hydrogen	C. Produces flammable gas
8. ___	Nitric acid	D. Reacts violently with hydrogen and organic materials
9. ___	Solvents	
10. ___	Sulfuric acid	

11. Define criticality accident.

12. What factors must be controlled in order to prevent criticality?

13. List three methods by which criticality safety can be achieved.

14. What standby utility would provide pressure for pneumatic instrumentation, as well as an inert gas for purging process piping and vessels during an electric power failure?

15. Preventive measures against corrosion are implemented by careful ________.

16. What part of the computer control system design software is responsible for improving reliability, thus minimizing downtime and operational loss?

17. Which notice informs licensees who use chemicals in nuclear fuel production activities of the importance of establishing procedures to adequately identify, store, and handle incoming shipments of chemicals?

    a. NUREG-1601, Chemical Process Safety at Fuel Cycle Facilities (August 1997).

    b. NRC Information Notice No. 90-20, Personal Injuries Resulting From Improper Operation of Radwaste Incinerators.

    c. NRC Information Notice No. 91-44, Improper Control of Chemicals in Nuclear Fuel Fabrication.

    d. NRC Regulatory Guide 3.32, General Design Guide for Ventilation Systems for Fuel Reprocessing Plants (September 1975).

18. What actions should be considered in establishing procedures to adequately identify, store, and handle incoming shipments of chemicals?

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

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

Learning Objective

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

7.1.4 Identify selected engineering controls and preventive measures in the nuclear fuel cycle.

SELECTED CONTROLS IN THE FUEL CYCLE

There are some control and preventive measures that are important throughout the nuclear fuel cycle.

Fire Protection

Fire prevention is undoubtedly the most important component of fire protection. Administrative controls on combustibles, hot work, and detection and suppression systems are also important parts of fire protection. Facilities should be designed to limit fire risks through the institution of measures to ensure that fires do not break out and, if a fire occurs, that its consequences will be limited. During the facility design phase, consideration should be given to the following:

- Minimizing the fire loads of individual rooms
- Choosing materials of adequate functional and fire-resistant criteria
- Compartmentalizing the buildings as much as possible to prevent fire spread
- Ventilation systems

The design of the ventilation systems, with their ducts and filter units, may provide weak points in the system. Fire dampers may be mounted in the ventilation systems to close automatically if a fire- detection signal is activated. Electrical code specifications must be strictly adhered to, to prevent the spread of fire and the release of toxic fumes or corrosive gases.

The nuclear fuel cycle presents certain fire protection difficulties not found in general industry:

- The difficulty or impossibility of gaining access to the fire (danger of irradiation, special clothing required)
- The need to maintain a certain level of containment
- Restriction in terms of extinguishing agents that may be used

Uranium fires are not extinguished by water spray, CO_2, or halon. Halon may be explosive if directed at burning uranium and will produce toxic fumes and gases. Halon should not be used on metal fires. Small uranium fires can be smothered by a mixture of sodium chloride and potassium carbonate (Met-L-X). Larger fires (storage drums) can be controlled by immersing the burning container in water. However, this will not immediately extinguish the fire because the hot uranium metal dissociates the water into H_2 and O_2, providing more fuel for the fire. If the quantity of water is sufficient, it will eventually provide enough cooling to extinguish the fire. However, the burning will resume if the uranium is not kept immersed in the water. In the case of accidents involving a risk of criticality where moderation is a control, the use of water is prohibited.

To ensure that the fire protection system is effective, it is important that periodic testing, inspection, and maintenance of fire protection equipment be accomplished. Fire-fighting plans, drills, and training must be properly maintained and revised as needed.

Containment/Confinement

Containment is defined as keeping something within limits. Confinement is defined as keeping something enclosed. This course will use the term containment. A containment barrier may be any of the following:

- Process equipment
- Surrounding cell or glove box
- Room or building in which the process is located

Primary containments vary depending on the products involved and the radiotoxicity of the radionuclides present. They are located as close as possible to the radioactive material being handled. In uranium enrichment, containment is provided by the equipment, which is highly leaktight as a fabrication quality requirement. The radionuclides are handled in leakproof cells located, whenever possible, inside a second containment. The building that houses the facility acts as the final containment barrier to the environment. The uncontrolled release of each radioactive substance to the environment can occur only if each successive containment barrier, separating the substances from the environment, is impaired.

