MODULE 5.0: FUEL FABRICATION

Introduction

Welcome to Module 5.0 of the Fuel Cycle Processes Directed Self-Study Course! This is the fifth of nine modules available in this directed self-study course. The purpose of this module is to assist the trainee in describing fuel fabrication and Nuclear Regulatory Commission (NRC) regulation of fuel fabrication facilities; the ammonium diuranate (ADU) wet conversion and intergrated dry route (IDR) chemical processes; ceramic process conversion; loading of rods and assemblies; scrap recovery; radiological and nonradiological hazards; administrative and engineering controls and preventive measures; key contributing factors for fuel fabrication accidents; and mixed-oxide (MOX) fuel. There are 12 learning objectives in this module. This self-study module is designed to assist you in accomplishing the learning objectives at the beginning of the module. The module has self-check questions and an activity to help you access 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 70, Domestic Licensing of Special Nuclear Material

Complete the following prerequisites:

- 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 in this module.
4. Check off the tracking form as you complete each activity.
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. 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 Trainee Self-Study Course Guide and review the steps for course completion.

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MODULE 5.0: FUEL FABRICATION

LEARNING OBJECTIVES

5.1 Upon completion of this module, you will be able to describe fuel fabrication and NRC regulation of fuel fabrication facilities, ammonium diuranate (ADU) and integrated dry route (IDR) chemical processes, ceramic process conversion, loading of rods and assemblies, scrap recovery processes, radiological and nonradiological hazards, administrative and engineering controls and preventive measures, key contributing factors for fuel fabrication accidents, and mixed oxide (MOX) fuel.

5.1.1 Describe fuel fabrication and NRC regulation of fuel fabrication facilities.

5.1.2 Identify the steps associated with the wet or ammonium diuranate (ADU) chemical process.

5.1.3 Identify the steps associated with the dry or direct conversion or integrated dry route (IDR) chemical process.

5.1.4 Identify the steps associated with the ceramic process conversion of UO_2 powder to pellets.

5.1.5 Identify steps encountered in the mechanical process of loading UO_2 pellets into rods/assemblies.

5.1.6 Identify steps encountered in the scrap recovery process.

5.1.7 Identify radiological and nonradiological hazards associated with fuel fabrication processes.

5.1.8 Describe administrative and engineering controls and preventive measures for fuel fabrication processes.

5.1.9 Describe key contributing factors for fuel fabrication process accidents.

5.1.10 Describe mixed oxide (MOX) fuel and its use in fuel fabrication.

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Learning Objective

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

5.1.1 Describe fuel fabrication and NRC regulation of fuel fabrication facilities.

FUEL FABRICATION OVERVIEW

Fuel fabrication is the final step of the “front end” of the nuclear fuel cycle. Fabrication refers to the chemical and mechanical processes that physically transform the uranium after conversion and enrichment into a sufficiently robust form that it can be used to sustain criticality and generate power in a reactor. In the U.S., all current and planned power reactors use low-enriched uranium (LEU) fuel. Consequently, LEU fuel fabrication facilities are regulated under 10 CFR Part 70 “Domestic Licensing of Special Nuclear Material,” with the overall goals of:

- protecting the health and safety of the public, plant workers, and the environment from radiological and certain chemical hazards; and
- safeguarding special nuclear material (SNM) – the LEU – from loss, theft, or diversion.

The fuel is a very concentrated form of energy and, without compatible fuel, the reactor does not function. Fuel compatibility, integrity, and durability often determine the reliability of the reactor system, affecting both safety and economics. The fuel provides the first two layers of confinement - the fuel form itself and the metal cladding around the uranium form. Leaking fuel often requires reactor shutdown and subsequent identification and removal of the leaking fuel. Additional decontamination and waste usually result. The end results of leaking fuel are increased dose release, volume of waste, and costs.

The fuel must keep its integrity for decades. Fresh fuel is usually used in the reactor within a few years of its initial fabrication; with U.S. power reactors, the average irradiation time for fuel in the core is approximately five years. The used fuel - or spent nuclear fuel (SNF) - is stored in a spent fuel pool adjacent to the reactor for a minimum of five years (wet storage of SNF); and for older SNF, most utilities use or plan to use dry storage of SNF for a minimum of 20 years. Some power reactor SNF is over thirty-five years old. Repository operations might last another hundred years or so and rely on fuel integrity for part of that time period.

Reactor type and operations influence fuel choice. All power reactors in the U.S. are thermally moderated by the light water coolant and utilize low energy neutrons (circa 1 ev of energy). Thus, fuel choice considers steam/water corrosion, thermal/hydraulic, and neutronic behavior. Gas reactors also use thermally moderated neutrons but have higher temperatures, and chemical and thermal considerations become more important. Fast reactors utilize high energy neutrons (typically > 1 Mev), and neutronic considerations, such as swelling, become more important.

All U.S. and the majority of the world's power reactors utilize LEU fuel which starts as UF_6 from the enrichment facilities. The hexafluoride is not suitable for reactor fuel for many reasons; it requires chemical conversion into a more stable, non-volatile, and robust form, and a higher density is desirable for adequate nucleonic properties. Some chemical forms of uranium that have been used for nuclear fuel include:

Uranium metal
This has a high density (17-19 g/cc) and thermal conductivity. However, it has complex metallography, relatively low phase transformation temperatures, and is reactive with air, water, and other coolants. Currently, metal fuels are used for research reactors.

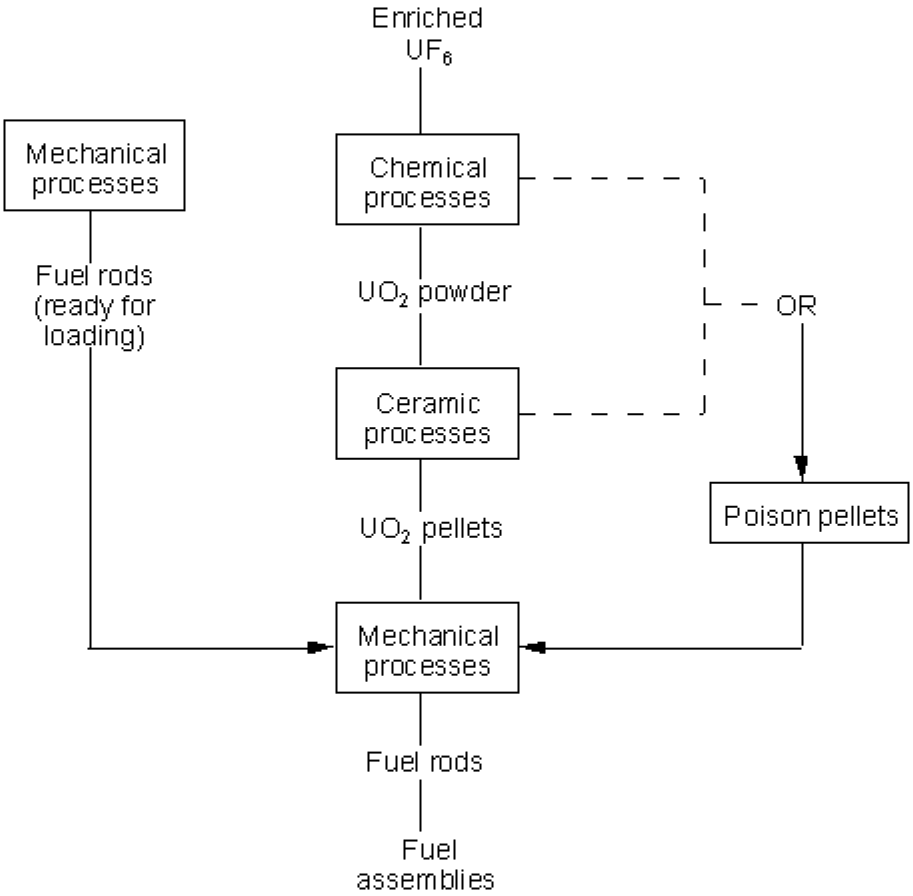
Mixed oxide (MOX)
Mixed oxide, or MOX fuel, is a blend of reprocessed uranium and plutonium and depleted uranium which behaves similarly to the enriched uranium fuel for which most nuclear reactors were designed. MOX fuel is an alternative to low-enriched uranium fuel used in the light water reactors which predominate nuclear power generation.

Uranium carbides
These have a high density (12-14 g/cc) and thermal conductivity. Uranium carbides also accommodate higher temperatures. However, carbides are reactive with air and water and require coatings for adequate inertness. They also introduce additional waste management concerns via the production of the biologically active carbon-14 isotope. Carbide fuels are not currently used in any significant quantities. Coated fuel consisting of uranium dioxide and some uranium carbide is proposed for high temperature gas reactors. Coated oxycarbide fuel is discussed further in the Supplemental Reading at the end of this module.

Uranium dioxide
Sintered uranium dioxide (UO_2) has lower but reasonable densities (9-10 g/cc) and thermal conductivities. It has reasonable temperature limits and, in the sintered form, is relatively non-reactive to water and air. Uranium dioxide represents a workable compromise of the properties. All power reactors in the U.S. use sintered uranium dioxide as the fuel form.

Thus, fuel fabrication facilities include chemical processes that convert the uranium hexafluoride to UO_2 powder and a ceramic process that converts the powder to pellets that are heated to form a bonded mass with reduced density (sintering). Finally, the resulting uranium fuel form is contained - or clad - in a metal structure. This last step is a mechanical process that loads the fuel pellets into metal rods or tubes that are then grouped in special fuel assemblies and used to build up the nuclear core of a power reactor. Details of these processes are in sections 5.1.2 - 5.1.5. Figure 5-1 shows a basic flow diagram for fuel fabrication.

Figure 5-1. Flow Diagram for Fuel Fabrication



Historically, several materials for cladding have been used:

Stainless steel

Stainless steel cladding has durability and strength. Its properties are well known and it is kinetically inert due to low corrosion rates. However, it has less desirable nucleonics (essentially absorption) in the thermal energy range. Stainless steel cladding has been used for research and fast reactors.

Light metals
Magnesium and aluminum have low neutron absorption cross sections. However, both metals can be reactive with air and water, and have relatively low melting points. Durability - particularly during SNF storage - has encountered some problems. Aluminum has been used in research reactors and magnesium has been used in gas reactors.

Coatings
Dense carbon and silicon carbide coatings effectively prevent contact between the environment and the uranium fuel form. They are durable and possess good nucleonics. The coatings can be difficult and expensive to apply. In use, the coatings increase the carbon-14 generation. Coated fuel has been used in high temperature gas reactors.

Zirconium
Zirconium and its alloys have reasonable durability and strength. Nuclear-grade zirconium has a very low hafnium content and, thus, has a low neutron cross section. It has reasonable strengths at temperatures. It has some reactivity concerns at higher temperatures. Zirconium alloys have proven themselves as a workable compromise for water cooled reactors.

All U.S. power reactors and most overseas power reactors use zirconium alloys as the cladding material.

Light water reactors (LWR) require LEU fuel for operations. Typical enrichment levels are 2.5-4.5% for pressurized water reactors (PWR) and 3-5% for boiling water reactors (BWR); the latter require slightly higher enrichment levels due to less efficient moderation in the core (more steam bubbles). The enrichment level determines the maximum operating time between shutdown for refueling. Most U.S. power reactors operate on 18-month cycles which require circa 4.3-4.5% enrichment.

Nuclear fuel utilization is termed burnup. Burnup represents the fission thermal energy recovered from using the fuel. It also conveniently measures fuel irradiation history and radioactivity. It is normally expressed in megawatt-days per metric ton of (initial) heavy metal, or simply MWD/MTHM. Typical values for power reactors range 30,000 - 62,000 MWD/MTHM. Longer cycles have higher burnups; burnups around 30,000 MWD/MTHM approximate annual refueling cycles, while burnups around 62,000 MWD/MTHM represent 20-24 month cycles. A cautionary note - many texts and reports use burnups of 30,000 or so MWD/MTHM. These values are indicative of the original approach envisioned some 30 years ago and do not represent current power reactor practice in the U.S.

The trend is towards higher enrichments and burnups, as these allow for longer cycles between refueling. Figure 5-2 shows the U.S. trend in burnups. It is unlikely these trends will continue indefinitely due to enrichment and fabrication plant license and capability limits of around 5%, irradiation effects upon the fuel and its cladding, and reactor accident analysis limits. See also Module 6.0, Back-end of the Fuel Cycle. Figure 5-3 shows facility capacities.

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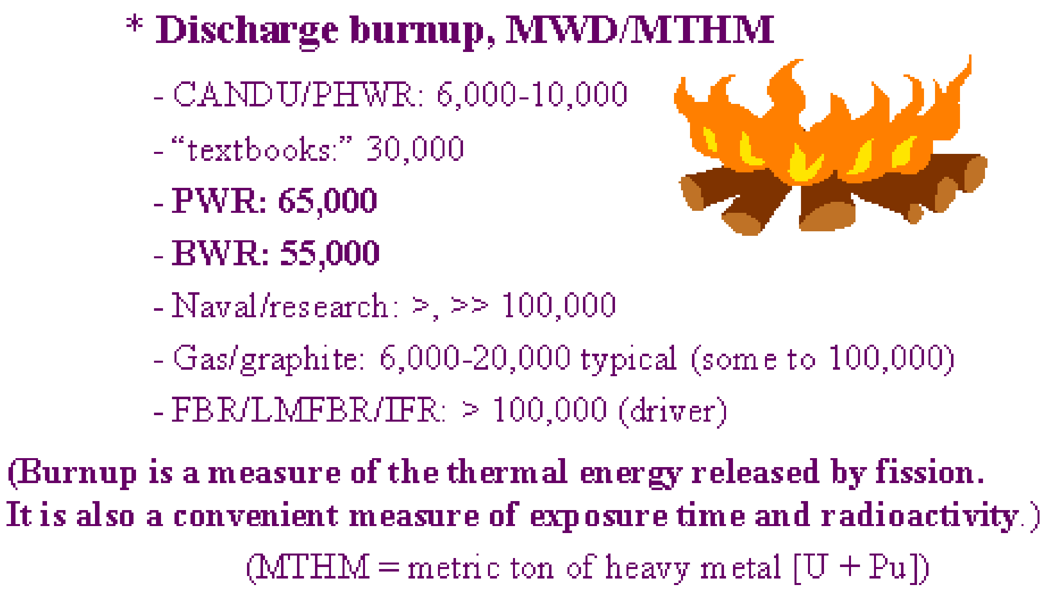
Fresh fuel is unirradiated and has relatively low radiation fields and distance effects. Little, if any, shielding is needed. Fuel is irradiated in most reactors for five years or so. Irradiated fuel is often called spent nuclear fuel and is very radioactive.

Some 10,000 to 14,000 MTHM of SNF are created annually from the world's power reactors. Approximately 2,000-2,500 MTHM are generated annually in the U.S., and the current inventory in storage is about 50,000 MTHM. A typical power reactor (PWR type) of nominally 1,000 MWe capacity contains around 100 MTHM in 193 fuel assemblies containing about 51,000 fuel rods. There are approximately 18 million fuel pellets total in the core. Typical rework rates are 1-3% on the pellets, 0.1 to 0.3% on the rods, and very low on the assemblies. "Teething" problems are sometimes encountered with new designs. A typical power reactor operates on 18-month cycles with a one-third fuel changeout during refueling. Fuel remains in the reactor for three cycles or about five years.

On a mass basis, nuclear fuel is relatively expensive. Table 5-1 provides approximate unit costs taken from the literature. Tables 5-2 and 5-3 provide ballpark cost estimates for a reload, including "back-end" costs. Figure 5-4 provides a pie chart breakdown. Front-end and back-end costs are approximately equal; however, fuel cycle costs are only around 20% and 5% of the total cost of current and new nuclear electricity, respectively. See Figure 5-5.

Figure 5-2. U.S. Nuclear Fuel Burnup



*** Discharge burnup, MWD/MTHM**

- CANDU/PHWR: 6,000-10,000
- "textbooks:" 30,000
- **PWR: 65,000**
- **BWR: 55,000**
- Naval/research: >, >> 100,000
- Gas/graphite: 6,000-20,000 typical (some to 100,000)
- FBR/LMFBR/IFR: > 100,000 (driver)

(Burnup is a measure of the thermal energy released by fission.
It is also a convenient measure of exposure time and radioactivity.)

(MTHM = metric ton of heavy metal [U + Pu])

Figure 5-3. Facility Capacities

- **About 1,000 te U/yr for large facilities**
- **About 4,000 te U/yr capacity in U.S.**
- **About 14,000 te/yr in world (with Russia)**
- **Running at about 60% of capacity**

NOTE:

- Licensed for %% assay maximum
- Capacity available to accommodate some new PWR/BWR evolutionary designs
- “Gen IV” designs would need new lines/plants

Table 5-1. Approximate Unit Costs for Nuclear Fuel

Front End (Before Irradiation)	Back End (After Irradiation)
◙ Ore: \$40/lb (\$90/kg U) □ Includes tailings, remediation etc. ◙ Conversion: \$10kg U ◙ Enrichment: \$100/SWU ◙ Fuel fab: \$200/kg U	◙ DU: \$10/KG U (conversion and disposal) ◙ SNF Dry Storage: \$40/kg U ◙ Direct disposal or Reprocessing: \$1,000/kg U

Table 5-2. Cost Estimates for a Reload

- Mining/Milling: 20,000 te of ore (1%), gives 195 te U (230 te as oxide), \$18 M
- Conversion: 288 te UF6 (195 teU): \$2 M
- Enrichment: 35 te UF6 (24 te U) LEU, 5 SWU/kg: Gives 120,000 SWU and \$12 M
- Fabrication: 27 te U02 (24 te U), \$200/kg: gives \$ 5 M
- Total: \$37 M/reload (about \$1,500/kg or \$750,000 for a PWR assembly)

Table 5-3. Backend Fuel Costs (1 Reload)

- Depleted Uranium: about 170 te U gives about $2 M (assumes disposition as waste)
- SNF Dry Storage: about $1 M
- Direct Disposal or reprocessing: 24 te U gives $24 M (no Uranium credit)
- Note that longer burnups reduce costs of fuel use and power production significantly

Total is about $64 M per reload

Figure 5-4. Cost Pie Chart

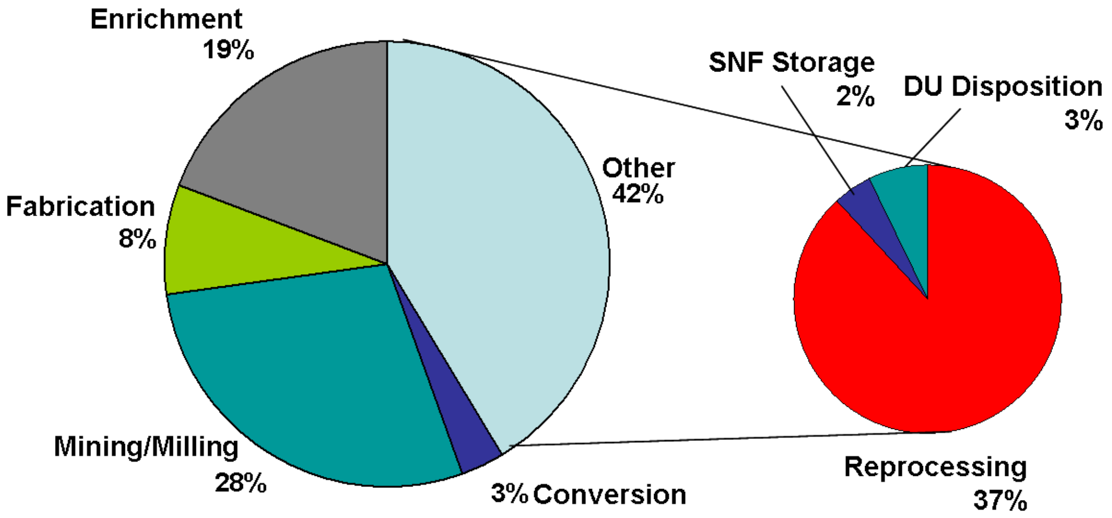
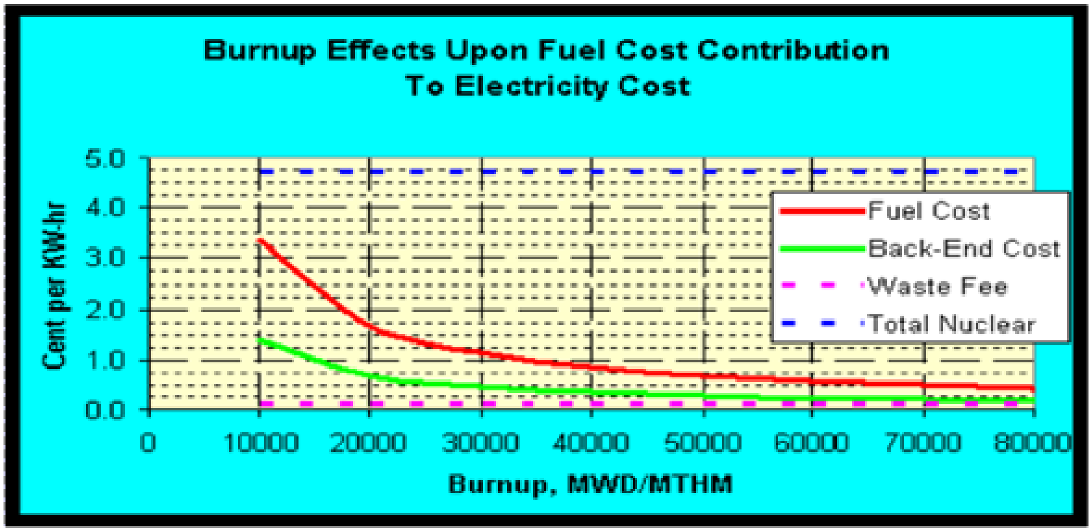


Figure 5-5. Contribution to Electrical Cost Estimate



Fuel Fabrication Facilities

Six fuel fabrication facilities are licensed to produce fuel for light water reactors in the United States. Four of the facilities produce low enriched uranium fuels for commercial nuclear reactors, and two facilities, BWX Technologies, Inc. and Nuclear Fuel Services, Inc., produce highly enriched uranium (HEU) fuel elements for the U.S. Navy. Facilities producing HEU receive the UF_6 enriched to over 90% U-235 and follow a classified process to produce fuel elements and fabricate complete reactor cores.

Table 5-4 lists the active fuel fabrication facilities licensed by the NRC. Figure 5-6 shows the AREVA-R facility located in Richland, WA.

Table 5-4. Fuel Fabrication Facilities Licensed by the NRC

Licensee	Facility Location	Typical Operations	Conversion Process	Final Product(s)
AREVA-L	Lynchburg, VA	LEU pellet loading, assemblies	None	LWR Assemblies
AREVA-R	Richland, WA	LEU conversion, pellets, assemblies	Dry	LWR Assemblies, pellets
BWX Technologies, Inc.	Lynchburg, VA	HEU/RTR fuels, Downblend	Several	HEU/RTR assemblies, LEU materials
Global Nuclear Fuels-Americas	Wilmington, NC	LEU conversion, pellets, assemblies	Dry	LWR assemblies
Nuclear Fuel Services, Inc.	Erwin, TN	HEU/RTR fuels, Downblend	Several	HEU/RTR assemblies, LEU materials
Westinghouse (BNFL; Toshiba)	Columbia, SC	LEU conversion, pellets, assemblies	Wet (dry standby)	LWR assemblies

Figure 5-6. AREVA-R, WA

Two fuel fabrication facilities have undergone decommissioning: The General Atomic facility in San Diego, CA, and Westinghouse Electric Company, LLC, in Hematite, MO. The Hematite facility ceased conversion and removed all UF_6 from the site as of March 31 2001. The operating fuel fabrication facilities have been remediating portions of their facilities by removing or stabilizing radioactive contamination in areas that are no longer in use. NRC frequently inspects all these fuel fabrication facilities and has resident inspectors at the BWX Technologies, Inc. and the Nuclear Fuel Services, Inc., facilities.

The regulation of commercial nuclear fuel facilities is primarily the responsibility of the NRC, although these facilities are also subject to applicable requirements of the Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA).

NRC Regulation

The objectives of the NRC regulations are to protect the health and safety of the public and plant workers and the environment from radiological and certain chemical hazards present at fuel cycle facilities. In addition, for those facilities that store or process special nuclear material, the NRC requires that facilities safeguard such material from loss, theft, or diversion.

Fuel fabrication is regulated under 10 CFR Part 70, “Domestic Licensing of Special Nuclear Material,” because of SNM. 10 CFR 70 applies to enrichment, fuel fabrication, and MOX facilities. The regulation was revised to include a risk-informed, performance-based approach that requires an integrated safety analysis (ISA). New requirements are summarized in Table 5-5.

Table 5-5. 10 CFR Part 70 - Domestic Licensing of Special Nuclear Material

Subpart	Description
E-Licenses Part 70.34, Amendment of Licenses	Sets forth terms and conditions for licenses. Applications for amendment of a license shall be filed in accordance with Part 70.21(a) and must specify what the licensee wants amended and the grounds for such amendment. Full documentation and updates are required by the licensee/facility.
H- Additional Requirements for Certain Licensees Authorized to Possess a Critical Mass of Special Nuclear Material Part 70.61, Performance Requirements	Sets forth performance requirements that require an Integrated Safety Analysis (ISA); establishes safety program and the ISA; establishes content and approval requirements for license applications. Each applicant or licensee must evaluate its compliance with the following performance requirements using an integrated safety analysis (ISA): ◙ Risk of a credible high-consequence event must be limited and engineered controls, administrative controls, shall be applied to reduce likelihood of occurrence. High consequence accidents are chemical or radiological affecting the worker and public.] ◙ Risk of each credible intermediate-consequence event must be limited and engineered controls, administrative controls, shall be applied to reduce likelihood of occurrence. Intermediate consequence accidents include chemical and radiological affecting the worker, public, and the environment. ◙ Risk of a nuclear criticality accident must be limited by assuring under normal or abnormal conditions nuclear processes are subcritical. Preventive measures and controls are primary means of protection. Each engineered or administrative control used for compliance shall be designated as an item to be relied on for safety. Each licensee must establish a controlled area.
Part 70.62 Safety Program	Each licensee or applicant must establish and maintain a safety program to comply with requirements of Part 70.61. The three elements of the safety

Table 5-5. 10 CFR Part 70 - Domestic Licensing of Special Nuclear Material

Subpart	Description
and ISA	program are: process safety information, integrated safety analysis, and management measures.
Part 70.64, Requirements for New Facilities	Licensees must address Baseline Design Criteria (BDC), including Quality Standards, NPH, Fire, Environmental, Chemical, Emergency Capability, Utilities, Inspections, Criticality Control, and Instrumentation (I & C). Design and layout must be based on Defense-in-Depth practices with preference given to Engineering Controls over Administrative Controls. Safety can be enhanced by reducing challenges to IROFS.
Part 70.65, Additional Content of Applications	Each application must include a description of applicant's safety program established under Part 70.62. The integrated safety analysis summary (ISA Summary) must be submitted with the license or renewal application (or amendment application). Full documentation and updates are required by the licensee/facility.
Part 70.72, Facility Changes and Change Process	The licensee must establish a configuration management system to evaluate, implement, and track each change. This system must be documented in written procedures. Any change to the site, structures, or processes must be evaluated in accordance with the system. Amendment is dependent on the ISA. If changes are made that affect the ISA summary, a revised summary must be submitted. Full documentation and updates are required by the licensee/facility.

Self-Check Questions 5-1

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

1. What are the three basic steps for fabricating fuel for light water reactors?

2. Which fuel fabrication facilities produce low-enriched uranium fuels for commercial nuclear reactors?

3. What two fuel fabrication facilities produce highly enriched fuel elements for the United States Navy?

4. Are there fuel fabrication facilities that are currently decommissioning?

5. What is the NRC's responsibility in the fuel fabrication process of the nuclear fuel cycle?

6. One of two chemical processes is typically used to convert UF_6 to UO_2 powder. What are these processes?

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

Learning Objective

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

5.1.2 Identify the steps associated with the wet or ammonium diuranate (ADU) chemical process.

CHEMICAL PROCESS: WET OR ADU PROCESS

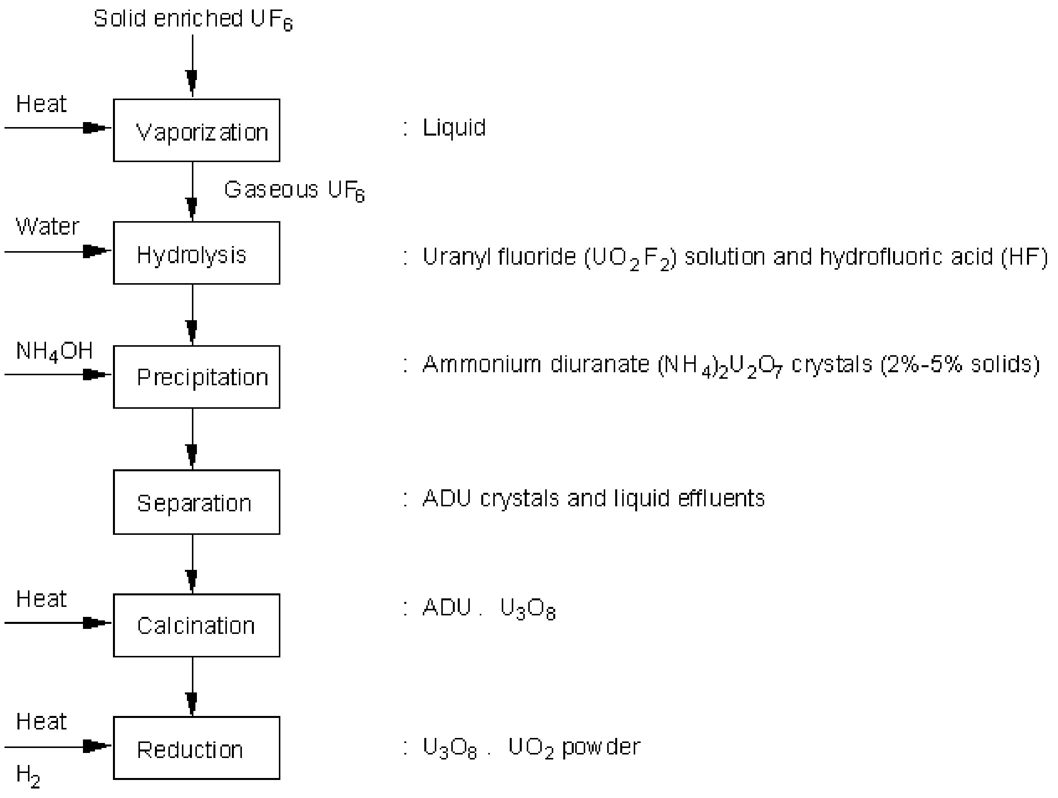
In the wet or ammonium diuranate (ADU) process, the UF_6 is vaporized and transferred to reaction vessels, hydrolyzed with water, and neutralized with NH4OH to form a slurry of ADU in an aqueous solution of ammonium fluoride and ammonium hydroxide. The ADU is recovered by centrifuging and then is clarified, dried, and calcined to form UO_2 powder. Figure 5-7 is a flow diagram for the ADU process to convert UF_6 to UO_2 powder. The left-hand side of the figure shows the six basic steps that are performed to chemically convert UF_6 (a solid at room temperature) to UO_2 powder. The UO_2 powder will then be used for the ceramic processing into fuel pellets.

The six steps are:

- Vaporization – conversion of a solid or liquid into a gaseous state by adding heat
- Hydrolysis – a chemical process by which the oxygen or hydrogen in water combines with an element, or some element of a compound, to form a new compound
- Precipitation – formation of finely divided solids in a chemical reaction.
- Separation – remove or separate solid particles from the liquid effluent
- Calcination – reduce to powder by heat; to expel water and other volatile substances by heat
- Reduction – reaction of hydrogen with another substance

Each of these steps is discussed in this section.

Figure 5-7. Wet or ADU Process



Vaporization

After receiving the enriched UF_6 from the Paducah, Kentucky, enrichment facility, the UF_6 (a solid at room temperature) is vaporized by adding heat. UF_6 is a colorless, volatile crystal that sublimes (changes directly from solid to vapor phase) at atmospheric pressure and approximately 134°F. Under pressure UF_6 will be in the liquid state.

Note: Upon receipt of feed cylinders, some fabrication facilities may assay and confirm enrichment of material in the cylinder container. U-235 enrichment is analyzed at the enrichment facility and reverified at the fuel fabrication plant prior to introduction of the material to the fuel fabrication process. In the event such analysis is not available, a substitute sample could be collected at the fuel fabrication facility for analysis after the material is converted to uranium oxide.

The shipping cylinder is used as part of the vaporization system. It is typically placed in a vaporization chamber. The cylinder is heated by steam or heated air with the valve closed, which liquefies the solid UF_6. When the valve is opened, the material is released as a gas. The UF_6 is then fed to the hydrolysis system. Other methods, such as the use of electric blankets to heat and vaporize the UF_6 for hydrolysis, have been used.

- At one commercial facility, cylinders are heated in a vaporization chamber, consisting of a steel steam chest designed to enclose the cylinder as well as any connections to the vaporization system. A flexible pigtail is connected to the cylinder valve to allow flow of vaporized UF_6 to the processing system.
- Another facility uses an almost identical system, except that electrically heated air is circulated within the chamber to heat the cylinders.
- At a third facility, an electric blanket is used to heat the cylinder. The fluoride compound vaporizes through pigtail pipes into a hydrolysis tank.

Hydrolysis

After vaporization, gaseous UF_6 is reacted with deionized water to form uranyl fluoride (UO_2F_2) solution and hydrofluoric acid (HF) as in the equation below. As with conversion prior to enrichment, this chemical process must be carefully controlled due to the presence of fluorine.

$$UF_6 + 2\ H_2O \longrightarrow UO_2F_2 + 4\ HF$$

Uranyl fluoride is a complex salt in water solution and will dissolve to form a 66% solution at 77°F; however, solubility is limited by the presence of hydrofluoric acid. As a result, the hydrolysis of UF_6 yields a saturated solution at 86°F that contains only 32% uranyl fluoride.

Water reacts vigorously with UF_6 during this exothermic reaction.
(H= +50,500 kcal/kg-mole or about 258 BTU/lb UF_6)

In one process, gaseous UF_6 is mixed with water in a continuous process, using a liquid-gas mixing nozzle to bring the aqueous phase in contact with the UF_6 vapor. A steady stream of UF_6 is fed to the mixing nozzle, where it mixes with recirculating uranyl fluoride solution. The concentration and product removal rate are controlled by the amount of water that is metered to the system.

The diameter of the nozzle is sized to ensure a rapid flow of UF_6 through the aperture, which minimizes the back diffusion of water vapor into the aperture of the nozzle or into the UF_6 feed line. UF_6 flow rates in the range of 100 to 150 lbs/hour are achievable, with product concentrations controlled to within 1.5%. The UF_6 feed line is purged with nitrogen to prevent clogging with the hydrolysis products. Teflon and fluoroethene have demonstrated corrosion resistance and are found suitable for processing UF_6 in hot aqueous solution at about 200°F.

In another hydrolysis process, vaporized UF_6 flows through corrosion-resistant pipe to a vertical hydrolysis tower (made of steel and lined with polypropylene or teflon) approximately 16 feet high by 10 inches in diameter.

The hydrolysis tower consists of a water reservoir section (maintained on level control) at the bottom, a void section with a UF_6 entrance nozzle located approximately 18 inches above the water level, a polypropylene Tellerette-packed contact region located above the UF_6 entrance nozzle, and a water-spray section at the top of the tower. The hydrolysis tank is vented and thus provides a siphon break to the UF_6 cylinder. In addition, manual block valves (two valves in series) are provided to isolate the UF_6 cylinder from the main gas header. A positive flow of N_2 is maintained, by procedure, through the main header when the UF_6 flow is shut off. Thus, the siphoning of water from the hydrolysis tower to the UF_6 cylinder is precluded.
In the hydrolysis tower, UF_6 is contacted with water to produce a uranyl fluoride solution containing hydrofluoric acid HF. The relative quantities of UF_6 and water are accurately metered to produce a uranyl fluoride solution, which is closely controlled about a specified uranium concentration (approximately 160 gm U/liter). Control of the concentration is maintained by sampling and analysis for specific gravity.

In a third process used for hydrolysis of UF_6, vaporized UF_6 is introduced into the hydrolysis receiver tank at a level beneath that of the water. Columns of water are recirculated through the receiver tank during this process. Adequate mixing of UF_6 and water for hydrolysis is ensured by the constant agitation of the column system.

