MODULE 2.0: GASEOUS DIFFUSION

Introduction

Welcome to Module 2.0 of the Uranium Enrichment Processes Directed Self-Study Course! This is the second of seven modules in this directed self-study course. The purpose of this module is to assist the trainee in describing the general principles of the gaseous diffusion enrichment process and general facility and component layout, identifying the uses of the gaseous diffusion process in industry and the production amounts of enriched uranium, and identifying the hazards and safety concerns for the process, including major incidents. This directed self-study module is designed to assist you in accomplishing the learning objectives listed at the beginning of the module. The module has activities and self-check questions to help you assess your understanding of the concepts presented in the module.

Before You Begin

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

- ☐ Trainee Guide

Complete the following prerequisite:

- ☐ Module 1.0 Introduction to Uranium Enrichment

How to Complete This Module

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

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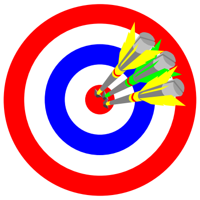
Learning Objectives



2.1 Upon completion of this module, you will be able to describe the gaseous diffusion enrichment process.

2.1.1 Describe the principles of the gaseous diffusion enrichment process.

2.1.2 Describe the basic steps of the gaseous diffusion enrichment process.

2.1.3 Identify the uses of gaseous diffusion in industry and the required production amounts of uranium hexafluoride.

2.1.4 Identify the hazards and safety concerns for the gaseous diffusion process, including major incidents.

Learning Objective

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

2.1.1 Describe the principles of the gaseous diffusion enrichment process.

PRINCIPLES OF THE GASEOUS DIFFUSION ENRICHMENT PROCESS

After concentrated uranium ore is received at a uranium conversion facility, it is converted to a chemical form called uranium hexafluoride (UF_6). The UF_6 is produced in liquid form, drained into 14-ton cylinders, and allowed to cool and solidify.

The next stage of the nuclear fuel cycle is to enrich the uranium hexafluoride. This enrichment process, also known as "isotope separation," must occur at an enrichment facility. It is an essential stage in the nuclear fuel cycle because it "concentrates" the desired uranium isotopes for delivery to fuel fabrication facilities where it can be produced into uranium fuel that can be used in commercial nuclear power plants in the United States and abroad.

Enrichment is the process of separating different isotopes of the same element into two components, one with a higher concentration than the other. Uranium has three naturally occurring isotopes: uranium-234, uranium-235 and uranium-238. Because uranium-235 can fission (split) to produce heat, it is the most efficient isotope of uranium that can be used to fuel nuclear power plants. Uranium-235 makes up less than 1% of natural uranium, but most nuclear power plants require 3% to 5% concentrations of uranium-235 for a usable fuel.

A process known as gaseous diffusion is currently used in the United States to enrich uranium. UF_6 is transported as a solid from the conversion plant to the enrichment plant via cylinders. During enrichment, UF_6 goes through several phases as a solid, liquid, and gas.

Gaseous diffusion is a uranium enrichment process based on the difference in rates at which uranium isotopes in the form of gaseous uranium hexafluoride diffuse through a porous barrier. The rate of diffusion of a gas is inversely proportional to the square root of the mass. Thus, at any given temperature lighter molecules have higher average velocities than heavier molecules to diffuse through a porous barrier faster than heavier molecules. In the separation of uranium isotopes, the only gaseous compound of uranium, the fluoride of uranium, UF_6, is used. The uranium hexafluoride is pumped continuously through porous tubes referred to as barriers. The difference in weight between uranium-235 and uranium-238 is slightly greater than 1%, but the difference in weight between the fluorides is slightly less than 1%. The enrichment factor, which depends on the square root of the above difference, is theoretically 0.43% for an instantaneous process or 0.30% for a continuous process, but in practice an enrichment factor of only about 0.14% per stage has been achieved. A stage consists of a converter (or diffuser) containing the barrier tubing, a compressor, and a stage control valve. To produce 99% uranium-235 from natural uranium, which contains about 0.7% uranium-235, 4,000 such stages are required.

Background

The first large-scale separation of uranium isotopes ever achieved implemented the gaseous diffusion and the electromagnetic methods. The problem of separating uranium-235 from uranium-238 arose in 1940 after the demonstration of the susceptibility of the uranium-235 isotope to fission by neutrons. Uranium-235 exists in naturally occurring uranium at the ratio of 7 parts to 1,000 of uranium-238. As part of the atomic bomb project, various methods for separating isotopes were considered. Both the gaseous diffusion and the electromagnetic methods were put into large-scale operation for the production of about 1 kg (2.2 lb) per day of uranium-235 to be used in atomic bombs.

A full scale gaseous diffusion plant was operated in Oak Ridge, Tennessee, from August 1945 until 1985 (Figure 2-1). The Paducah Gaseous Diffusion Plant was constructed from 1951 to 1954 (Figure 2-2). The Portsmouth Gaseous Diffusion Plant located in Piketon, Ohio, was built in 1953 to 1956 (Figure 2-3). These are historical photographs. The three facilities are very large. The three gaseous diffusion plants' output was nearly all highly-enriched uranium for the weapons program between 1946 and 1964. The plants also produced low-enriched uranium to be used as production reactor fuel during this period. After 1964, the GDPs' mission evolved to support the commercial nuclear power industry. In 1992, Congress passed the Energy Policy Act and, under its provisions, uranium enrichment operations at the Portsmouth and Paducah Plants were leased by the Department of Energy (DOE) to the newly-created United States Enrichment Corporation (USEC). At this time, USEC has operational responsibility for the plants, and DOE has retained the responsibility for managing the environmental legacy left from prior operations.

In July 1998, the USEC corporation was transitioned to a private company under the regulatory oversight of the NRC. By late 1999, the influx of the Russian HEU combined with expansion of enrichment capability in Western Europe had created significant global over-capacity of enriched uranium for nuclear reactors. This global increase in production resulted in USEC's operating the Portsmouth and Paducah GDPs at about 25% capacity. After an evaluation of its GDP operations, USEC announced it would cease its Portsmouth enriching operations and seek regulatory approval to produce higher assay enrichment at Paducah.

Today only the U.S. and France use the process on any significant scale. The gaseous diffusion process accounts for about 40% of world enrichment capacity. However, though they have proved durable and reliable, most gaseous diffusion plants are now nearing the end of their design life and the current focus is on centrifuge technology for meeting enrichment requirements.

Figure 2-1. Oak Ridge Gaseous Diffusion Plant (Historical Photograph)