For UO_2 fuel fabrication facilities, containment is required for the furnaces converting UF_6 to UO_2 and wherever the material is found in powder form (crusher, mixers, and compacting presses). The latter equipment is not leaktight, and systems are installed to draw off dust and aerosols to keep atmospheric contamination in the buildings within acceptable limits. When plutonium is used in fabrication, all operations are carried out in highly leaktight glove boxes. The glove box becomes the containment barrier for operators.

Containments cannot be absolutely leaktight in all circumstances, either due to technical impossibilities or to operations that cause temporary breaks. The introduction or removal of equipment or the event of an incident such as a pierced glove during glove box operations may occur. Containment systems are assisted by a ventilation system, which is designed so that the pressure inside the containment is always lower than the outside pressure. Ventilation of these containments, with discharge of exhaust gases through a stack via a gas-cleaning process, can reduce discharges of radioactive materials to the environment. In such cases, the ventilation system might also be regarded as a containment barrier.

Ventilation

Ventilation systems used in industrial plants are of two basic types: supply and exhaust. The supply system provides air, usually tempered to the work space. The exhaust system removes contaminants generated by an operation in order to maintain a healthy work environment. Often the supply and exhaust systems are coupled, as in dilution control systems.

Plant ventilation control systems, as defined in NRC Regulatory Guide 3.32, General Design Guide for Ventilation Systems for Fuel Reprocessing Plants (1975), have several tasks. They are designed to supply properly conditioned air to the occupied and unoccupied areas of the building; confine air to a prescribed flow path discharging through a final filter or treatment system and stack; and ensure proper monitoring, filtration, and treatment.

The air cleaning devices are available in a wide variety; the selection will depend on the degree of cleaning needed, the quantity and characteristics of the contaminant to be removed, and the conditions of the air or gas stream. In addition, fire safety and explosion control must be considered in all selections.

Exhaust ventilation systems are classified in two generic groups:
(1) general exhaust systems and (2) local exhaust systems. General exhaust systems can be used for heat control and removal of contaminants by flushing with a large volume of air. The dilution ventilation is usually used for contaminant control only when local exhaust is impractical and is not as effective as local exhaust ventilation for control of health hazards.

Local exhaust ventilation systems operate on the principle of capturing a contaminant at or near the source and are more effective. Local exhaust systems are composed of up to four parts: the hood(s), the duct system (including the exhaust stack and/or recirculation duct), the air-cleaning device, and the fan. The emphasis should be placed on reducing total quantities of effluents released to the environment. Filter systems should be designed so that concentrations of effluents do not exceed the guidelines established during normal operation. All effluent streams should be sampled and monitored to ensure accurate measurements of all releases during normal and emergency conditions.

Air cleaners for radioactive material and/or highly toxic dusts should meet these criteria:

- High efficiency

- Low maintenance
- Ability to concentrate the material collected within criticality safety limits and safely dispose of it

High efficiency is important because of the extremely low tolerances for the quantity and concentration of stack effluents and the high cost of the materials handled. In addition, the legal requirements for accountability of all radioactive material are important considerations. The need for low maintenance is an important consideration when exhausting any hazardous material. For many radioactive processes, the changing of bags in a conventional fabric collector may put the workers at increased risk of radiation exposure. The disposal of radioactive or toxic materials by air, water, or land is a serious problem. With these factors considered, it is necessary to choose an air-cleaning device that will meet the efficiency requirements without causing problems in handling and disposal.

For particulate contaminants, air-cleaning devices are divided into two basic groups: (1) air filters and (2) dust collectors. Air filters are designed to remove low dust concentrations similar to those found in atmospheric air. Dust collectors are usually designed for a much heavier load from industrial processes where the air comes from local exhaust systems or process gas effluents. The four main types of dust collectors for particulate contaminants are electrostatic precipitators, fabric collectors, wet collectors, and dry centrifugal collectors.

Process off-gas treatment systems in the fuel cycle usually consist of one or more of the following:

- Wet scrubbers: Used in dusty processes where large amounts of uranium are present. They are capable of removing and processing large quantities and serve as prefilters for other cleanup units.
- Prefilter systems: Bag filters or other rough/coarse filters. They are used to remove significant quantities of particulate material from the air off-gas and may be placed before HEPA filters to extend the life of the more expensive filters.
- HEPA filters: The final filters in the process off-gas that reduce the particulate effluent to insignificant or permissible levels. They may be placed in a series to improve their efficiency.