Precipitation

Addition of NH_3 to the uranyl fluoride solution causes the precipitation of uranyl fluoride to ammonium diuranate [(NH4)2U2O7], according to the following reaction:

$2\ UO_2F_2 + 8\ HF + 14\ NH_3 + 3\ H_2O \longrightarrow (NH_4)_2U_2O_7 + 12\ NH_4F$

Depending on the specific process used at a facility, ammonium diuranate may also be precipitated by adding NH4OH to the hydrolysis solution as follows:

$2\ UO_2F_2 + 6\ NH_4OH \longrightarrow (NH_4)_2U_2O_7 + 4\ NH_4F + 3\ H_2O$
$8\ HF + 8\ NH_4OH \longrightarrow 8\ NH_4F + 8\ H_2O$

The uranyl fluoride solution is pumped to a precipitation tank, where ammonium hydroxide (NH_4OH) is added to produce ADU crystals. These tanks are typically constructed of fiberglass or plastic but may be plastic-lined stainless steel. A lining is required to prevent fluoride attacking weld areas. The tanks are 10 inches in diameter (for criticality control) by approximately 6 feet high. To prevent settling of the solids in the tank, the contents have to be kept in suspension by recirculation. The need to recirculate the contents and to transfer the solution through piping limits the solution to a maximum of 5% solids; the operating level is 2%-3% solids.

Separation

ADU slurry is pumped from the bottom of the precipitation tank to a filtration unit to concentrate the crystals by separating out the liquids. This process is typically accomplished by means of a centrifuge or filter press. The centrifuge uses rotational forces to separate the solid particles from the liquid, while a filter press uses mechanical force to push the liquids through a porous medium, leaving the solid particles behind.

Solids are separated in a rapidly revolving horizontal bowl by centrifugal force and removed from the unit by a conveyor screw that turns at a speed slightly higher than that of the bowl. The slurry enters the centrifuge at the centerline of the bowl and is flung outward, becoming concentrated along the outer wall of the rotating bowl. The screw conveyor, which extends the full length of the bowl, forces the concentrated ADU crystals out of the centrifuge and into a receiver tank or hopper. The liquid effluent is processed again before being sent to waste treatment. (Global Nuclear Fuels and Westinghouse use a second stage centrifuge or clarifier.)

Once the ADU crystals have been concentrated, they are either dried further or fed directly to the calciner. At one facility, ADU slurry is pumped from the ADU receiver tank to a surface-heated drier. The ADU slurry is carried through the drier by rotating paddles while the water content of the slurry is reduced from approximately 50% to about 5%. The resulting crystals are then transferred via a bucket elevator transfer system to the calcining furnace.

Calcination

The calcination process is used for the conversion of ADU crystals to UO_2 powder in the presence of steam and hydrogen. ADU is calcined (at approximately 700°F) and converted to uranium oxide (U_3O_8).

$$3\ (NH_4)_2\ U_2O_7 \longrightarrow 2\ U_3O_8 + 6\ NH_3 + 3\ H_2O + O_2$$

Reduction

The U_3O_8 is reduced to UO_2, in a hydrogen-rich environment, at 700°F to 930°F. The chemical reaction governing this process is:

$$2\ U_3O_8 + 4H_2 \longrightarrow 6\ UO_2 + 4H_2O$$

A typical horizontal calciner is designed to calcine and transport the UO_2 powder within a geometrically safe (10-inch by 26 feet) inconel alloy tube, ultimately discharging the UO_2 powder into a geometrically safe hopper. Steam, hydrogen from cracked ammonia, and nitrogen are injected into the discharge end of the calciner to carry out the conversion.

Heat for drying and oxidation is provided by burning natural gas in multiple burners along the length of the calciner.

The next step of the fuel fabrication process is the ceramic process for pellet production.

Self-Check Questions 5-2

INSTRUCTIONS: Match the steps for the wet or ammonium diuranate process in column A with its description in column B. Answers are located in the answer key section of the Trainee Guide.

Column A **Steps**	**Column B** **Description**
A. Vaporization	1._____Remove solid particles from the liquid effluent.
B. Hydrolysis	2._____Formation of finely divided solids in a chemical reaction.
C. Precipitation	3._____Reaction of hydrogen with another substance.
D. Separation	4._____Conversion of a solid or liquid into a gaseous state by adding heat.
E. Calcination	5._____Reduce to powder by heat; to expel water and other volatile substances by heat.
F. Reduction	6._____A chemical process by which the oxygen or hydrogen in water combines with an element, or some element of a compound, to form a new compound.

Complete the following questions.

7. After vaporization, gaseous UF_6 is reacted with deionized water to form what?

8. What is added to the uranyl fluoride solution to cause the precipitation of uranyl fluoride to ammonium diuranate?

9. In the precipitation step, how is settling of solids in tanks prevented?

10. How does a centrifuge and filter press work in the separation step?

11. The calcination process is used for the conversion of ADU crystals to UO_2 powder in the presence of what?

12. In the reduction step, what is injected into the discharge end of the calciner to carry out the conversion?

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

Learning Objective

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

5.1.3 Identify the steps associated with the dry or direct conversion or integrated dry route (IDR) chemical process.

CHEMICAL PROCESS: DRY OR DIRECT CONVERSION OR INTEGRATED DRY ROUTE (IDR) PROCESS

The dry or direct conversion process, also referred to as the integrated dry route (IDR) process, is a continuous flow process that converts solid UF_6 to UO_2 powder.

In the IDR process, the cylinders of UF_6 are heated in steam cabinets; the vaporized UF_6 goes into a reactor containing a steam-fluidized bed of UO_2F_2 particles. The UF_6 gas reacts with the steam on the hot, wet surfaces of the particles to form a coating of UO_2F_2. The UO_2F_2 particles overflow to a product hopper. These particles are transferred to a second reactor vessel, and the bed is fluidized by steam and cracked ammonia to reduce the UO_2F_2 to UO_2; this is repeated in a third reactor to ensure complete conversion to UO_2.

Because the uranium is never in a liquid solution, equipment capacity is not limited by criticality concerns, because for low-enriched uranium fuel (enriched to ≤5 weight percent U-235), a moderator must be present to attain criticality. The process basically involves a hydrolysis step to convert vaporized UF_6 to uranyl fluoride and a defluorination step to strip the fluoride from the resulting powder. Sinterable UO_2 powder is recovered from the process as a free-flowing granular product.

Advantages of the dry process include:

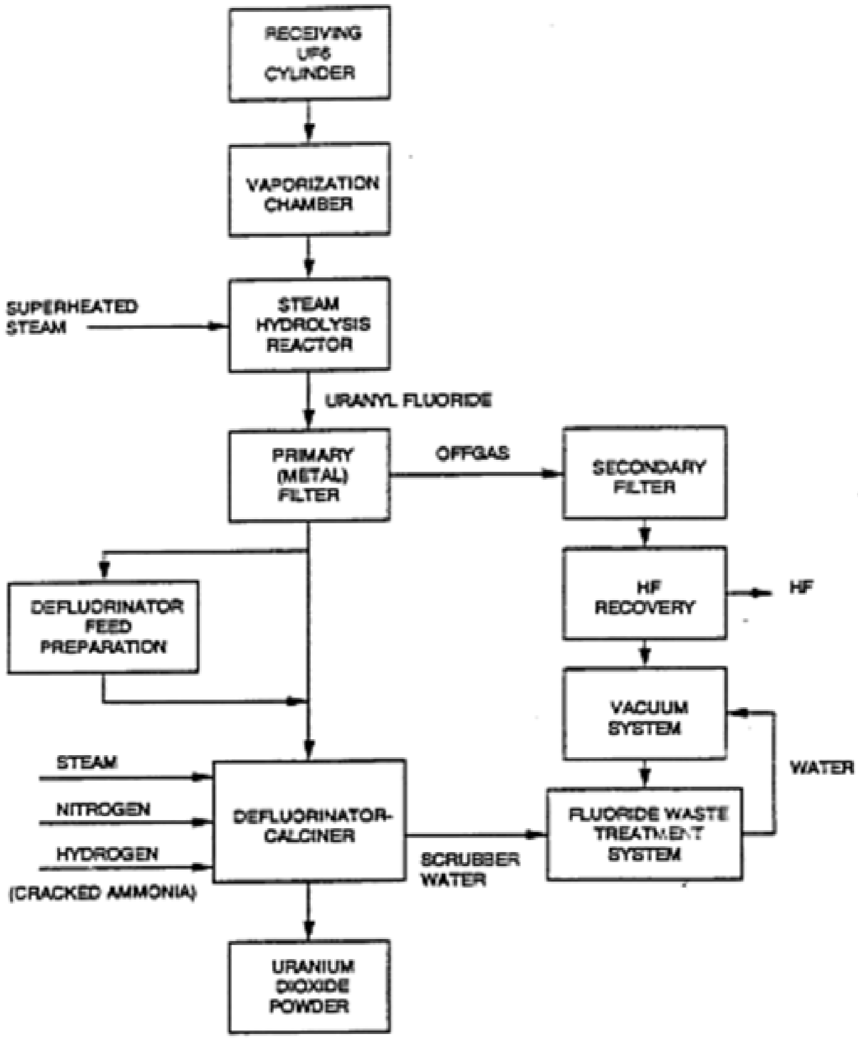
- Stable and reproducible powder characteristics
- Ultra-pure UO_2 powder with high sinterability
- High product volumes with low manpower requirements
- Minimal liquid wastes

The IDR process is divided into the following basic steps:

- Vaporization
- Hydrolysis
- Defluorination/Calcination

Each of these steps is discussed in this section. Figure 5-8 shows an IDR process flow diagram.

Figure 5-8. IDR Process Flow



Vaporization

Solid UF_6 is sublimed to a gas by adding heat to the shipping cylinder. The processes used to vaporize the UF_6 are identical to those used as part of the ADU process. The primary methods used to heat the cylinders are to place the cylinders in a vaporization chamber and heat by circulating either hot water, steam, or electric heat through the chamber. The gaseous UF6 is then fed through pigtail pipes to the hydrolysis reactor.

Hydrolysis

Gaseous UF_6 from the vaporization process and dry superheated steam are injected into the hydrolysis reactor. Here, the UF_6 and steam undergo dry hydrolysis to form uranyl fluoride (UO_2F_2) powder and HF gas in an instantaneous and highly exothermic reaction according to:

$$UF_6 + 2\ H_2O \longrightarrow UO_2F_2 + 4\ HF$$

Complete conversion of UF_6 to uranyl fluoride is ensured when the mole ratio of steam to UF_6 is greater than the stoichiometric requirement of 2.

At one commercial facility, UF_6 and superheated steam are continuously introduced, via a UF_6/steam jet, into a slab-shaped disentrainment chamber of a conversion kiln. When the superheated steam and vaporized UF_6 come in contact, the resultant hydrolysis reaction takes place in the disentrainment chamber at approximately 450°F to 500°F, yielding uranyl fluoride powder and hydrogen fluoride gas. The uranyl fluoride powder falls to the bottom of the chamber, where it is continuously removed from the chamber by a scroll, after which the powder slowly tumbles down a slightly slanted rotating cylindrical kiln barrel, where the defluorination process occurs.

Defluorination/Calcination

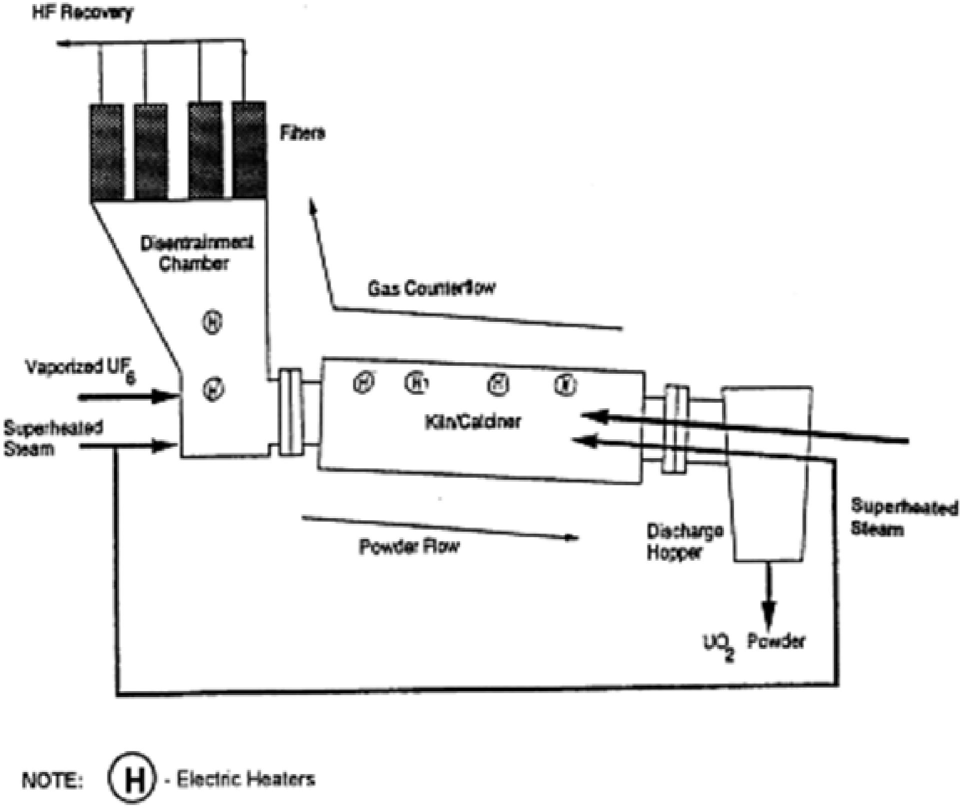
The defluorination process involves the removal of residual hydrofluoric acid gas from the hydrolysis products, as well as the stripping of the fluoride from the uranyl fluoride powder. The hydrofluoric acid gas is typically removed by using metal filters to separate the powder from the gas. The uranyl fluoride powder is calcined and reduced to UO_2 in the presence of hydrogen according to:

$$UO_2F_2 + H_2 \longrightarrow UO_2 + 2\ HF$$

One method used to defluorinate involves a continuous flow of uranyl fluoride powder through a rotating gas-fired kiln (i.e., calciner) coupled with a counterflow of hydrogen and superheated steam. As the uranyl fluoride powder falls to the bottom of the disentrainment chamber, it tumbles through a slanted rotating kiln. At the discharge end of the kiln, hydrogen and superheated steam are constantly injected to form a counterflow current that passes through the kiln, the disentrainment chamber, and a set of mechanical filters on top of the chamber.

In the kiln barrel, the uranyl fluoride powder contacts the flow of hydrogen and steam to strip the remaining fluoride and reduce the uranium to UO_2 powder. Figure 5-9 illustrates this continuous flow process.

Figure 5-9. Sample of Dry Conversion (IDR) Process



The conversion kiln is maintained under positive pressure of approximately 12 inches of water by means of the off-gas system. Nitrogen purged seals (seal pressure > kiln pressure) at each end of the kiln enable rotation without loss of containment. The reduction process takes place in the kiln at temperatures in excess of 900°F. Off-gases (hydrogen, hydrogen fluoride, nitrogen, and steam) are continuously removed from the system and processed through a series of sintered metal filters. These filters are periodically blown back with nitrogen to recover entrapped uranium powder.

The above example illustrates how one facility produces UO_2 powder via the dry or IDR process. Although the concept is similar at all facilities that use this process, the exact steps and equipment may vary among facilities. For example, one plant is set up to separate uranyl fluoride powder from hydrogen fluoride gas and steam prior to calcining and reduction. In this case, hot reaction products pass from the bottom of the steam hydrolysis reactor to a primary filter for separation of powder from hydrogen fluoride gas and steam. The primary filter is either a 20-inch or 16-inch outside diameter Monel cylinder. The cylinder has a conical collecting chamber on the bottom and a plenum on top. Porous metal tube filters are mounted inside the cylinder with the tube bottom plugged and the top open to the plenum. A vacuum maintained on the plenum causes the gases to flow through the porous metal and out of the filter, depositing the entrained powder on the outside of the porous tubes. The efficiency of these filters is 99.999%.

Periodically the filter tubes are reverse-pulsed to remove the accumulated powder that then falls into the conical collection chamber. The powder is then routed through rotary air locks to the rotary kiln or to the defluorinator feed preparation unit from which the treated material passes to the kiln.

The off-gas from the top plenum of the primary filter is piped to a safe geometry secondary filter and then to a hydrogen fluoride recovery system. This generally consists of bubbling the HF gas into water to produce hydrofluoric acid.

The next step of the fuel fabrication process is the ceramic process for pellet production.

Self-Check Questions 5-3

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

defluorination
integrated dry route
sinterability
gaseous
liquid
vaporization
greater
metal filters
hydrogen
moderator
hydrolysis
reproducible

1. The dry or direct conversion process, also referred to as the_________process, is a continuous flow process that converts solid UF_6 to UO_2 powder.

2. Because the uranium is never in a liquid solution, equipment capacity is not limited by criticality concerns, because, for low-enriched uranium fuel, a___________must be present to attain criticality.

3. Advantages of the dry process include stable and____________powder characteristics, ultra-pure UO_2 powder with high____________, high product volumes with low manpower requirements, and minimal_________wastes.

4. The IDR process is divided into three steps: vaporization,__________, and defluorination/calcination.

5. The primary methods used to heat the cylinders are to place the cylinders in a _______________chamber and heat by circulating either hot water, steam, or electric heat through the chamber.

6. In the second step of the IDR process,______________UF_6 is injected into the hydrolysis reactor.

7. Complete conversion of UF_6 to uranyl fluoride is ensured when the mole ratio of steam to UF6 is___________than the stoichiometric requirement of 2.

8. The______________process involves the removal of residual hydrofluoric acid gas from the hydrolysis products, as well as the stripping of the fluoride from the uranyl fluoride powder.

9. The hydrofluoric acid gas is typically removed by using ________________to separate the powder from the gas.

10. The uranyl fluoride powder is calcined and reduced to UO_2 in the presence of _______________.

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

Learning Objective

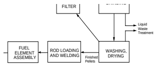
When you finish this section, you will be able to:

5.1.4 Identify the steps associated with the ceramic process conversion of UO_2 powder to pellets.

CERAMIC PROCESS: PELLET PRODUCTION

Mechanical processing involves (1) pretreating the UO_2 powder by blending, slugging, and granulating it to a desired size distribution; (2) pelletizing; (3) sintering the pellets under a reducing atmosphere; (4) grinding; (5) washing and drying the pellets; (6) loading the pellets into zircaloy tubes, and fitting and welding end caps to form fuel rods; and (7) assembling the completed fuel rods into finished fuel elements. Completed fuel assemblies are stored at the fabrication plant before being transported to the reactor. This storage area should be regarded as part of the fabrication plant. Figure 5-10 is a flow diagram for pellet production.

Figure 5-10. Pellet Production Diagram



PRETREATMENT STEPS

Conversion of Enriched UO_2 Powder to Pellets

The process to convert raw UO_2 powder, produced via the ADU, IDR, or other processes, involves several "pretreatment" steps to obtain optimal consistency of the powder prior to pelletizing and sintering. Performance of the fuel in the reactor can be influenced by the characteristics of the UO_2 powder; therefore, it is very important to control particle size distribution, density, etc., during the pellet manufacturing process. The steps typically performed to achieve the required powder characteristics for pelletizing include:

- Hammer milling
- Blending
- Slugging
- Granulating

(Slugging and granulating may also be referred to as bulk rolling.)

The resulting powder is then:

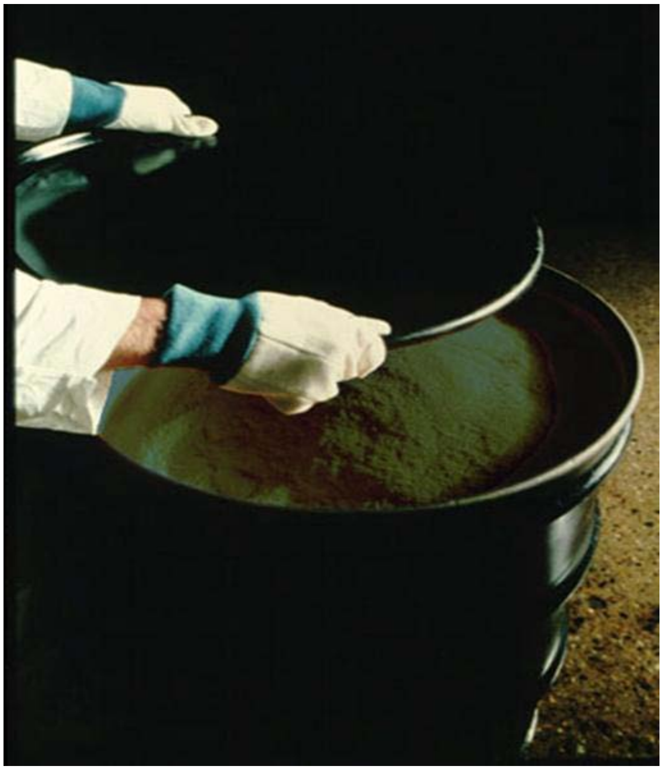
- Cold-pressed into pellets
- Sintered in a reducing atmosphere
- Ground to finished dimensions
- Pellets are washed and dried (optional)
- Pellets are given final inspection

Each of these basic steps is discussed in this section.

Hammer Milling

The hammer milling operation is performed on the raw UO_2 powder produced from the calcination process in either the ADU or IDR conversions. In the hammer mill, the powder is pulverized to break up clumps and obtain the desired small final particle size by using high-speed, rotating hammers. The hammer heads are typically cooled by the flow of nitrogen gas. The finely ground UO_2 powder is then stored in geometrically safe bins or containers prior to pretreatment for pelletization (Figure 5-11).

Figure 5-11. Typical $U0_2$ Powder



Blending

Dry UO_2 powders may be blended together or with small amounts of additives to achieve desired physical and chemical characteristics, as required by product or process specifications. Blending operations may be performed to:

- Ensure homogeneity of the UO_2 powder by distributing imperfections among a larger volume
- Adjust uranium enrichment
- Provide added flowability and/or cohesiveness to the powder for pelletizing
- Introduce die lubricant, such as stearic acid, into the powder
- Control porosity and increase the sinterability of the powder

The additives used for blending to achieve these desirable powder characteristics are typically confidential to the manufacturers.

Product samples may be taken for analysis to verify powder property requirements.

Blending operations may take place prior to slugging or following granulation, depending on the additives and/or powders being blended as well as the required characteristics of the final product. In either case, blending is performed in safe geometries that control criticality by limiting the total volume of powder in the blender or in moderation controlled areas because of the volume of powder present.

Slugging

UO_2 powder is pressed into "slugs" using low-pressure compaction equipment. At one facility, the powder is transferred to a hopper, which gravity-feeds into a press- or roll-type powder compaction unit. Although slug sizes may vary by manufacturer, one plant compacts the powder in a 2.625-inch diameter by 3-inch die cavity. The slugging operation is a ceramic process to start grain growth.

Granulating

The pressed slugs are then granulated or crushed into powder of a more uniform particle size. There are different ways to conduct the granulation process:

- Bulk blenders: (up to 1,700 kgs. of powder) are tumbled with an excentric motion; the pressure on the powder at the bottom produces the desired grain growth, and the rotation moves the pressure effect among the powder.
- Slug press-granulator: the powder is pressed into a puck (about 2.5-inches to 3-inches diameter by 1-inch thick), which is then broken up in a granulator to produce a powder that has a grain structure to it and more uniformity of the powder.
- Roll compaction-granulation: the powder is passed through two counter-rotating rollers and then to the granulator.

The powder may pass through a screening process to ensure a properly balanced particle distribution. The powder is then collected in geometrically safe containers (for criticality control) for storage prior to pelletization. Additives may be blended with the powder before pelletizing. The additive lubricates the powder so it flows through the press lines and helps hold the powder together in a "green" pellet. The additive is considered a "fugitive material" because, when the process is over, it is gone. Because additives are also moderators, control of the amount added must be strictly controlled for nuclear safety considerations.

Throughout the powder handling operations, a potential exists for a hazardous condition known as "burn back" where the highly reactive UO_2 powder oxidizes ("burns") to U_3O_8 with the concurrent damage to transfer lines and enclosures.

Direct Conversion (DC)

The direct conversion processes produce a much more uniform product that is spherical in structure. Consequently, the mill-blend-slug-granulate steps can be bypassed, although some milling is accomplished as the powder is fed to the pressing step. (This is true for the "newer" systems with better process systems; older systems still may use the mill-blend-slug-granulate steps for powder preparation.) The spherical nature of DC powder makes it harder to "stack" in green pellets; this makes the use of the binder more important. DC processes tend to handle large quantities of powder (500-kg transport containers, 5,000-kg storage containers) so moderation control is important. Some facilities have tried to make powder transfer, using nitrogen as a carrier fluid; however, these have had very limited success. Therefore, bulk powder transfers are common. BNFL (United Kingdom) has designed a pilot plant where all powder flows are by gravity with nitrogen as a "helper" to eliminate the bulk handling problem.

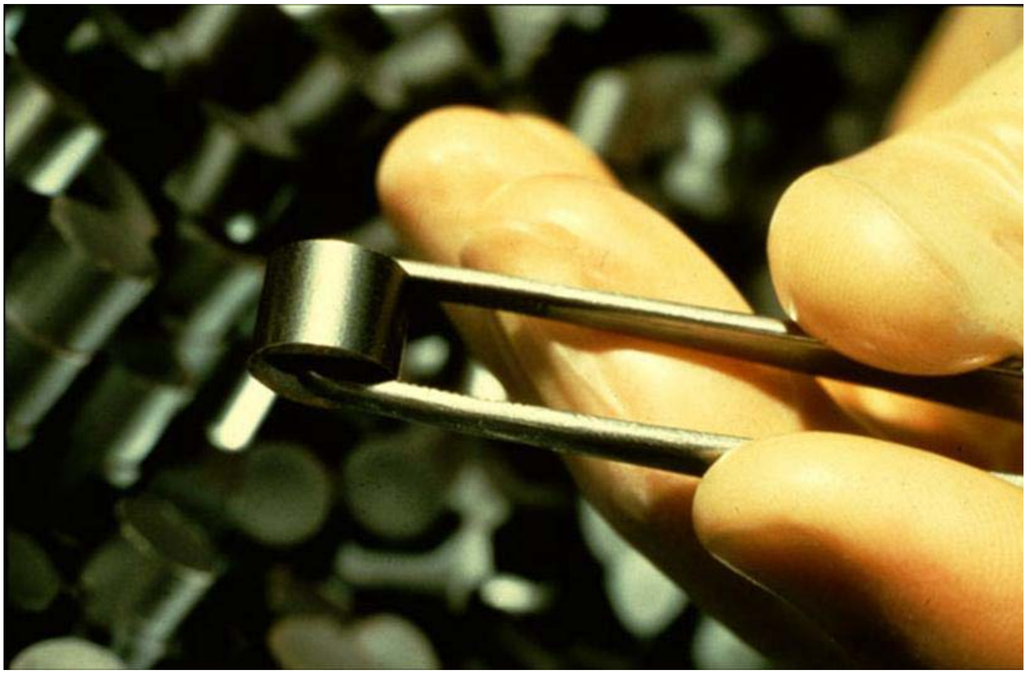
PELLET PRODUCTION STEPS

Pelletizing

After implementation of careful process controls to ensure proper particle size distribution, additive blending ratios, uranium enrichment concentrations, moisture content, etc., the powder is fed into high-speed presses where the fuel pellets are compacted. The pellets produced by this cold-compacting technique are referred to as green (unsintered) pellets. Green pellets have form and limited strength but are subject to breaking or powdering. The size and overall dimensions of the green pellets will determine the final size and density of the fuel pellet; therefore, this process is carefully controlled to ensure that pellets of uniform size and density are produced. Press pressure is about 12 to 15 tons per square inch.

Pellets are marked to identify the percentage of U-235 enrichment and then placed on molybdenum furnace boats for sintering (Figure 5-12). During sintering, the "fugitive" binder is vaporized and creates micro cracks in the ceramic structure (when the pellet is in operation in a reactor, these cracks provide a release pathway for fission gases and prevent pellet swelling or cracking). Criticality is controlled during the pellet manufacturing process by employing safe geometry transfer hoppers and lines for the powder, as well as by using a physical design for conveyors and furnace boats that limits pellet stacking to a maximum "slab" thickness. After cooling, the pellets are passed through a centerless grinder to remove extraneous material and provide a uniform diameter (grinding can be wet or dry; both methods are used).

Figure 5-12. Sample Sintered Pellets



Sintering

The sintering of pellets serves to consolidate the powder particles, resulting in shrinkage and densification of the final pellet. During this process, green pellets are placed on sintering boats, typically made from molybdenum metal, and conveyed through an electric furnace. As the boats pass through the controlled atmosphere furnace, the pellets sinter (i.e., form a coherent bonded mass without melting) to approximately 95% of the theoretical density of UO_2. The electric furnaces used to sinter the pellets operate at temperatures around 3,270°F in a hydrogen atmosphere to prevent oxidation at these high temperatures.

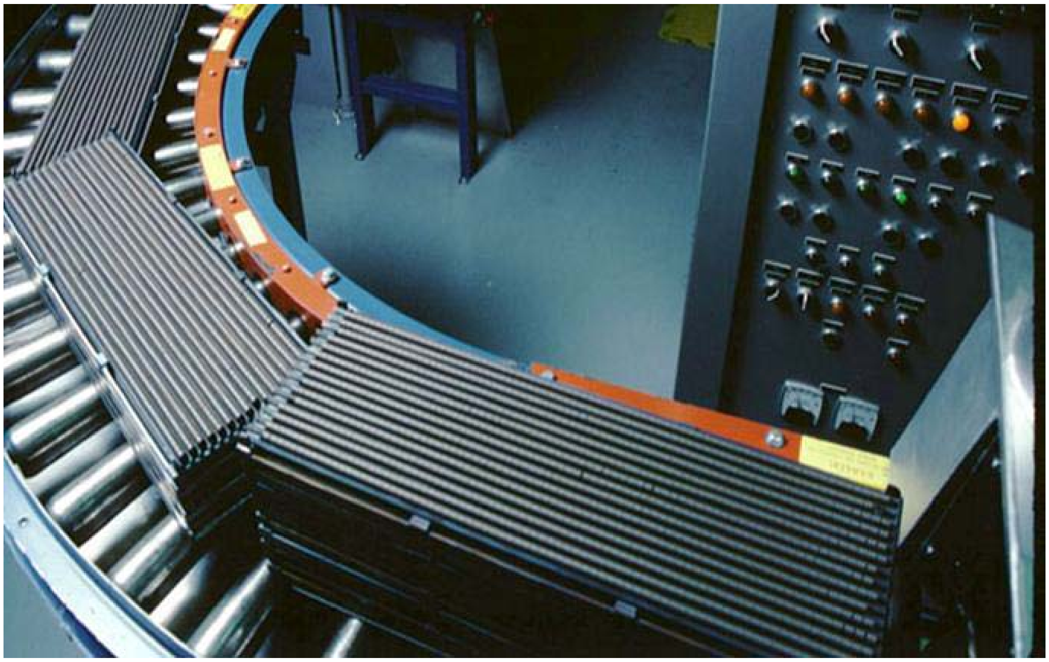
Grinding

During the pelletizing and sintering processes, pellets are intentionally formed slightly larger than the final size required for fuel rod assembly. Grinding of each pellet is performed by using centerless grinders to machine each pellet to exact dimensions. This machining, performed with diamond grit work wheels at one or more facilities, can be performed dry or using a liquid coolant. In either case, scrap materials generated during grinding are collected (dry or in slurry) for recovery and reuse.

The final machined pellets, typically about 0.5 inch in length and about 0.33 inch in diameter, are cylindrical and are "dished" slightly on each end. This end taper allows the pellets to expand and contract through drastic temperature changes inside the reactor without damaging the fuel or cladding materials. The final pellet dimensions achieved via grinding operations are critical, because cladding materials used for rods do not have the same coefficient of thermal expansion as UO_2. In particular, zircaloy has a smaller coefficient than UO_2, which means that at high temperatures the fuel pellets will expand more than the tube containing the pellets. Therefore, pellets must be precisely sized, such that the differential between the coefficient of expansion results in direct contact between the fuel and cladding at reactor operating temperatures without exerting considerable stress to either the fuel or the cladding.

During the grinding operations, criticality is controlled by limiting processes to "safe geometries." Physical barriers prevent the stacking of pellets, and pellet trays are (Figure 5-13) designed to maintain a specified distance and are perforated so they do not retain water.

Figure 5-13. Pellet Trays



Washing, Drying, and Inspection of Pellets

After the grinding operation, pellets may be washed with water or blown with air to remove any excess scrap materials and then loaded onto trays and transferred to an electrically heated dryer oven where any excess moisture is removed. Each pellet is thoroughly inspected for defects and dimensional accuracy prior to being used for fuel rod manufacture.

Here again, criticality is controlled via safe geometries that limit the proximity of pellets and pellet trays. Pellets that do not pass inspection are collected and stored for subsequent processing in the uranium scrap recovery process.

The next step of the fuel fabrication process is the mechanical process of loading UO_2 pellets into rods/assemblies.

BURNABLE POISONS

A separate pellet process is the development of burnable poisons. With the increase in fuel enrichments and longer fuel burn-up in the last few years, more fuel designs include the use of burnable poisons to aid in core physics control. Fuel assemblies may contain certain rods that are "poisoned" for core performance requirements; these may be "poison rods" or "poisoned rods." Poison rods contain no fuel and are full of the poison material. Poisoned rods contain fuel and the poison material. These poisons may be blended in the powder before pelletizing (such as gadolinia or erbium oxide) or deposited on finished pellet outer surfaces (such as zirconium diboride). Older designs used separate poison rods (containing boron carbide) in the initial core load. Early poison rods contained borosilicate glass but were subject to thermal cycle cracking, which affected the performance.

Whichever poison is used, fabrication processes for rods containing the poisons are conducted in separate areas of the plant to prevent contamination of fuel components with the poison. The poisons can be removed in the solvent extraction system (with slight process adjustments), permitting the uranium to be reclaimed and recycled.

Self-Check Questions 5-4

INSTRUCTIONS: Match the pellet production steps in column A with their description in column B. Answers are located in the answer key section of the Trainee Guide.

Column A
Pellet Production Steps

A. Hammer Milling
B. Blending
C. Slugging
D. Granulating
E. Pelletizing
F. Sintering
G. Grinding
H. Washing, Drying, and Inspection of Pellets

Column B
Description

1._____Adjusts uranium enrichment and introduces die lubricant, such as stearic acid, into the powder.

2._____Operation to start grain growth. UO_2 powder is pressed, using low-pressure compaction equipment.

3._____Performed by using centerless grinders to machine each pellet to exact dimensions.

4._____Powder is pulverized to break up clumps and obtain the desired small final particle size.

5._____Washed with water or blown with air to remove any excess scrap materials and then loaded onto trays and transferred to an electrically heated dryer oven where any excess moisture is removed.

6._____Formation of green pellets.

7._____Pressed slugs are crushed into powder of a more uniform particle size

8._____Consolidates powder particles, resulting in shrinkage and densification of the final pellet.

9. What poisons may be blended in the powder before pelletizing to form poison pellets?

10. What precautions should be taken in the fabrication of fuel components to prevent contamination with poisons?

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

Learning Objective

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

5.1.5 Identify steps encountered in the mechanical process of loading UO_2 pellets into rods/assemblies.

MECHANICAL PROCESS: LOADING OF UO_2 PELLETS INTO RODS/ASSEMBLIES

The fuel pellets produced from the ceramic processes must be placed in tubes made of suitable cladding materials and assembled into specified configurations for use in power reactors. The cladding material protects the pellets from the reactor coolant while containing the fission products within the fuel element. The cladding and fuel pellets form fuel rods, which are configured into arrays for the production of fuel assemblies.

The cladding material used for the fuel rods is critical to fuel efficiency. Several requirements of the cladding material are:

- Capable of withstanding high temperature, pressure, and radiation over a long period of time
- Nearly transparent to neutrons (e.g., low thermal neutron cross-section)
- Provide adequate structural stability at thicknesses thin enough to minimize neutron resistance
- Excellent resistance to corrosion in the harsh reactor environment

Certain stainless steels and zirconium alloys have been shown to provide the best properties for fuel cladding. The material most commonly used to manufacture fuel rods for use in commercial power reactors is zircaloy (Zircaloy 2 for boiling water reactors [BWR], Zircaloy 4 for pressurized water reactors [PWR]). Tubing made from zircaloy is fabricated from ingots produced to exacting specifications relative to metallographic characteristics and dimensions. The basic steps encountered during the loading and assembly operations are:

- Cleaning/Inspection of Tubing
- Lower End-Plug Welding
- Pellet Loading
- Upper End-Plug Welding
- Laser Drilling

- Helium Charge
- Final Weld
- Helium Testing
- Inspection
- Fuel Assembly
- Inspection/Storage
- Loading of Shipping Container

Each of these steps is discussed below.

Cleaning/Inspection of Tubing

Each tube is thoroughly inspected by using nondestructive examination (NDE) techniques, such as eddy current or ultrasonic tests. Obviously, complete integrity of the tube is required to minimize the potential for failure/rupture during reactor operation.

Lower End-Plug Welding

Before each tube is loaded with enriched UO_2 pellets, an end plug that has been precision-machined of zircaloy is inserted in one end, using an air cylinder at low pressure. The insertion results in a press fit between the plug and the tube. The plug is then welded automatically in place by using electronically programmed tungsten-inert gas welding equipment to seal the end of the tube.