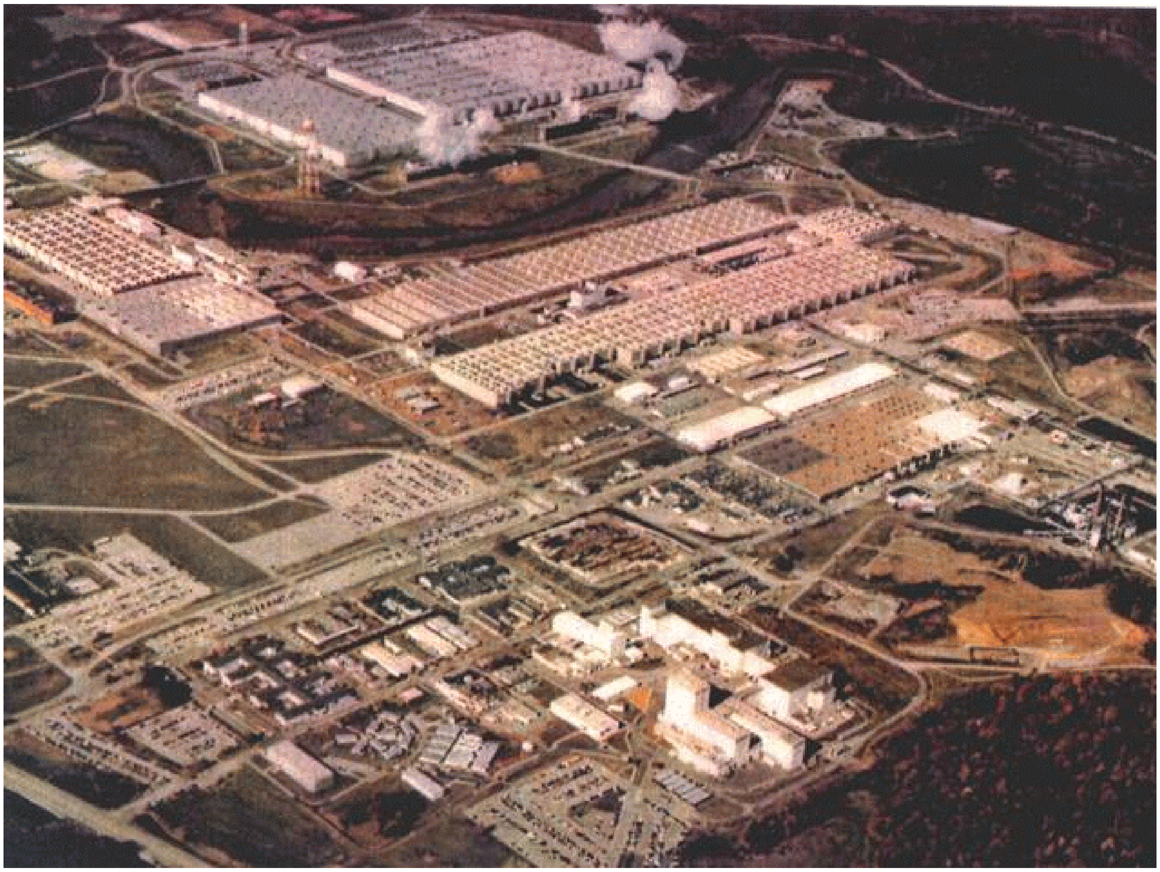


Figure 2-2. Paducah Gaseous Diffusion Plant

Figure 2-3. Portsmouth Gaseous Diffusion Plant

Higher Assay Upgrade Project

USEC pursued certification for higher assay enrichment through its initiative of the Higher Assay Upgrade Project (HAUP). Prior to HAUP, the Paducah GDP enriched uranium at between 1% and 2.75%, its licensed limit. The material was then shipped to the Portsmouth GDP for final enrichment to commercial assays. The HAUP approval on March 19, 2001, and subsequent NRC licensing allows the Paducah GDP to enrich to the 4% to 5% levels required by nuclear power plants.

Enriching operations ceased at Portsmouth in June 2001; at that time, the Portsmouth GDP was put into “cold standby”. However, some NRC regulated activities, such as cylinder sampling and transferring operations are continuing.

To enrich uranium at Paducah to the levels required by nuclear power plants requires that the Paducah product be re-circulated into the cascade to effectively increase the number of enrichment stages. In addition to the modifications for re-feeding, the HAUP included approximately 20 other physical plant modifications. Existing plant controls were examined to determine if they were adequate for safe operation at the higher assay or if additional controls would be required.

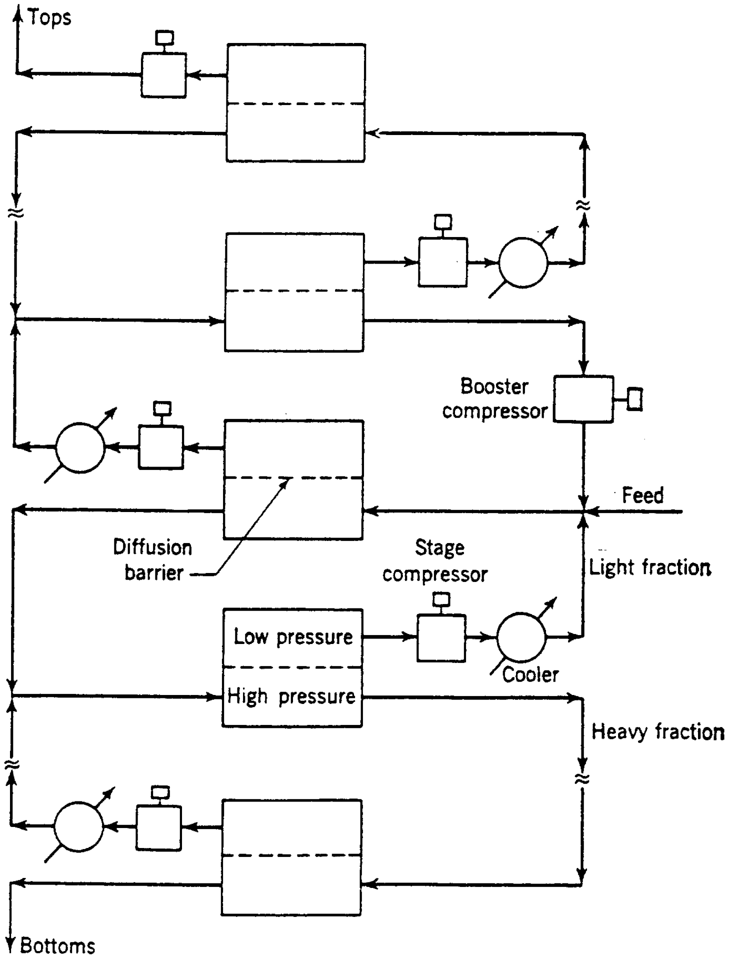
Fundamental Principles of Gaseous Diffusion

The gaseous diffusion method makes use of the phenomenon of molecular effusion to effect separation. In a vessel containing a mixture of two gases, molecules of the gas with the lower molecular weight travel faster and strike the walls off the vessel more frequently, relative to their concentration, than do the molecules of the gas with higher molecular weight. If the wall of the vessel has holes just large enough to allow passage of the individual molecules without permitting bulk flow of the gas as a whole, more of the lighter molecules flow through the wall, relative to their concentration, than the heavier molecules. This flow of individual molecules through minute holes is known as molecular effusion. The possibility of separating gases by effusion through porous media was discovered experimentally by Thomas Graham over a 100 years ago. James Clerk Maxwell showed that this separation was due to the fact that the relative frequency with which molecules of different components enter a small hole is inversely proportional to the square roots of their molecular weights.

Figure 2-4 illustrates a simple type of gaseous diffusion cascade. The mixture entering the diffuser on a stage flows past a diffusion barrier, while a portion of the gas flows through the barrier into the region of lower pressure on its downstream side. The gas flowing through the barrier is enriched in the component of lower molecular weight and constitutes the light fraction fed to the stage nearer the top of the cascade. Similarly, the gas that does not flow through the barrier is enriched in the component of higher molecular weight and constitutes the heavy fraction fed to the stage nearer the bottom of the cascade.

On each stage a pump compresses the gas from the pressure prevailing on the downstream side of the diffusion barrier to the pressure on the upstream side, and the cooler removes the heat of compression from the stage feed. Since only a limited degree of separation is attainable in a single stage, it is necessary to repeat the process a number of times before a practical degree of separation is secured. Stages are arranged in a countercurrent cascade in the same manner to use booster compressors at intervals to compensate for pressure drop in the high-pressure gas as it flows down the cascade.

Figure 2-4. Gaseous Diffusion Cascade. Source: Benedict and Pigford, 1957

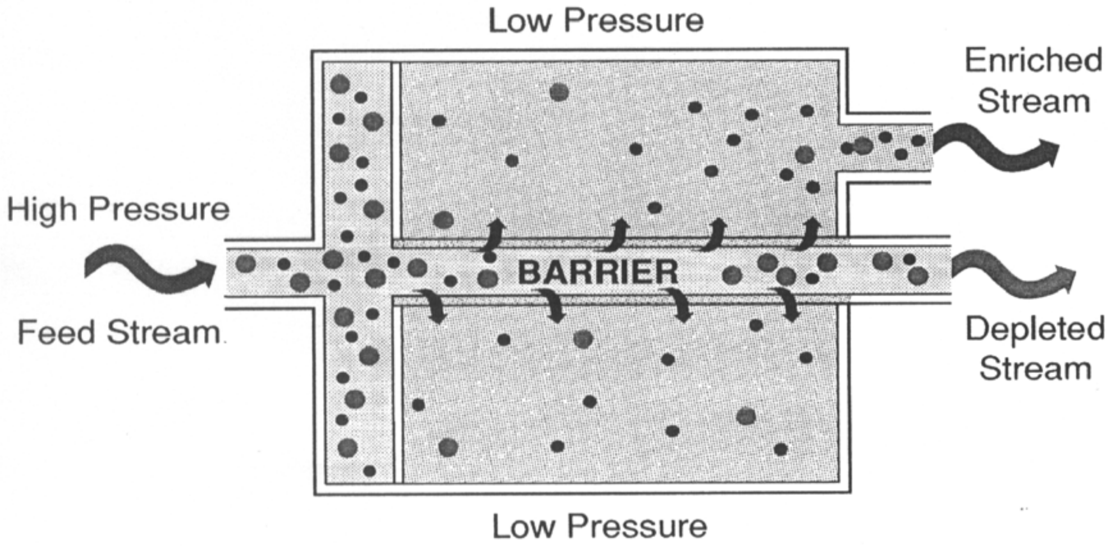


Steps of the Gaseous Diffusion Process

As stated earlier gaseous diffusion method uses molecular diffusion to effect separation. The isotopic separation is accomplished by diffusing UF_6 gas through a porous membrane (barrier) and utilizing the different molecular velocities of the two isotopes to achieve separation.