Equipment designed specifically to control gas or vapor contaminants can be classified as the following:

- Absorbers: Remove soluble or chemically reactive gases from an airstream by contact with a suitable liquid. Water is the most frequently used absorbent, but additives and other chemical solutions can be used (e.g., packed towers).

- Adsorbers: Remove contaminants by collection on a solid; this is a physical process in which molecules of a gas adhere to surfaces of the solid adsorbent (e.g., activated carbon).

- Thermal oxidizers: Afterburners; may be used where the contaminant is combustible. The contaminated air is introduced to a heated chamber where combustibles are oxidized, producing carbon dioxide and water vapor.
- Direct combustors: Introduce the contaminated gases and auxiliary air directly into the burner as fuel. Auxiliary fuel, usually natural gas or oil, is generally required for ignition.
- Catalytic oxidizers: Used for combustible contaminants; the contaminated gas stream is preheated and passed through a catalyst bed, which promotes oxidation of the combustibles to carbon dioxide and water vapor.

The combustible contamination concentration must be below the lower explosive limit when thermal or catalytic oxidizers are used. Solid particulates can plug absorbers, adsorbers, and catalysts and, if noncombustible, will not be converted in thermal oxidizers and direct combustors.

Airstreams containing both solid particles and gaseous contaminants may require appropriate control devices in a series.

Low-efficiency, low-cost filters are used as parts of hoods or glove boxes. These filters serve to keep high concentrations from entering the main exhaust system. Before they are changed, they can be sprayed while in position with an acrylic spray to fix any radioactive dust. Effluents generated by fire can also be contaminated and must be filtered.

Self-Check Questions 7-4

INSTRUCTIONS: Complete the following questions. For short-answer Questions 1 through 4, 7, 8, 12 through 17, and 19, write the appropriate responses in the spaces provided. For Question 5, circle the appropriate response. For completion Questions 6, 9 through 11, and 18, fill in the blanks. For matching Questions 20 through 24, select the appropriate responses. Answers are located in the answer key section of the Trainee Guide.

1. What is the most important component of fire protection?

2. What fire protection concerns should be considered during the facility design phase?

3. What fire prevention equipment is designed to reduce the risk of property damage and personal injury where explosive mixtures of dust and air are probable?

4. List fire protection difficulties specific to the nuclear fuel cycle.

5. Uranium fires are extinguished by:

6. In the case of accidents involving a risk of criticality where moderation is a control, the use of water is___________________.

7. What is the difference between containment and confinement?

8. List possible containment barriers:

9. In uranium enrichment, containment is provided by__________________, which is highly leaktight as a fabrication quality requirement.

10. When plutonium is used in fabrication, all operations are carried out in____________________, which become the containment barrier for operators.

11. Containment systems are assisted by a__________________, which is designed so that the pressure inside the containment is always lower than the outside pressure.

12. What are the two basic types of ventilation systems?

13. What is the difference between a general exhaust ventilation system and a local exhaust ventilation system?

14. What are the four parts of a local exhaust system?

15. What criteria should be met by air cleaners for radioactive material and/or highly toxic dusts?

16. Describe the difference between air filters and dust collectors.

17. What are the four main types of dust collectors for particulate contaminants?

18. Process off-gas treatment systems in the fuel cycle usually consist of:

19. The following classifications and functions identify equipment designed specifically to control gas or vapor contaminants. Match each classification in Column A with its function in Column B.

Column A
Classification

20. ___ Absorbers

21. ___ Adsorbers

22. ___ Thermal oxidizers

23. ___ Direct combustors

24. ___ Catalytic oxidizers

Column B
Function

A. Afterburners; may be used where the contaminant is combustible. The contaminated air is introduced to a heated chamber where combustibles are oxidized, producing carbon dioxide and water vapor.

B. Used for combustible contaminants; the contaminated gas stream is preheated and passed through a catalyst bed, which promotes oxidation of the combustibles to carbon dioxide and water vapor.

C. Remove contaminants by collection on a solid; this is a physical process in which molecules of a gas adhere to surfaces of the solid (e.g., activated carbon).