Pellet Loading

Uranium fuel pellets are inserted into the zircaloy tubes at the loading station. Prior to insertion, pellet stack lengths are determined based on design specifications. At one commercial facility, pellet trays are transferred to rod loading fixtures. The fuel pellets are placed in fuel rod mock-up channels, prior to loading into empty fuel rods. Trays of rods are then transported to a drying oven to remove any excess moisture. The rods are heated at temperatures in excess of 250°F in an inert atmosphere. Criticality is controlled via plant layout/design consideration by not allowing pellets or rods to stack (or be collected together) greater than a specified thickness, based on enrichment of the UO_2.

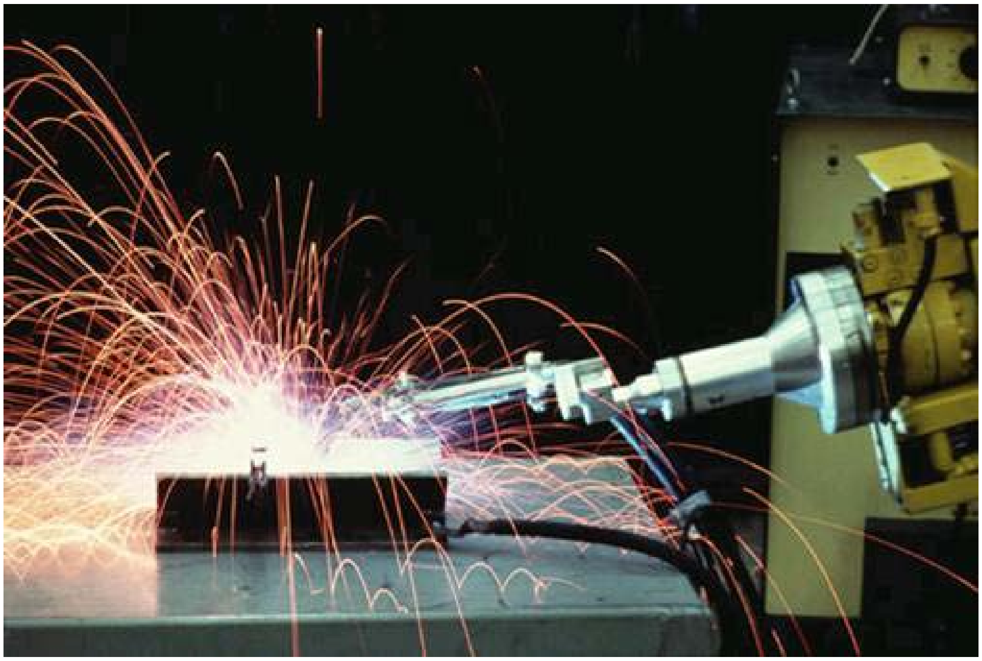
Upper End-Plug Welding

Prior to the insertion of the top end plug (also made of zircaloy), a spring is typically inserted into the fuel rod to prevent movement of the fuel column during handling and shipping. The void space at the top of the fuel rod between the fuel and the end plug allows for fission gas accumulation and axial thermal expansion of the fuel column. Following insertion of the end plug by low-pressure air cylinder, the plug is girth welded automatically, using programmed welding equipment (Figure 5-14).

Laser Drilling

After the plug is welded, a hole is "drilled" in the plug with a laser.

Figure 5-14. Seal Rods



Helium Charge

Each rod is then evacuated of all air and backfilled with helium at a specified pressure in order to minimize compressive clad stresses and creep due to coolant operating pressures.

Final Weld

The hole in the plug is then laser welded to close the hole.

Helium Testing

Each rod is thoroughly tested to verify that it is perfectly leak-tight. One method used to test for leaks is to place the rods in a chamber designed to be evacuated of all air. Defective welds are then detected by monitoring for the presence of helium inside the sealed chamber.

Inspection

The fuel rods are then transported to an area where they are thoroughly inspected for defects. All welds are x-rayed and/or checked by other NDE methods to verify integrity. Each rod also receives 100% dimensional and visual inspection. Welds are thoroughly checked for burrs, pits, cracks, gouges, discoloration, and other imperfections. Each rod is inspected (rolled on a flat table) to make sure that it is perfectly straight and that it did not get bent or bowed during the manufacturing process see Figure 5-15, Visual Inspection of Rod Ends. In addition, all dimensions are verified and the rods are weighed to ensure that each rod contains the specified amount of uranium. Rods are also tested by using neutron interrogation to check enrichment and proper pellet loading.

Completed fuel rods are stored on racks while awaiting assembly. These specially designed racks prevent criticality through spacing and by limiting the number of the rods per storage rack.

Figure 5-15. Visual Inspection of Rod Ends

Fuel Assembly

In this section, typical fabrication steps are described for a PWR fuel assembly. Figure 5-16 illustrates the basic fuel assembly components for a pressurized water reactor. It is important to note that fundamental differences between PWR and BWR designs result in different fuel assembly configurations for these two types of plants. See Figures 5-17, 5-18, and 5-19.

Figure 5-20 illustrates some of the differences between PWR and BWR assemblies. For reference, Figures 5-21 and 5-22 are provided to illustrate typical BWR fuel assembly details. The remaining portion of this section refers specifically to the fabrication of PWR assemblies.

Figure 5-16. PWR Fuel Assembly

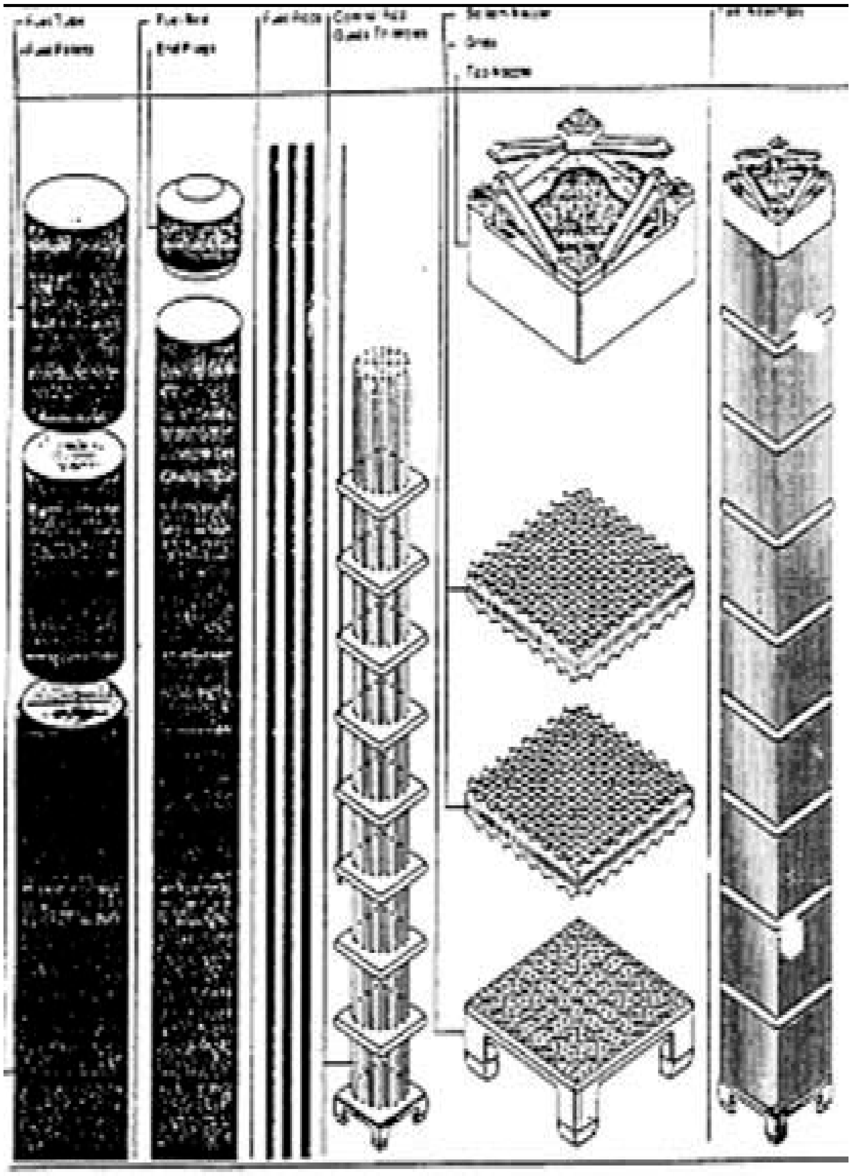


Figure 5-17. PWR Assembly

Figure 5-18. BWR Assembly

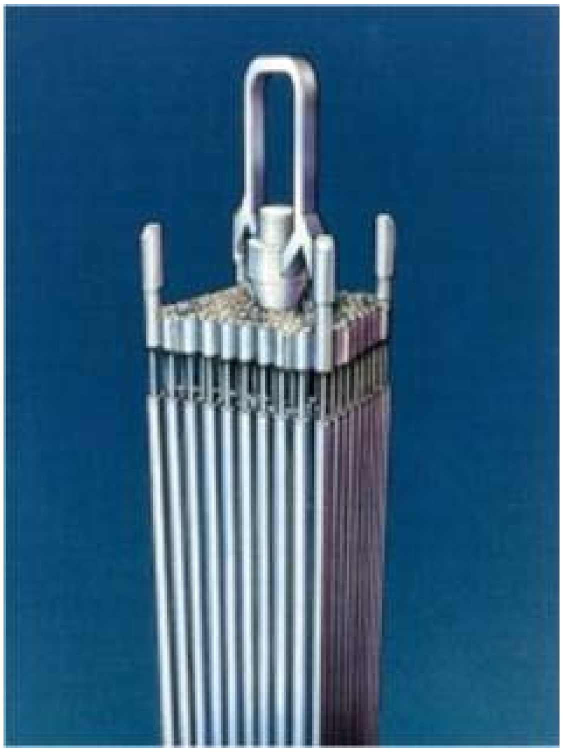
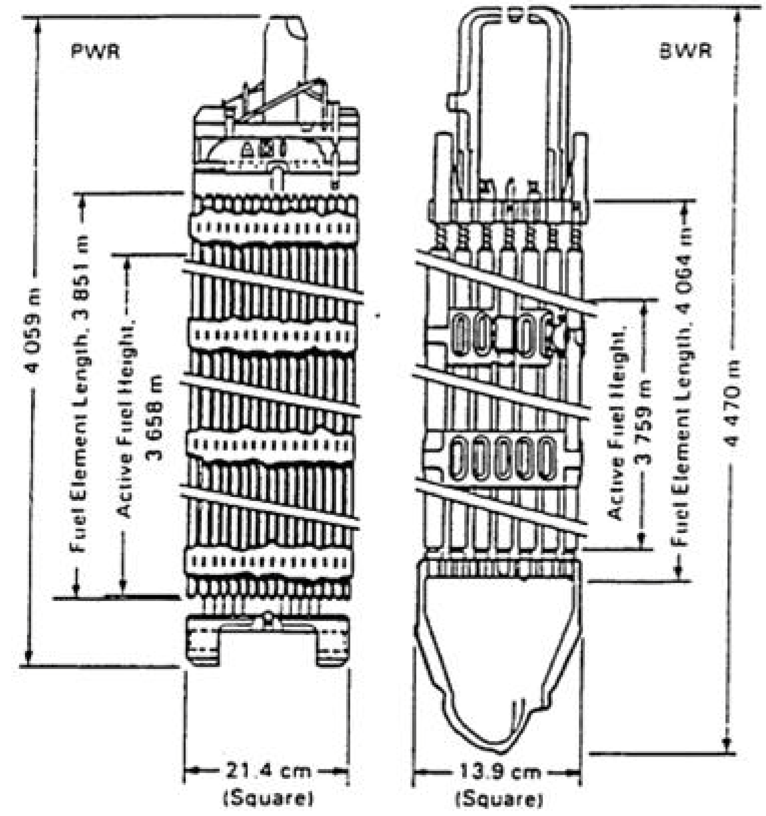


Figure 5-19. PWR/BWR Assemblies

Figure 5-20. Typical LWR Fuel Assemblies



	PWR	BWR
Fuel element array	17 x 17	8 x 8
Assembly total weight, kg	657.9	319.9
Uranium/assembly, kg	461.4	188.7
UO_2/assembly, kg	523.4	208.0
Zircaloy/assembly, kg	108.4(a)	99.5(b)
Hardware/assembly, kg	26.2(c)	12.4(d)
Total metal/assembly, kg	134.6	111.9
Fuel element OD, cm	0.950	1.252
Fuel elements/assembly	264	63
Nominal volume/assembly, m^3	0.186(e)	0.864(e)

(a) Includes Zircaloy control-rod guide thimbles.
(b) Includes Zircaloy fuel-element spacers and fuel channel
(c) Includes stainless steel nozzles and Inconel-718 grids
(d) Includes stainless steel tie-plates, Inconel springs and plenum springs.
(e) Based on overall outside dimension

Figure 5-21. BWR Fuel Assembly Schematic

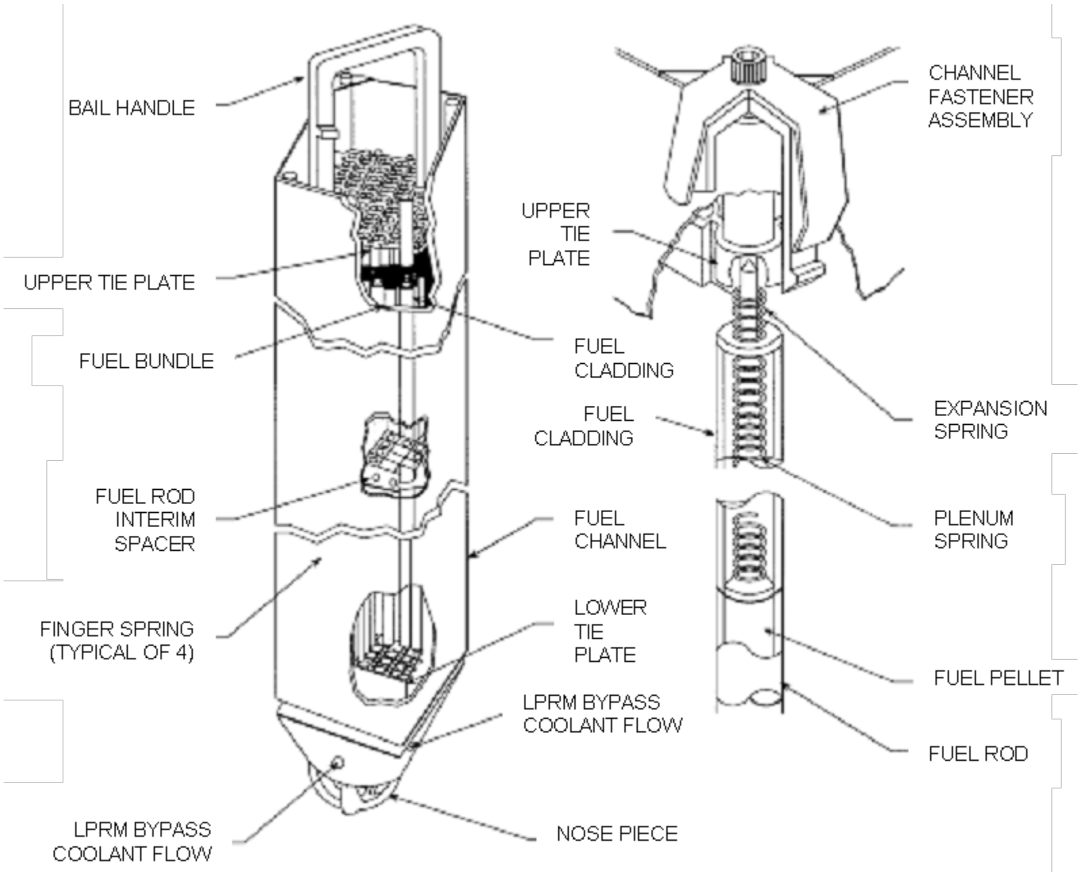
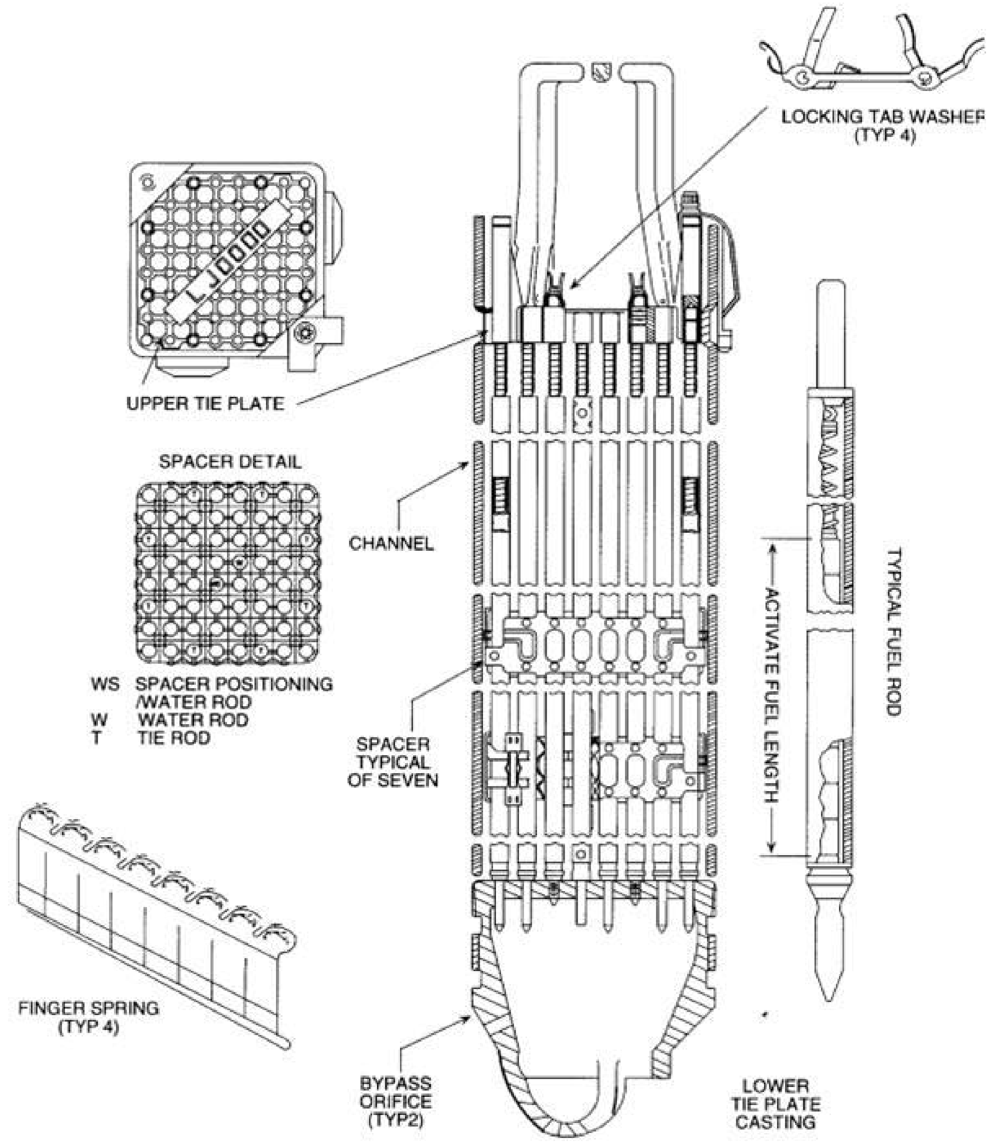


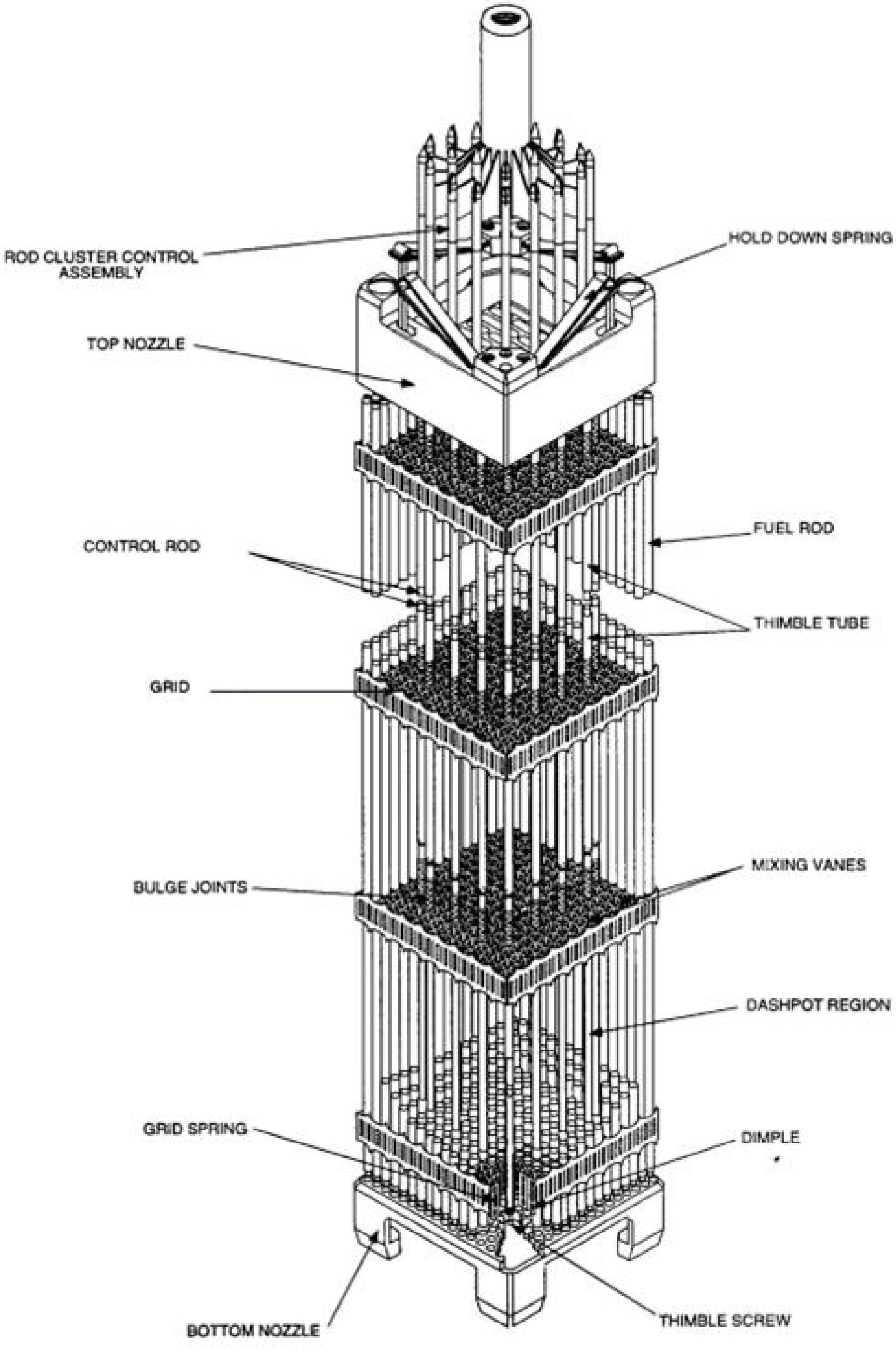
Figure 5-22. BWR Fuel Assembly Details



To configure the fuel rods into a completed fuel assembly, a skeleton assembly is first constructed consisting of a bottom nozzle, control rod guide thimble tubes, and a series of spacer grids. The skeleton assembly provides the framework that will eventually contain up to 264 full rods, based on a 17 x 17 array. Most PWR designs utilize arrays ranging from 14 x 14 to 17 x 17 fuel rods per assembly (BWRs typically utilize arrays ranging from 6 x 6 to 9 x 9), but newer designs include 11 x 11 or 13 x 13. See Figure 5-23, Spacer BWR Grid. A typical 17 x 17 PWR fuel assembly is shown in Figure 5-24.

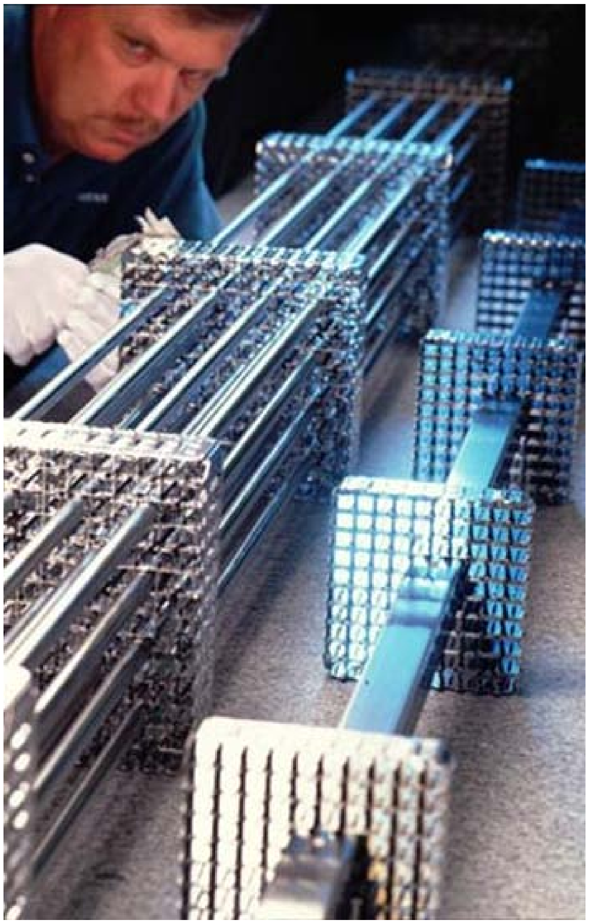
Figure 5-23. Spacer BWR Grid

Figure 5-24. Typical PWR 17 x 17 Fuel Assembly



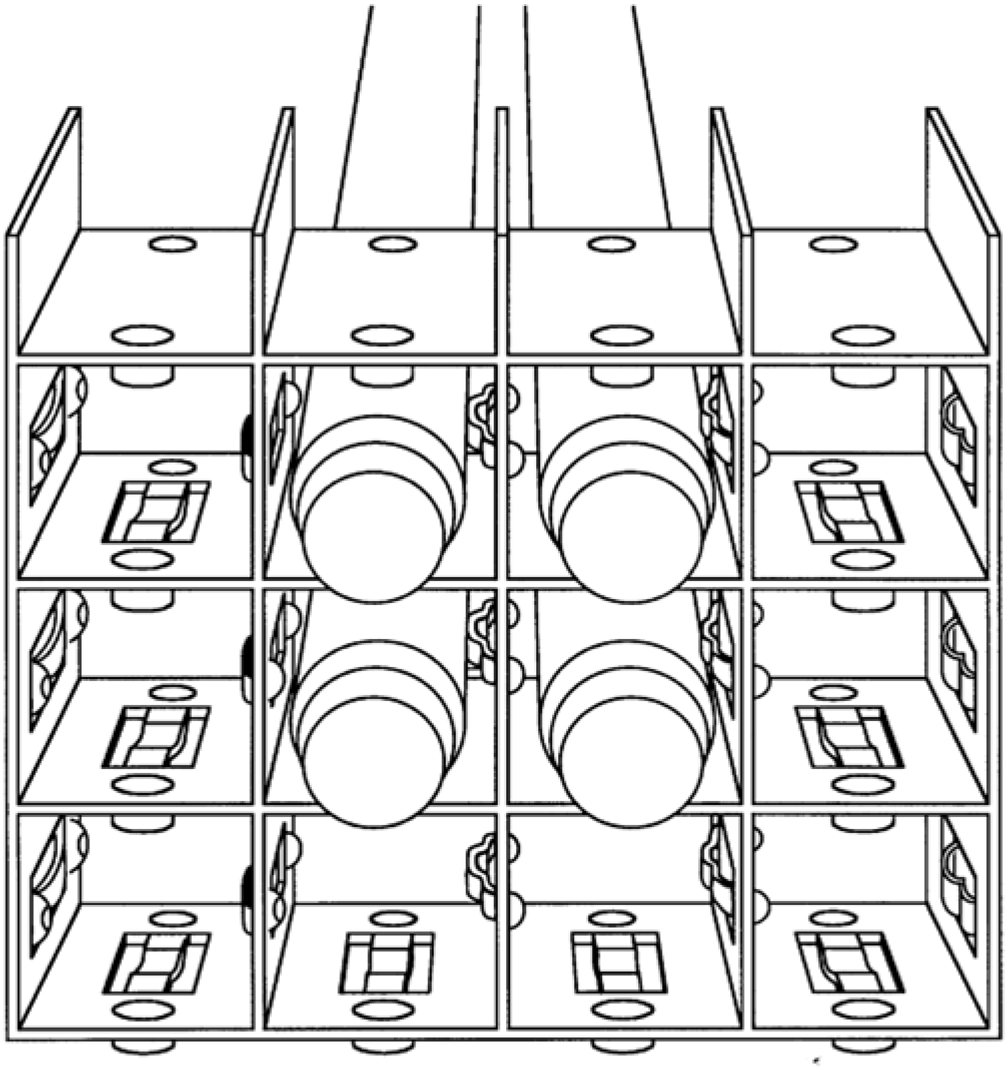
In forming skeleton assemblies, see Figure 5-25, the process starts with the placement of the control rod guide thimbles and instrument tubes into a predetermined number of spacer grids. The grids are designed to maintain a consistent distance between the fuel rods and the position where the control rods are inserted (i.e., the control rod guide thimbles) to regulate the reaction through the use of neutron-absorbing poisons. The grids also create turbulence in the water that carries the heat generated during the fission process. The number and distance between grids vary based on specific design parameters.

Figure 5-25. Skeleton Assemblies



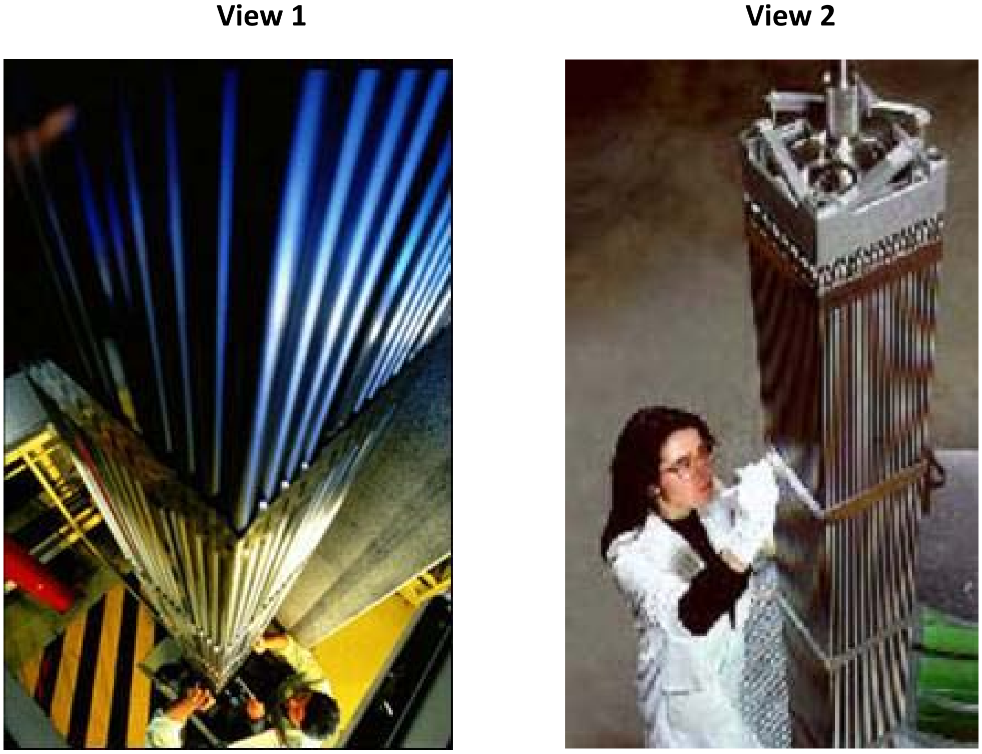
The grids are typically made from zircaloy or Inconel and are produced from individually unclad and formed grid straps. Punch presses from 65 to 150 tons are used to punch-press the straps that make up each well of the grid assembly. Following punching operations, the straps are then assembled and brazed. The straps contain a combination of springs and support dimples, as shown in Figure 5-26, to laterally support each fuel rod at approximately eight grid assembly locations. The grids are laser welded at each intersection for strength. Upon completion, each grid is subjected to more than 800 individual measurements during inspection for quality and dimensional accuracy.

Figure 5-26. Detail of Grid Assembly



Following placement of the guide tubes into the space grids, the skeleton is completed by attaching the bottom nozzle to the guide tubes, using weld-lock screws. The bottom nozzle is typically constructed of stainless steel and serves as the bottom structural element of the fuel assembly. When the skeleton is completed, it is thoroughly inspected to verify dimensions, welds, and other safety and integrity criteria. See Figures below.

Figure 5-27. Visual Inspection



View 1 **View 2**

Note: With automated loading techniques, the lower nozzle plate is installed <u>after</u> the fuel rods are loaded into the grid.

During the final assembly operations, fuel rods are inserted into the skeleton assembly by inserting each rod through the appropriate spacer grids. The rods are inserted so that when the top nozzle is attached to the assembly, there is clearance between the ends of the fuel rods and the top and bottom nozzles. The top nozzle is attached to the completed fuel assembly (following fuel rod loading) by welding the nozzle's adapter plate to the control rod guide thimbles. Finally, the top nozzle is stamped to show the proper location and orientation of the fuel assembly in the reactor.

Inspection/Storage

Following assembly operations, the fuel assembly is washed and inspected. Quality control checks are run on channel measurements (the spacing of the fuel rods in the final assembly), the envelope of the final assembly, and the overall length and visual appearance of the assembly.

Assemblies are stored in special racks that maintain minimum separation and preclude water accumulation.

Loading of Shipping Container

Upon final acceptance of the fuel assembly, the units are packed in an NRC- and Department of Transportation (DOT)-approved shipping container for transfer to a utility power reactor site. The assembly is shock-mounted so that damage does not occur during transport to the customer. Transport to an electrical utility power site is usually by truck.

At the site, new fuel assemblies are inspected and loaded into the reactor core, where the U-235 in the fuel fissions produces heat for electric power generation.

Self-Check Questions 5-5

INSTRUCTIONS: Match the mechanical process steps in column A with their description in column B. Answers are located in the answer key section of the Trainee Guide.

Column A **Mechanical Process Steps**	**Column B** **Description**
A. Cleaning/Inspection of Tubing	1._____Each rod is evacuated of all air and backfilled with helium at a specified pressure.
B. Lower End-Plug Welding	2._____Each rod is thoroughly tested to verify that it is perfectly leak-tight.
C. Pellet Loading	3._____Each tube is thoroughly inspected by using nondestructive examination techniques, such as eddy current or ultrasonic tests.
D. Upper End-Plug Welding	4._____To configure the fuel rods into this, a skeleton assembly is first constructed, consisting of a bottom nozzle, control rod guide thimble tubes, and a series of spacer grids.
E. Laser Drilling	5._____The hole in the plug is then laser welded to close the hole.
F. Helium Charge	6._____Prior to the insertion of the top end plug, a spring is typically inserted into the fuel rod to prevent movement of the fuel column during handling and shipping.
G. Final Weld	7._____Assemblies are stored in special racks that maintain minimum separation and preclude water accumulation.

H. Helium Testing
I. Inspection
J. Fuel Assembly
K. Storage
L. Loading of Shipping Container

8.____Uranium fuel pellets are inserted into the zircaloy tubes at the loading station.

9.____Before each tube is loaded with enriched UO2 pellets, an end plug that has been precision machined of zircaloy is inserted in one end, using an air cylinder at low pressure.

10.____After the plug is welded, a hole is "drilled" in the plug with a laser.

11.____Upon final acceptance of the fuel assembly, the units are packed in an NRC- and DOT-approved shipping container for transfer to a utility power reactor site.

12.____Each rod is rolled on a flat table to make sure that it is perfectly straight and that it did not get bent or bowed during the manufacturing process.

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

Learning Objective

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

5.1.6 Identify steps encountered in the scrap recovery process.

SCRAP RECOVERY

Scrap recovery operations involve the recovery and reuse of uranium by-product materials generated during virtually all phases of the fuel fabrication process. Waste materials that are typically recycled to recover the uranium for reuse include:

- Off-specification pellets
- Solids residue/cleanout from chemical conversion processes (ADU, UO_2, U_3O_8)
- Filter blowback
- Machined scrap from grinding operations
- Dust collected during hammer milling and granulating, other collection processes

Waste/scrap materials are typically collected throughout the facility for batch processing. As illustrated in Figure 5-28, representing one commercial facility's scrap recovery process operations, input materials may require different process steps, depending on the initial waste stream characteristics.

The major process flow path typically used to recover uranium from off-specification pellets and the chemical, ceramic, and mechanical conversion processes follow the same processes as described earlier in this module.

The primary steps to recover uranium from the fabrication process, following collection and/or pretreatment from various waste processing systems, include:

- Head End Treatment
- Acid Dissolution
- Filtration
- Solvent Extraction
- Uranium Concentration
- Return of Uranium to Powder Production

These processes as shown in Figure 5-29, illustrate the uranium recovery and waste treatment operations at a commercial fuel fabrication facility. Each of the basic steps is discussed in this section.