Three basic requirements must be met to apply the gaseous diffusion process. These are a stable process gas UF_6, a porous membrane, and a driving force to cause selective diffusion of the molecules through the porous membrane. The uranium-235 enrichment through each stage is so minute that literally thousands of stages are required to increase the assay from 0.711% (naturally occurring) to the desired assay, typically 4% to 5%. By cascading or connecting the basic separation stages in a series, the desired level of enrichment can be achieved. Figure 2-5 is a functional diagram of a single gaseous diffusion converter.

Figure 2-5. Schematic of United States Gaseous Diffusion Stage



The following formula shows the factor of separation of uranium-238 from uranium-235 that one can expect in a single gaseous diffusion stage:

$$\sqrt{\frac{\text{mol wt } U_{238}F_6}{\text{mol wt } U_{235}F_6}} = \sqrt{\frac{352}{349}} = 1.004$$

Theoretically, it would take 347 stages to enrich uranium-235 from 0.711% to just 1.0%.

The the gaseous diffusion process may be separated into the following eight steps:

- Step 1 - UF_6 Feed Storage
- Step 2 - Feed Supply Autoclave
- Step 3 - Enrichment Cascade
- Step 4 - Tails Condensation and Withdrawal
- Step 5 - Tails Storage
- Step 6 - Product Condensation and Withdrawal
- Step 7 - Product Storage
- Step 8 - Product Shipping

Note: In the following sections, step descriptions are generic and are not intended to provide a detailed explanation of operations at a gaseous diffusion plant.

Self-Check Questions 2-1

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

1. What is gaseous diffusion?

2. Give the location and operational status of USEC’s two gaseous diffusion plants.

3. What are the three basic requirements needed to apply the gaseous diffusion process?

Learning Objective

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

2.1.2 Describe the basic steps of the gaseous diffusion enrichment process.

STEP 1 - UF$_6$ FEED STORAGE

Normal assay UF$_6$ (0.711% U-235) for the enrichment plant may be received by truck or by rail. The normal feed can be received in 2.5-, 10-, and 14-ton cylinders with the UF$_6$ in a solid state. The feed cylinders are unloaded, inspected, weighed, and cold pressure checked.

A statistically determined number of the feed cylinders are liquefied in a steam-heated containment-type autoclave for sampling to ensure conformance with feed material specifications and for uranium accountability. The cylinders of UF$_6$ are then removed from the autoclaves and permitted to resolidify by ambient cooling in an interim storage area. Upon receipt of acceptable analytical results, the feed cylinders are transported to the cascade feed facilities.

The Portsmouth GDP has historically utilized a second source of feed. That feed was an enriched product up to 2.75% assay U-235 from the Paducah GDP. This feed material was received by cylinder and went through the same processes as described previously for the other feed materials.

Another source (rarely used) of feed has come from UF$_6$ tails material withdrawn from the gaseous diffusion cascades with U-235 assay above the currently programmed tails assay. This material, in 14-ton cylinders, is transported from the tails storage area to a feed vaporization facility. The cylinders are weighed, inspected visually, pressure checked, and placed in steam-heated containment-type autoclaves for vaporization and feeding to the cascade. When emptied, these cylinders are transported to the tails withdrawal facility for filling with depleted tails material for long-term storage. Figure 2-6 shows typical cylinders used for tails storage.

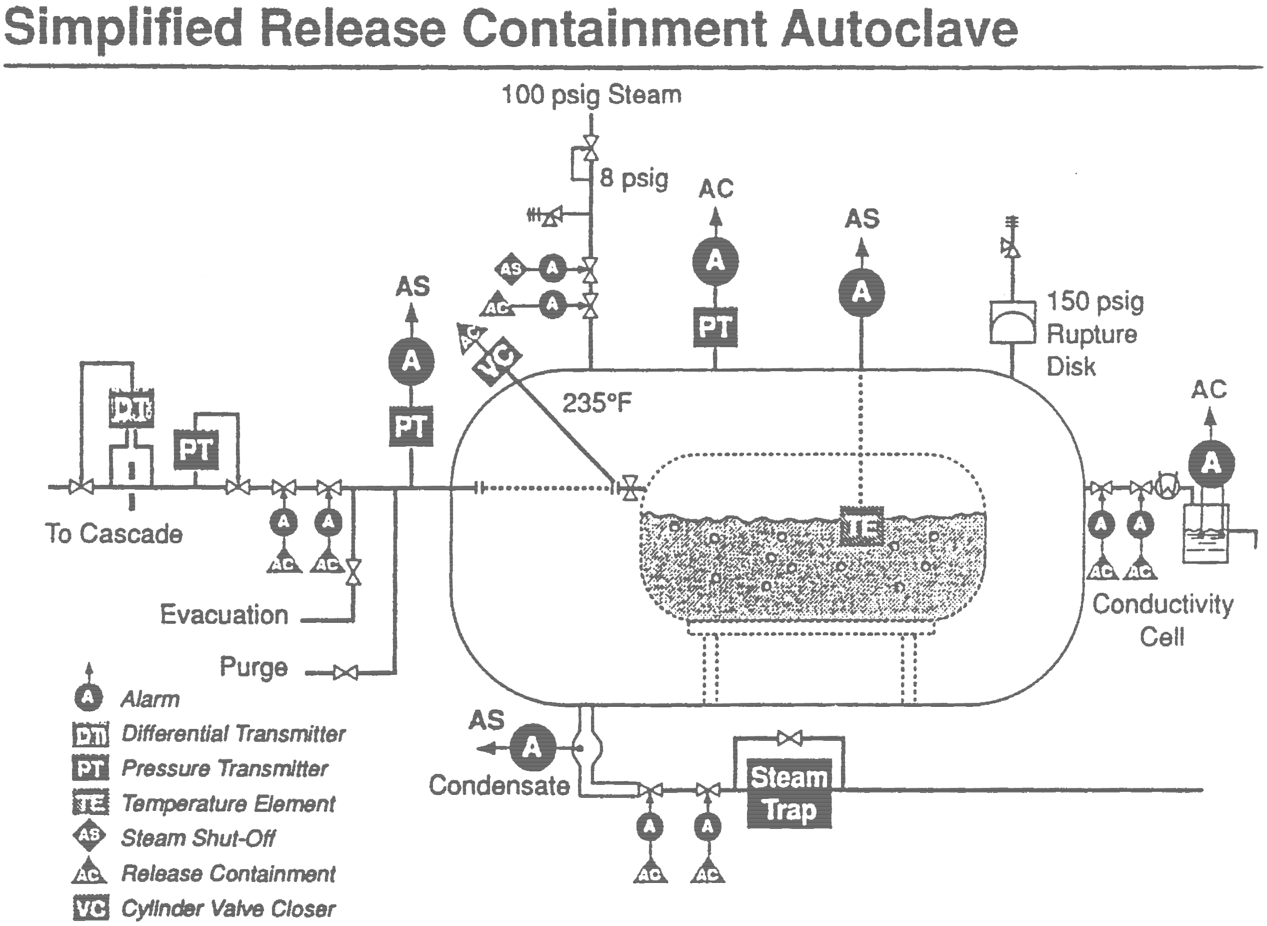
Figure 2-6. Typical UF_6 Cylinders

These are 48Y cylinders. In the U.S., these cylinders are used for natural UF_6. Overseas, the 48Y cylinder is sometimes used for DU storage.