D. Remove soluble or chemically reactive gases from an airstream by contact with a suitable liquid. Water is the most frequently used, but additives and other chemical solutions can be used (e.g., packed towers).

E. Introduce the contaminated gases and auxiliary air directly into the burner as fuel. Auxiliary fuel, usually natural gas or oil, is generally required for ignition.

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

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

PROGRESS REVIEW MEETING FORM

Date Scheduled: ________________________________Location:______________________

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

- ◙ Fundamental concepts of health and safety
  - ☐ Hazard classifications
  - ☐ Memorandum of Understanding between NRC and OSHA
  - ☐ Hazard identification
  - ☐ Radiation
  - ☐ Toxicity and its effect
  - ☐ Routes, types, and rates of exposure
  - ☐ Carcinogens
  - ☐ ALARA
  - ☐ Risk and risk assessment
  - ☐ Controls
  - ☐ Resources and guidelines
  - ☐ Quality assurance
- ◙ Hazards associated with uranium and selected by-products
  - ☐ Radionuclides
  - ☐ Uranium toxicity
  - ☐ Transportability
  - ☐ Biological effects
  - ☐ Radiological versus toxic limits
  - ☐ Effects of material characteristics
- ◙ Uranium compounds and by-products
  - ☐ Hydrogen fluoride
  - ☐ Uranium hexafluoride
  - ☐ Nitric compounds
  - ☐ Hydrogen gas
  - ☐ Ammonia
  - ☐ Chlorine trifluoride
- ◙ Abnormal occurrences
  - ☐ Fire
  - ☐ Explosions
  - ☐ Criticality and controls
  - ☐ Equipment and instrument failure
- ◙ Selected controls in fuel cycle:
  - ☐ Fire protection
  - ☐ Containment/confinement
  - ☐ Ventilation

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

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

III. As a Regulator:

- Tell me more about similarities of hazards in various fuel cycle facilities.
- Tell me more about chemical versus radiological hazards.
- What is the NRC's position on accepting/declining licensees' hazard assessments?
- What documentation related to hazards would you recommend that I review prior to going to a specific fuel cycle facility?

Use the space below to write your specific questions.

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

Suggested Supplemental Reading Material:

- 10 CFR Part 70 Subpart H
- March 2003, memorandum on Chemicals Regulated by NRC
- NUREG-1601, Chemical Process Safety at Fuel Cycle Facilities (August 1997)
- NRC Information Notice No. 90-20, Personnel Injuries Resulting From Improper Operation of Radwaste Incinerators
- NRC Information Notice No. 90-70, Pump Explosions Involving Ammonium Nitrate
- NRC Information Notice No. 91-44, Improper Control of Chemicals in Nuclear Fuel Fabrication
- NRC Regulatory Guide 3.32, General Design Guide for Ventilation Systems for Fuel Reprocessing Plants (September 1975)
- Memorandum of Understanding between NRC and OSHA
- OSHA-related Performance Standard
  - ☐ Title 29 CFR Part 1910.119
  - ☐ Title 29 CFR Part 1926.64
- OSHA Hazard Communication Standard, Title 29 CFR Part 1910.1200

- National Fire Protection Association 68-1978, Guide for Explosion Venting

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

MODULE 7.0: HEALTH AND SAFETY FUNDAMENTALS AND HAZARDS WITHIN THE NUCLEAR FUEL CYCLE

MODULE SUMMARY

Key Points:

- *Hazards* in the nuclear fuel cycle are classified as chemical, physical, or radiological. Table 7-9 summarizes selected hazards.
- Radiological hazards result from the emission of energy during spontaneous decay in the form of alpha, beta, or gamma radiation from the nucleus of an atom.
- Alpha particles are the most massive and highly charged type of radiation. These particles cannot penetrate the outer layer of dead skin, and alpha radiation is not considered an external exposure hazard. This radiation is, however, an internal exposure hazard.
- Beta particles are high-energy electrons that originate from within the nucleus. Beta particles will travel a few millimeters in tissue and will not usually reach internal organs (one important exception is the eyes).
- Gamma rays and X rays are chargeless and consist of massless waves of electromagnetic energy (photons). Gamma and neutron radiation, both high external hazards, penetrate tissue and will pass through the whole body. Gamma rays are also high internal hazards. Neutrons are rarely internal hazards.
- Chemical compounds in the form of liquids, gases, mists, dusts, fumes, and vapors cause harm to the body by ingestion (eating or drinking), injection, skin absorption (direct contact), and inhalation.
- "As Low As Reasonably Achievable" (ALARA) describes a radiation protection approach that manages exposures to the workforce and general public. ALARA is not a dose limit, but a process that seeks to attain dose levels as far below applicable levels as is practical.
- To be licensed by the NRC, facilities must meet safety requirements. Factors to be considered in a risk/safety assessment are listed in Subpart H of 10 CFR Part 70.
- *Control* of hazards involves:
    - Engineering controls
    - Administrative controls
    - Personal protective equipment (PPE)
- NUREG-1520, Standard Review Plan (SRP) for the Review of a License Application, provides guidance for evaluating hazards and assessing likelihoods and consequences from identified accidents. The SRP lists 11 areas for evaluation.
- The chemical toxicity of uranium is the primary concern in the establishment of control limits and procedures. Uranium, a heavy metal, is toxic to the kidneys.