Figure 5-28. Typical Scrap Recovery Process Operations Flow Sheet

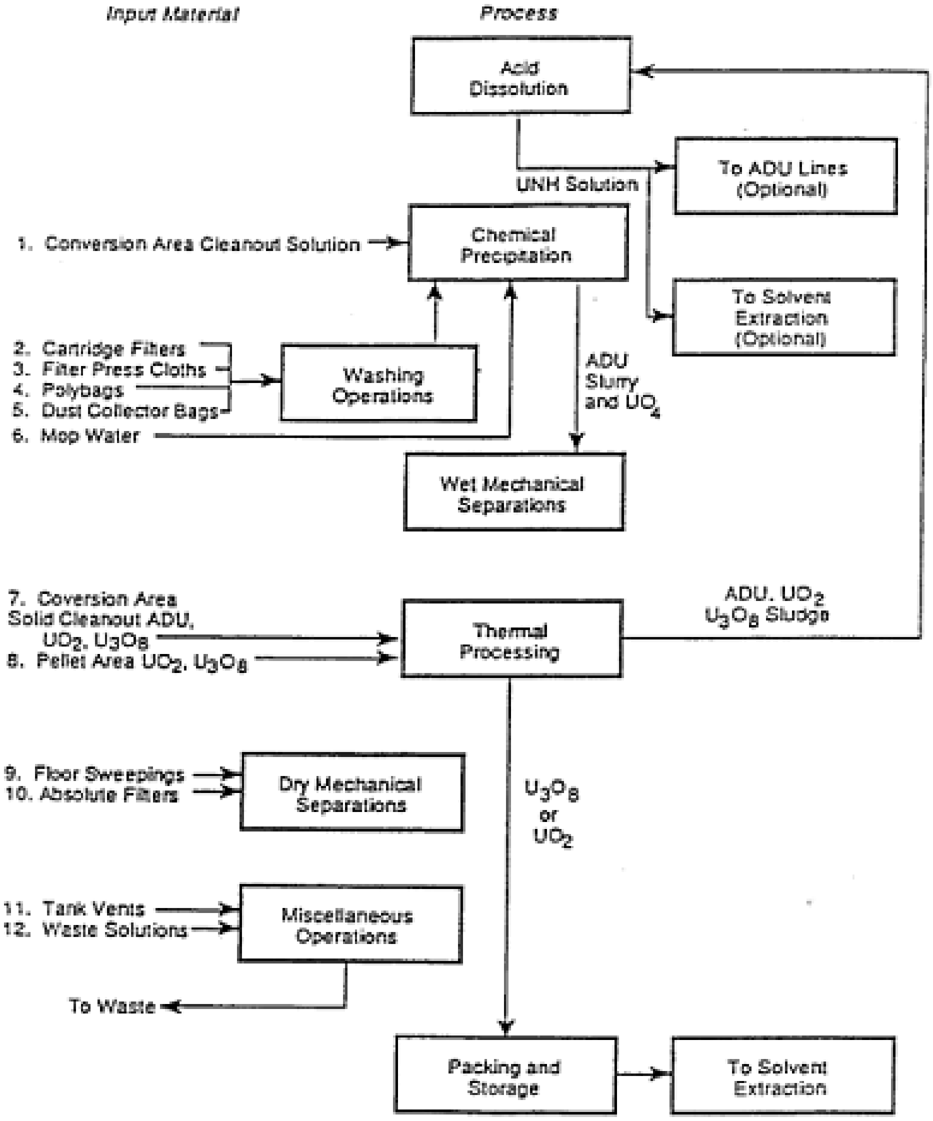
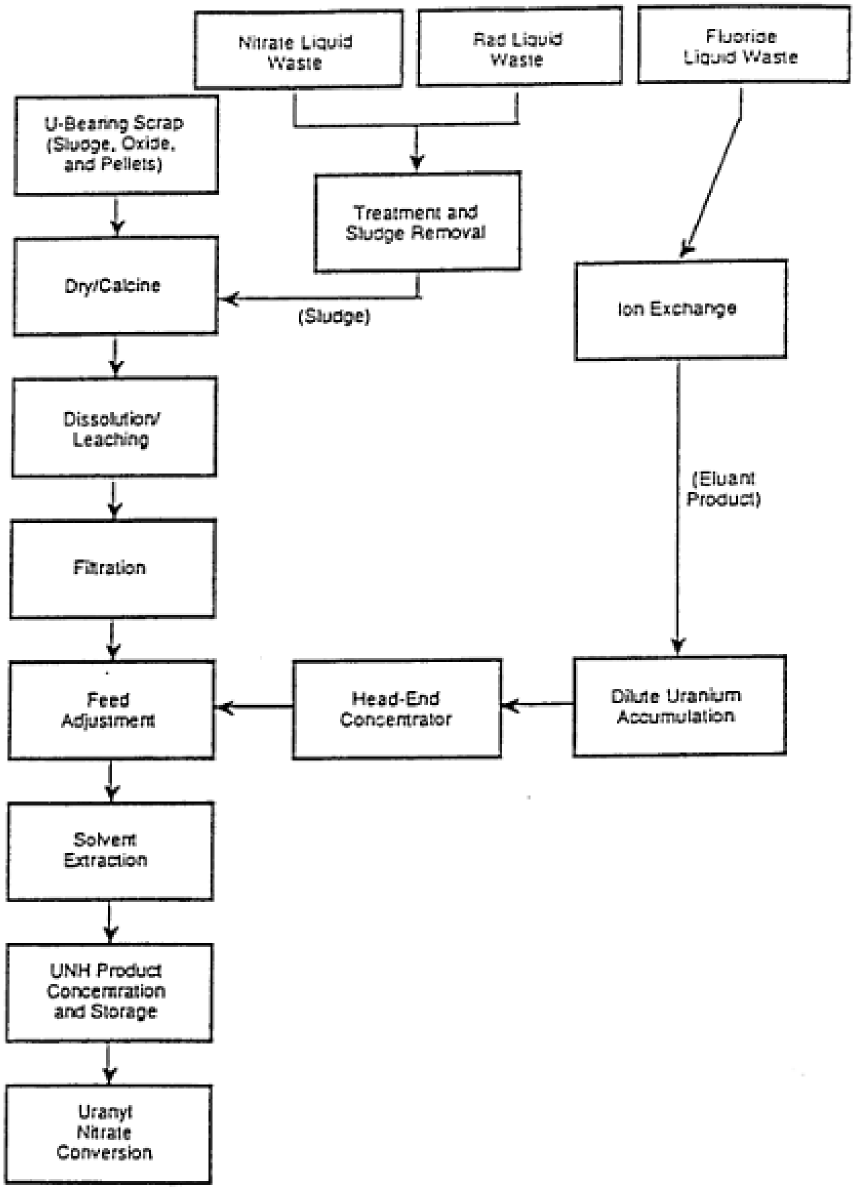


Figure 5-29. Uranium Recovery and Waste Treatment Operations



Head End Treatment—Dry/Calcine

Prior to acid dissolution and solvent extraction operations to recover and convert the uranium into a form suitable for recycle, uranium-bearing scrap materials (wet sludges and dry powder/pellets) are roasted in an oxidation furnace. This initial treatment serves to remove impurities, such as volatile materials and excess moisture. The oxidation process converts the UO_2 to U_3O_8, which is more easily dissolved. A muffle furnace, or an externally heated furnace where the walls radiate heat for the contents of the chamber, is used for this application at one commercial facility.

All scrap, prior to transfer to the oxidation furnace, is packed in 3- or 5-gallon geometrically safe metal cans. The cans are then transported to the scrap recovery input conveyors by special transport carts or pallets. The cans are conveyed one at a time to a boat dump hood where the contents are dumped into open furnace boats. Each furnace boat is designed to hold one can of scrap. The boats are loaded into the furnace one at a time and are cycled through the process via enclosed conveyors or pushed through with a ram.

As each boat exits the furnace, it can be routed to one of two enclosed stations to either inspect the contents of the boat for tramp metal or dump the oxidized scrap into a safe geometry delumper, which then discharges to a roll crusher. The roll crusher discharges the crushed scrap into 3- to 5-gallon cans, which are automatically weighed during filling operations to limit the contents of each can to a safe mass. The crushing process aids in the dissolution of the oxidized scrap materials.

Acid Dissolution

Acid dissolution of oxidized scrap materials is typically carried out in stainless steel tanks (which may or may not be lined for corrosion resistance) by using a nitric acid solution. The dissolution process results in a crude uranyl nitrate solution (see equation below), which is then typically filtered and processed by solvent extraction to produce a product more suitable for recycle.

$$U_3O_8 + 8\,HNO_3 \longrightarrow 3UO_2(NO_3)_2 + 2NO_2 + 4H_2O$$

For wastes containing high fluorides, aluminum nitrate may be added to complex the fluorides and protect the vessel welds.

At one commercial facility oxidized scrap, in safe geometry containers, is dumped into the dissolution tank in an automated process that controls the dumping sequence, chemical additives, ventilation, temperature, pumping operation, and other parameters to ensure safe and proper dissolution.

Nitric acid vapors generated during dissolution are vented from the tank, through deentrainment pads and then fed into a condenser. The majority of these vapors are condensed in the condenser and routed back to the dissolution tank for reuse. Normally, condensed vapors contain such a weak acid that they are used as dilution water or are routed to the nitrate waste system for disposal.

Filtration

The crude uranyl nitrate (UN) solution UO_2 $(NO_3)_2$ generated during the dissolution process contains some insoluble solids. The solution is pumped from the dissolution tank to a filtration unit to remove the suspended solids. The separation is performed by using either a centrifuge or a filter press or by using a mechanical in-line filter or a pressure filter. In any case, solids are filtered out and the filtrate is pumped to a feed adjustment tank. There, uranium and nitric acid concentrations are adjusted before being used as feed to the solvent extraction process.

Solvent Extraction

The solvent extraction process is used to remove dissolved impurities from the uranium-bearing solutions resulting from acid dissolution and filtration operations. Solvent extraction process equipment includes an extraction column, scrub column, and stripping column. The functions of the three columns are to extract the bulk of the uranium nitrate from the feed, scrub the uranium-bearing solvent with water, and then strip the uranium back into the aqueous phase. The solvent most often used for this process is tri-butyl phosphate (TBP) in high purity organic.

In one representative process, uranium is extracted from the acidified feed solution in an eight-inch safe diameter column containing spaced sieve plates and pulsed by a piston pump. The high enriched uranium (HEU) plant has two-inch and four-inch columns, whereas a low enriched uranium (LEU) plant uses eight-inch columns. The extracting solvent is a TBP mixture.

Solvent extraction columns used at various facilities vary in height; however, they are generally in the 25 to 35 foot range. Some small diameter columns have been as high as 46 feet.

Solvent extraction systems can be operated with the columns full of organic, aqueous, and/or a combination solution. A typical combination system operates with the strip and scrub columns full of organic and strip column full of water.

The uranium-bearing nitric acid stream (the "heavy" stream with a specific gravity of about 1.3) is introduced near the top of the column, while the organic stream (the "light" stream with a specific gravity of about 0.85) is introduced near the bottom of the column. Within the column are sieve plates (perforated plates) with about two to six inch separation between plates. Due to the difference in the specific gravities, the two solutions pass through each other, but the sieve plates break up the flow and promote mixing. Imposed on this process is pulsing created by a positive displacement (piston) pump. The plates and the pulsing promote intimate mixing of the streams, which promotes transfer of the uranyl nitrate from the aqueous to the organic through the formation of a "coordination complex." The spent acid feed (uranium depleted, but containing impurities and the uranium progenys) collects in a zone at the bottom of the column and is released as aqueous waste ("raffinate"). The uranium-rich organic collects at the top of the column and overflows to the scrub feed tank.

In the scrub column, the same process occurs: aqueous in the top and organic in the bottom. The scrub solution may be deionized water or a very weak nitrate solution. The scrub removes any acid feed carryover and returns it to the strip column. The organic again overflows to the strip feed tank. In the strip column, the organic counter-flows with deionized water. The process chemistry is such that the uranyl nitrate is transferred to the aqueous stream. The aqueous stream goes for recovery of the uranium. The organic stream goes back to a storage tank for reuse.

Uranium Concentration

The solvent extraction process results in a pure, dilute uranyl nitrate solution. This solution is then fed to a product concentrator to concentrate the uranyl nitrate by evaporating excess water from the solution. In this concentration, low-pressure steam is used to percolate the uranyl nitrate solution to the desired concentrations. Product density is automatically monitored and controlled by throttling the steam supply valve.

Return of Uranium to Powder Production

The process describes conversion of scrap materials in uranyl nitrate; however, uranium-bearing materials can be chemically decontaminated, returned to the process cycle, and converted to uranium dioxide.

The uranyl nitrate solution that is recovered is typically precipitated to ADU with ammonium hydroxide (NH4OH), according to the following reaction:

$$2UO_2(NO_3)_2 + 6NH_4OH \longrightarrow (NH_4)_2U_2O_7 + 3H_2O + 4NH_4NO_3$$

The precipitation is performed in a geometrically safe tank. The ADU slurry is converted to uranium dioxide powder by the same calcination process discussed earlier in this module for ADU.

Self-Check Questions 5-6

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

1. What waste materials are typically recycled to recover the uranium for reuse?

2. Prior to acid dissolution and solvent extraction operations to recover and convert the uranium into a form suitable for recycle, uranium-bearing scrap materials are roasted in an oxidation furnace. Why is this initial treatment done?

3. Acid dissolution of oxidized scrap materials is typically carried out in stainless steel tanks using what kind of solution?

4. For wastes containing high fluorides, what may be added to complex the fluorides and protect the vessel welds?

5. How are suspended solids removed during the dissolution process?

6. Why is the solvent extraction process used?

7. What does solvent extraction process equipment include and what are their functions?

8. What is the solvent most often used in the solvent extraction process?

9. In uranium concentration, is low- or high-pressure steam used to percolate the uranyl nitrate solution to the desired concentrations?

10. What happens to uranyl nitrate solution that is recovered?

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

Learning Objective

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

5.1.7 Identify radiological and nonradiological hazards associated with fuel fabrication processes.

5.1.8 Describe administrative and engineering controls and preventive measures for fuel fabrication processes.

5.1.9 Describe key contributing factors for fuel fabrication process accidents.

ACCIDENTS

Potential accidents at fuel fabrication facilities include both typical industrial mishaps and those involving radiation. Fabricating fuel for nuclear reactors involves the chemical processing of enriched uranium. The major radioactive materials at the facilities are UO_2, used to form the fuel pellets, and UF_6. The low-enriched uranium used at most of the facilities has a low specific activity. Except for the potential for rupture of UF_6 cylinders or criticality accidents, the environmental impacts from postulated accidents at a fuel fabrication facility should be similar to those of a large manufacturing facility with a large nonradioactive chemical inventory.

In the design of fuel fabrication plants, internal safety hazards (such as fires, explosions, releases of UF_6, and criticality accidents) have to be considered. Adequate precautions must be incorporated in the design to reduce the probabilities of these accidents to an acceptable level. Of equal importance is the safe and reliable operation of the facility, because operational experience clearly indicates that nonroutine operations and human error are main contributors to incidents.

The main hazards to personnel during normal plant operations are associated with the following:

- The potential inhalation of fine uranium oxide particles when working with powders
- Exposure to external radiation during fuel inspection and storage

Chemical Hazards

Fuel fabrication facilities characteristically have large, diverse inventories of hazardous chemicals and thus the greatest potential for major accidents with serious consequences; however, the potential for off-site releases of these hazardous chemicals is either nonexistent or extremely low because of the characteristics of the individual chemicals, the processes used, or the small quantities involved.

A typical hazardous materials inventory for a fuel fabrication facility would include the following:

- Uranium hexafluoride (UF_6)
- Hydrofluoric acid (HF)
- Ammonium hydroxide (NH_4OH)
- Anhydrous ammonia (NH_3)
- Nitric acid (HNO_3)
- Propane (LPG)
- Diesel and gasoline
- Sodium hydroxide (NaOH)

UF_6 gas is a hazard because of its radiological toxicity and the chemical properties of its hydrolysis products. Therefore, consequences are assessed by evaluating the resultant downwind radiation dose and HF concentrations.

The dose rates in Table 5-6 result primarily from beta radiation from the decay products at fuel cycle facilities.

Table 5-6. Beta Surface Dose Rates From Equilibrium Thickness of Uranium Metal and Compounds

Source	Surface Dose Rate* (mrad/hr)
Natural uranium metal slab	**233**
UO_2	**207**
UF_4	**179**
$UO_2(NO_3)_2 6H_2O$	**111**
UO_3	**204**
U_3O_8	**203**
UO_2F_2	**176**
$Na_2U_2O_7$	**167**
***Beta surface dose rate in air through a polystyrene filter 7 mg/cm^2 thick.**	

The chemical toxicity of UF_6 is a greater concern than its radiological hazard. The potential release of UF_6 as the result of a process upset and/or accident is the primary risk to workers at all fuel cycle facilities. UF_6 is a corrosive poison. Exposure to UF_6 and associated HF can result in skin burns and lung impairment. The inhalation of fumes for more than a few breaths may result in lung impairment soon after the exposure and, in some instances, mild but repairable kidney damage within a few days.

Fuel fabrication facilities use or generate a number of nonradiological chemicals that can be released to the air and potentially cause off-site impacts. These include fluorides, ammonia, and nitrogen oxides, which are discussed separately below.

Fluorides: There are no federal ambient air standards for fluorine, but the Occupational Safety and Health Administration (OSHA) has established permissible exposure limits for fluorides. Time weighted averages over an eight-hour period are 2,500 μg/m^3 for fluoride dust and 2,000 μg/m^3 for hydrogen fluoride. Typical stack emission concentrations are 2 μg/m^3 from fuel manufacturing and 460 μg/m^3 from fuel components. Annual averages at the nearest property lines from normal operations at one fuel fabrication facility are calculated to be 0.005 μg/m^3 and 0.75 μg/m^3, respectively. These levels are far below OSHA limits and are insignificant from a human health perspective.

Ammonia: Ammonia may be used in some of the facilities in such processes as steel nitriding in the service components operations; it is released from the stacks in small amounts. Exposures to ammonia are more significant when coming from bulk handling systems. Exposures to workers may result from spills, leaks, and venting of storage tanks. Typical emissions of 16 lb/hr will result in a calculated nearest fence- line concentration of 0.2 ppm ammonia. This is far below the threshold level of 50 ppm for detection of ammonia odor and OSHA's short-term or 15-minute exposure limit of 35 ppm or 24 mg per cubic meter.

Nitrogen oxide: Off-gases from the dissolution of uranium compounds in nitric acid contain nitrogen oxide and are treated by absorber systems to convert the NOx to usable nitric acid. System efficiencies are greater than 90%; fence-line concentrations (NO_2) are estimated to be about 0.004 ppm, well within the Environmental Protection Agency (EPA) primary and secondary ambient air quality standard (Title 40 Code of Federal Regulations [CFR] Part 50.11) of 0.053 ppm.

Nonradiological Accidents

Environmental impacts at low-enrichment fuel fabrication plants are most likely to result from accidents associated with potentially harmful chemicals rather than from radioactive material.

The following information is an example of how Westinghouse has categorized accidents.

Category 1 accidents occur within the manufacturing building and are typified by a pipeline leak or minor liquid spills (10 gal. or less) of acids, ammonium diuranate, uranyl nitrate, and oil. Operators can quickly detect these spills and take appropriate corrective action, so no release to the outside environment is expected. Spills and contamination are normally cleaned up promptly with no residual effects.

Category 1 accidents that occur outside can include minor process equipment leaks or small spills (50 gal. or less); these would be quickly detected and remediated. Another Category 1 accident could result from a leak in the liner of a waste storage lagoon. This situation could continue for a considerable period of time without detection and contaminate the underlying soils and groundwater. Category 1 accidents generally result from aging equipment coupled with inadequate preventive maintenance.

Category 2 accidents occurring in a chemical storage area could result in complete or partial emptying of a bulk chemical storage tank. Such a release is considered very unlikely, because the storage tanks are constructed using best engineering practices and are filled using safe operating procedures. Rupture or failure would require some catastrophic event or simultaneous failure of all current safety systems. The most reasonable failure scenarios involve an intense, prolonged fire with subsequent release of vapors through pressure relief valves or tank rupture caused by a projectile from an adjacent explosion.

Standard practice is to dike all aboveground storage tank areas with sufficient freeboard to contain the maximum tank contents plus projected precipitation from 50- or 100-year storms. This should be adequate to contain spillage from ruptured tanks until remediation measures can be implemented.

Excessive concentrations of airborne vapors could occur but are not expected to require evacuation of off-site residents. Some of the potential vapors, ammonia and HF, have pungent, suffocating odors and could cause congestion and discomfort, forcing exposed individuals to flee the area and thus limiting exposure periods.

There has been one event that has fallen marginally within this category since 1987. This involved an acid release that required the evacuation and treatment of nine workers. The accident apparently resulted from worker error.

Category 3 accidents are catastrophic in magnitude and are considered extremely unlikely during the lifetime of a plant.

Radiological Accidents

The chemical and physical characteristics of uranium contamination contribute considerably to the risk of workers being exposed to radiological hazards. Uranium contamination encompasses a wide range of particle sizes, significantly influencing the dispersibility and thus the transferability of the contamination. For example, UF_6, when released from process equipment, reacts with moisture in the air to form a finely dispersed aerosol of uranyl fluoride and hydrogen fluoride, which is thermodynamically buoyant. The released uranium settles as a very fine dust over a large area and is easily dispersible and transferable. Uranium contamination exposure, coupled with the potential inhalation of fine uranium oxide particles, and external radiation exposure during inspection and storage of nuclear materials present the greatest risks for worker exposure.

Due to the low radiotoxicity of slightly enriched uranium, only limited off-site environmental consequences are to be expected following accidents; however, as in the case of the enrichment process, the safety significance of accidental releases may require a more careful assessment if recycled uranium arising from spent fuel reprocessing comes to be used on a larger scale.

Very few accidents involving significant radiological hazards and substantial releases of radioactive material to the environment have been reported from the nuclear fuel fabrication industry. The main exceptions to the above are UF_6 conversion and wet scrap recovery, which require liquid processing.

The Nuclear Regulatory Commission analyzed potential radiological accidents (NUREG 6410, Nuclear Fuel Cycle Facility Accident Analysis Handbook) for 15 types of fuel cycle and other radioactive material licensees prior to issuing its emergency preparedness requirements in

1988. The most potentially hazardous accident was determined to be the sudden rupture of a heated multi-ton cylinder of UF_6. Other possible accidents with a potential for significant hazard include a radiation release from a large fire in certain facilities handling large quantities of alpha-emitting radionuclides or radioiodines, and the occurrence of a long-term pulsating criticality at fuel cycle facilities handling highly enriched uranium or plutonium in aqueous solution.

A radiological accident considered to be significant would result in a release that could cause a person on the plume centerline outside the plant to receive an effective dose equivalent of more than 1 rem, a thyroid dose of more than 5 rems, or an intake of soluble uranium exceeding 2 mg. In contrast, under 10 CFR 20.1201, workers are allowed to receive 10 mg/week of soluble uranium intake during routine operations.

UF_6 Accidents

UF_6 is stored in 2.5-ton shipping cylinders at six of the fuel fabrication facilities, either under cover or in a secure outside area.

Recent accident analyses for Nuclear Fuel Services' Erwin, Tennessee, facility (NRC Docket 70-143, Environmental Assessment for Renewal of SNM-124) for both UF_6 releases and criticality are discussed in the following. These analyses focus on Nuclear Fuel Services' processing of highly enriched UF_6 into a classified U.S. Navy nuclear fuel and residual contamination from past plutonium activities.

The UF_6 accident scenario postulated the release of the contents of one cylinder containing about 15 kg of highly enriched uranium. In this scenario, UF_6 is charged into the vaporization lines and, because of the failure of a water supply line for the mixing tee of the hydrolysis unit, the UF_6 is released directly into the ventilation system simultaneously with a complete failure of ventilation scrubbers and filters. It is assumed that 10% plates out in the ventilation system and that the release lasts one hour. Atmospheric dispersion assumptions included an effective stack height of 21 m, a wind speed of 0.5 m/s, and credit for plume meander.

The resultant average air concentrations at 250 m (the nearest residence) were 0.56 mg/m3 of uranium and 0.21 mg/m3 of HF. At a uranium enrichment of 95%, the radioactivity concentration would be 0.04 µCi/m3. An adult remaining in the plume for one hour would take in 0.51 mg of uranium, producing a dose well below EPA's protective action guide of 1 rem. The calculated concentration of HF at the nearest residence would be about 0.21 mg/m3, greater than the level of odor detection but well below the 25 mg/m3 that could cause respiratory discomfort.

Nuclear Criticality Accidents

Fuel fabrication facilities, due to their large inventories of special nuclear material (SNM) and diverse production processes, have the greatest potential for criticality occurrences. A criticality could occur within several process areas of a fuel fabrication facility, but the UF_6-UO_2 conversion area is considered most likely to trigger an accidental criticality.

Most fuel facilities handle only low-enriched uranium (with enrichments up to 5% U-235). In addition, fabrication steps made under dry conditions are inherently safe in the absence of a moderator. In the steps in which hydrogenated fluids are used, mass or geometry controls are applied. In some cases, fixed neutron absorbers are additionally used to maintain subcriticality, even in the event of accidental moderation and neutron interaction. Off-site exposures from any fission products generated in criticality accidents are likely to be insignificant. The main hazard will be the local high-radiation fields that are produced by the nuclear excursion.

Low-enriched uranium. A criticality accident at these facilities is possible but unlikely. In over 200 plant-years of operation, no such accident has occurred at a low-enrichment fuel fabrication facility. Achievement of criticality with low-enriched uranium requires carefully controlled conditions.

Highly enriched uranium. Criticality incidents have occurred at facilities that conduct operations with aqueous solutions of highly enriched uranium or plutonium. Table 5-3 of NUREG-6410 summarizes seven previous criticality incidents that have occurred at fuel cycle facilities in the United States. Given the types of radiation involved, it was estimated that 3,600 rad would be roughly equivalent to 10,000 rem.

Analyses of the root causes for criticality-related events indicate that failure to follow procedures, lack of procedures, mechanical failure, design error, and poor maintenance were the major causes cited.

FIRES AND EXPLOSIONS

The principal process-related fire protection concerns in fuel fabrication facilities arise from storage, handling, and process use of hydrogen and flammable solvents. The high-temperature processes of calcining (1300°F) and sintering (3200°F) also present fire hazards.

The grinding of the fuel pellets produces uranium oxide fines, which ignite spontaneously under certain circumstances; however, this is normally not a threat, since these fines are continuously collected and channeled to the scrap recovery system.

Fires

The electric arc welding of zircaloy tubes loaded with fuel pellets is performed in an inert atmosphere inside the welding machine. Zircaloy is a combustible metal, especially in thin scrap or powdered form. The fire potential in the welding process arises from possible malfunction of the machine and impairment of the inert atmosphere. In another operation, defective loaded fuel rods are cut open and the pellets removed. Extinguishing agents for Class D fires involving combustible metals such as MBT-L-X may be used on small zirconium fires. This operation produces zircaloy scrap, which has the potential for spontaneous ignition.

The zircaloy fuel rod manufacturing system also presents a fire hazard. This process involves machining operations, producing combustible scraps of the zircaloy metal. As a preventive measure, any cutting, grinding, or welding operation with this metal should provide for collection and removal of the scrap. This hazard is of somewhat lesser concern because radioactive materials are not involved.

Glove boxes used for manual operations with enriched uranium present a fire hazard. Glove boxes are provided with arm-length synthetic gloves, attached to flanges around handholes, so that the uranium can be handled without any of the material leaving the system. Manufacturing operations with fire potential are usually performed in an inert atmosphere in a glove box, but operations are also performed in air with a slightly negative pressure inside. A glove-box fire starting in the process material and involving the gloves is a credible threat.

Process materials, such as oxides of uranium, are not themselves flammable, but some items of equipment, such as glove-box panels, may be made of combustible materials. In addition, a fire risk might be present from stored combustible waste, combustible fluids, and possible leaks of flammable gas.

The main plant's high-efficiency particulate air (HEPA) filters should normally be located some distance from such equipment. This remoteness, along with the provisions of a valve and, in some cases, an extraction duct cooling arrangement located some distance upstream of these filters, are usually sufficient to protect them against the effects of fire. In safety assessments the fire is, however, assumed to destroy the local filters located on the glove boxes so that any uranium oxides that become airborne reach the final main plant filters. Therefore, these filters, which should include at least two HEPA filters, should be designed to retain these oxides. Blockage of filters in fire situations is a condition that requires consideration. Fires involving glove boxes give rise to substantial local releases of radioactivity within the plant, and this can lead to occupational hazards.

The waste recovery process may involve hydrogen production during the dissolving operation when rod scrap is separated from uranium. Usually the hydrogen is controlled by a ventilated hood over the dissolving tank.

Waste recovery may also involve the solvent extraction process which uses combustible liquids such as tributyl phosphate and dodecane in glass process vessels. For low enriched uranium, water sprinkler protection is usually the means of fire protection.

Plant-specific studies are recommended on the complex protection system in case of a fire and on the requirements for ongoing ventilation, smoke removal, and rescue of personnel. The effects of various fire-fighting agents on the plant and the safety of the ventilation system are also of specific interest.

Explosions

In fluidized bed or sintering furnaces, hydrogen is used as a reducing agent, usually diluted with inert gas to prevent the risk of explosion; however, explosive mixtures can develop from incomplete removal of air from a cold furnace at start-up, or from in-leakage of air into the furnace. Control mechanisms have a low probability of failure, but the possibility of the development of an explosive air-hydrogen mixture cannot be completely excluded. The pressures developed would be sufficient to blow out large quantities of UO_2 powder if an explosion occurred in a fluidized bed furnace. For a sintering furnace explosion, UO_2 would be blown out of the ends of the furnace in the form of pellets. The release of UO_2 to the environment would be small, and its off-site consequences would be of no significance. In general, analysis has shown that explosions will not yield large releases unless they are followed by fires.

Major Fires

A major fire would involve complete burning of operational HEPA filters servicing the exhaust from conversion and scrap recovery processes building.

Filter housings and ductwork may be combustible in existing plants and are more typically located on the roof of the manufacturing. Assuming a production level of 1,600 tons per year, the ADU process filtering efficiency of 99.97% and a maximum of 26 weeks between filter changes, the maximum activity in the filters would be 1.4 Ci.

An adult exposed to the plume at a distance of 1,000 m would receive, through inhalation, an effective whole-body dose of about 9 x 10-3 rem, well below EPA's protective action guide of 1 to 5 rems for emergency preparedness. Chemical toxicity was not considered, since the fire would convert any soluble uranium to the insoluble, biologically nontransportable form.

There have been 19 reported fires at fuel fabrication plants and two other Part 70 facilities since 1987, all relatively minor and quickly extinguished. Table 5-7 of NUREG-6410 summarizes fires and explosions involving uranium and thorium through 1986.

Natural Phenomena

Various kinds of external events could have significant consequences for both the fuel fabrication facility and the environment. The main hazard in the case of an external event, such as an earthquake, arises from the possible release of uranium hexafluoride; however, analysis has shown that earthquakes should not lead to significant releases of radioactive materials at fuel fabrication facilities unless they are followed by fires. Tornadoes might cause large releases, but they would disperse the materials so widely that significant doses would not result.

Flooding the facility could create the risk of a criticality accident; therefore, the plants are usually built in areas with very low flood risk. However, if flooding cannot be prevented completely, design precautions should be taken to ensure the plant does not become critical if flooded.

A list of accidental releases from uranium fuel fabrication plants through 1986 is presented in Table 5-8 of NUREG-6410.

Table 5-7. NUREG-6410: Fires and Explosions Involving Uranium and Thorium Through 1986

Date	Facility	Release	Description
6-27-49	Los Alamos Laboratory, NM	None reported	Fire broke out in a drum containing uranium metal turnings
10-29-52	Truck in Kansas City, MO	Considerable	Truck carrying uranium metal burned. Uranium ignited and much was lost.
12-9-52	AEC facility	None	Molten uranium metal was being cast in a vacuum. Spill ruptured vacuum. Uranium then burned.
6-12-53	U.S.	Onsite contamination up to 15,000 dpm/100 cm^2.	Explosion of powdered uranium and CCl_4 in glovebox.
8-20-56	AEC contractor	100,000 dpm/100 cm^2 onsite. 500 dpm/100 cm^2 offsite.	Thorium explosion.
9-21-56	Truck in Detroit, MI	None	Drum containing thorium metal started to burn. No contamination. No exposures.
6-23-58	AEC contractor Attleboro, MA	No material loss	Fire in slightly enriched uranium scrap in perchloroethylene.
9-26-60	M&C Nuclear Attleboro, MA	Enriched U No exposures.	Magenesium explosion in vacuum induction furnace.
9-20-63	Controls, Inc. Attleboro, MA	None detected	Fire in filter box exhausting enriched uranium. No contamination on or offsite.
6-29-67	Kerr-McGee Crescent, OK	Minor	Explosion in ion exchange column.
9-2-72	United Nuclear Fuel fabrication facility	Uranium at 15 times MPC	Flash fire caused by organic contaminants in ductworks. Considerable damage.
3-12-81	Nuclear Metals Concord, MA	Minor inplant contamination	Fire in scrap packaging building from spontaneous combustion of 10 lbs of uranium turnings. No overexposures.

Table 5-8. NUREG-6410: Other Accidental Releases from Uranium Fuel Fabrication Plants Through 1986 (UF_6 Releases, Fires, and Explosions Excluded)

Date	Facility	Release	Accident description
4-2-71	Babcock and Wilcox Research Facility Lunchburg, VA	10 Microcurie in plant	Contamination outside a hot cell due to a plug being installed without a sealing bellows.
2-28-73	General Electric Wilmington, NC	Below MPC	HEPA filter failed.
8-24-73	Babcock and Wilcox Apollo, PA	Decontamination required on- and offsite. Release was 6.3 microcuries.	Enriched uranium released when corroded scrubber spray nozzle did not provide enough scrubbing.
12-8-73	Babcock and Wilcox Apollo, PA	Offsite release of natural uranium 4 times MPC. Offsite decontamination required.	Inadequate ventilation of calciner allowed uranium to escape through canopy exhaust.
9-6-74	Westinghouse Columbia, SC	UO_2	Leak in a roughing filter allowed UO_2 powder to be discharged directly to the air.
1-24-75	Babcock and Wilcox Apollo, PA	Enriched uranium	Malfunction of scrubber/ ventilation system.
1-79	General Electric Wilmington, NC	62 Kg of low enriched UO_2 powder stolen	Two cans of powder stolen and used in extortion attempt. Thief arrested, convicted and imprisoned. Powder recovered.

CONTAINMENT

At UO_2 fuel fabrication facilities, containment is required for the furnaces converting UF_6 to UO_2 and when UO_2 is present in powder form (crushers, 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.

Releases of UF_6 caused by failures of pipe connections or valves have occasionally occurred in fuel fabrication plants. The main result of these incidents was minor or major contamination with UO_2F_2 within the conversion building, from the reaction of the released UF_6 with moisture. No off-site consequences occurred. To prevent the need for major cleanup after a UF_6 release, a separation or enclosure of the UF_6 conversion plant area is recommended. Rupture of a heated UF_6 cylinder in the evaporation station at the head end of the conversion process represents the most severe possibility for a large UF_6 release. No accident of this kind and severity has ever occurred in a fuel fabrication plant.

In the case of enriched uranium, the capacity of UF_6 cylinders of Type 30B is 5,020 lb. Studies indicate that in the case of a rupture of a heated cylinder for enriched uranium, the maximum release of UF_6 would be in no more than approximately one-half of this quantity. Rupture of the conversion furnace itself would give rise to only a small leakage because of the restricted inflow rate used. Modern evaporation stations for UF_6 are equipped and operated with remotely controlled or automatic valves to keep the quantities of UF_6 released in case of an accident as low as possible.

ENVIRONMENTAL CONTROLS

Fuel fabrication facilities licensed under Part 70 are required to have NRC-approved waste management procedures and environmental monitoring programs in place to address the wide range of gaseous, liquid, and solid wastes produced during facility operations. These include low- or high-level radioactive, nonradioactive, hazardous, and mixed wastes. Waste management procedures include process monitoring as well as waste minimization, treatment, volume reduction, and sampling prior to release. Environmental monitoring includes routine air and water quality sampling to demonstrate compliance with 10 CFR Part 20 as well as EPA and state standards or permits. In addition, under 10 CFR Part 20.1302, monitoring or periodic sampling of groundwater, soils, and vegetation may be utilized to demonstrate compliance with public dose limits.

Gaseous Emissions

Gaseous effluents from operations contain both radioactive and nonradioactive pollutants. Streams containing measurable quantities of radioactive material or nonradioactive pollutants are passed through some combination of HEPA filtration and/or scrubbing prior to release.

Liquid Discharges

Liquid waste streams from facility operations include radioactive, nonradioactive, and sanitary wastes. Each of these is collected and treated separately before release. Treatment for liquid wastes includes one or more of the following: evaporation, neutralization, chemical processing, settling ponds, or recycling.