STEP 2 - FEED SUPPLY AUTOCLAVE

A typical autoclave and its associated piping and valves are shown in Figure 2-7. The autoclave is a containment shell that opens to accept a cylinder inside for heating, usually by saturated steam. Once a cylinder is placed inside, the containment shell is closed and locked. Safety systems are activated to sense the internal operations as the cylinder is heated. Pressure, temperature, and conductivity are the parameters used to ensure that the heating is proceeding properly and that the cylinder integrity is maintained.

Figure 2-7. Autoclave



UF_6 is not introduced into the cascade until assurance is obtained that it meets feed composition and weight specifications. An external inspection is performed on each cylinder to detect any physical damage that might have occurred during shipment or during in-plant handling.

Verifying Product Specification Prior to Feeding the Cascade

The UF_6 is liquefied and homogenized (approximately 10 hours) prior to drawing a liquid sample for chemical purity and isotopic concentration. The cylinder is placed in the autoclave with the cylinder valve in the 12 o'clock position and with the pigtail connected from the cylinder valve to the cascade feed and sampling manifold; this leads to the sample bottles. At Paducah, sampling can also be conducted in a stand-alone sampling facility. The manifold also has instrumentation for continuous pressure monitoring. See Figure 2-8, “Typical Sampling System”, and Figure 2-9, “Cylinder Model 2S”. A sample is obtained by either rotating the cylinder until the valve is below the liquid level, or the autoclave (or cylinder) can be tilted to allow the liquid UF_6 to drain by gravity into the sample bottles. Afterwards, the cylinder is moved so the valve is above the liquid level. Following the sample withdrawal and prior to opening the sampling system to atmosphere, and removing the sample bottle the system is purged of UF_6 and evacuated to about 1 psia or as low a vacuum as possible.

Figure 2-8. Typical Sampling System

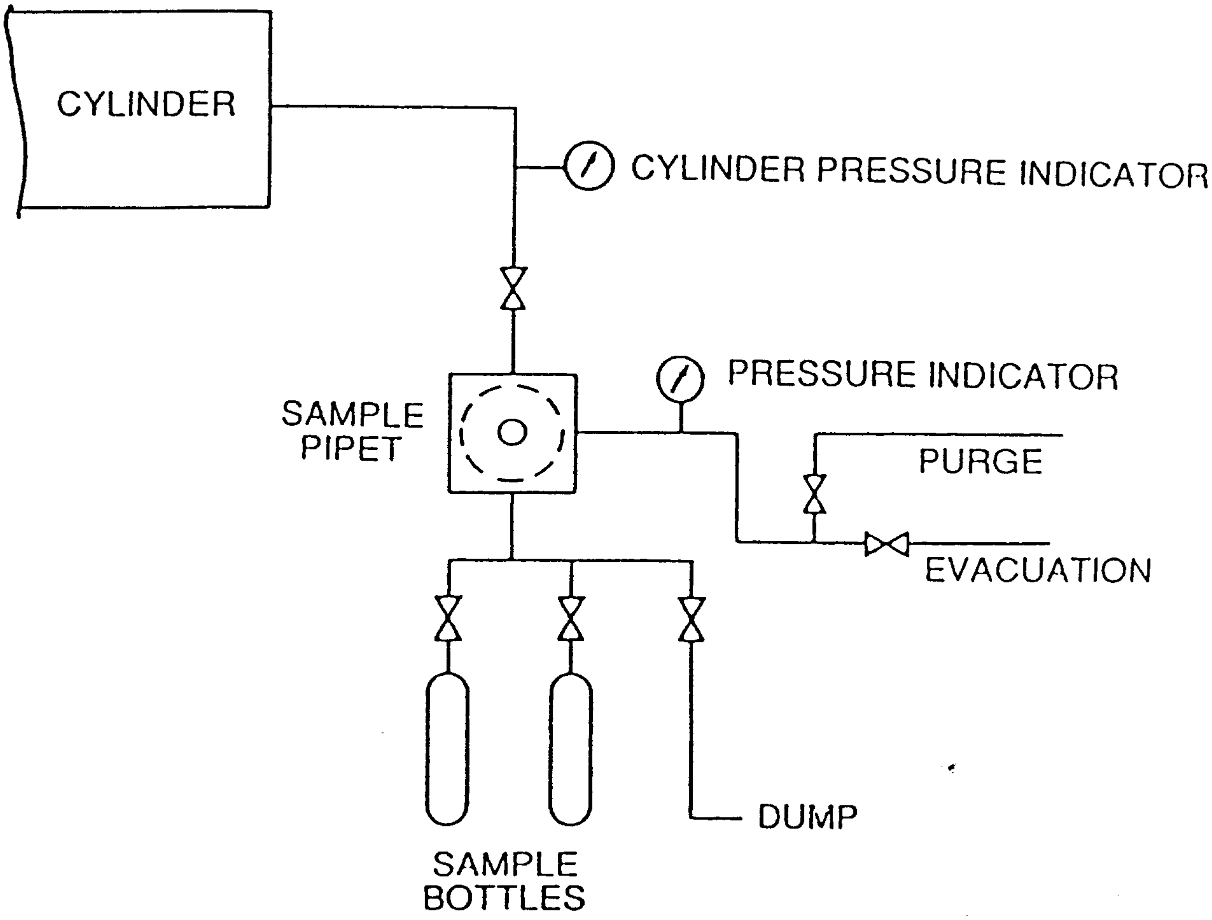
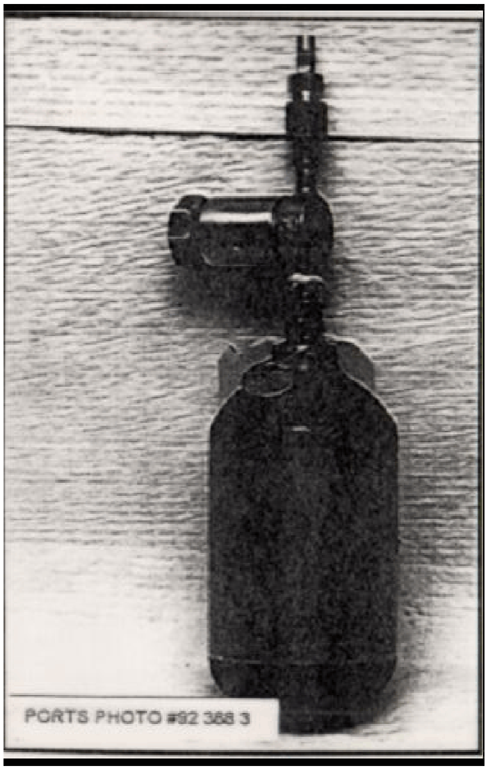


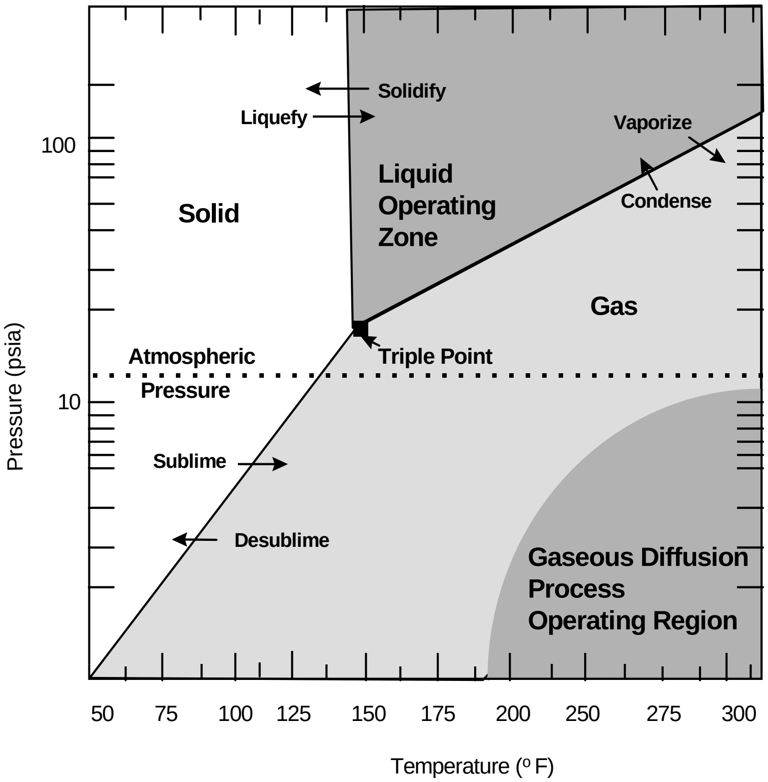
Figure 2-9. Cylinder Model 2S (for sampling)



After analytical results of feed cylinder samples are available, the cylinders are scheduled for feeding on a first in/first fed basis. Cylinders are sequentially moved to one of the feed autoclaves where they are heated; the cylinder contents vaporized; and transferred to the cascade through a manifolded system of feed headers, metering stations, and cascade feed piping.