- For low enrichment, the chemical toxicity is the limiting hazard; for high enrichment, radiological effects are the limiting hazards. The radiological impact should be considered for all intakes, even when chemical toxicity is the limiting hazard.
- Hydrogen fluoride is an extremely corrosive acid that is relatively volatile in its anhydrous form. External contact with HF causes chemical burns and irritation of the skin; airborne exposure causes chemical burns and irritation to the eyes, nose, and throat.
- Uranium hexafluoride reacts with almost all metals and reacts, often explosively, with organic material. The radioactivity of the UF_6 will vary according to the U-235 enrichment.
- Nitric acid is used to digest uranium metal and for "pickling" metal products to inhibit oxidation. Concentrated nitric acid gives off fumes that cause irritation to the eyes, mucous membranes, and skin.
- Hydrogen gas (H2) is often generated by dissociating ammonia; thus, ammonia is often identified as the reactant.
- Anhydrous ammonia is a source material for the production of hydrogen for use in reduction processes, e.g., hydrofluor process of UF_6 production. Contact with anhydrous ammonia is irritating to the mucous membranes, eyes, and skin and may cause corrosive skin burns or blister formation.
- Chlorine trifluoride (CIF3) is used as a barrier treatment gas in the cascade and is a powerful oxidizing agent, igniting many organic compounds on contact and reacting violently with water. It can cause eye and respiratory irritation.
- The potential for an explosion in some areas of the nuclear fuel cycle may occur due to:
  - Production and use of hydrogen throughout the fuel cycle
  - Chemical or corrosion reactions through finely divided, oxidizable dusts or pyrophoric materials
  - Certain nitric acid/heavy metal/organic matter reactions
- A *criticality accident* is an uncontrolled nuclear chain reaction occurring in an assembly or facility containing fissile materials.
- Factors that must be controlled to prevent criticality include the following: mass and volume, enrichment, geometry, interaction and separation, moderation, reflection, concentration and density, neutron absorber or poisons, and heterogeneity.
- Criticality safety can be achieved through the following:
  - Equipment design
  - Process control instrumentation

  - ☐ Compliance with operating procedures

- ◙ Criticality control should depend on safety features incorporated in the equipment or instrumentation rather than administrative controls.
- ◙ Fire is a hazard that must be considered throughout the fuel cycle due to the potential for release of radioactive material. Fire prevention is the most important component of fire protection.
- ◙ Facilities should be designed to limit risks of fire. Ventilation systems, with their ducts and filter units, may be weak points in the system. The nuclear fuel cycle presents fire protection difficulties not found in general industry. Considerations to address are:
  - ☐ Difficulty in gaining access to the fire (danger of irradiation; special clothing required).
  - ☐ The need to maintain a certain level of containment.
  - ☐ Restriction of extinguishing agents. Uranium fires are not extinguished by water spray, CO2, or halon. In accidents involving a risk of criticality where moderation is a control, water is prohibited.
- ◙ A containment barrier may be any of the following:
  - ☐ Process equipment.
  - ☐ Surrounding cell or glove box.
  - ☐ Room or building in which the process is located.

- ◙ Ventilation systems are of two basic types:
  - ☐ The supply system provides air.
  - ☐ The exhaust system removes contaminants. Process exhaust off-gas treatment systems may consist of: wet scrubbers, prefilter systems, and/or HEPA filters.

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