Solid Wastes

Solid wastes include contaminated packaging materials, floor sweepings, filters, decontamination residues, contaminated equipment, process sludges, incineration wastes, and distillation or evaporation residues. These low-level wastes must be disposed of off site by a licensed contractor at an approved site.

WESTINGHOUSE COLUMBIA FUEL FABRICATION FACILITY

The following is a process analysis of the hazards and administrative and engineering controls/preventive measures associated with ADU conversion operations at the Columbia Fuel Fabrication Facility in Columbia, South Carolina.

The major processing operations performed on nuclear materials at Columbia can be divided into five distinct categories:

1. Conversion operations. Wet and/or dry chemical process to convert uranium gas to uranium powder.

2. Fabrication operations. Mechanical process to produce fuel assemblies containing encapsulated uranium pellets.

3. Analytical and developmental operations. Include a variety of wet chemical, metallographic, and instrumental tests on small samples of material to ensure product specifications are being met, as well as chemical and mechanical process development activities on a laboratory scale.

4. Scrap recovery operations. Permit material to be recycled back into production or to be more closely controlled for disposal. Such treatment includes chemical dissolution and precipitation, solvent extraction, and/or dry separation processes.

5. Waste disposal operations. Include incineration of combustibles. These processes greatly reduce the volume of waste materials to be dispositioned and enable increased accuracy of measurements used to determine the nature and quantity of nuclear material being discarded.

WESTINGHOUSE'S COLUMBIA PLANT: ADU CONVERSION OPERATIONS

The starting material for the chemical conversion process is UF_6, which is received from enrichment facilities around the world. The Columbia plant is licensed to process UF_6 up to a maximum of 5.0 weight percent U-235. The product from this process is UO_2 powder. The plant's six conversion lines utilize the ADU process for converting UF_6 or uranyl nitrate (UN) to uranium oxides (U_3O_8 and UO_2). This is a wet conversion application, which involves continuous processing of solutions and slurries of nuclear material.

ADU conversion operations occur in the plant's conversion area.

The following are examples of potential hazards and controls for activities at the Columbia plant.

Potential Hazards

- The potential exists for receipt of U-235 enriched beyond the authorized 5.0 weight percent.
- There is a potential criticality concern for the ADU process.

Administrative and Engineering Controls/Preventive Measures:

- U-235 enrichment is verified by analysis of samples.
- The mechanical design of ADU equipment systems has been analyzed and determined safe under both normal and abnormal operating conditions for criticality safety.

UF_6 Receipt, Handling, and Storage

UF_6 is received from an enrichment facility supplier, in Model 30 cylinders within NRC- and DOT-authorized packaging. The cylinders are removed from the outer packages, individually weighed, and transferred to a UF_6 pad. UF_6 receipt, handling, and storage occur at the plant's conversion area.

The primary concerns for the systems analyzed in this section are the atmospheric release of UF_6 and worker exposure to radioactive contamination.

Potential Hazards:

- Workers could be exposed to radioactive contamination and direct radiation from packages and cylinders.
- The potential exists for receipt of U-235 enriched beyond equipment design criteria for criticality safety.
- A dropped or damaged cylinder could result in release of UF_6.
- UF_6 may be released from a damaged cylinder valve.

- Workers could be exposed to radioactive contamination from processed cylinders.
- There could be a fire hazard adjacent to the UF_6 pad storage area.
- There could be a fire and explosion hazard from UF_6 cylinders contaminated with organic materials.
- Workers could be crushed and pinched.

Administrative and Engineering Controls/Preventive Measures:

- UF_6 packages are surveyed for radioactive contamination and direct radiation.
- Cylinders are individually weighed upon arrival.
- U-235 enrichment is verified by analysis of samples prior to introducing the material to the conversion process. (Note: Only Westinghouse will routinely sample.)
- Cylinders are inspected for damage upon receipt.
- At no time is a cylinder more than a few feet above an unyielding surface.
- Cylinders are moved with special provisions for protecting their valves.
- Cylinders are resurveyed for radioactive contamination and/or direct radiation after processing the contained UF_6.
- Combustibles are strictly minimized and controlled in the UF_6 pad storage area.
- The waste storage area is separated by spacing from the cylinder storage area and is covered by fire protection sprinklers.
- Cylinders must be in good condition, with properly maintained valves and caps, to prohibit entry of organic contaminants.

Vaporization and Hydrolysis, or Uranyl Nitrate Preparation

The primary concern for the systems in this section is the risk that a process upset or accident involving radioactive material might be the cause of a severe chemical accident. Vaporization and hydrolysis occur in the plant's conversion area.

Potential Hazards:

- UF_6 releases may occur as a result of damage to cylinders and/or cylinder valves during transport.
- There is a possibility of massive releases of UF_6 from heated cylinders.
- Overweight cylinder – If a cylinder has been inadvertently overfilled by the vendor, an excess accident, resulting in cylinder rupture, could occur when the cylinder was heated to operating temperature.
- Workers could be exposed to UF_6 release during connection and disconnection of the vaporizer to the conversion system.

- Vaporizer high steam pressure – Steam from a boiler, to be used for vaporization heat supply, passes through pressure reducing station(s) to provide a preset pressure at each vaporizer. If steam at a higher pressure were supplied, a cylinder could overheat.
- Vaporizer high condensate level – Liquid condensate, from steam used to heat a cylinder in a vaporizer chest, drains out of the chest bottom, through a steam trap, into a drain header. Should the drain lines become plugged, the liquid could back up into the vaporizer, creating a nuclear criticality hazard.
- Vaporizer UF_6 leak – Each cylinder arrives with a cylinder valve installed. Prior to vaporization, the valve is mechanically connected to the process header using a flexible pigtail. A leak test is performed before the cylinder is heated; however, a leak could develop during the subsequent heating, resulting in a gaseous mixture of UF_6/UO_2F_2 and HF.
- Vaporizer instrument failure – Several sensor, transmitter, and indicator instruments are needed to run the vaporizer system. Failure of such an instrument could produce a reading on the control panel that would provide false information to an operator.
- Vaporizer electrical supply failure – Loss of electrical power to vaporizer sensor, transmitter, and indicator instruments could lead to loss of system control.
- Vaporizer-to-hydrolysis-tower plugged UF_6 line – UF_6 could react with moisture or other contaminants in a vaporizer-to-hydrolysis-tower transfer line and form a solid plug. This plug could block gas flow in the line, causing an increase in pressure upstream of the blockage due to continued cylinder heating.
- Hydrolysis tower liquid siphoning into UF_6 feed lines – UF6 combines with water in a strong exothermic reaction. Should water be drawn into the UF_6 system, the resulting reaction could be severe enough to rupture the system.
- Hydrolysis tower high temperature – The reaction of UF_6 with water is highly exothermic. A feed-bleed operation cycle, with makeup water, enables heat removal from the tower. A process upset allowing high temperature could cause the liquid in a tower to boil.
- Hydrolysis tower electrical supply failure – Loss of electrical power to hydrolysis tower sensor, transmitter, and indicator instruments could lead to loss of system control.

Administrative and Engineering Controls/Preventive Measures:

- Vaporizer chests are designed to enclose a UF_6 cylinder and all of its connections to the conversion system.
- Heated cylinders are provided an escort in addition to regular transport operation during movement.
- Operations personnel wear supplied air respirators during the connection and disconnection activities.

- Overweight cylinder – Cylinders are weighed upon arrival, then again upon transfer into the plant for processing.
- Vaporizer high steam pressure – Vaporizer steam pressure is continuously monitored. A high-pressure alarm would activate if the pressure went above the preset level; an interlock would close the vaporizer steam supply valve if the pressure reached a higher preset level. Further, each vaporizer has a pressure relief valve that would intervene if the interlock failed to shut off the steam and the pressure continued to rise above an even higher preset level.
- Vaporizer high condensate level – Each vaporizer is provided with liquid level probes that activate high- and high high-level alarms and interlocks that cut off the steam supply.
- Vaporizer UF_6 leak – Each vaporizer is connected to a steam condensate drain header system, which includes a conductivity monitor. UF_6 gas released into a vaporizer would react with steam condensate to form conductive solution. A high conductivity reading would then indicate the leak, and the resultant alarm would cause the steam header supply valve to close and shut off steam to all vaporizers on the line. The cylinder and connections within the vaporizer could then be cooled causing UF_6 to solidify and terminate the leak.
- Vaporizer instrument failure – The process computer is programmed with control parameter values and preset control deviations. Instrument failure would either cause a low reading alarm for the controlled parameter or give a deviation alarm from loss of signal. The operator would then investigate the cause of the alarm and initiate corrective actions.
- Vaporizer electrical supply failure – Upon loss of electrical power, vaporizer steam supply header valves and UF_6 supply header valves would automatically close, thus stopping cylinder heating and terminating gas flow. When power was restored, an operator would reset the steam supply valves, thus ensuring the system would be brought back on line in a controlled manner.
- Vaporizer-to-hydrolysis-tower plugged UF_6 line – UF_6 headers are provided with pressure sensors. Given a blockage of a transfer line, with subsequent loss of flow, a low-pressure alarm would activate if the blockage was before the pressure transmitter. Hydrolysis tower alarms would also activate when the UF_6 feed flow was interrupted. Further, the pressure transmitters and gauges installed at various points in the system would aid an operator in identifying the site of the blockage, so corrective actions could be initiated.
- Hydrolysis tower liquid siphoning into UF_6 feed lines – UF_6 connections on the hydrolysis tower discharge the gas into a void above the high level. A high-level interlock would close the UF_6 valve before water could rise into the void space. Further, a tower operates at near-atmospheric pressure and is vented through its scrubber system, which would prevent creation of a siphon effect.

- Hydrolysis tower high temperature – A temperature sensor is installed at the bottom of each tower. A high-temperature alarm would cause the UF_6 valve to shut, thus terminating flow of the heat-producing reactant.
- Hydrolysis tower electrical supply failure – Loss of electrical power would stop the drain pumps, and UF_6 and makeup water supply valves would close to isolate the system.

Precipitation and Centrifugation

Diluted aqueous UO_2F_2 solution from the hydrolysis process is converted to ADU by reaction with ammonium hydroxide, in a precipitation tank, where the ADU forms as a slurry. As an alternate, HF "spiked" uranyl nitrate from nitric acid scrap recovery and acid washing processes can be used as feed material for precipitation.

From the precipitation tank, the ADU slurry is pumped to a decanter. This unit consists of a centrifuge with a rapid-revolving horizontal housing in which solids are separated by centrifugal force and are then removed by an axial conveyor screw that turns at a speed faster than the bowl itself. The solids discharge, through a closed chute, to an ADU receiver tank, located below the decanter; the liquid discharges, under pressure of an internal centripetal pump, into a centrate receiver tank.

ADU from the receiver tank is pumped to the next step in the process, which is drying; the centrate is pumped through a filter to remove most remaining solids, and then to process liquid quarantine tanks. Precipitation and centrifugation occur in the plant's conversion area.

<u>Potential Hazards:</u>

- Workers and the environment could be exposed to hazardous fumes from process chemicals (i.e., HNO_3, NH_4OH, and UO_2F_2).
- Workers and the environment could be exposed to hazardous liquids from process chemical leaks and spills (i.e., HNO_3, NH_4OH, and UO_2F_2).
- Workers and the environment could be exposed to radioactive contamination from process chemicals.
- A potential exists for a mechanical hazard from the operation of the centrifuge.

<u>Administrative and Engineering Controls/Preventive Measures:</u>

- Precipitation and centrifugation processing steps are conducted in open vented systems.
- Precipitation vessel level controls, with alarms, are provided to prevent system overflows.
- Detectors are provided for fume surveillance and monitoring.
- Acid-resistant personal protective equipment (PPE) is provided for use by operators.

Drying

Wet ADU slurry is pumped from the receiver tank to the surface-heated dryer. The ADU is moved through the dryer by rotating paddles; the water content is substantially reduced. Dried ADU is then discharged into a bucket elevator system for transfer to calcining. Drying occurs in the plant's conversion area.

Potential Hazards:

- Workers and the environment could be exposed to hazardous fumes from process chemicals and gases (i.e., HNO_3, NH_4OH, and UO_2F_2).
- Workers and the environment could be exposed to hazardous liquids from process chemical leaks and spills (i.e., HNO_3, NH_4OH, and UO_2F_2).
- Workers and the environment could be exposed to radioactive contamination from process chemicals.
- Extreme temperatures from drying system heaters could result in process fires and/or possible burns to workers.

Administrative and Engineering Controls/Preventive Measures:

- Drying takes place in a closed system.
- Off-gases from the dryer pass through bag filters prior to entering a heat exchanger for separation of condensate and entrained particulates from the filtered gases.
- Condensate is discharged to a centrate receiver tank prior to waste treatment.
- Noncondensible gases, and vapors from the dryer, are discharged to an ammonia scrubber.
- Heat detectors monitor drying system electric heaters.

Calcining

A motor-driven auger conveys dried ADU into a rotating, natural gas-fired, cylindrical calcining furnace. In the furnace, the ADU decomposes to U_3O_8 and is subsequently reduced to UO_2 in a nitrogen, hydrogen, and steam atmosphere.

The primary concern for this process is the risk that a process upset or accident involving radioactive material might be the cause of a severe industrial accident. Calcining occurs in the plant's conversion area.

Potential Hazards:

- Workers and the environment could be exposed to radioactive contamination from process chemicals and gases.
- Heat stress to workers could result from extreme temperatures.

- Hydrogen leaks could cause fire and explosions.
- Loss of combustion air – Natural gas is burned to provide heat for the calcining reactions. Air is supplied to the calciner burners to enhance combustion of the gas. Reduction or loss of combustion airflow could result in physical damage to the equipment, and the discharge of a flammable mixture to the calciner vent system.
- Air in a calciner – Air in a calciner as it comes to operating temperature could form an explosive mixture and cause detonation when hydrogen is introduced.
- High pressure in a calciner – High pressure in a calciner could result from a process upset, such as plugging of the vent system. This pressure could then result in damage to confinement seals and a release of calciner process gases to the plant area.

Administrative and Engineering Controls/Preventive Measures:

- Insulation, heat-reflecting materials, and airflow mitigate the effect of heat.
- Gas detectors are placed in areas using hydrogen to alert workers.
- Calcining takes place in a closed system.
- Furnace off-gases pass through a scrubber, and the scrubber solution is filtered to remove uranium-bearing solids and pumped to quarantine tanks prior to transfer to liquid waste treatment.
- Loss of combustion – Combustion air also serves as control air for the natural gas system valves. A reduction in combustion air would cause a commensurate reduction in gas flow; loss of air would shut off the gas supply.
- Air in a calciner – Prior to initiating hydrogen flow to the calciner on start-up, operating procedures require a preestablished steam and N_2 purge of the calciner. Systems are interlocked such that loss of hydrogen flow due to low calciner pressure only would automatically close the steam and hydrogen supply valves, thus stopping feed of these gases.
- High pressure in a calciner – The system is designed such that high pressure in a calciner would automatically close the steam and hydrogen supply valves, thus stopping feed of these gases.

Comminution

Dried UO_2 powder is conveyed from a calciner exit chute, through a milling operation to achieve required particle properties, into polypak containers. The containers are then sampled (to verify powder property requirements), identified, and placed on movable storage carts. Comminution occurs in the plant's pelleting area.

Potential Hazards:

- Workers could be exposed to radioactive contamination (beta-gamma exposure from nuclear materials and inhalation of UO_2 dust).
- Workers could be exposed to excessive noise during milling operations.
- Environmental release of radioactive materials (i.e., UO_2 dust) could occur.
- Depending on the particle size, a fire hazard could result from burn-back oxidation of UO_2.

Administrative and Engineering Controls/Preventive Measures:

- Comminution mills and their associated conveyors are closed systems, maintained at a positive pressure.
- Sound absorbers have been placed around the mills to enhance hearing protection.
- Ventilation exhaust from the mill enclosure is passed through HEPA filtration prior to discharge.
- Polypak containers are wiped to reduce external contamination.
- Burn-back oxidation of UO_2 is addressed by sealing the system control air leakage, minimizing combustible materials in the system, and using metal collection containers.
- Containers are plastic and of sufficient thickness to reduce beta-gamma exposure.

Interim Polypak Storage

Closed polypak containers of dry uranium oxide powder are kept in racks that are secured to movable storage carts of all-steel construction.

Potential Hazards:

- Workers could be exposed to contamination (i.e., beta-gamma exposure and UO_2 dust).
- Workers and the environment could be exposed to radioactive materials from fire hazard or dust explosion.

Administrative and Engineering Controls/Preventive Measures:

- Polypaks are wiped to reduce external contamination prior to placement on carts.
- Carts are stored in remote locations to reduce external radiation exposure potential.
- Housekeeping in the interim powder storage areas is monitored to ensure strict control of combustible and flammable materials.

Blending and Bulk Container Storage

Carts of polypak containers are transported, as required, from interim storage to the bulk and storage area for further processing. Uranium oxides in the containers include both powders from the milling operations and recycle materials. Operations conducted in the blending/storage area include loading of bulk containers, installation and removal of cover plates from bulk containers, blending, powder transfer and rework, sampling, and bulk container storage.

Potential Hazards:

- Workers could be exposed to airborne radioactive contamination (i.e., uranium oxide powders).
- Pinching, crushing, and lifting hazards could result during loading of bulk containers, installation and removal of cover plates from bulk containers, blending, powder transfer and rework, sampling, and bulk storage.
- The potential exists for fire hazard in the blending and bulk container areas.

Administrative and Engineering Controls/Preventive Measures:

- Secondary containment and ventilation are provided to control airborne radioactivity during powder transfers.
- Vent hoses are provided to control airborne radioactivity during installation and removal of bulk container cover plates and/or feeds.
- Bulk containers constitute closed systems requiring only routine radiological safety during blending operations.
- Connections between containers are sealed during powder transfer and rework operations.
- Secondary containment and ventilation are provided to control airborne radioactivity during connection and disconnection steps.
- The sampler station has integral containment and ventilation in order to control airborne radioactivity during sampling operations.
- Sealed polypak containers and bulk containers constitute closed systems requiring only routine radiological safety precautions.
- Class A combustible materials are prohibited; the limited wastes are kept in closed containers that are removed from the area when filled.
- Class B materials, except for approved lighting and ventilation equipment, are prohibited.
- Class C hazards are minimized.

WESTINGHOUSE'S COLUMBIA PLANT: ADU FABRICATION OPERATIONS

Following homogenization in the conversion area, blended uranium oxide powder is transferred to the fabrication area for further processing. In the fabrication area, the powder is stored until needed, then it is compacted, granulated, and pressed into pellets. Pressed pellets are loaded into boats, which are subsequently charged to heated furnaces where the pellets are transformed into high-density ceramics by sintering in a reducing atmosphere. Sintered pellets are then processed through a grinding operation to attain specified dimensions. Ground pellets are loaded into prepared metal tubes, springs and plugs are inserted, and the resultant fuel rods are hermetically sealed by welding. Finished rods are inspected, tested, then transferred for final assembly. The fuel rods are loaded into designated positions in a prefabricated support skeleton consisting of thimble tubes and structural grids. Top and bottom nozzles are then attached to complete the final fuel assembly.

The ADU fabrication lines are designed and operated to process enrichments up through 5.0 weight percent U-235. ADU fabrication operations occur in the plant's pelleting area.

UO_2 Receipt, Handling, and Storage

Closed dry powder containers, whether received from an outside supplier or from the conversion area, are stored in the blending/storage area previously described, on the portable steel carts previously described, or on fixed steel storage shelves. Moderated material, such as sludge from grinding operations, is also in the fabrication area. This material is placed in stainless steel pans, which are then stored on fixed steel storage shelves.

Potential Hazards:

- Workers and the environment could be exposed to radioactive contamination (UO_2 powder).
- Moderated material, such as sludge from grinding operations, is stored in the fabrication area.
- There is a potential for fire and explosion hazards in the fabrication area.

Administrative and Engineering Controls/Preventive Measures:

- Containers are monitored for radiological safety.
- Containers are closed and sealed except during sampling; they remain closed during package unloading and container weighing.
- Containers selected for sampling are opened in a ventilated enclosure equipped with HEPA filtration.
- Steel container storage carts and racks are designed with a minimum safety load factor.
- Housekeeping is monitored, and there is strict control of combustible and flammable materials in the fabrication area.

Powder Preparation and Pelleting

When bulk containers are used to provide powder feed to pelleting, they are transported from storage by using a hydraulic lift truck. In the pelleting area, the containers are lifted by hoist to a support stand and are next attached to an unloading station via a feeder device. The powder can then be fed, upon demand, to elevator trays. Filled trays are placed into an elevator system for transport to a feed hopper for dumping. The powder is subsequently fed to powder compaction processes. When polypak containers are used to provide powder feed to pelleting, they are transported from storage with the movable carts. The containers are transferred to a feed hood and opened, and the contained powder is emptied into the elevator trays for subsequent processing.

Powder gravity-flows from the hopper into a roll-type compaction unit. The compacted powder then gravity-flows to a mechanical granulator. Granulated powder is collected into blending containers, in a hood, where it is roll-mixed with small quantities of binder-lubricant. The prepared feed material is then transferred to the feed hopper of a pellet press.

Feed materials gravity-flow from the hopper into the pellet press die, where product pellets are formed. The pellets are then transferred directly into molybdenum sintering boats for subsequent processing.

Potential Hazards:

- Workers and the environment could be exposed to radioactive contamination (UO_2 powder).
- Workers could be exposed to respirable dust and toxic fumes from the binder-lubricant chemical process.
- Pinching, lifting, and crushing hazards could result during transport of containers.
- Fire and explosion hazards could result.

Administrative and Engineering Controls/Preventive Measures:

- Bulk containers are kept closed during transport and connection to the pelleting system.
- Polypak containers are kept closed during transport to and into the pelleting system.
- Manual powder transfers from polypaks to elevator trays are conducted within ventilated, HEPA-filtered enclosures.
- The elevator system is also enclosed.

- Roll compaction and granulation are conducted in closed systems.
- Granulated powder collection, binder-lubricant addition, and mixing are carried out in ventilated hoods.

- Exhaust air from the hoods passes through HEPA filtration prior to recirculation.
- Pellet pressing takes place in a ventilated, HEPA-filtered enclosure.
- Continuous air sampling is conducted to monitor the effectiveness of respirable dust controls.
- Bulk containers are transferred and handled in accordance with safety criteria for lifting devices.

Pellet Sintering

Pellet-filled boats are conveyed to the sintering furnace area and charged one at a time, in a single line, into a specified furnace. As the boats pass through the heated, reducing-atmosphere furnace, the pellets are sintered to near-theoretical density. Upon discharge from the furnace, the boats are transferred to the grinding area for further processing.

Potential Hazards:

- Workers could be exposed to radioactive contamination (respirable dust).
- Heat stress could result due to high temperatures generated by sintering furnaces.
- There is a potential for severe industrial accident risk from process upset.
- Excess furnace temperature – Sintering furnaces are electrically heated. Excess furnace temperature could lead to system damage and/or fire.
- Air in a furnace – Air in a sintering furnace as it comes to operating temperature could form an explosive mixture and cause detonation when hydrogen is introduced.
- Failure of flame curtain pilot lights – To prevent leakage of sintering furnace process hydrogen to room atmosphere, the furnace entrance and exit doors are protected by flame curtains with pilot lights. Failure of the pilot lights could allow leakage to occur.

Administrative and Engineering Controls/Preventive Measures:

- The pelleted form of the radioactive material diminishes the generation of respirable dusts in the sintering area.
- Protective clothing is required, and continuous air sampling is conducted to confirm the efficacy of controls.
- Supply-air fans are provided to remove heat generated by the furnaces.
- Heated air and room air are discharged through exhaust fans and HEPA filtration prior to release from the facility.
- The hydrogen flow rate to the sintering furnace is strictly controlled and monitored.

- Excess furnace temperature – Heat detectors are located above each sintering furnace to detect unusual temperature rate-of-rise. The heat detectors are tied into the plant emergency alarm system and, upon sensing an upset condition, would alert plant personnel to the location of the alarm.
- Air in a furnace – Prior to start-up of a furnace, a nitrogen purge is maintained to sweep any air from the system. The purge is continued as the furnace is brought to operating temperature, to ensure explosive mixtures cannot be formed. Systems are interlocked such that loss of hydrogen flow would automatically introduce the nitrogen purge. The furnace entrance and exit doors are interlocked to prevent both doors from being opened at the same time, thus minimizing the potential for an air draft to enter the system.
- Failure of flame curtain pilot lights – The pilot lights are monitored by peeper devices, which sense the flame. An alarm condition prevents the doors from opening. The system must then be relit by authorized personnel before the doors will open.

Pellet Grinding

To attain precise pellet dimensions, all sintered production pellets are passed through a grinding operation. Pellets to be ground are contained in sintering boats, or temporary storage pans, on an input conveyor adjacent to a grinder. Grinding takes place under a stream of coolant, which also carries away abraded particles. The liquid stream is passed through a centrifuge to remove solids and recirculated. After pellets are ground to the specified dimensions, they are automatically loaded onto trays on an output conveyor adjacent to a grinder. Loaded trays are then transferred to an electrically heated dryer oven to evaporate moisture from the pellets; after the pellets are dried and inspected, the trays are transferred to storage to await release for rod loading.

<u>Potential Hazards:</u>

- Worker exposure to respirable dust is a minimal risk.
- Operations in the pellet-grinding area require only routine industrial safety and hygiene practices (i.e., housekeeping and personnel protective equipment [PPE]).
- Mechanical hazards are associated with grinding operations.

<u>Administrative and Engineering Controls/Preventive Measures:</u>

- The pelleted form of the radioactive material and use of liquid coolant for grinding diminish the generation of respirable dusts in the grinder area.
- Grinders are fitted with ventilated, HEPA-filtered containments.
- Routine surveys and use of protective clothing provide contamination control.

Fuel Rod Loading, Inspection, and Storage

Pellet trays are taken from their storage sites to prepared rod-loading fixtures. The pellets are removed from the trays and loaded into empty fuel tubes. Loaded tubes are cleaned, fitted with springs, plugged, and transferred to a weld station, where they are inserted into a fixture, pressurized with an inert filler gas, and sealed. The finished fuel rods are then subjected to a variety of specified inspection operations, including visual examination, weighing, dimensional examination, and weld integrity inspection by radiography or ultrasonics inspection. Fuel rod loading, inspection, and storage begin in the plant's rods area.

WESTINGHOUSE'S COLUMBIA PLANT: SCRAP RECOVERY

The fuel fabrication processing operations previously described were selected and/or developed to be highly efficient, in order to generate only minimal quantities of off-specification scrap materials; for example, equipment is designed to minimize material holdup and to promote run-out of materials during enrichment changes, physical inventories, and maintenance. However, as in any modern industrial facility, generation of some scrap materials by manufacturing, maintenance, and/or cleanup operations at the facility is unavoidable. The processes described in the following paragraphs are utilized at the facility to recover uranium values from such scrap materials in order to minimize disposal of such values as wastes.

UF_6 Cylinder Washing and Recertification

UF_6 cylinders, weighed to ensure they contain only residual heels, are washed and recertified for Westinghouse and customers. Such cylinders are campaigned in convenient batches for processing. A campaign begins with a cleaned, inspected, and released system:
(1) all hydrolysis/wash solutions and wet filter cake from previous campaigns are processed through oxidation/defluorination to U_3O_8 for eventual dissolution, solvent extraction, and processing to UO_2, and (2) all filtrates from previous campaigns are sampled and discharged to the plant waste treatment systems. Air filtration devices are not inspected for holdup.

Cylinder recertification procedures include visual checks for shell and head defects (i.e., localized corrosion, cracks, bulges), wall thickness, valve and plug inspections, and hydrostatic testing.

Potential Hazards:

Workers and the environment could be exposed to radioactive contamination (beta-gamma radiation from short-lived uranium progeny products and Tc-99 contaminants).

- Pinching, lifting, and crushing hazards could result.
- UF_6 reacts with moisture to form HF and UO_2F_2.
- UF_6 reacts violently with organic compounds.

Administrative and Engineering Controls/Preventive Measures:

- Liquid forms of radioactive materials in UF_6 cylinder washing and recertification operations diminish the generation of respirable dust.
- Cylinders to be washed are stored to allow decay of short-lived materials.
- Cylinder surface contact exposures are limited at the time of washing.
- The tilt table and filter press are provided with ventilated containment; exhausts are discharged through the conversion area scrubber system.
- Liquid discharges to the wastewater storage tank are kept below a specified concentration.
- Water used in hydrostatic testing is stored, sampled, and analyzed prior to release.
- Interlocks prevent introduction of wash water to a cylinder containing more than the specified maximum mass of UF_6.
- Engineered guards and warning signs are provided over pinch-and-nip points on the rotation/tilt table.
- Emergency shower and eyewash stations have been installed.
- To protect UF_6 cylinders from foreign contaminants, especially organics, visual checks and inspections are conducted to prevent contaminant ingress.

Scrap Batch Processing

This is an area of the process that is often neglected by the licensees. It is at this point that criticality is a concern.

Uranium recovery involves batch processing of a variety of scrap input forms. Preliminary operations concentrate and purify the materials, if necessary; subsequent operations convert the materials to a form that enables processing to U_3O_8 or UO_2 powders, for reuse in manufacturing. Some licensees use the following categories to describe the process. The basic processing operations include (1) Category A: Dissolution—dissolving of solids; (2) Category B: Precipitation—converting dissolved material to slurry by precipitation of ADU from the solution; (3) Category C: Washing and Category D: Wet Mechanical Separation—dewatering the slurry to sludge, by wet mechanical separation; (4) Category E: Thermal Processing—oxidizing the sludge by calcining in furnaces; (5) Category F: Dry Mechanical Separation—uranium oxides are crushed to form a powder in a mechanical granulator; (6) Category G: Miscellaneous—trash solids and liquid effluents are prepared for waste disposal; and (7) Packaging and Storage—packaging and storing the oxide product until it is sampled, analyzed, and released to the manufacturing component for subsequent processing.

Potential Hazards:

- Workers and the environment could be exposed to radioactive contamination (respirable dust and process off-gases).
- Workers could be exposed to toxic chemicals (HNO_3 and NH_4OH) due to leaks and spills.

Administrative and Engineering Controls/Preventive Measures:

- Occupational safety and health controls for activities in the scrap batch processing area are the same as those applied to corresponding activities in ADU conversion operations.
- In Category A operations, off-gases from dissolution tanks are routed through a flux condenser and scrubber to remove vapors and entrained particles prior to HEPA filtration and release. Detectors are provided for fume surveillance and monitoring. Special protective measures have been provided to control nitric acid hazards. Acid-resistant PPE and respiratory protection for nitric acid operations are provided.
- In Category B operations, special protective measures are provided to control ammonia hazards. Caustic-resistant PPE and respiratory protection are provided for operations involving hazardous chemicals.
- In Category D operations, ventilation hoods are installed above the filter presses; exhaust passes through HEPA filtration prior to release from the facility.
- In Category E operations, off-gases from the furnaces are vented through hoods installed above the furnace doors, near the points of potential gas releases; exhausts are passed through a scrubber to remove vapors and entrained particles prior to HEPA filtration and release.
- In Category F operations, materials with a propensity to suspend in air are handled in hoods, hopper dry boxes, or other ventilated and HEPA-filtered enclosures.
- In Category G operations, trash solids and liquid effluents from precipitation, wet separation, and exhaust scrubbing are routed to appropriate facility waste treatment systems for disposal processing.
- Continuous air samplers are located at specified points throughout the scrap batch processing area to monitor the efficacy of contamination control.

Solvent Extraction

Impure uranium scrap from various plant operations can be passed through solvent extraction to purify the uranium. Typical material to be purified is uranyl nitrate solution prepared from such scrap components as impure uranium oxides, filter press cake, and incinerator ash. Major processing units of the solvent extraction system include scrap preparation equipment, dissolvers, a feed concentrator, mechanical-pulsed extraction and stripping columns, and product evaporators; ancillary units include liquid storage vessels and system instruments and controls.

A process upset or accident involving radioactive material in solvent extraction operations could result in a severe chemical accident.

Potential Hazards:

- Solvent spill – Solutions of tributyl phosphate with kerosene, and tributyl phosphate with perchloroethylene, are used in the solvent extraction process. A spill of either of these organic solutions could pose serious fire and/or pollution threats if not contained.
- Dissolver high uranyl nitrate – Dissolution of U_3O_8 in nitric acid, to uranyl nitrate, is a batch operation in a vessel with a limited maximum capacity. Overfilling would result in leaks at the vessel's top flange and/or at the dump hood.
- Dissolver high temperature – Dissolution is conducted at elevated temperatures; excessive temperature could cause boil-over of liquid and release of toxic nitrogen oxides.
- Dissolver batch boil-over – A boil-over of liquids during batch dissolution could cause uranyl nitrate to enter the system vent line and scrubber, causing a release of nitrogen oxides.
- Dissolver release of nitrogen oxides – Dissolution using U_3O_8 as feed material, and/or dissolution in overheated nitric acid, could cause a violent reaction and subsequent release of nitrogen oxides.
- Bulk storage tank uranyl nitrate reaction with strong base – If caustic was inadvertently added to a bulk storage tank of uranyl nitrate, a violent exothermic reaction would take place, perhaps rupturing the tank.
- Uranyl nitrate bulk storage tank high level – A spill of uranyl nitrate from an overfilled tank could cause acid burns and hazardous conditions on the storage pad.
- Uranyl nitrate bulk storage tank rupture – Accidental rupture of a uranyl nitrate storage tank, or intentional release of a tank's contents, could cause a nuclear criticality incident, resulting in a severe environmental impact.

Administrative and Engineering Controls/Preventive Measures:

- Solvent spill – Tributyl phosphate, kerosene, and perchloroethylene are brought into the area, in closed containers, only as needed. Quantities of these materials are limited; the solvent extraction system contains a total of some tens of gallons. Solvent extraction is a closed process; the solvent supply, makeup tanks, and extraction columns are vented to a closed scrubber system. A trap in the vent line collects all solvent tank overflows from any of the containment vessels; the trap is equipped with a high-level alarm to alert an operator that emptying is required.

The vent line trap can be drained into an approved container, so that the trapped solvent can be removed for disposal in an approved manner. The solvent extraction area has no floor drains; thus, any spills outside the system would be contained for approved cleanup and disposal.

- Dissolver high uranyl level – Water and acid are batch-measured into the system; U3O8 powder additions are weighed. Each dissolver vessel is equipped with a liquid-level probe with a high-level alarm, to prevent excessive additions of material.
- Dissolver high temperature – The temperature of a dissolving batch is continuously monitored. A temperature exceeding the upper-level setpoint would close the steam control valve to inhibit further increase of the reaction temperature.
- Dissolver batch boil-over – UO_2 is oxidized to U_3O_8 prior to dissolution to enhance control of reaction temperatures that might cause system boil-over.
- Dissolver release of nitrogen oxides – UO_2 and reaction temperature controls are as previously described. Further, the dissolver vessels are vented to a pack scrubber to quench any nitrogen oxides released. Scrubber water is continuously bled off, and fresh makeup water is automatically added via level controls in the surge tank to ensure the system's capacity to scrub dissolution off-gases.
- Bulk storage tank uranyl nitrate reaction with strong base – There are no physical connections of caustic lines to any part of the uranyl nitrate storage system. Each batch of liquid pumped to storage is sampled and shown to have a minimum percentage of free HNO_3. A pH probe is installed in the transfer line, and detection of a high reading causes a valve to close and terminate transfer.
- Uranyl nitrate bulk storage tank high level – Liquid levels in the storage tanks are continuously monitored, with a high-level alarm for manual stoppage of batch transfers. Each tank is also equipped with a level probe that signals a high level and imminent tank overfilling. In the event of a tank overfill, solution will leave the tank from an overfill and spill onto the diked pad. The level probe of either of the two favorable geometry drain sumps will alarm a high sump level condition.
- Uranyl nitrate bulk storage tank rupture – Some uranyl nitrate storage tanks are located on one of the outside containment pads; the other tanks are located on an adjacent pad. The pads are interconnected by a common wall, penetrated to permit spillage between pads. The combined capacity of the two pads, as determined by the perimeter wall, will contain the leakage from more than one tank. If this volume were exceeded, the overflow would be contained by using emergency methods, such as soil diking, until appropriate cleanup could be implemented.

CASE STUDY/ACCIDENT HISTORY

Among the accidents that have occurred in processing uranium are criticality accidents, fires, and releases of UF_6. Fuel fabrication facilities have accounted for a large portion of the reported events, releases, and criticality-related incidents that could be precursors to more serious accidents.

NRC licensees were required to report events in which there was personnel overexposure, leaking or contaminated sources, release of material, loss or potential loss of criticality control, or loss of material. Factors that contributed to these events include instances of equipment malfunctions, unsafe operating practices and conditions, violations of NRC regulations and procedures, design flaws, fires, and electrical problems.

Adverse occupational or environmental consequences included worker injury and/or exposure or unplanned release of contaminants to the confined workplace or to the outside environment. In the reported events, contamination was generally limited to an enclosed work area. While spilled materials were immediately cleaned up and the work area decontaminated, it is likely that, especially where liquids were involved, some contamination may have escaped from the building through floor cracks and joints. This is indicated by site survey reports showing contaminated slabs, foundations, footings, and soils under and adjacent to buildings.