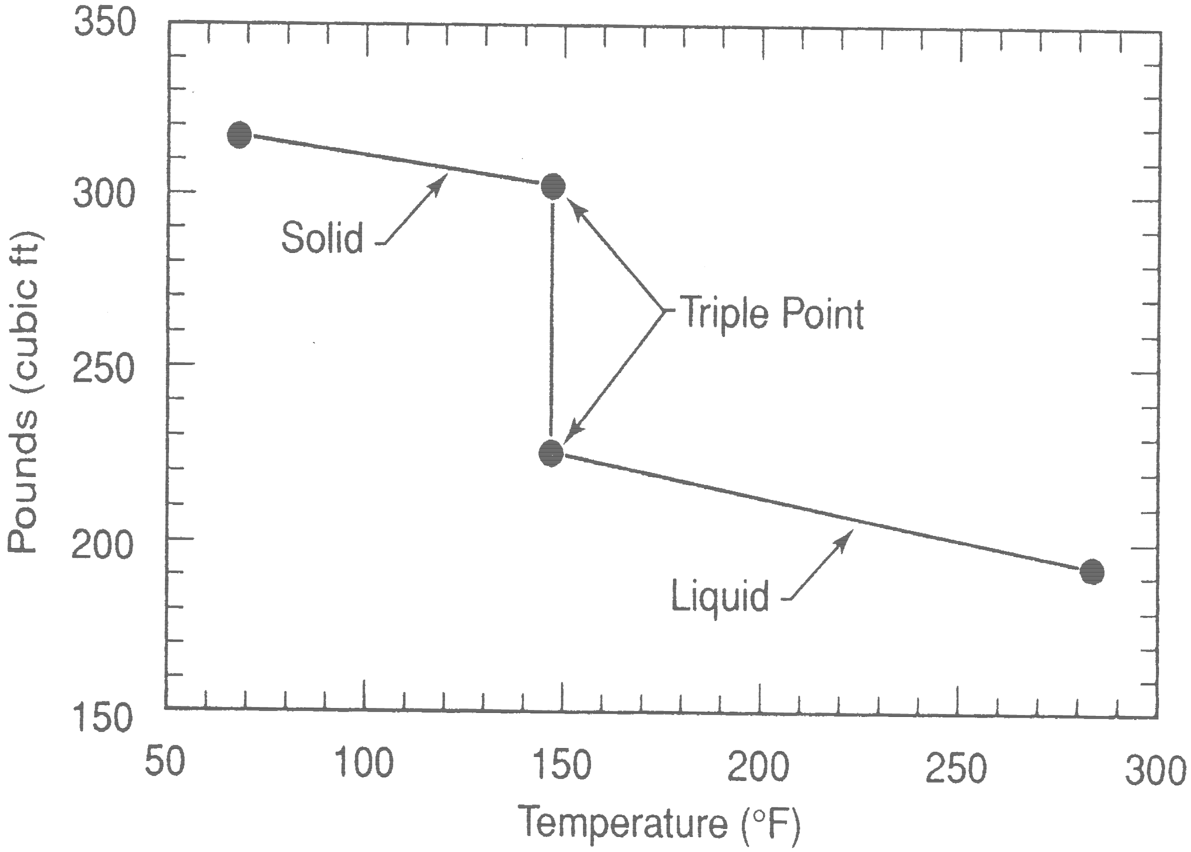
As in sampling the solid cylinder contents are heated to the liquid phase (above the triple point). See Figure 2-10, “UF_6 Phase Diagram”. Contents are then fed to the cascade as a gas (UF_6 feed cylinder valve is at the twelve o’clock position) which is above the level of the UF_6 liquid phase. The cylinder is connected to a manifold with a pigtail. The pigtail is fabricated from copper tubing which has passed a hydrostatic test to 400 psig. Prior to connection, the pigtail is visually inspected for defects and a new pigtail gasket is installed. The pigtail and its connections are tested by opening the manifold evacuation valve and evacuating the pigtail to 5 psia or less. The manifold valve is closed and a one- to two-minute leak rate test is performed. If no detectable leaks are observed, the pigtail is pressurized with dry air to a minimum test pressure of 40 psig and the connections are soap tested. The cylinder valve is opened to relieve the pressure in the pigtail to the cylinder and the emergency cylinder valve closer is attached. (Each autoclave has a cylinder valve closer that consists of an air motor outside the autoclave head and a telescoping shaft to connect to the cylinder valve.) A loss of pressure indicates valve clarity and no loss of pressure indicates a plugged or faulty valve. If the valve is not clear, the cylinder will not be heated and will be removed from the autoclave for proper tagging and disposition.

Figure 2-10. UF_6 Phase Diagram



If the pigtail and valve pass the tests, the cylinder pressure is noted and recorded. A pressure of less than or equal to 10 psia indicates that the cylinder does not contain significant amounts of impurities and is acceptable for feed. A cylinder pressure of above 10 psia indicates noncondensibles or impurities in the cylinder. Figure 2-11, “Density of UF_6”, shows a significant density change, and therefore, volume change going from solid to liquid. Thus, an important part of cylinder safety is control of noncondensibles (oxygen, nitrogen, etc.), impurities (such as Freon), and heating. With supervisory approval, the cylinder can be “cold burped” (carefully purged to a vacuum) in order to lower the pressure to below 10 psia.

Figure 2-11. Density of UF_6



After the operator has determined that all conditions have been met, the autoclave shell is hydraulically closed and a locking ring is rotated to seal the shell as a containment vessel around the cylinder.

As a protection against over pressure, each autoclave is provided with a rupture disc backed by a 3-inch by 4-inch pressure relief valve.

Self-Check Questions 2-2

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

1. What is an autoclave?

2. What are the parameters used to ensure that autoclave heating is proceeding properly and that cylinder integrity is maintained?

3. What assurances should occur before a UF_6 cylinder is heated in an autoclave?

4. What should happen prior to drawing a liquid sample for chemical purity and isotopic concentration?

5. Following the sample withdrawal and prior to opening the sampling system to atmosphere, and removing the sample bottles, what should occur?

6. What form of UF_6 (solid, liquid, or gas) is fed to the cascade?

7. How is a cylinder connected to a manifold?

8. After pigtail and valve testing, what does a cylinder pressure of less than or equal to 10 psia indicate?

9. What does a cylinder pressure of above 10 psia indicate?

10. What is each autoclave provided with to protect against over pressure?

STEP 3 - ENRICHMENT CASCADE

At least three basic requirements must be met in order to apply the gaseous diffusion process to a separation task: a stable process gas, a porous membrane, and a driving force to effect separation.

The separation of U-235 from U-238 is accomplished by passing uranium hexafluoride gas through many hundreds of stages, as described previously. The gas flows into the stage, where it comes in contact with the surface of a material called a barrier. This barrier is what actually accomplishes the separation of the U-235 from the U-238. It is necessary that the uranium be in the form of a gaseous compound for the operation of diffusion through the porous barrier.

Cascade Configuration

A number of factors influence the cascade shape. A cascade with very efficient barrier will be shorter than one with less efficient barrier. A cascade producing a high product rate must have higher flow rates between stages than one producing a lower product rate. Stages in the middle of a cascade must have higher flow rates than those near the ends of the cascade if the power is to be used efficiently. The schematic representation of an efficient cascade is usually drawn with a diamond shape to illustrate that the flow rates are largest near the middle and smallest at the ends. See Figure 2-12, “Typical Cascade Schematic.”

Figures 2-13 and 2-14, “Cascade Configuration Charts”, show how Paducah and Portsmouth operated together and how Paducah operated, respectively. For example, Figure 2-13 shows the output of the Paducah cascade was a second input to the Portsmouth cascade, along with the normal feed. The endpoint product for the customer came from the Portsmouth output. The Paducah GDP operated as two enrichment cascades in an overlap arrangement set-up to provide a “shorter” cascade with higher through-put (lower % assay) or a “longer” cascade with a higher enrichment (% assay) output (lower through-put). After HAUP, Paducah operates with the longer cascade.

The length of the cascade is determined by the needed enrichment. A 4% enrichment requires many more stages than a 2.6% enrichment. This required length, that is, number of stages, to enrich normal feed to a desired percent enrichment can be calculated with the formula from Figure 2-15. Knowing the needed enrichment in the product (top concentration 3% to 5% assay) and the programmed enrichment for the tails (bottom concentration 0.2% to 0.4% assay) sets the theoretical minimum number of stages needed, as well as the ideal number of stages. The ideal number of stages is that number which allows an optimum use of power in the normal operating range of temperatures and pressures in the cascade equipment. A plot of the ideal number of stages can be developed to show the number of stages required to generate various product assays. For example,

Figure 2-16 shows a plot for the number of stages required to produce various product assays with 0.3% tails assay and a separation factor of 1.004. The separation factor represents the enrichment per stage.

Figure 2-12. Typical Cascade Schematic

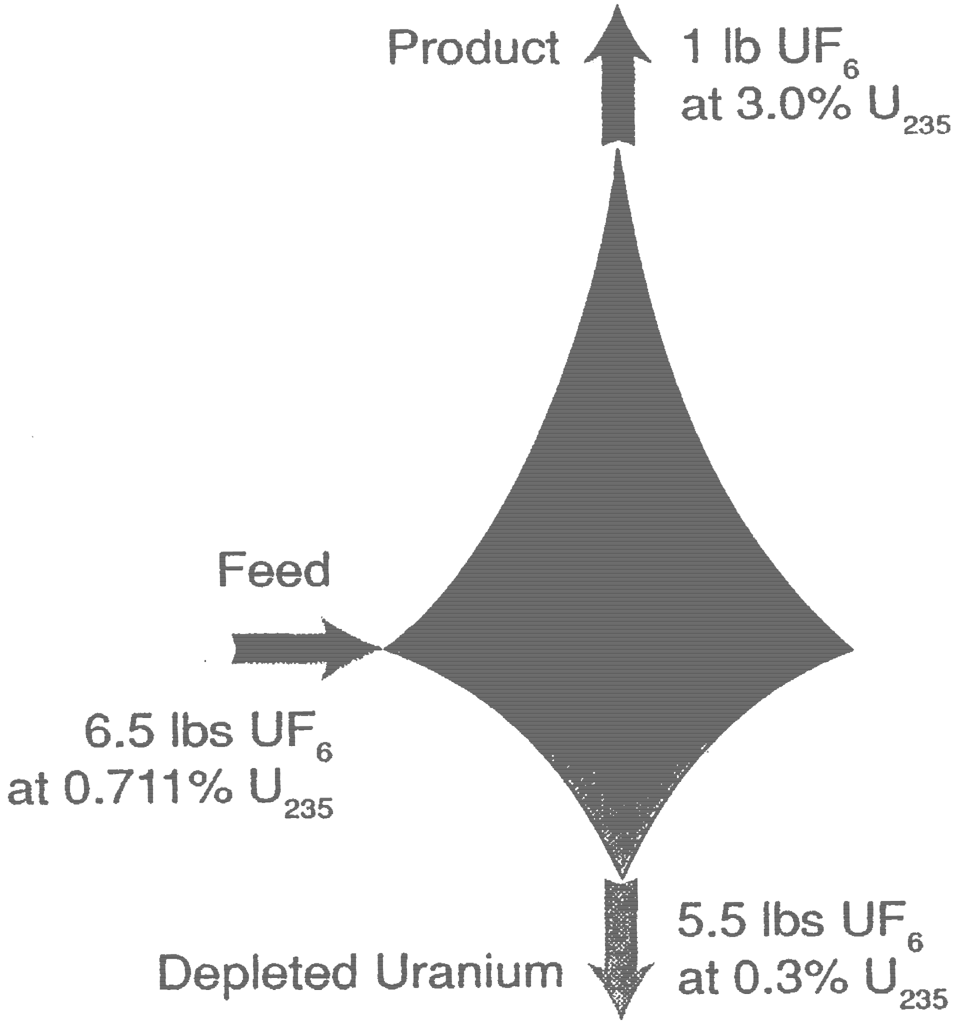


Figure 2-13. Cascade Configuration Charts

THE PADUCAH CASCADE OPERATES IN CONJUNCTION WITH THE PORTSMOUTH CASCADE TO FORM THE OPERATING COMPLEX

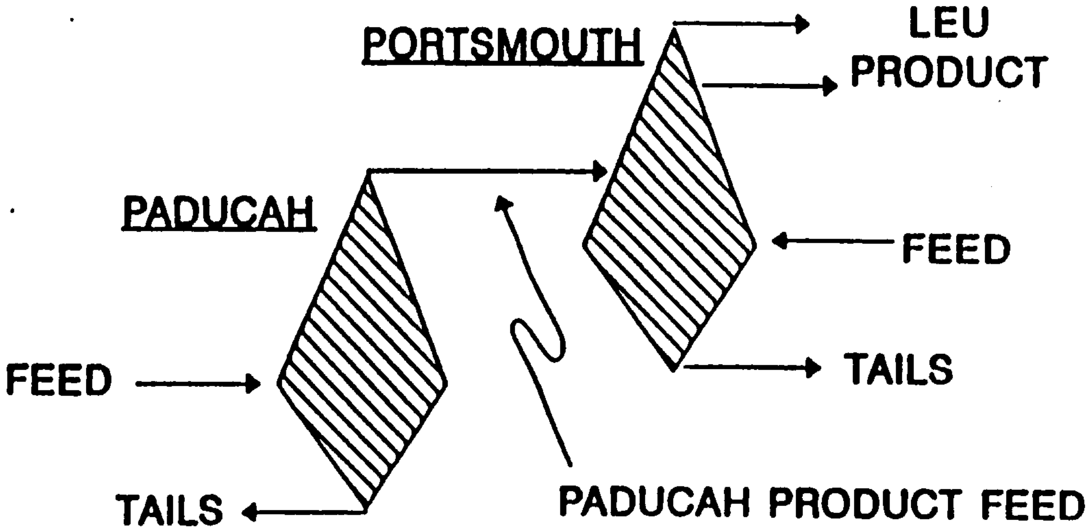


Figure 2-14. Cascade Configuration Charts

THE PADUCAH CASCADE IS MADE UP OF TWO SEPARATE CASCADES OPERATING IN A PARALLEL CONFIGURATION

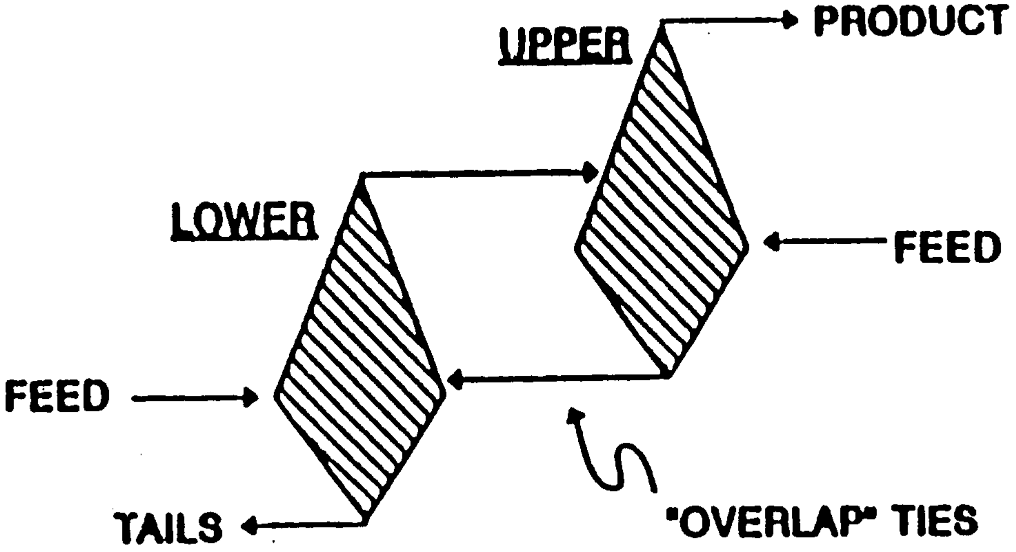


Figure 2-15. Required Number of Gaseous Diffusion Stages

$$\text{Minimum Number of Stages} = N_{min}$$

$$\ln\left(R_T / R_B\right) / \psi$$

where

$$R_T = \frac{U_{235}\ \text{Top Concentration}}{\left(1 - U_{235}\ \text{Top Concentration}\right)}$$

$$R_B = \frac{U_{235}\ \text{Bottom Concentration}}{\left(1 - U_{235}\ \text{Bottom Concentration}\right)}$$