In events where contaminants escaped into the open environment, contamination was generally limited to a small area and any necessary remedial measures were promptly carried out.

The following are examples of events in which contaminants traveled off site:

- Three events involved workers: two in which personnel left the facility with contamination on their shoes and one in which an injured worker was admitted to and released from a hospital with contamination on clothes and body.
- In one instance, radioactively contaminated liquids were discharged to local sewage treatment facilities.
- Two events involved discharges of radioactively contaminated water to local storm drains.
- Two cases involved releases to local streams: one a spill of diesel fuel and one a leak from an on-site waste pond to a stream.
- One case was an outside fire; no radioactive material was involved, but normal combustion-related gases and particulates were dispersed off site.
- Three instances were solid waste disposal violations.

A review of the events reported indicates that most of these are either equipment- and/or human-related; a few were attributable to natural (weather) or undeterminable (fire) causes. This strongly suggests that most of the events probably could have been either avoided or their effects lessened by proper design, construction, and maintenance of equipment; proper training and supervision of workers; and having appropriate controls in place.

Table 5-9 lists some of the possible accidents at fuel fabrication facilities.

Table 5-9. Possible Accidents at Fuel Fabrication Facilities

Area and Material Involved	Typical Accidents	Pollutants of Concern
Tank farm		
Ammonium hydroxide Anhydrous ammonia Sodium hydroxide Nitric acid	Pipeline or tank rupture, spills, fire	Ammonia Nitrate Caustic and acid solutions
Lagoons		
Ammonium nitrate Calcium fluoride Uranium	Leak, massive dike/liner failure, flooding	Ammonia Nitrate Fluoride Uranium
Outside storage/inside vaporization area		
Uranium hexafluoride (solid)	Ruptured cylinder, vapor release	Uranium, hydrogen fluoride
(liquid/vapor)		Uranium
Uranyl nitrate	Ruptured drum	Nitrate
Chemical and manufacturing areas		
Uranium Uranium dioxide Ammonium diuranate Hydrogen fluoride	Pipeline or container rupture, spills, explosions, fires, filter failure, criticality	Uranium Ammonia Fluoride
Hydrogen	Explosion	Uranium
Transportation	Container rupture, spills	Uranium Miscellaneous chemicals

Source: Environment assessment for renewal of SNM--1107, Docket 70-1151, Westinghouse Electric Corp., Columbia, South Carolina.

Self-Check Questions 5-7

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

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

Absorber
criticality
ignite
maintenance
recycling
approved explosion
inert
nitrogen oxides
sintering
aqueous solutions
external
inhalation
NRC
solvents
containment
fire
in-leakage
pipe
special nuclear material
conversion
gaseous
leaks
powdered
UF_6

1. The main hazards to personnel during normal plant operations are associated with the potential______________ of fine uranium oxide particles when working with powders and exposure to_____________________ radiation during fuel inspection and storage.

2. Exposure to _____________________ and associated HF can result in skin burns and lung impairment.

3. Fuel fabrication facilities use or generate a number of nonradiological chemicals that can be released to the air and potentially cause off-site impacts. These include fluorides, ammonia, and _____________________.

4. Exposures to ammonia are more significant when coming from bulk handling systems. Exposures to workers may result from spills,_____________________, and venting of storage tanks.

5. Off-gases from the dissolution of uranium compounds in nitric acid contain nitrogen oxide and are treated by_____________systems to convert the NO_x to usable nitric acid.

6. Fuel fabrication facilities, due to their large inventories of and diverse production processes, have the greatest potential for criticality occurrences.

7. A criticality could occur within several process areas of a fuel fabrication facility, but the UF_6-UO_2_______________area is considered most likely to trigger an accidental criticality.

8. Criticality incidents have occurred at facilities that conduct operations with _________________________ of highly enriched uranium or plutonium.

9. Analyses of the root causes for criticality-related events indicate that failure to follow procedures, lack of procedures, mechanical failure, design error, and poor _______________________were the major causes cited.

10. The principal process-related fire protection concerns in fuel fabrication facilities arise from storage, handling, and process use of hydrogen and flammable_____________________.

11. The high-temperature processes of calcining and_____________ also present fire hazards.

12. The grinding of the fuel pellets produces uranium oxide fines, which _____________spontaneously under certain circumstances.

13. The electric arc welding of zircaloy tubes loaded with fuel pellets is performed in an ______________atmosphere inside the welding machine.

14. Zircaloy is a combustible metal, especially in thin scrap or _______________________ form.

15. Glove boxes used for manual operations with enriched uranium present a ________ hazard.

16. In fluidized bed or sintering furnaces, hydrogen is used as a reducing agent, usually diluted with inert gas to prevent the risk of _______________.

17. Explosive mixtures can develop from incomplete removal of air from a cold furnace at start-up or from_________________________of air into the furnace.

18. Flooding in a facility could create the risk of a _______________accident.

19. At fuel fabrication facilities, _____________is required for the furnaces converting UF6 to UO_2 and when UO_2 is present in powder form.

20. Releases of UF_6 caused by failures of__________connections or valves have occasionally occurred in fuel fabrication facilities.

21. Fuel fabrication facilities licensed under 10 CFR Part 70 are required to have _______-approved waste management procedures and environmental monitoring programs in place to address the wide range of gaseous, liquid, and solid wastes produced during facility operations.

22. ______________________ effluents from operations contain both radioactive and nonradioactive pollutants.

23. Treatment for liquid wastes includes one or more of the following: evaporation, neutralization, chemical processing, settling ponds, or ____________________.

24. Low-level solid wastes must be disposed of off site by a licensed contractor at an _________________ site.

Match the hazards listed in column A with preventive measures listed in column B.

Column A **Hazards**		**Column B** **Preventive Measures**
A. The potential exists for receipt of U-235 enriched beyond the authorized limit	25. ____	Gas detectors are placed in areas using hydrogen to alert workers.
B. A dropped or damaged cylinder could result in release of UF$_6$	26. ____	U-235 enrichment is verified by analysis of samples.
C. Workers and the environment could be exposed to radioactive contamination from process chemicals	27. ____	At no time is a cylinder more than a few feet above an unyielding surface.
D. Workers could be exposed to UF$_6$ release during connection and disconnection of the vaporizer to the conversion system.	28. ____	Operations personnel wear supplied air respirators during the connection and disconnection activities.
E. Hydrogen leaks could cause fire and explosions.	29. ____	Detectors are provided for fume surveillance and monitoring.

MODULE 5.0: FUEL FABRICATION

Complete the following questions.

30. What types of events are NRC licensees required to report?

31. What are factors that have contributed to events at fuel fabrication facilities?

32. What preventive measures could have been taken to either avoid or lessen effects of previous events at fuel fabrication facilities?

Activity 1: NRC Regulatory and Guidance Documents

Purpose: The purpose of this activity is to review a brief description of an actual incident that happened at the General Electric Company's Nuclear Fuel and Components Manufacturing facility in Wilmington, North Carolina. Note: This facility is now operated by Global Nuclear Fuels-Americas, LLC.

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

Reference: "Potential Criticality Accident at the General Electric Nuclear Fuel and Component Manufacturing Facility," U.S. Nuclear Regulatory Commission, NUREG-1450, May 29, 1991.

Introduction

On May 29, 1991, at the General Electric (GE) Company's Nuclear Fuel and Components Manufacturing (NFCM) facility approximately six miles north of Wilmington, North Carolina, an estimated 150 kilograms (kg) (320 lb) of uranium were inadvertently transferred to an unfavorable geometry waste treatment tank. ("Unfavorable geometry" refers to a container or vessel that can hold enough uranium to produce a criticality). Because of the tank configuration and type and quantity of material available, there was the potential for a nuclear criticality accident. Such an accident would yield a burst of neutron and gamma radiation that would likely be fatal to anyone within 10 ft and cause radiation exposures of approximately 5 rads at 45 ft. According to the licensee, however, there would be no expected off-site radiological impacts.

Facility Operations

The NFCM is licensed by the NRC to possess and use SNM. Authorized activities include UF6 conversion, fuel manufacturing, scrap recovery, process technology operations, laboratory operations, and waste treatment and disposal. As part of the fuel manufacturing process, the NFCM has established the Uranium Recycle Unit (URU) to recover uranium from certain waste and scrap materials. In this process, scrap materials are dissolved in nitric acid, passed through a filter, and fed to a solvent-extraction system. The recovered uranium is then returned to the fuel manufacturing process.

Description of the Accident

On the evening of May 28, 1991, the URU control room operator noted that the interface level between the organic and aqueous phases within the solvent-extraction process could not be maintained. Although the operators became aware of the interface problem around 9:30 p.m, the problem had actually started an hour earlier, apparently unnoticed by the operators. The interface problem was caused by a malfunction of the solvent-extraction Column A level control valve (LCV), LCV-300. When efforts by the control room operator to correct the level control valve problem were unsuccessful, attempts were made to control the process by throttling a manual valve located upstream of LCV-300. Manual throttling continued until shift turnover at 11:00 p.m.

The relief control room operator requested that maintenance investigate the problem with the LCV. Until maintenance personnel arrived approximately two hours later, the floor operator continued to throttle the upstream valve manually. After approximately an hour and a half of troubleshooting activities, maintenance personnel concluded that the valve could not be repaired because replacement parts were unavailable. At the direction of the control room operator, maintenance personnel forced LCV-300 open by redirecting air pressure in the valve actuator. Forcing the valve open caused the solvent-extraction process to be ineffective and created an open pathway for high concentrations of uranium to be transferred directly to the aqueous waste quarantine tanks.

From the onset of the problem, feed material (crude uranyl nitrate) continued to be sent to the solvent-extraction process. Aqueous waste from the solvent-extraction process was fed to two favorable geometry quarantine tanks. During a nine-hour period on May 28 and 29, the contents of approximately nine quarantine tanks were transferred to an unfavorable geometry waste accumulation tank located outside the fuel manufacturing building. Of these nine transfers, four were made without a measurement of their uranium concentration. Transfers that were made after sampling and measurement, which showed concentrations of less than the 150 parts per million (ppm) transfer limit, were questionable because of sampling system problems. These problems were later confirmed by a calculational method (i.e., system mass balance), which showed that some of the analyzed tanks transferred had to contain uranium concentrations greater than
12,000 ppm.

At approximately 5:20 a.m. on May 29, a measured sample from the quarantine tank indicated a uranium concentration of 6,977 ppm, compared to the transfer limit of 150 ppm. Based on this information, the control room operator transferred the contents to a safe geometry rework tank and then shut down the solvent-extraction process. Unaware of the uranium concentration problems, a waste treatment facility operator, approximately ten minutes later, pumped the contents of the 20,000-gallon waste accumulation tank to a comparable treatment tank with unfavorable geometry at the waste treatment facility, located approximately 0.25

mile from the fuel manufacturing building. Sample results for the material in the waste treatment tank at that facility revealed a uranium concentration of 2,333 ppm.

The licensee recognized the nuclear criticality potential of the problem but did not initially consider it an emergency condition. As a result of these high concentrations, the licensee assigned a technical evaluation team to develop nuclear criticality mitigation and uranium recovery plans. To minimize the nuclear criticality potential, operators continued air sparging (i.e., mixing) tank contents to prevent an accumulation of material in the bottom of the tank caused by precipitate settling.

The licensee advised the NRC of the incident on May 29; the NRC formed a response team and dispatched it to the site. By the evening of May 29, the licensee had finalized uranium recovery plans and began to remove uranium from the tank with a centrifuge. Although these actions were taken, the licensee continued to maintain that the incident did not meet the threshold required for implementation of its emergency plan. After continued prompting by the NRC, the licensee declared an Alert emergency classification, implemented provisions of the emergency plan, and notified federal, state, and local off-site authorities about 6:40 a.m. on May 30, 1991.

Uranium recovery operations continued through the early morning of June 1, 1991. At this time, the contents of the waste storage tank were reduced to a less-than-critical mass after a portion of the tank contents was transferred to two adjacent storage tanks. The licensee terminated the Alert classification at 3:20 a.m. on June 1. Centrifuge operations continued until June 3, and, upon completion of the operation, the licensee recovered approximately 150 kg of uranium. The sequence of events for the May 28-29, 1991, portion of the GE Wilmington incident is shown in the Chronology section.

Chronology

Note: Figures 5-30 through 5-36, depicting equipment and process flow charts, are located at the end of this section.

May 28, 1991

2:15 p.m. The pumping of waste tank V-103 to tank V-104 was initiated. Tank V-103 is located adjacent to the URU, and tank V-104 is located at the waste treatment facility (WTF). V-103 and V-104 are 20,000-gal. unfavorable geometry tanks.

4:00 p.m. Pumping from V-103 ceased, with only approximately 3,000 gal. remaining and with tank V-104 filled. Records indicate a transfer of 15,600 gal. A measured sample of tank V-104 contents indicated 99.2 ppm uranium (U).

Note: The waste streams subsequently transferred into tank V-103 contained the material transferred to tank V-104 that was found to contain an unauthorized amount of uranium.

8:30 p.m. Interface problems began to occur with the solvent-extraction (SX) column (as evidenced by historical data). Operators were apparently unaware at this point.

9:30 p.m. Control Room Operator A (CRO A) noted that SX Column A had interface and density problems. The process floor operator indicated that the SX Column A level control valve (LCV-300) was not actuating and did not respond to demand signals. The LCV-300 is a

1-inch globe valve with a pneumatic positioner actuator. SX operations continued when a worker throttled a manual valve adjacent to LCV-300.

9:35 p.m. Aqueous waste (AW) quarantine (Q) tank V-290 at the 90% level was transferred to V-103. A measured sample of V-290 contained 75 ppm U2. The release limit from V-290 to V-103 is 150 ppm U. V-290 is a 600-gal. criticality-safe geometry tank.

12:35 p.m. Q tank V-291 at the 90% level was transferred to V-103. A measured sample of V-291 indicated 69 ppm U. The release limit from V-291 to V-103 is 150 ppm U. V-291 is a 600-gal. criticality-safe geometry tank.

10:45 -
11:00 p.m. Control room shift turnover.

11:00 p.m. Q tank V-290 at the 90% level was transferred to V-103. The contents were transferred without a sample measurement.

The relief CRO noted SX Column A interface problems.

Note: Records show that SX column interface was recovered for a short period in this time frame.

11:15 p.m. CRO A called instrumentation maintenance to troubleshoot and repair LCV-300. Records show that SX interface was lost in this time frame.

CRO A instructed a floor operator to close the manual block valve upstream of LCV-300.

11:30 p.m. CRO A called the process engineer to notify him of SX control problems. The process engineer concurred with CRO A to place the SX system in "warm start-up" mode to attempt to get LCV-300 to cycle and position correctly.

~11:45 p.m. CRO A instructed a floor operator to reopen the manual block valve upstream of LCV-300.

11:55 p.m. The decant from waste neutralization tank V-104 was transferred to a lagoon. Analysis of the decant indicated <1 ppm U.

May 29, 1991

12:00 a.m. The SX "warm-up" mode attempt did not affect LCV-300 valve position.

12:10 a.m. Q tank V-291 was transferred at the 90% level to V-103. A measured sample of V-291 indicated 40 ppm U. The release limit is 150 ppm U.

12:15 a.m. SX column interface was regained. CRO A instructed a floor operator to close the manual block valve upstream of LCV-300.

1:05 a.m. Q tank V-290 at 89.5% full was transferred to V-103. A measured sample of 42 ppm U was attributed to tank V-290. The release limit is 150 ppm U.

1:35 a.m. Instrumentation technicians found LCV-300 in the open position. Troubleshooting/repair activities began. When the air supply to the valve was removed, the valve closed, as designed.

Q tank V-291 was at the 39% level and was discharged to V-103. Contents were not sampled and measured for uranium concentration.

2:30 a.m. Instrumentation personnel continued to troubleshoot the valve positioner on LCV-300 and search for repair parts.

2:55 a.m. Q tank V-290 at 90% full was transferred to V-103. A measured sample of 49 ppm U was attributed to tank V-290. The release limit is 150 ppm U.

3:00 a.m. Instrumentation informed CRO A that the valve could not be repaired due to unavailability of parts. CRO A believed that SX Column A was overflowing into Column B.

3:10 a.m. At the request of CRO A, instrumentation technicians blocked LCV-300 open by redirecting air pressure to the valve actuator. The AW flow from the SX column was operated manually by the process floor operator.

3:15 a.m. SX interface was lost.

4:00 a.m. Q tank V-291 at 81% full was transferred to V-103 without a sample measurement.

4:30 a.m. Instrumentation personnel reconfirmed to CRO A that LCV-300 could not be repaired because of parts' unavailability.

Q tank V-290 at 64% full was transferred (a split between V-103 and V-255 [a favorable geometry rework tank]). The contents were not measured for uranium concentration.

5:20 a.m. Q tank V-291 at 80.5% full was transferred to the safe geometry rework tank V-225. A measured sample of V-291 indicated 6,977 ppm U.

CRO A shut down the process.

5:30 a.m. The contents of tank V-103 were pumped to tank V-104 at the WTF.

7:00 a.m. A sample taken from tank V-104 indicated 2,333 ppm U.

Note: As a result of the high V-104 sample, GE management notifications were made and a technical evaluation team was convened. In addition, tank V-104 sparging was maintained in an effort to control density by keeping the uranium precipitate suspended.

Uranium Recovery Activities

3:45 p.m. The licensee advised Region II of the event.

5:15 - An NRC initial site team was assembled

5:30 p.m. and dispatched.

5:44 p.m. The NRC entered standby mode; Region II and the Headquarters Incident Response Center were activated to monitor the situation.

6:30 p.m. The licensee provided a status briefing and action plan to NRC Headquarters and Region II.

Region II notified the state of North Carolina radiological protection authorities.

7:00 p.m. The licensee initiated uranium recovery operations from tank V-104.
8:30 p.m. NRC commissioner assistants were briefed on the situation.

9:15 p.m. The NRC completed notification of appropriate federal agencies and other regions.

May 30, 1991

12:55 a.m. A Region II site team arrived at GE Wilmington. The licensee provided a briefing of the situation and actions being taken.

2:00 a.m. The NRC site team conducted an inspection of SX activities and the WTF. Verification was made concerning sparging of tank V-104 and backup sparging provisions.

4:00 a.m. The NRC site team briefed Region II and Headquarters on facility status.

6:38 a.m. The licensee declared an Alert.

8:30 a.m. U-235 enrichment in V-104 was determined to be 3.125% (3.2%, considering measurement uncertainty). Sludge removal continued.

6:30 p.m. Region II briefed a radiological protection representative from the state of North Carolina.

May 31, 1991 Centrifuge operations continued throughout the day to reduce the uranium mass in V-140 below the critical limit. Centrifuge equipment problems were experienced.

June 1, 1991

3:15 a.m. The contents of V-104 continued to be reduced by use of a centrifuge. The transfer of a portion of the contents of tank V-104 to tanks 109A and 109B was completed. A less-than-critical mass in each of the three tanks was achieved.

3:20 a.m. The Alert was terminated by the licensee.

The NRC went out of standby mode.

June 2, 1991 Centrifuge operations continued.

June 3, 1991

10:30 a.m. Centrifuge operations were completed. The licensee collected approximately 136 kg of the estimated 150 kg of uranium originally transferred.

Figure 5-30. Solvent Extraction in Process

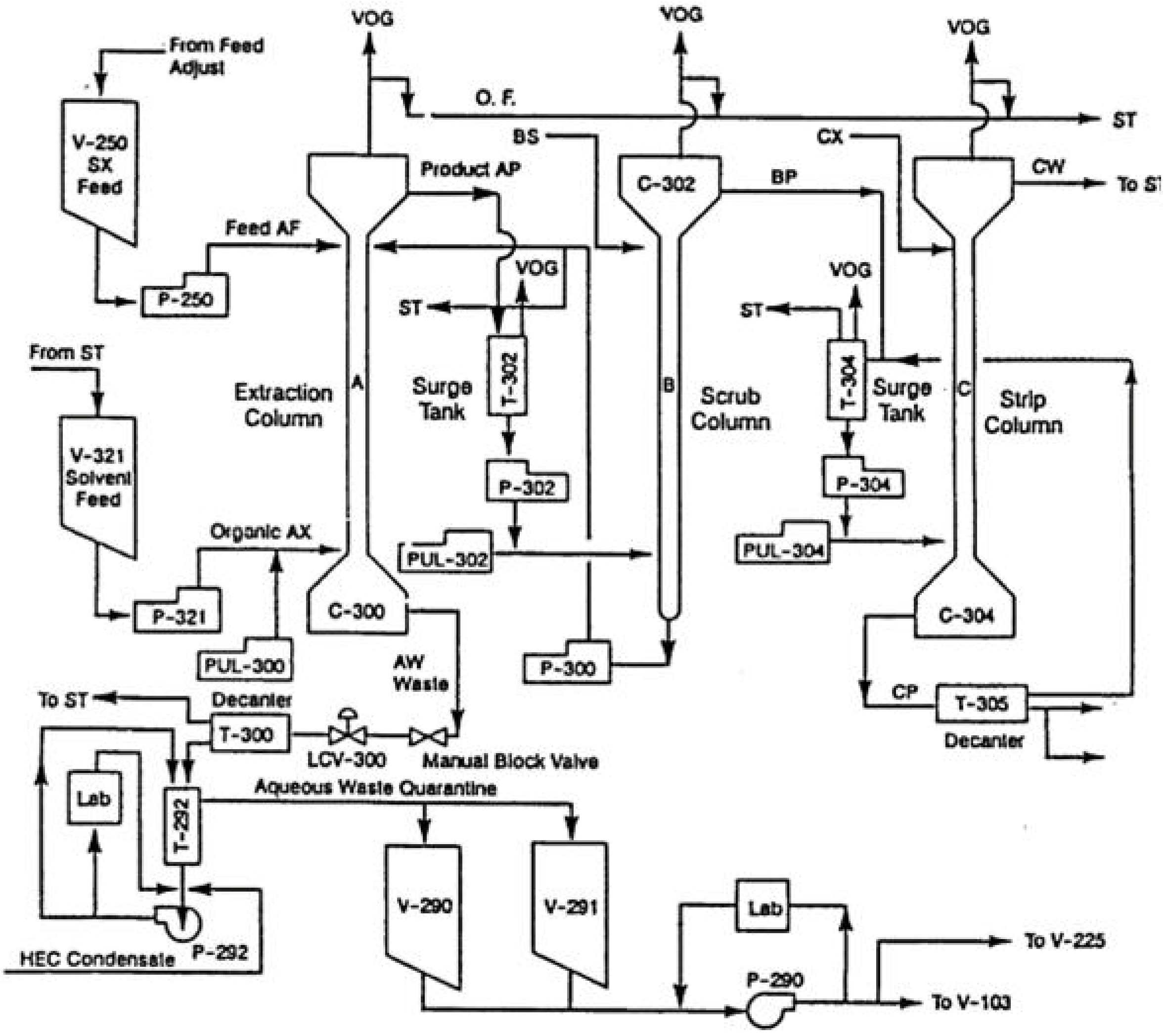


Figure 5-31. Nitrate Waste and Solvent Extraction Process Waste Flow

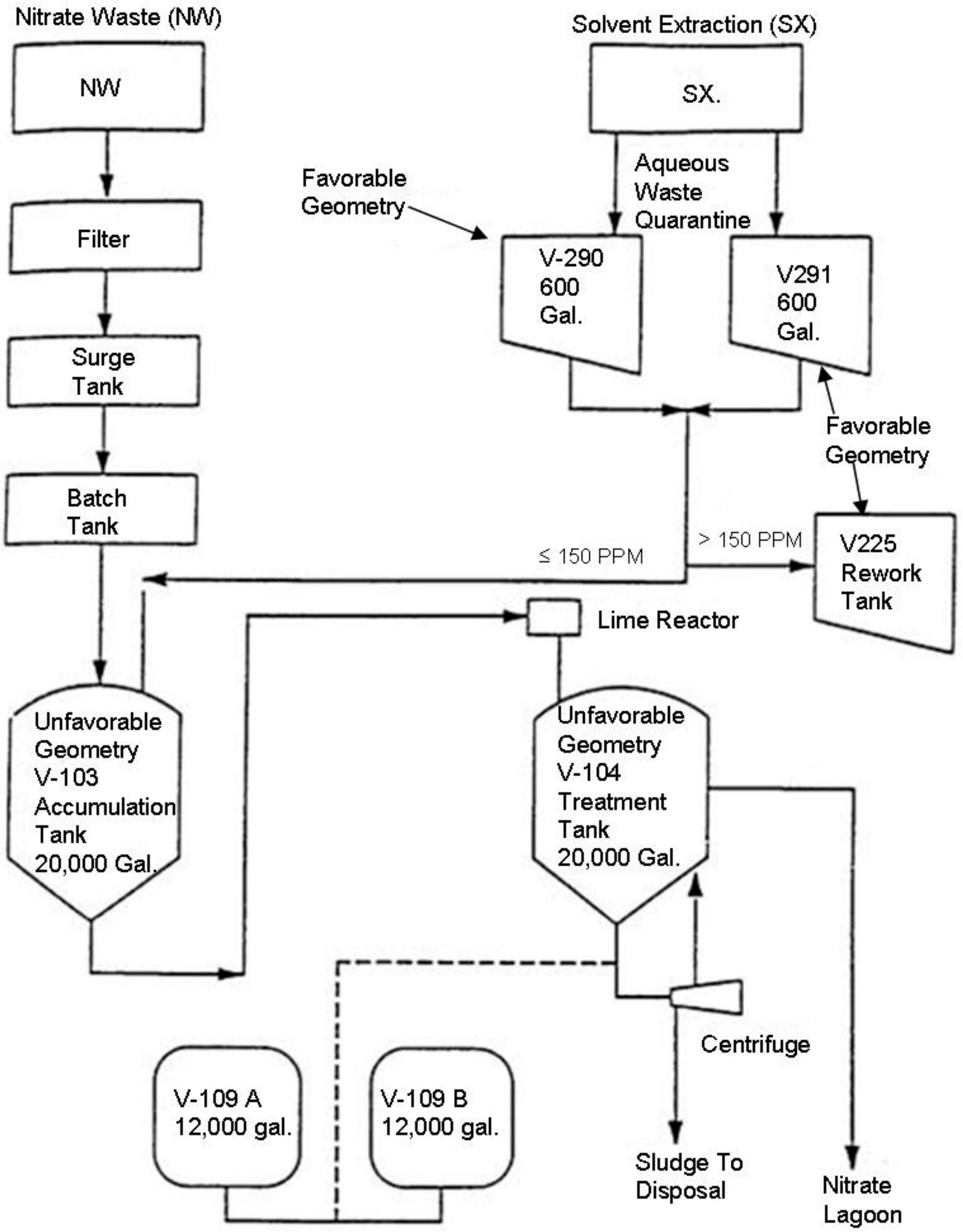


Figure 5-32. Tank V-103

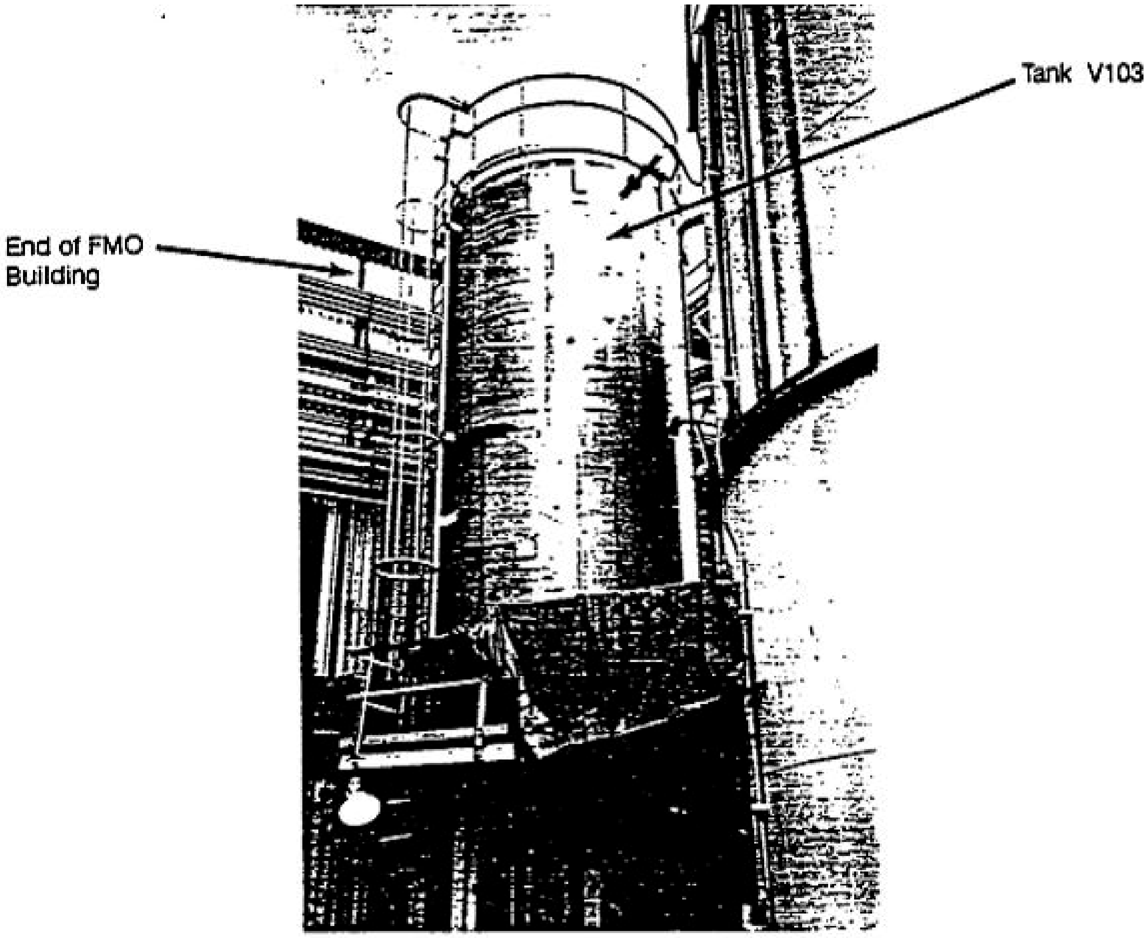


Figure 5-33. WTF and Tank V-104

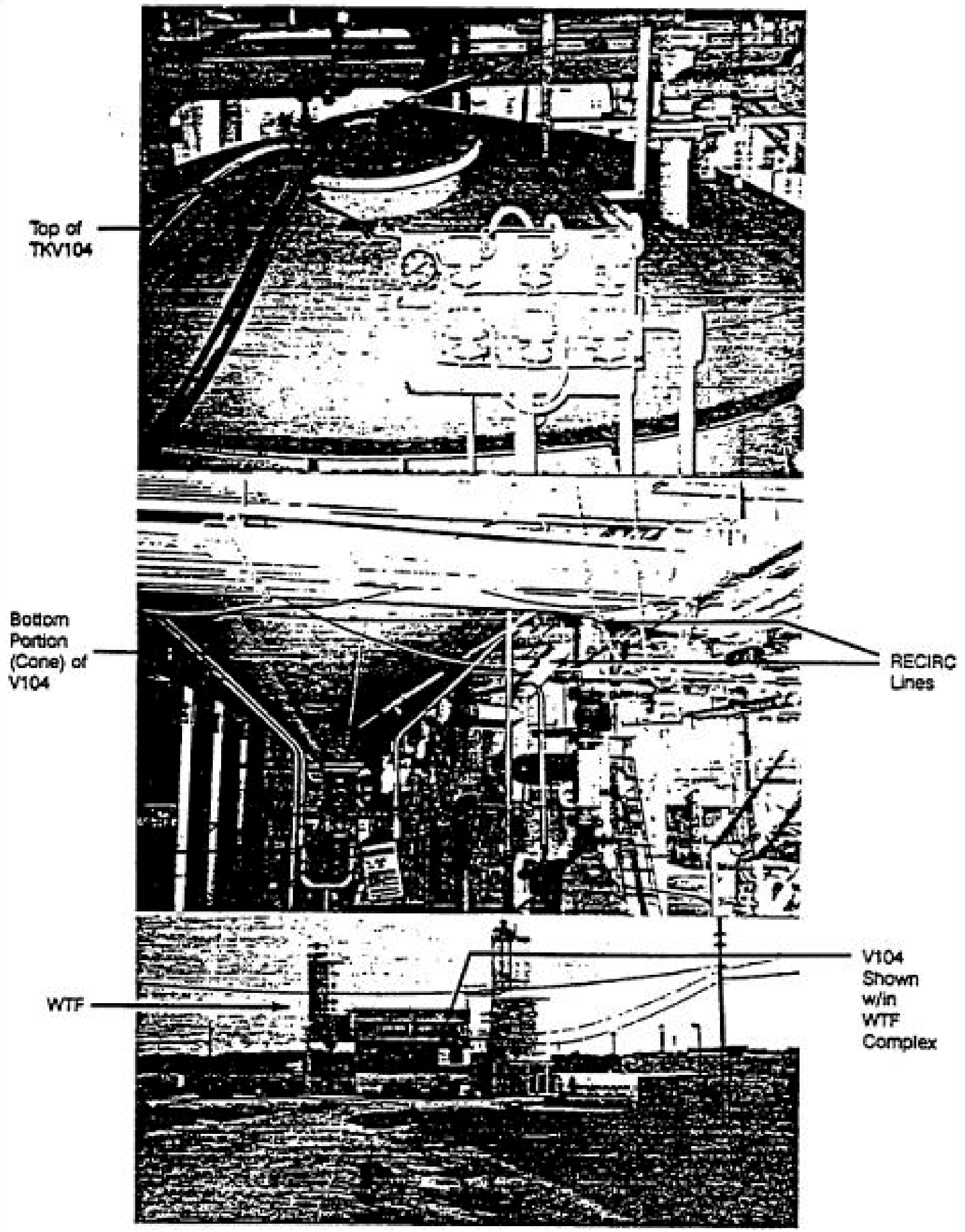


Figure 5-34. LCV-300 and Upstream Manual Valve

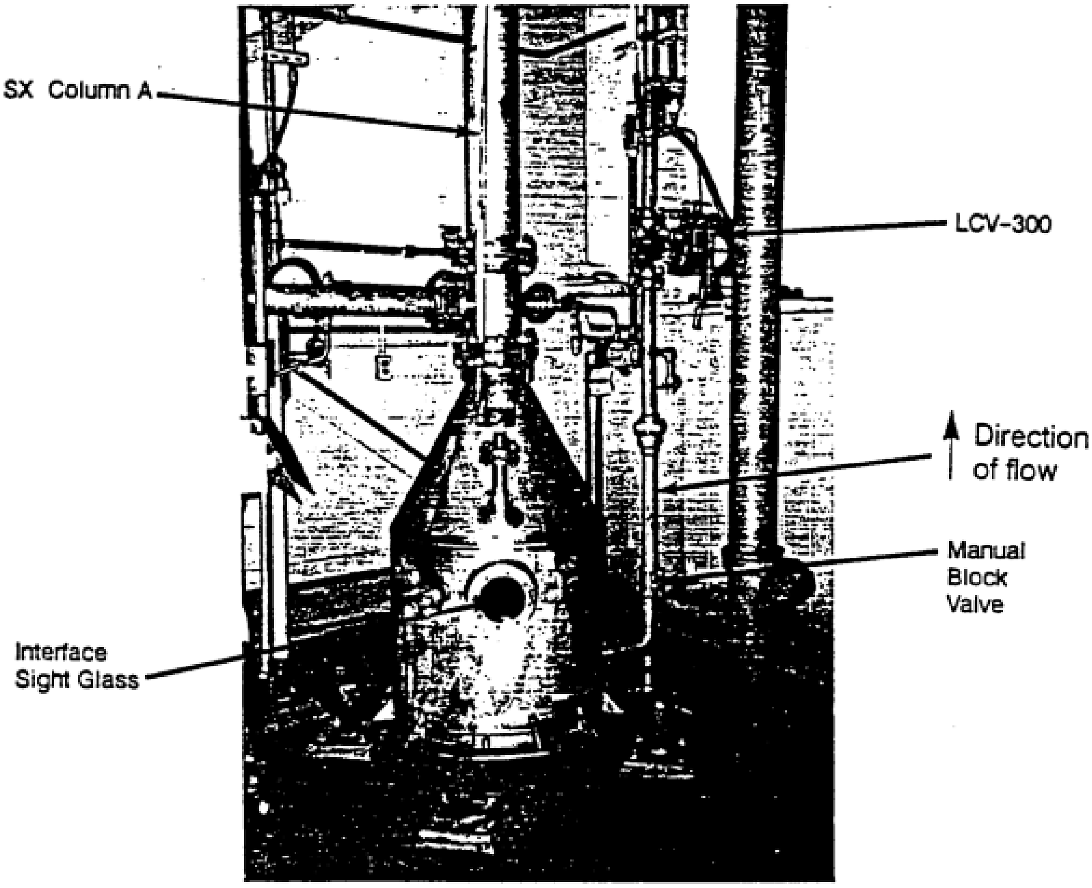


Figure 5-35. Transfer Pump and Top of Tank V-104 (Shown Disconnected)