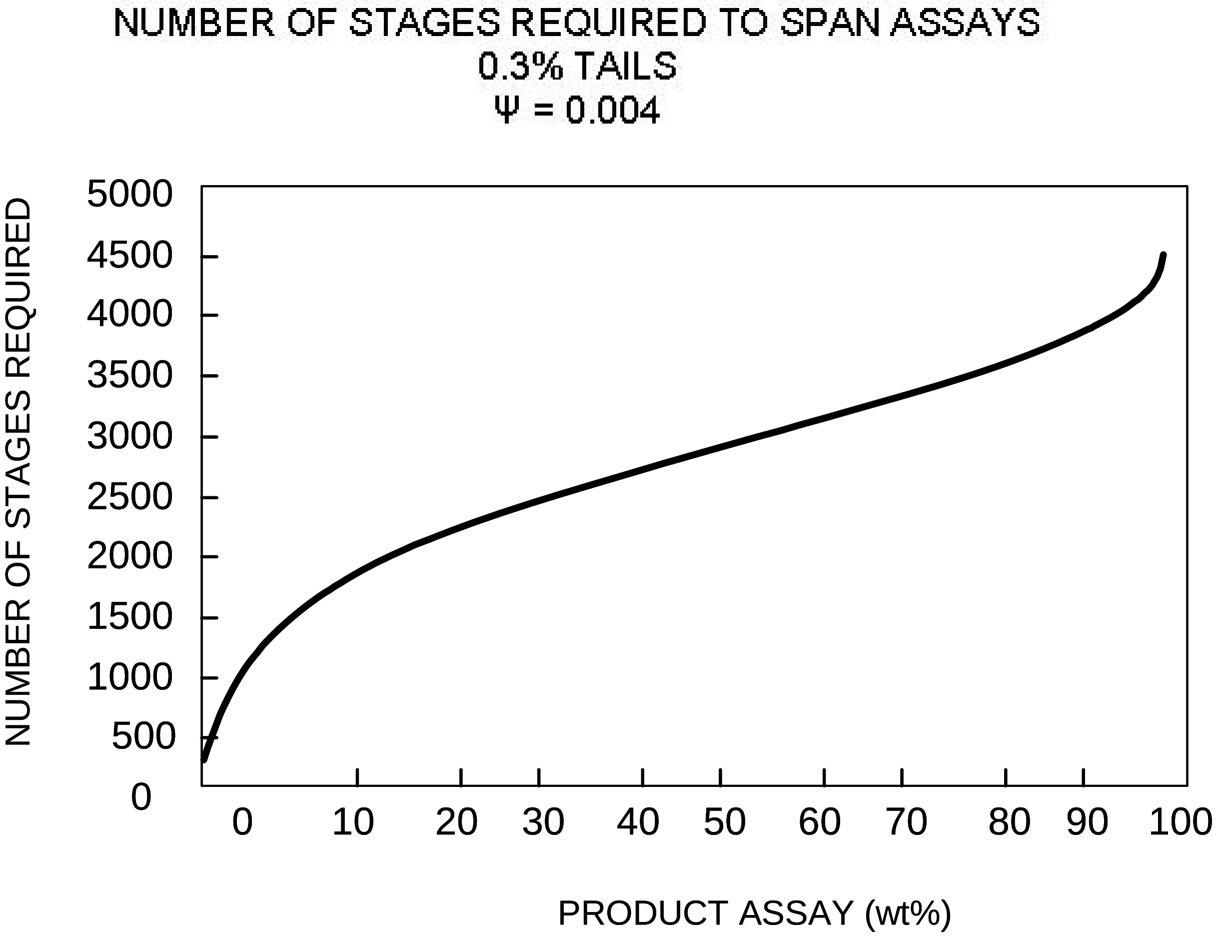
$$\psi = 0.004$$

$$\text{Ideal Number of Stages} = 2N_{min}$$

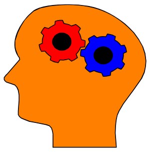
Legend

ln = natural log
ψ = separation factor
R_T = top concentration ratio
R_B = bottom concentration ratio
$2N_{min}$ = twice minimum number of stages

Figure 2-16. Number of Stages Required to Span Assays



Activity 1 - Calculating the Required Cascade Length



Purpose: Demonstrate an understanding of the relationship between cascade stages and percent enrichment.

Instructions: Using the formula for ideal number of stages in Figure 2-15, calculate the required number of stages to enrich normal feed (0.711%) to 15% assay assuming a 0.3% tails assay and a separation factor of 1.004. Using Figure 2-16, check your answer with the plot of stages versus product assay. The answer is located in the answer key section of the Trainee Guide.

Cell, Unit, Stage Configuration

Because many stages are needed in the gaseous diffusion process, it is necessary to give other names to groups of stages. A configuration of several stages in series is called a cell. A cell usually contains 8 to 10 stages with compressors, coolant condensers to remove the heat of compression, and block valves to isolate the cell from the rest of the cascade. Each cell is enclosed in a metal housing that maintains the temperature sufficiently warm to keep the UF_6 in the gaseous state. Generally, the heat of compression from the compressors is sufficient. The compressor motors are outside and immediately adjacent to the cell housing. A cell is the smallest section of the cascade that can be isolated from the rest of the enrichment plant operations.

A group of cells constitutes a unit, while several units constitute a cascade, the name given to the whole assembly of stages necessary to give the desired plant operation. The cascade is operated under several large divisions called areas. These divisions are made for ease of control and are monitored from the area control rooms.

The cascade configuration is represented by the cascade schematic previously discussed in Figures 2-12, 2-13, and 2-14. The diamond also indicates the relative physical size of the stages, the relative operating pressures, and the relative flowrates of UF_6 in the stages. The larger equipment, higher pressures, and higher flowrates can be found in the wider portion of the cascade diamond. The smaller equipment, lower pressures, and lower flowrates are found in the narrower portions of the diamond. Figures 2-16, 2-17, 2-18, 2-19 and 2-20 represent the Portsmouth and Paducah cascades.