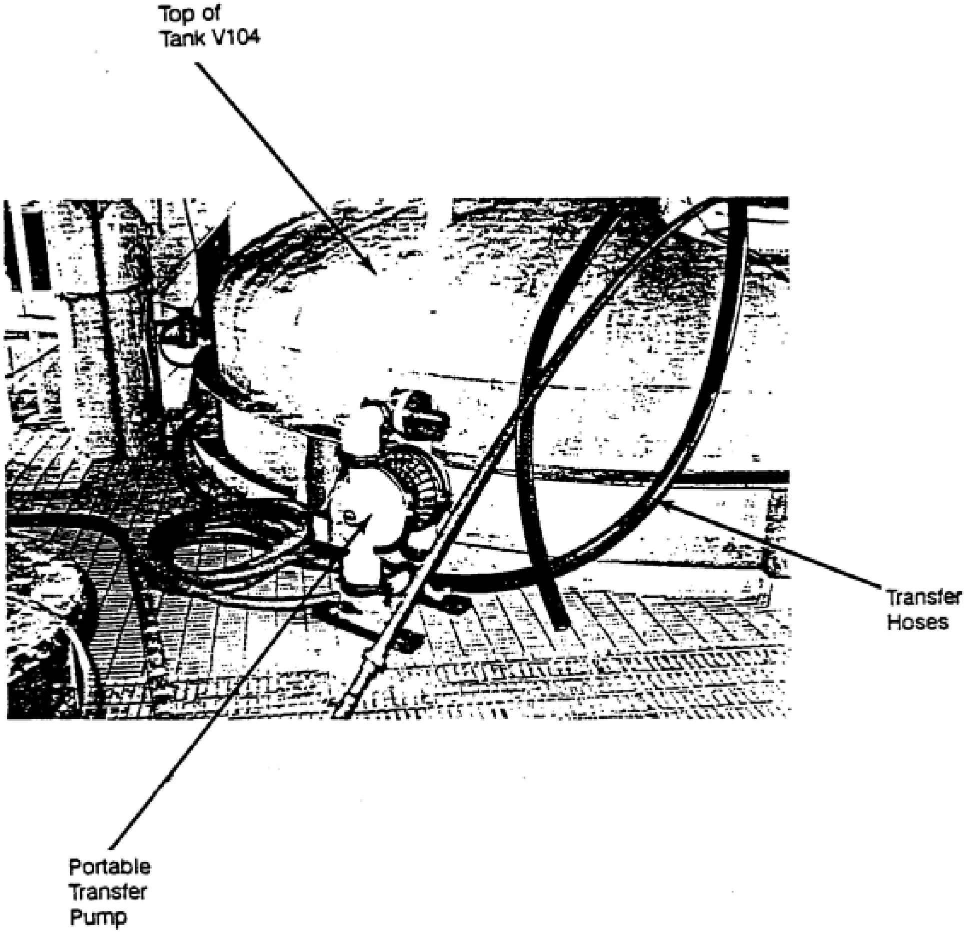
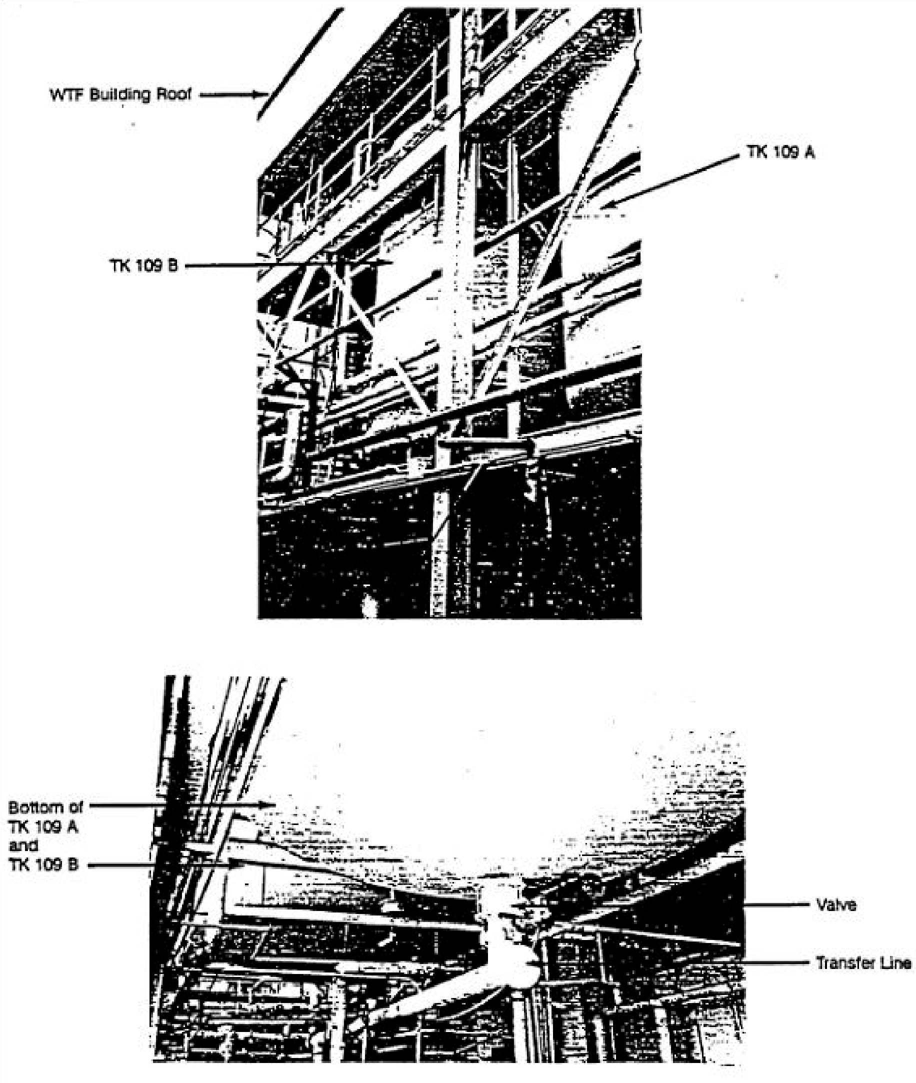


Figure 5-36. Tanks 109A and 109B



Contributing Factors

1. The licensee's radiological control emergency plan and implementing procedures were ambiguous and incomplete and did not consider a potential criticality. NRC requirements and guidance as written did not require licensees to assess incidents based on loss of nuclear criticality safety barriers or a potential nuclear criticality.

2. Area coordinators serve as the only direct management during non-daytime shifts and on weekends. They have a broad area of responsibility and a large span of control.

3. There was no technical support and maintenance supervision on site during non-daytime shifts and on weekends.

4. There is no distinction between process parameter and criticality safety parameter alarms in the control room.

5. A "safety first" attitude was not communicated throughout the facility.

6. Management's presence in the process and production areas was limited.

7. There was no quality assurance oversight of URU activities.

8. Nuclear criticality safety audits to ensure that criticality controls were implemented as intended focused on equipment changes, not operations.

9. Management was not aware of the extent to which the computer control system was being operated in the TUNE (manual override) mode.

10. Management was not aware of deviations from aqueous waste sampling and transfer procedures. There were no audits of compliance with procedures.

11. Operator performance was not measured or observed within a training/qualification program after initial training during URU start-up in 1984 through 1986. New operators received only on-the-job operations training from senior operators and area coordinators, nor was there requalification training for operators.

12. For abnormal conditions, operating procedures focused on continued operations rather than on bringing the process to a safe condition.

13. Changes and modifications had been made to plant equipment and systems without an adequate evaluation of their effect on operations.

14. Management meetings with plant personnel emphasized production goals without appropriate qualifications for safety considerations.

15. Management did not fully benefit from the investigation of incidents at the facility by using them to uncover unanalyzed routes to a criticality accident or to develop needed controls.

16. Neither a list of equipment important to criticality safety nor clear and unique labeling for this equipment was available to plant personnel.

17. Maintenance priorities and resources focused on meeting continued plant operation goals.

18. There was a lack of engineering involvement in the maintenance process, especially in the Facility Change Request process.

Investigative Team Findings

1. The licensee did not consider the incident serious enough to be classified as an emergency.

2. Once the Alert was declared, the licensee made appropriate notifications in accordance with the Radiological Contingency and Emergency Plan (RCEP).

3. The management organizational structure at GE NFCM dictated a wide span of control such that no single group had sole responsibility for the URU. This resulted in limited management presence in the process and production areas and a lack of ownership of the URU and assurance that activities were conducted in a safe manner.

4. Area coordinators' broad area of responsibility made it difficult for them to provide adequate supervisory oversight, especially when they served as the only direct management during non-daytime shifts and weekends. Without direct management oversight and guidance, operators had the flexibility to do whatever was necessary to meet management's expectations.

5. Management meetings with plant personnel emphasized that production was the facility's overriding concern. Similarly, operating procedures emphasized continuous operations rather than safe practices. Modifications to the computerized process control system served to promote production and eliminated features that were intended to support safe operations, such as alarms, interlocks, and subsystem shutdowns. These changes were made without adequate evaluation of the impact on criticality safety. Those alarms that were not eliminated did not convey any distinction between process parameters and criticality safety parameters.

6. Operators' prevalent attitude was to maintain continuous operations to the extent that procedures and automatic controls for the criticality control sampling system for SX AW

were circumvented. The operators' anxiety to keep the process running may be attributed in part to modifications in another part of the SX system that resulted in significantly increased inlet flow rates to AW tanks. These modifications did not include an evaluation of the impact that the increased flow rates had on operators and process operations.

7. Management's limited cognizance of URU activities was manifested in several ways. Routine evaluations of operator performance relative to procedural adherence and practices were nonexistent, and operators were questioned only when productivity was affected. The absence of requirements for control room operators to maintain logs made audits of operations nearly impossible, even if management chose to do so. Nuclear criticality safety audits performed to ensure that criticality safety was implemented as intended focused on equipment changes, not operations.

8. Operators exhibited ingenuity regarding production. For example, operators would, on occasion, dump AW Q tank contents with high uranium concentrations into a sump. This practice may be attributed in part to deficient operating procedures. The governing AW transfer procedure did not contain any contingency actions for situations when uranium concentrations in the AW quarantine tanks were higher than limits for transfer to the unfavorable geometry waste accumulation tank and the AW rework tank volume was not sufficient or available.

9. In reviewing the licensee's nuclear safety program, the team determined that the criticality safety staff was unusually strong for a low-enriched processing facility; however, the licensee lacked an effective multidisciplinary approach to take advantage of this staff's strengths to identify (1) each route to a criticality accident scenario, (2) necessary contingencies for each scenario, and (3) the formal controls necessary for each contingency.

10. Configuration control implementation did not follow the licensee's own procedure. No software configuration audit was performed by NSE. Interlocks and alarms were removed from the automatic system when the y became a nuisance to operations, without serious consideration of the criticality control implications of their removal.

11. The criticality controls and the process controls were performed by the same digital control system. There is no separation between the criticality safety-related instruments and the process control instruments.

12. Inadequate management oversight in implementing the Facility Change Request procedure resulted in some facility component changes that were made without management or nuclear safety reviews. Three such changes, including the replacement of LCV-300, complicated significant plant accidents.

QUESTIONS:

1. Based on the information provided, list the probable causes of this incident.

2. What recommendations would you make to prevent the reoccurrence of an incident of this type?

3. What are the lessons learned from this incident?

Lessons learned:

Learning Objective

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

5.1.10 Describe mixed oxide (MOX) fuel and its use in fuel fabrication.

MIXED OXIDE (MOX) FUEL FABRICATION

Background

The Department of Energy (DOE) has contracted for construction of a Mixed Oxide Fuel Fabrication Facility (MFFF) to convert surplus U.S. weapons-grade plutonium to mixed oxide (MOX) fuel for domestic commercial reactors. The U.S. Nuclear Regulatory Commission will regulate the construction and operation of the DOE-owned facility, located on the Savannah River Site (SRS) near Aiken, South Carolina.

Shaw AREVA MOX Services (MOX Services, a consortium of Shaw Project Services Group, Inc.) Shaw Environmental and Infrastructure, Inc.) and AVEVA, Inc.) has applied for a 10 CFR Part 70 license to possess and use special nuclear material in a MFFF. MOX Services is the license holder for the MFFF and has responsibility for the design, operation and ultimately deactivation of the facility. The facility is an integral part of the U.S. Government's strategy for the disposition of surplus plutonium in accordance with the following:

- Nonproliferation and Export Control Policy (White House 1993)
- Joint Statement by the President of the Russian Federation and the President of the United States on the Non-Proliferation of Weapons of Mass Destruction and the Means of Their Delivery (White House 1994)
- Joint Statement of Principles for Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes (White House 1998)
- Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation (White House 2000)

The Agreement commits the United States to convert 28.2 tons (25.57 metric tons) of plutonium to mixed oxide fuel and irradiate it in power reactors. The MFFF is designed to convert up to 36.4 tons (33 metric tons) of plutonium oxide to MOX fuel that meets the Spent Fuel Standard recommended by the National Academy of Sciences. The MOX fuel will be transported to and irradiated in four commercial nuclear power reactors: two units at the

Catawba Nuclear Station near York, South Carolina, and two units at the McGuire Nuclear Station near Huntersville, North Carolina. After the surplus plutonium is converted to MOX, the facility will be deactivated. The proposed action also involves the consumption of surplus depleted uranium from current stockpiles.

In 2005, the NRC issued the following documents that will allow the MFFF to proceed:

FEIS – NUREG-1767. “Final Environmental Impact Statement on the Construction and Operation of a Proposed Mixed Oxide Fuel Fabrication Facility at the Savannah River Site, South Carolina.” January 2005

FSER – NUREG-1821. “Final Safety Evaluation Report on the Construction Authorization Request for the Mixed Oxide Fuel Fabrication Facility at the Savannah River Site, South Carolina.” March 2005

Construction Authorization No. CAMOZ-001, March 30, 2005

The MOX fuel fabrication process and plant design are based on the operational AREVA, Inc. MELOX and La Hague plutonium processing facilities located in Marcoule and La Hague, France, respectively. The plant design has been modified to meet appropriate United States regulations and standards. The fuel fabrication subprocess is similar to what is operating in MELOX, while the aqueous polishing subprocess is similar to what is operating in La Hague. Figure 5-37 shows an existing MELOX facility in France where MOX fuel is made for European use.

Figure 5-37. MELOX Facility in France

MOX Fuel Fabrication Facility (MFFF)

On October 14, 2005, the DOE held a ceremony commemorating the beginning of site preparation activities for the construction of the MOX Fuel Fabrication Facility to be built in the F-Area of the Savannah River Site. The facility will consist of an aqueous polishing and fuel fabrication building, secured warehouse, and various support buildings and will use existing site-wide infrastructure and services, such as security, emergency management, radiation monitoring, environmental monitoring, and waste management. Figure 5-38 is a site schematic showing a large hardened structure for the MFFF. The facility is expected to provide over 300,000 sq. ft. and will be used to:

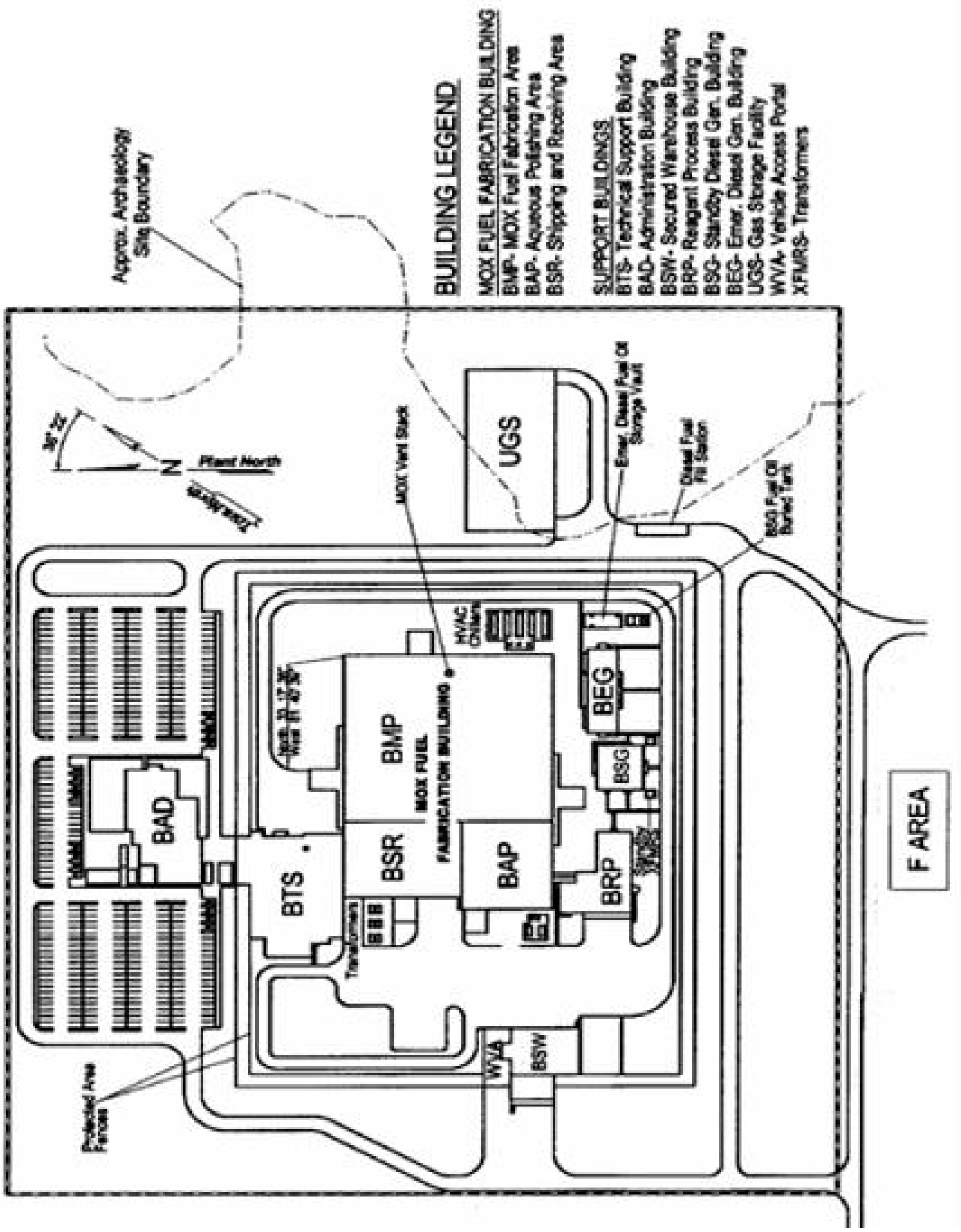
- mix plutonium oxide from the pit disassembly and conversion process with uranium oxide;
- form mixed oxide fuel pellets;
- fabricate mixed oxide fuel assemblies; and
- ship completed fuel assemblies to domestic commercial reactors for irradiation.

Figure 5-38. Proposed MOX Facility at Savannah River Site

The MFFF consists of the following buildings (Figure 5-39) described below:

- MOX Fuel Fabrication Building
- Reagent Process Building
- Emergency Diesel Generator Building
- Standby Diesel Generator Building
- Secured Warehouse Building
- Administration Building
- Technical Support Building

Figure 5-39. MFFF Building Layout



MOX Fuel Fabrication Building (BMP, BAP, BSR)

The MOX Fuel Fabrication Building is a multi-story, hardened, reinforced-concrete structure with a partial below-grade basement and an at-grade first floor. The building has an overall height above grade of 73 ft (22.3 m). The 20-ft (6-m) tall vent stack, mounted on top of the building, has a top elevation of approximately 93 ft (28 m) above grade. This facility meets all applicable requirements for processing special nuclear material (SNM).

The entire MOX Fuel Fabrication Building structure and the three component building areas are designed to withstand extreme natural phenomena, including design basis earthquakes, floods, and tornadoes, as well as a spectrum of potential industrial accidents that could impact the fissile process materials. The lowest floor level of the building (approximate elevation 256 ft (78 m) above mean sea level) is well above the F-Area calculated design basis flood level with a 100,000-year return period. Storm water runoff from the MFFF site is directed to retention basins where it is released at rates equivalent to pre-construction storm water runoff rates.

The MOX Fuel Fabrication Building is located within the protected area and has the requisite security measures in place to adequately safeguard the facility and prevent any attempts to illicitly remove SNM from the facility. The building is a multi-functional complex containing all of the plutonium handling, fuel processing, and fuel fabrication operations of the MFFF. The building is comprised of three major functional interrelated areas: the aqueous polishing area, the fuel fabrication area, and the shipping and receiving area. Functional areas and processes in the MOX Fuel Fabrication Building complex include the following:

- Aqueous polishing area
- Blending and milling area
- Pelletizing area
- Sintering area
- Grinding area
- Fuel rod fabrication area
- Fuel bundle assembly area
- Storage areas for feed material, pellets, rods, and fuel assemblies
- A laboratory area
- Shipping and receiving (i.e., truck bay) area
- Space for use by the International Atomic Energy Agency

Support equipment (e.g., heating, ventilation, and air conditioning [HVAC] components; high-efficiency particulate air [HEPA] filter plenums; inverters; switchgear; pumps) is also present within the building complex. Adequate space for waste packaging and its temporary storage is provided.

The MOX Fuel Fabrication Building contains the SNM processing areas. This building complex is a possible source of radiological releases to the environment. The building produces solid and liquid wastes and airborne effluents. Solid wastes and liquid waste streams are transferred to the appropriate SRS waste management facilities in accordance with the applicable SRS Waste Acceptance Criteria (WAC) (WSRC 2000b). Airborne effluents are treated and monitored before being released to the environment.

Reagent Process Building (BRP)

The Reagent Process Building, located inside the protected area adjacent to the aqueous polishing area of the MOX Fuel Fabrication Building, provides space for storage and mixing of the chemical reagents used in the aqueous polishing process.

A variety of chemicals are stored in the Reagent Process Building. The building has roof vents to allow for venting in emergency situations. No measurable gaseous emissions are expected from activities within this building.

The Reagent Process Building consists of a number of separate rooms/areas for the various chemicals. Liquid chemical containers are located inside curbed areas for containment of accidental spills. Safety showers and eyewash stations are located in each of the chemical rooms/areas. One end of the building has a loading dock for transfer of chemical drums in and out of the building. The building's floor level is slightly above grade with a below-grade collection tank room that receives waste chemicals from the aqueous polishing area and from the Reagent Process Building. The building contains shower, restroom, and locker facilities. Chemicals are transferred to the aqueous polishing area from the Reagent Process Building via piping located in a concrete, below-grade trench between the two buildings.

Emergency Diesel Generator Building (BEG)

The Emergency Diesel Generator Building, located inside the protected area adjacent to the MOX Fuel Fabrication Building, contains the diesel generators that provide the emergency power for items relied on for safety in the MFFF. The building is a single-story, slab-on-grade, reinforced-concrete building. The roof and walls of the building are of sufficient strength and thickness to protect against the effects of extreme natural phenomena (e.g., severe wind and tornado) and associated generated missiles, as well as to resist the design basis earthquake. Natural disasters considered in the design of the Emergency Diesel Generator Building are the same as those con-sidered for the MOX Fuel Fabrication Building.

The emergency onsite power is provided by two 1,000-kW seismically-mounted diesel generators. Located adjacent to the diesel generator rooms, but separated from them by firewalls, are the switchgear, motor control centers, and uninterruptible power supplies (UPSs). The UPS equipment uses sealed, maintenance-free batteries.

Associated with the Emergency Diesel Generator Building is a large fuel tank sited in a concrete bunker adjacent to the building. The top of this bunker is slightly above plant grade. This tank within a vault meets the design requirements of 40 CFR Part 280 for underground storage tanks. The diesel generator rooms contain a day tank that also stores fuel oil and is enclosed with a dike that can accommodate the full contents of the associated tank.

Standby Diesel Generator Building (BSG)

The Standby Diesel Generator Building is located inside the Protected Area and contains the normal operation electrical generators that provide the onsite power source for the major loads in the event of a loss of offsite power. The building is a single-story, slab-on-grade structure with pre-engineered steel framing and insulated metal siding and roof.

The building contains two 2,000-kW standby diesel generators. The normal switchgear, load centers, motor control centers, power panels, and dry type transformers are located adjacent to the diesel generator rooms and are separated from them by firewalls.

Secured Warehouse Building (BSW)

The Secured Warehouse Building is a single-story, slab-on-grade, pre-engineered, metal building. The exterior walls and roof consist of insulated metal panels. The office area is constructed of light-gauge steel framing. Two receiving bays with roll-up doors and a canopy roof are provided on the front of the building.

The Secured Warehouse Building, located near the MOX Fuel Fabrication Building, supports the MFFF operations by receiving and storing materials, equipment, and supplies inside the protected area near the MOX Fuel Fabrication Building, making them readily available when needed. All materials entering the secured area pass through the Material Access Portal inside the building. The Material Access Portal is equipped with screening equipment that allows identification of all materials prior to passing through the portal. Security personnel occupy the office area adjacent to the Material Access Portal. The building is not for personnel access through the PIDAS; however, the Vehicle Gatehouse is equipped for Safe Secure Transport (SST) driver/escort admittance into the Protected Area. Depleted uranium dioxide (UO_2), a MOX feedstock, is stored in drums in the Secured Warehouse Building.

The Secured Warehouse Building also provides storage locations for 16 new-fuel shipping packages and space for incidental periodic maintenance of these shipping packages.

The two-story Parts Washing Facility is located in the Secured Warehouse Building. Maintenance/service personnel utilize the Parts Washing Facility, and inventory control personnel occupy an office area located in the Secured Warehouse Building. The Parts Washing Facility is where new fuel rod assembly parts are cleaned prior to use in the MOX Fuel Fabrication Building. This facility has a separate ventilation/exhaust system and is equipped with a hood for worker protection. Wastes from parts washing are nonradioactive and will be managed as hazardous wastes and disposed of through the SRS waste management infrastructure.

Administration Building (BAD)

The Administration Building, located outside of the protected area of the MFFF complex, provides space for administrative support functions to the MFFF and its operations. The building is a two-story, slab-on-grade, steel-framed structure and is accessed from the main project personnel and public parking area. The following functions are performed within the Administration Building:

- Facility management
- Facility operations
- Facilities engineering
- Material accountability administration
- Finance and administration
- Health and safety evaluations
- Quality assurance
- Personnel management

Also located in the Administration Building is the Programmable Logic Controller Software Simulation Laboratory where operations computer software maintenance and development are conducted.

The Administration Building does not emit any gaseous or liquid effluents, with the exception of sanitary waste that is routed to the Central Sanitary Waste Treatment Facility (CSWTF).

Technical Support Building (BTS)

The Technical Support Building, located adjacent to the MOX Fuel Fabrication Building, provides personnel access control to the MOX Fuel Fabrication Building and support facilities for building personnel. The Technical Support Building is a slab-on-grade, steel-framed structure. The two-story portion of the building contains the service-oriented facilities, such as the electronic maintenance lab, mechanical maintenance shop, and building mechanical equipment room. The one-story portion contains the personnel-oriented facilities, such as the locker and change rooms, toilet facilities, work and anti-contamination protective clothing storage and access, dosimeter and respirator issue, first aid station, and lunch/break room.

Activities such as badging, photo identification, search, and pass-through take place in the Personnel Access Portal. Security monitoring at the Portal includes metal detectors, explosive detectors, and radiation monitors. The building also houses the following:

- Security operations center and support facilities
- Secondary alarm monitoring station
- Safeguards vault
- Security response ready room
- Armory
- Emergency power room
- Computer and telecommunications room
- Building mechanical equipment room

The secondary alarm monitoring station is considered a vital area and is designed and constructed as a hardened bulletproof area with its own support systems. Additional security identification is required for entrance into this area. The Technical Support Building is not directly involved in the principal processing functions of the MFFF.

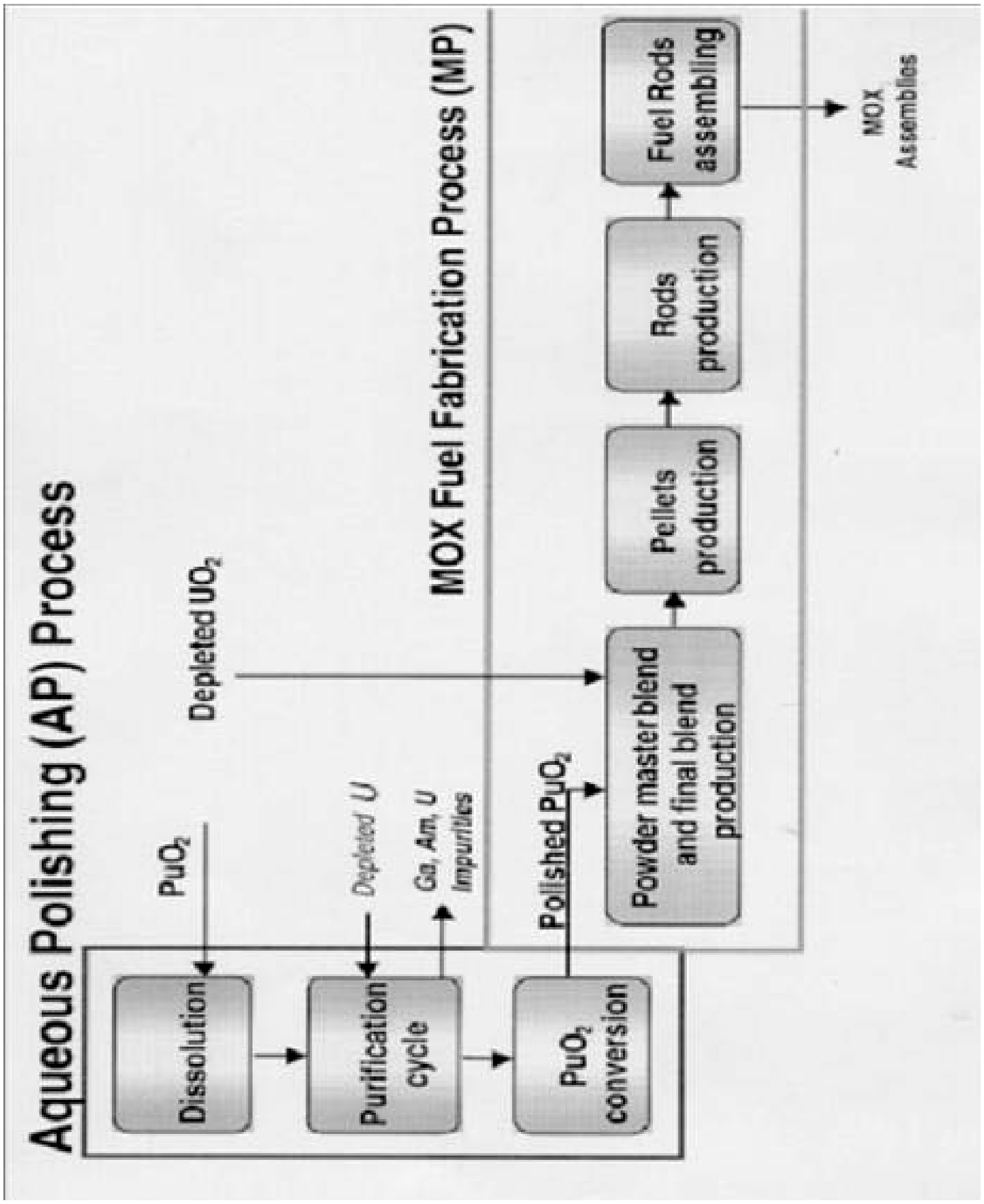
MOX Fuel Fabrication Process

The MOX fuel fabrication process is divided into two major subprocesses.

- Aqueous polishing – Removes impurities (i.e., gallium, americium, and uranium) from the weapons-grade plutonium oxide.
- Fuel fabrication – Blends plutonium and uranium oxides and recycled scraps to a mixed oxide, converts the MOX powder to a fuel pellet, loads the MOX fuel pellets into fuel rods, and bundles the rods into fuel assemblies.

The aqueous polishing subprocess produces most of the liquid waste streams and employs extensive reuse of reagents to minimize plutonium losses and waste. The fuel fabrication subprocess produces solid scrap material, which is reused in the overall process. Both subprocesses generate small amounts of contaminated solid wastes related to maintenance activities. The building and glovebox ventilation systems are essential for contamination control. The associated airborne emissions are collected from the process ventilation (i.e., gloveboxes and equipment) and building ventilation in the controlled area. See Figure 5-40 for a production process flow diagram.

Figure 5-40. MOX Fuel Fabrication Production Process Flow



Aqueous Polishing (AP) Process

Aqueous polishing is performed to remove impurities from the plutonium and produces most, but not all, of the liquid waste that will be transferred to the Waste Solidification Building (WSB). Extensive reuse of reagents in the process results in a significant reduction of waste generated from the process. The polishing process consists of four steps:

1. Plutonium oxide (PuO_2) is first electrochemically dissolved with silver (Ag^{2+}) in nitric acid.

2. The plutonium nitrate solution is solvent extracted using tributyl phosphate in an aliphatic hydrocarbon to remove impurities. The solution containing plutonium nitrate is washed with nitric acid. The plutonium is removed from the solvent by an aqueous solution of hydroxylamine nitrate, hydrazine, and nitric acid.

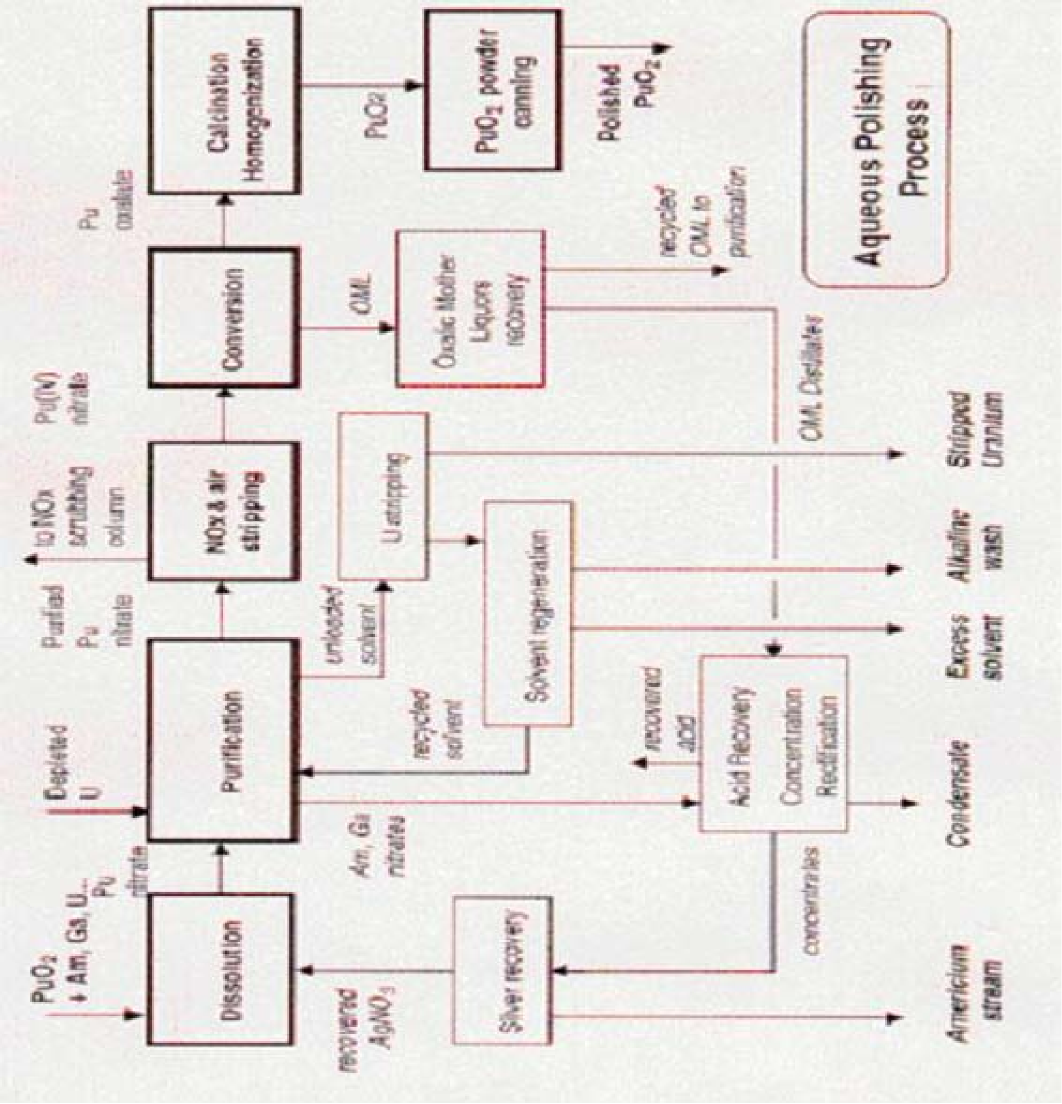
3. The plutonium valence is oxidized back to Pu(IV) by driving nitrous fumes (NOx) through the plutonium solution.

4. The plutonium is then precipitated with excess oxalic acid as plutonium oxalate that is collected on a filter. The moist oxalate is dried and calcined to PuO_2 that is packaged in cans for use in the MOX fuel fabrication process.

The plutonium losses and liquid waste generation are maintained as low as technically and economically possible by specific solvent treatment and by reuse of nitric acid and silver in the polishing process. The MFFF design has a stringent requirement imposed for plutonium loss in accordance with the DOE contract.

Plutonium polishing is schematically represented in Figure 5-41.

Figure 5-41. Plutonium Polishing Block Diagram



Plutonium oxide (PuO_2) is electrochemically dissolved with silver (Ag 2+) in nitric acid. A solvent (tributyl phosphate) in an aliphatic diluent then extracts the plutonium nitrate from the nitrate solution. Nitrate impurities (i.e., americium, gallium, and silver) remain in the aqueous (i.e., raffinate) phase. After diluent washing, the raffinate stream is routed to an acid recovery unit.

The extracted plutonium is washed with nitric acid. The plutonium is then reduced to trivalent plutonium by the introduction of hydroxylamine nitrate. The plutonium is removed from the solvent using a solution of nitric acid, hydrazine, and hydroxylamine nitrate. The organic solvent that has had the plutonium removed is mixed with an additional stripping solution in a plutonium barrier before being routed to the uranium removal process. Uranium impurities are removed from the organic solvent with dilute nitric acid. The solvent that has had the plutonium and uranium removed is routed to solvent recovery mixer-settlers to be recycled back into the process.

After the extraction steps, the plutonium is oxidized back to tetravalent plutonium by driving nitrous fumes (NOx) through the plutonium solution. Nitrous acid is removed in an air-stripping column. The NOx -containing gas stream is demisted to limit plutonium loss, then treated through an NOx scrubbing column, before being released to the process off-gas treatment unit. Recombined acid is routed to acid recovery.

The oxidized plutonium is reacted with excess oxalic acid ($H_2C_2O_4$) to precipitate plutonium oxalate, which is collected on a filter, then dried in a screw calciner, to produce purified plutonium oxide powder (PuO_2), which is stored in cans. Off-gas from the screw calciner is treated before discharge to the downstream Very High Negative Pressure main filters. The filtered oxalic mother liquors are concentrated, reacted with manganese to destroy the oxalic acid, and recycled to the beginning of the extraction cycle to minimize plutonium loss from the process.

Acid Recovery

Spent acid, consisting of oxalic mother liquor distillates, raffinates, calcination concentrates, and recombined acid, is mixed in a buffering tank and injected into an evaporator. The first evaporator of the acid recovery unit is a concentration step. After an additional evaporation step, the vapor is injected into a distillation column dedicated to acid rectification. Nitric acid is recovered from the rectification evaporator bottoms and partly reused as reagent feedstock for the plutonium dissolution subprocess. Distillates from the rectification evaporator are collected and partly reused in the process. The off-gas is routed to a cooler and a demister before treatment.

Stripped Uranium Collection

Before the commencement of the purification cycle, HEU impurities are present, which are diluted to approximately 30% with depleted uranium. After the uranium stripping process, uranium removed from the plutonium stream is diluted with depleted uranium to approximately 1%. The diluted uranium is collected in storage vessels prior to subsequent processing within the SRS waste management infrastructure.

Solvent Regeneration

The regeneration of spent solvent from the plutonium separation step is accomplished by washing with sodium carbonate, sodium hydroxide, and nitric acid to remove degradation products from organic compounds, including trace amounts of plutonium and uranium. The regenerated solvent is adjusted with the addition of tributyl phosphate and reused in the purification process.

MODULE 5.0: FUEL FABRICATION

Fuel Fabrication Processes

The mixed oxide fuel fabrication process blends plutonium and uranium oxides, converts the mixed oxide powder to fuel pellets, loads fuel pellets into rods, and bundles the rods into fuel assemblies. This process produces solid scrap material, which is recycled in the overall process. Airborne emissions are collected from process ventilation (gloveboxes and equipment) and from building ventilation in the fuel fabrication building. Those emissions are treated, filtered, monitored, and released. Small amounts of contaminated solid waste are produced during maintenance activities at the MOX Facility. The MOX fuel fabrication processes (i.e., powder, pellet, and rod processing) are dry subprocesses and are illustrated in Figure 5-42. The solid wastes produced are listed in Table 5-10.

In fuel fabrication, polished plutonium oxide is mixed with uranium oxide and recycled scraps to produce an initial MOX mixture that is 20% plutonium. This mixture is subjected to a micronized homogenization process in a ball mill and mixed with additional uranium oxide and recycled scraps to produce a final blend with the required plutonium content of 2.3% to 4.8%. The MFFF design is capable of producing MOX with a plutonium content of 6%. This final blend is further homogenized to meet the stringent plutonium distribution requirements. During the final homogenization process, lubricants and poreformers are added to control specific gravity.

Powder processing is performed in closed containers located in gloveboxes to contain any contamination. Gaseous exhaust points from the gloveboxes are equipped with HEPA filters to contain particulate emissions.

The homogenized powder is pneumatically transferred from the homogenizer to the press feeding hopper under negative pressure. The powder is then transferred by gravity to the press shoe. “Sintering" is the slow baking (24 hrs) at high temperature (~1600 C) that transforms the pressed powders into a hard ceramic material.

The sintering process is performed in a furnace by heating the fuel pellets to a temperature of 3,092°F (1,700°C) under gas scavenging, using a nonexplosive mixture of argon and hydrogen. This specific furnace atmosphere controls sintering and pellet stoichiometry and is not subject to inadvertent detonations and deflagrations due to low hydrogen content. The pellet boats, which contain 22 lb (10 kg) of pellets each, are positioned on a molybdenum plate and then transferred to the furnace. An inlet and outlet furnace airlock is required for changes in atmospheric pressure. A pusher system provides continuous motion of the sets (i.e., boat on shoe) through the furnace. The last set introduced in the furnace pushes the preceding ones. See Figure 5-43.

Table 5-10. Solid Waste Generated by MFFF Fuel Fabrication Processes

Waste Stream	Annual Volume (Mass)[a]	Contamination[b] (Mg Pu/kg)
Uncontaminated, nonhazardous solid waste	575 yd^3 1,150 yd^3 (max)	
Potentially contaminated solid waste[c]	302 yd^3 604 yd^3 (max)	Under detection limit Free of contamination waste collected in controlled area
UO^2 area LLW	9 yd^3 18 yd^3 (max)	Uranium contamination
Zirconium swarfs and samples	2 yd^3 4 yd$_3$ (max)	< 0.2
Stainless steel inner and outer cans	10 yd^3	< 0.2
Building and U area ventilation filters	100 yd^3	< 0.3
Nonroutine Low-Level Waste (LLW)	< 1 yd^3 2 yd^3 (max)	< 0.2
Cladding area TRU	9 yd^3 11 yd^3 (max)	< 2.8
Low contamination TRU waste	60 yd^3 72 yd3 (max)	< 10
High contamination TRU waste	83 yd^3 100 yd^3 (max)	approximately 250
PuO$_2$ convenience cans	7.9 yd^3	approximately 1670
Filters	43.3 yd^3 50 yd^3 (max)	approximately 600
Nonroutine TRU waste	1.6 yd^3 6.6 yd^3 (max)	approximately 600

[a] Values are approximate based on preliminary design.

[b] Estimates for plutonium mass collected in solid waste is about 7 kg.

[c] Potentially contaminated waste will be surveyed and released as nonradioactive if determined to be below NRC release limits.

(max) represents maximum expected annual volume due to unplanned change-overs.

Figure 5-42. MOX Fuel Fabrication Processes

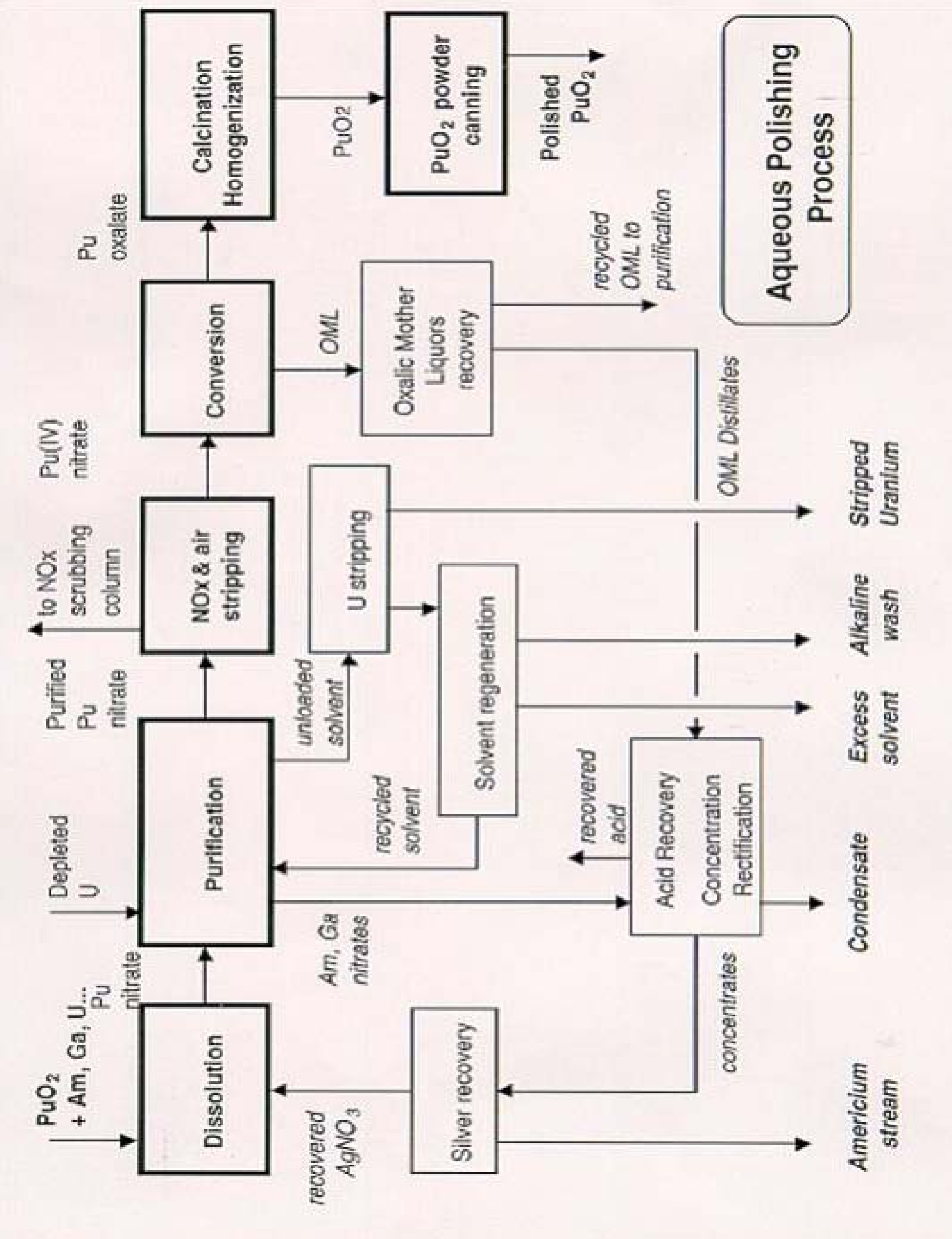
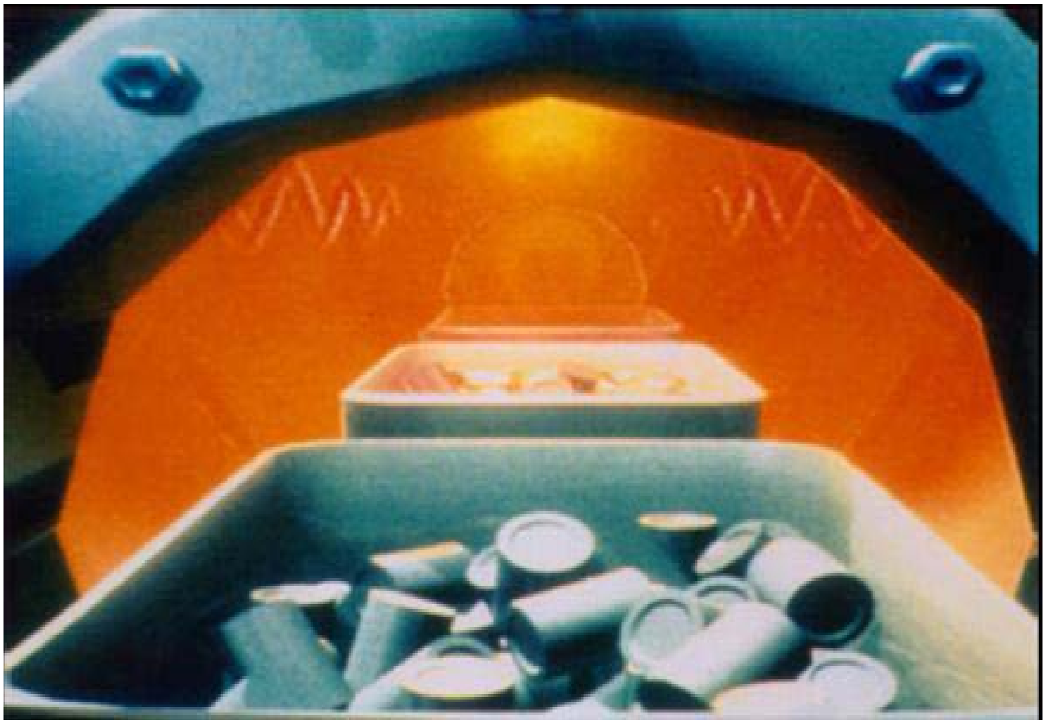


Figure 5-43. Sintering Process



The sintered pellets are dry ground to meet the size and roughness of the fuel specifications for the specific reactor. The grinding process is performed in four dedicated gloveboxes. A dust removal system, composed of an extractor and a decloggable filter, is installed in the unit to minimize the spread of powder in the gloveboxes. This dust abatement technique minimizes waste production in the form of disposable filters and allows recovery and recycle of the captured dust. Grinding dust and pellet chips are routed back as feedstock to the scrap recycling process.

Pellet processing is performed in gloveboxes with HEPA filters on the vents to contain any dust. Glovebox exhausts are equipped with HEPA filters to contain any particulate emissions.

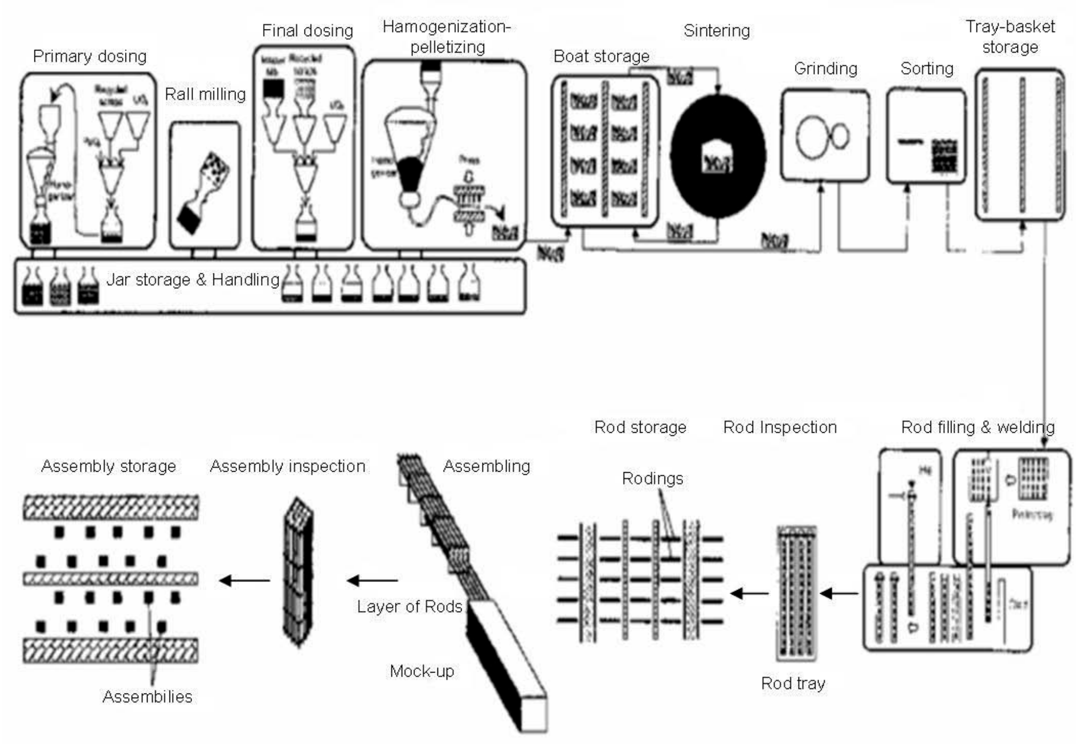
After the pellets are ground, they are automatically and visually inspected and sorted. Pellets that meet specifications are lined up and loaded into rods. Discarded pellets are routed to scrap processing and reintroduced to the blending feedstock. Within a glovebox environment, the rods are capped, welded, pressurized with helium, sealed, and then decontaminated. The decontaminated rods are removed from the gloveboxes and placed on trays for inspection and assembly.

Figure 5-44. Fuel Pellets and Rods

Rods are inspected by testing for leaks and performing x-ray analysis of welds. The rods are then gamma-scanned to ensure that the plutonium content and length of the pellet column are correct. Bundles of three different plutonium content rods are assembled into the fuel assembly skeleton. The fuel assembly is subjected to a final inspection prior to shipment.

Rod processing, until the decontamination step, is performed in gloveboxes with HEPA filters on the vents to contain the minute amounts of particulates. Any air exhaust from the gloveboxes is equipped with HEPA filters to contain particulate emissions.

Figure 5-45. MP Block Diagram



VENTILATION AND CONFINEMENT

The aqueous polishing process ventilation system, which is part of the process ventilation off-gas treatment system, is used to:

- remove plutonium from off-gases released during dissolution and from the oxidation and degasing columns of the purification cycle;
- decontaminate the off-gas effluents from all of the aqueous polishing units;
- maintain negative pressure in the tanks and equipment connected to the process ventilation system (i.e., more than 500 Pa with respect to the cell or glovebox in which equipment is placed); and
- provide continuity of the first confinement barrier.

Process Ventilation Off-Gas Treatment System

NO_X and air scrubbing columns generate most of the plutonium released to the ventilation. The NO_X off-gases are routed through a specific NO_X scrubbing column after demisting through a can impactor to maximize plutonium recycling to the process. The scrubbed exhaust gas is diluted with process ventilation air and cleaned through a final scrubbing column. The exhaust is filtered through two final HEPA filter stages prior to being released through the MFFF stack.

The exhaust from the air pulsation columns is passed through two final HEPA filters before being released through the MFFF stack. A continuous air monitor is used to monitor stack releases to the environment.

There is a separate ventilation system for the calcination furnace exhaust. Exhaust gas from the calcination furnace is filtered through a metallic filter to remove most of the dust, cooled, and filtered through two HEPA filter stages before extraction by the very high negative pressure duct.

Building and Glovebox Ventilation Systems

Areas within the facility with the highest potential for contamination are maintained at the lowest, or most negative, pressure compared to the adjacent room. Airflow cascades progressively from the areas of least potential contamination to the areas of highest potential contamination. Figure 5-46 shows a typical glovebox for MOX fuel handling.

Figure 5-46. Typical Glovebox

Confinement Zones

The MFFF ventilation systems maintain pressure gradients between the different confinement zones to ensure that leakage air flows from the zones of lowest contamination potential to zones of increasing contamination potential. Confinement zone classification is based on the fuel fabrication process, material handling, and the level of potential airborne and transferable contaminants generated in the various process areas. The confinement zone classification scheme is summarized as follows:

- Class Level C4 – gloveboxes and process equipment located in process cells after gloveboxes that contain dispersible radioactive material in the fuel fabrication and aqueous polishing areas.
- Class Level Process Cells – rooms in the aqueous polishing areas containing all welded process vessels and piping with no discontinuities where there is very low likelihood of contamination, but if contamination occurred it could be moderate to large.
- Class Level C3 zones are subdivided into two sublevels:
    - Class Level C3b – fuel fabrication and aqueous polishing areas, such as laboratories, waste drum storage, hoods, and areas enclosing gloveboxes where there is a moderate occasional contamination risk.

  - □ Class Level C3a – fuel fabrication and aqueous polishing areas, such as airlocks and intermediate filter rooms, where there is a low occasional contamination risk.
- ◙ Class Level C2 – fuel fabrication and aqueous polishing areas, such as process rooms containing rods or assemblies and corridors around C3 areas, where there is a very low occasional contamination risk.
- ◙ Class Level C1 – areas with zero occasional contamination risk located within the shipping and receiving area and areas with an opening to the outside.

Confinement systems are used to confine dispersible radioactive contamination within specific controlled areas under all normal, abnormal, and accident conditions. The dynamic confinement systems maintain pressure gradients between the different confinement zones.

Three confinement systems (primary, secondary, and tertiary) are used in the MFFF. Each confinement system consists of a static confinement subsystem and a dynamic confinement subsystem. The static confinement systems include building walls, barriers, equipment gloveboxes, cells, enclosures, filters, piping, tanks, portions of supply and exhaust ductwork, plenums, and vessels. The dynamic confinement systems consist of the static confinement systems and the HVAC exhaust subsystems and equipment out through and including the stack.

Ventilation systems and components have features that provide for alarm indication. HVAC and dynamic confinement systems are designed to withstand any credible fire and continue to function without the loss of confinement. The HVAC and dynamic confinement systems operate continuously to protect personnel from exposure to airborne and transferable contamination. Redundancy and defense-in-depth features ensure continuous operation of an HVAC system in the event of the failure of an active component, such as a fan, during normal or off-normal conditions.

Very High Negative Pressure Ventilation System

Primary Confinement

The primary confinement system consists of gloveboxes constituting the C4 confinement zones and their associated ventilation systems. The dynamic confinement of class C4 enclosures is ensured by a Very High Negative Pressure Ventilation System, which maintains a negative pressure of 300 to 500 Pa in C4 enclosures relative to the C3b rooms in which they are installed. Each process glovebox supply and exhaust is fitted with two HEPA filter stages within the process rooms. Inside the grinding gloveboxes, contamination is collected with an additional decloggable pre-filter to reduce the airborne concentration. The exhaust from the C4 enclosures prior to exhausting through the MFFF stack is routed through two additional final HEPA filters.

High Negative Pressure Ventilation System

Secondary Confinement

The secondary confinement system consists of walls, floors, and roofs surrounding gloveboxes, process cells, C3 confinement zones, and their associated ventilation systems. The process cell confinements in the aqueous polishing area are served by the aqueous polishing area exhaust system. The secondary confinement C3 areas are served by the High Negative Pressure Ventilation System.

Dynamic confinement of C3a and C3b rooms within the secondary confinement system is provided by the High Negative Pressure Ventilation System, which maintains a negative pressure of 120 to 160 Pa in C3a rooms and 160 to 180 Pa in C3b rooms relative to the atmosphere. This room ventilation air is normally not contaminated. The exhaust from the C3 rooms is routed through a HEPA filter at the boundary between the C3 and C2 areas, and then through two final HEPA filters before exhausting through the MFFF stack.

Medium Negative Pressure Ventilation System

Tertiary Confinement

Dynamic confinement of class C2 rooms within the tertiary confinement system is provided by the Medium Negative Pressure Ventilation System, which maintains a negative pressure of 60 to 100 Pa in C2 rooms relative to the atmosphere. The exhaust from the Class C2 areas is passed through two final HEPA filter stages before being released through the MFFF stack.

NRC SAFETY EVALUATION

The NRC issued a Final Safety Evaluation Report (NUREG-1821). Potential accidents evaluated in the Construction Authorized Request (CAR) by the applicant included loss of confinement, fire, load handling events, explosions, nuclear criticality, natural phenomena events, external man-made events, external exposure, and those related to chemical interactions. Natural phenomena hazards evaluated by the applicant included earthquakes, high wind, tornadoes and tornado-generated missiles, extreme temperatures, rain, snow, ice, lightning, and fires external to the facility.

The NRC staff is currently reviewing a license application by MOX Services to use and possess special nuclear material under Part 70.

Overview of Chemical and Process Safety

The more significant chemical and process safety aspects involve reactive chemical intermediates, chemical toxicity hazards estimation, the electrolyzer area, wastes, and powder events.

Reactive Chemical Intermediates

These include a red oil, HAN/hydrazine, and azides. In the presence of a nitrate of heavy metals or in nitric acid solutions, the TBP will form nitrate complex compounds that could react exothermically. Exothermic TBP-nitrate reactions are frequently referred to as red oil reactions because of the reddish color that has been observed in nitrated TBP/diluent mixtures and residues found during experiments and after the incidents. Red oil is an organic mixture, consisting of TBP and its complexes with uranium/plutonium nitrate and nitric acid, degradation products of TBP (e.g., DBP), and possibly various nitrated hydrocarbons. The applicant intends to prevent exothermic reactions by limiting the maximum heating fluid temperature to 275°F (135°C). However, several destructive events have occurred even in the presence of safety controls and at relatively low temperatures. Extended contact between heated mixtures of TBP and nitric acid, nitrates, and/or heavy metal nitrate salts can form degradation products and intermediates (including nitrated esters and adducts) that, under certain conditions, may lead to violent exothermic reactions of potentially explosive force (NRC 2001). Several explosive incidents have occurred in the United States (Savannah River in 1953 and 1975; Hanford in 1953), and the former Soviet Union (Tomsk-7 in 1993). The resulting safety trend as a result of those events is towards more conservative controls and operating conditions, including lower design basis temperatures.

The NRC review also found that energetic hydroxylamine-nitric acid reactions can occur under the right conditions, as evidenced by DOE investigation of an accident at Hanford and several other incidents (NRC 2001). As a result of this explosion, DOE investigated the situation and concluded the HAN phenomena involved the interdependence between multiple parameters. DOE derived an instability index and a graph to link these parameters and a general account for the behavior of the system, which involves controls beyond those proposed by the applicant. The applicant has subsequently proposed hydrazine addition and maintenance as the principal control strategy for addressing HAN/nitric acid reactions.

The presence of hydrazine under these conditions leads to the formation of hydrazoic acid and azides, which can become unstable and explosive. The NRC found that appropriate controls, including pH and dilution, are needed.

Chemical Toxicity Hazards

These hazards include appropriate chemical consequence limits, a design basis for habitability in the Emergency Control Room, the impacts from DUO_2, and a safety strategy for hazardous chemical releases from the loss of confinement of radioactive materials. The CAR identified chemical consequence limits based upon TEELs (Temporary Emergency Exposure Levels). The review indicated lower concentration levels based upon regulator values, such as IDLHs and STELs (Immediately Dangerous to Life and Health and Short Term Exposure Limit, respectively), may be more appropriate. Such values could also be used for guidance on hazardous chemical limits and habitability in the control room. NRC analyses indicated the potential for significant chemical toxicity from uranium dioxide releases, although radiation doses would be low.

Electrolyzer Area

The electrolyzer is an important component in the process. Protection of the electrolyzer against overheating is planned as a safety feature. Additional features may be needed to address potential fires/explosions from reaction excursions, flammable gases around and in the electrolyzer, and events involving titanium (the corrosion resistant alloy used for most of the electrolyzer circuit).

Wastes

Wastes generated in MOX processing are presently expected to go to various DOE waste processing facilities depending on the contents of the waste. High alpha waste will go to the Waste Solidification Building (WSB) operated by DOE, which is still under construction.

Powder

Powder-related events are possible in the MOX Process (MP) areas of the proposed facility. UO_2 powders can undergo burn back reactions that involve further oxidation to higher oxides (e.g., U_3O_8), accompanied by a release of heat. Events involving such reactions have occurred in uranium fuel facilities (NRC 2001). Substoichiometric plutonium dioxide can have similar reactions. In addition, plutonium oxides can over-pressurize storage containers by alpha radiolysis of impurities, such as water and other volatiles. MP includes sintering of the MOX powders after cold-pressing into pellets. Sintering uses a hydrogen-argon mixture in a high temperature (e.g., 1,300-1,700 C) furnace to coalesce and densify the pellets. Sintering presents potential hydrogen and steam explosion hazards.

ENVIRONMENTAL AND HEALTH IMPACTS

Although the processing of mixed oxides does have some environmental impact, these are small and consequently acceptable. The environmental impacts are outweighed by the benefit of enhancing nuclear weapons reductions.

Because the MOX facility does not use process storage or treatment ponds, there will not be any liquid effluent released to the environment, so there are no expected impacts on surface water or groundwater. The MFFF site will have a storm water collection and routing system that will discharge through the existing Savannah River Site storm water National Pollutant Discharge Elimination System outfall or new outfalls. There may be slight temporary impacts from construction runoff, but these impacts should disappear once construction is completed.

The cumulative impacts resulting from transport of feedstock and mixed oxide fuel are also low. The total dose to the transportation workers associated with plutonium feedstock is estimated at 7.8 person-rem. The total dose to the transportation workers associated with the uranium hexafluoride and uranium oxide shipments is estimated to be 1.06 and 0.78 person-rem, respectively. Total dose to the public associated with plutonium feedstock is estimated at 4.1 person-rem. The dose to the public associated with the uranium hexafluoride and uranium oxide shipments is estimated to be 0.21 and 0.14 person-rem, respectively. The cumulative dose to the transportation workers associated with the mixed oxide fuel shipments is estimated to be 34.1 person-rem and the dose to the public is estimated to be 9.98 person-rem.

The incident-free dose per shipment (in person-rem) for the plutonium recycle shipments in NUREG-0170 (NRC 1977c) was calculated to be 0.17, versus a maximum of 0.03 person-rem per shipment for the mixed oxide fuel shipments from the MOX facility to the mission reactor sites. The dose to the maximally exposed individual for the person in traffic next to a shipment of mixed oxide fuel is 2.0 mrem. These doses are a small fraction of the 360-mrem annual dose received from natural background radiation and is consistent with the conclusions of NUREG-0170.

The radiation protection and waste management programs for the MOX facility are guided by the principles of dose minimization through As Low As Reasonably Achievable (ALARA) design and administrative programs, waste minimization, and pollution prevention. Liquid and solid wastes will be transferred to the appropriate Savannah River Site waste management facilities and will meet applicable waste acceptance criteria for those facilities.

Because the MOX facility does not use process storage or treatment ponds, there will not be any liquid effluent released to the environment, so there are no expected impacts on surface water or groundwater. The MFFF site will have a storm water collection and routing system that will discharge through the existing Savannah River Site storm water National Pollutant Discharge Elimination System outfall or new outfalls. There may be slight temporary impacts from construction runoff, but these impacts should disappear once construction is completed.

The MOX facility will have emergency and standby diesel generators that will be tested periodically, which will result in criteria pollutant emissions during the testing periods. Incremental increases in ambient concentrations of these criteria pollutants will be well below the ambient air quality standards for southwestern South Carolina. The mixed oxide fuel fabrication process also will release small quantities of nitrogen oxides. The annual releases are accounted for in the nitrogen dioxide projections for the facility. Radiological dose to the public will be well below the criteria of the Nuclear Regulatory Commission and U.S. Environmental Protection Agency and below background radiation levels.

The construction and operation of the Mixed Oxide Fuel Fabrication Facility will have no impacts on sensitive ecological areas. The construction of the facility will require the excavation and recovery of an archaeological site. Although the site is not expected to contain any human or sacred artifacts, the excavation and recovery of the artifacts would represent a benefit through the preservation of the artifacts.

The greatest impact of operations at the MOX facility will be the amount of waste generated. The facility will generate a liquid high alpha activity waste, which is a transuranic form. With the exception of liquid high alpha activity waste, the amounts generated are a small fraction of annual waste generation at the Savannah River Site. The liquid high alpha activity waste generated by the facility will be transferred to the Waste Processing Building. This waste will be converted to a solid form for disposal at the Waste Isolation Pilot Plant in New Mexico.

Cumulative impacts in the geographic vicinity of the MOX facility and the Savannah River Site are dominated by the impacts of existing activities at the Savannah River Site. The SRS is currently in substantial compliance with all federal, state, and local air quality regulations and would continue to remain well within compliance, even with the consideration of the cumulative effects of all surplus plutonium disposition activities. All three surplus plutonium disposition facilities would cause the cumulative dose to the public from all SRS activities to increase by about 2.6%. All wastes from the fuel fabrication facility represent very small (<10%) additions to the current SRS waste generation rates and should not represent any significant cumulative impact.

The Environmental Report relied on the mission reactor impacts analysis provided in the Surplus Plutonium Disposition Final Environmental Impact Statement (DOE 1999c). The Environmental Impact Statement determined that there should be no change in impacts to the environment during normal operations at the mission reactors resulting from the irradiation of mixed oxide fuel. This conclusion is reinforced by operating experience from Electricite de France, which operates mixed oxide fuel power plants in France.

Self-Check Questions 5-8

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

1. What is the current intent of the MOX program?

2. Explain what MOX fuel is.

3. What facility/country is the MOX plant based upon and where will it be built?

4. Name the three principal impurities in weapons-grade plutonium.

5. This portion of the MOX process removes impurities from plutonium and has many controls to address process hazards.

6. Identify the three basic confinement approaches at the proposed MOX facility.

7. What are red oil and HAN?

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

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:

- Wet or ADU chemical process
- Dry, direct, or integrated dry route chemical process
- Ceramic process
- Mechanical process
- Scrap recovery
- Radiological and nonradiological hazards
- Fuel fabrication process accidents
- GE Wilmington event
- MOX fuel fabrication

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

III. As a Regulator:

- Tell me about some of the problems that have occurred at fuel fabrication facilities.
- What documentation would you recommend I review before visiting a certain facility?
- Tell me about some of the similarities and differences in operations among fuel fabrication facilities.
- Who would be a good resource person for me to talk with about fuel fabrication processes?

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.

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 5.0: FUEL FABRICATION

MODULE SUMMARY

Key Points:

- ◙ Most operating nuclear reactors and all power reactors in the United States use low enriched uranium dioxide as the nuclear fuel material, encased in zirconium alloy tubes (cladding).
- ◙ LEU provides for reasonable economics, acceptable reactor designs and power densities, straightforward safeguards/MC&A, and manageable spent fuel volumes.
- ◙ Uranium dioxide is used as the uranium form because it represents a practical compromise of properties, safety, and economics.
- ◙ Zirconium alloy cladding use represents a similar compromise.
- ◙ The two main types of power reactors licensed by the NRC in the United States (PWR and BWR) use essentially the same type of fuel. There are subtle differences in fuel pellets and rods due to specific core designs and optimizations. PWR assemblies typically weigh around 1,000 kg each; uranium accounts for about 50% of the total weight. BWR assemblies have fewer fuel rods and weigh around 450 kg each; uranium amounts to about 200 kg of the total 450 kg.
- ◙ There are six operating commercial fuel fabrication facilities licensed by the NRC in the United States. There are an additional two facilities undergoing D&D (General Atomic and Westinghouse Hematite).
- ◙ Four of the six facilities manufacture LEU for commercial power reactors. Two facilities manufacture HEU fuel for naval applications.
- ◙ Commercial nuclear fuel fabrication consists of three major processes: conversion (of the uranium hexafluoride into uranium dioxide powder), ceramic (production of ceramic uranium dioxide pellets from the powder), and mechanical (loading of the pellets into fuel rods and assemblies).
- ◙ The wet conversion process precipitates ammonium diuranate, which is subsequently calcined into uranium dioxide (could list the steps too).
- ◙ The dry conversion process directly produces uranium dioxide from steam and hydrogen reactions with uranium hexafluoride at elevated temperatures.
- ◙ Pellet production involves pretreatment of the powder, pelletizing, sintering at high temperatures, and grinding to final dimensions.
- ◙ The mechanical process loads the pellets into fuel rods and makes the fuel assemblies.
- ◙ Uranium containing scrap materials are recovered by solvent extraction and other processes, and recycled.

MODULE 5.0: FUEL FABRICATION

- Potential hazards and accidents at fuel fabrication facilities include UF_6 handling, fine uranium powders, radiochemical uranium uptake, chemical hazards, fires and explosions, and criticality.
- The applicable regulation is 10 CFR Part 70. This requires the analysis of potential hazards and accidents via an Integrated Safety Analysis (ISA), with safety controls (IROFS) identified if certain consequence/frequency limits are exceeded. These limits are also called performance requirements (70.61).
- MOX fuel fabrication adds the radiotoxicology and radiochemistry of plutonium. This generally requires greater confinement of the fuel handling operations and more process and safety controls.
- Advanced water reactor designs will likely use uranium dioxide fuel and fabrication methods similar to those in the existing facilities.
- Advanced gas reactor designs will likely use spherical particles of uranium dioxide/oxycarbide with coatings for fission product retention. This is expected to introduce more fire and chemical hazards into fuel fabrication. Higher enrichments (8-18% assay) may also be used, resulting in the need for more stringent criticality controls.
- MOX uses a single cycle Purex solvent extraction process to remove impurities from the plutonium. The principal impurities are gallium, uranium, and amercium.
- Principal hazards at the proposed MOX facility are criticality, flammability (e.g., from the solvent), chemical reactivity (e.g., red oil), fire suppression/re-ignition, and chemical toxicity. Waste requires careful management and integration with the DOE SRS facilities.

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