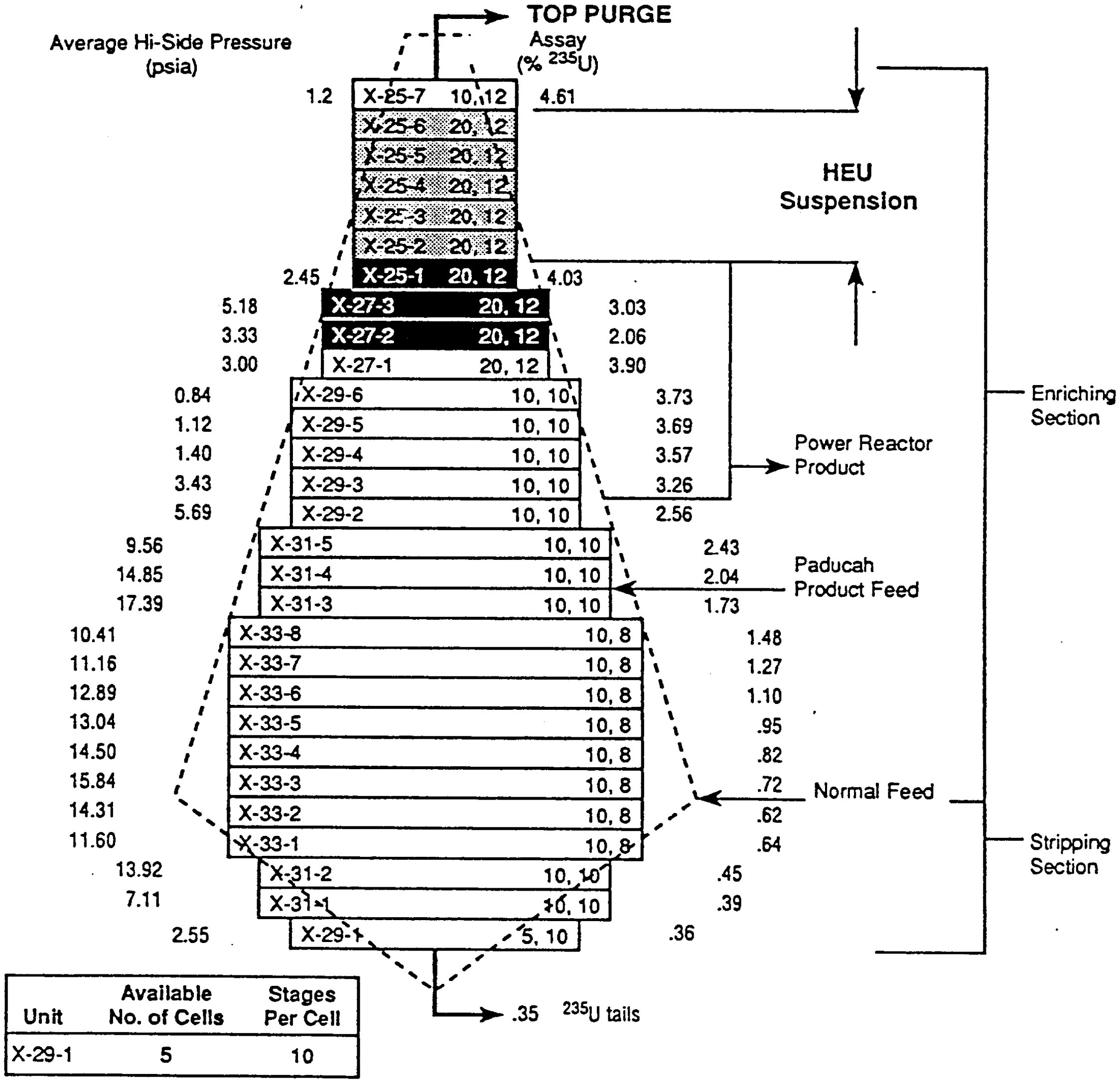
The largest equipment is usually housed in a single building for commonality of operations and maintenance. This building as diagramed in Figure 2-21, is arranged in a U-shape to minimize piping and building size. Likewise, each unit in the building is arranged in a U-shape, as detailed in Figure 2-22, “Typical Process Unit Configuration.”

To reiterate, a cascade unit is constructed of cells. Cells are groupings of stages that can be isolated from the remainder of the cascade for maintenance and emergency response purposes. The cell layout minimizes piping, connection, heated housing and auxiliary equipment needs. The result is a slightly confusing view of the system when viewed in the plant because only alternating stage equipment can be seen outside the heated housing at one time.

The cell can be isolated, or blocked, by a series of large process system valves that block the enriching flow path, the depleting flow path, and the bypass flow path. The enriching flow path is called the “A” stream and the depleting flow path is called the “B” stream. The valves that isolate the “A” stream (enriching) are AB1 (A stream block valve no. 1- inlet) and AB2 (A stream block valve no. 2- outlet). Likewise, the valves that isolate the “B” stream (depleting) are BB1

(B stream block valve no. 1 - inlet) and BB2 (B stream block valve no. 2 - outlet).

Figure 2-17. PORTS Cascade Configuration (Flow, Pressure, and Average Assays @ 1900MW)



Unit	Available No. of Cells	Stages Per Cell
X-29-1	5	10

Figure 2-18. PAD Cascade Configuration (Interstage Flow vs Stage for Ideal Cascade)

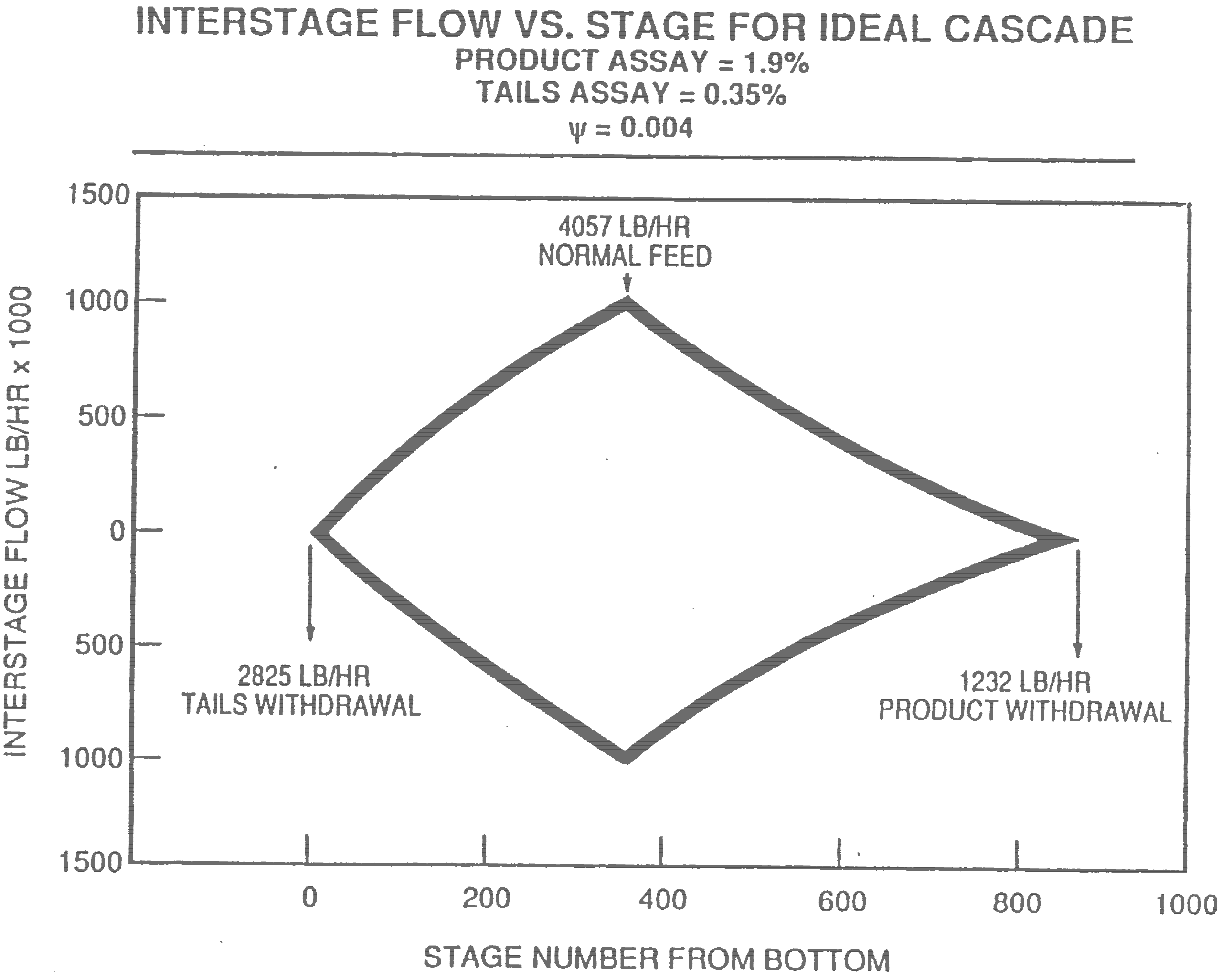


Figure 2-19. Typical Paducah Configuration @ 1.9% Top Product Assay

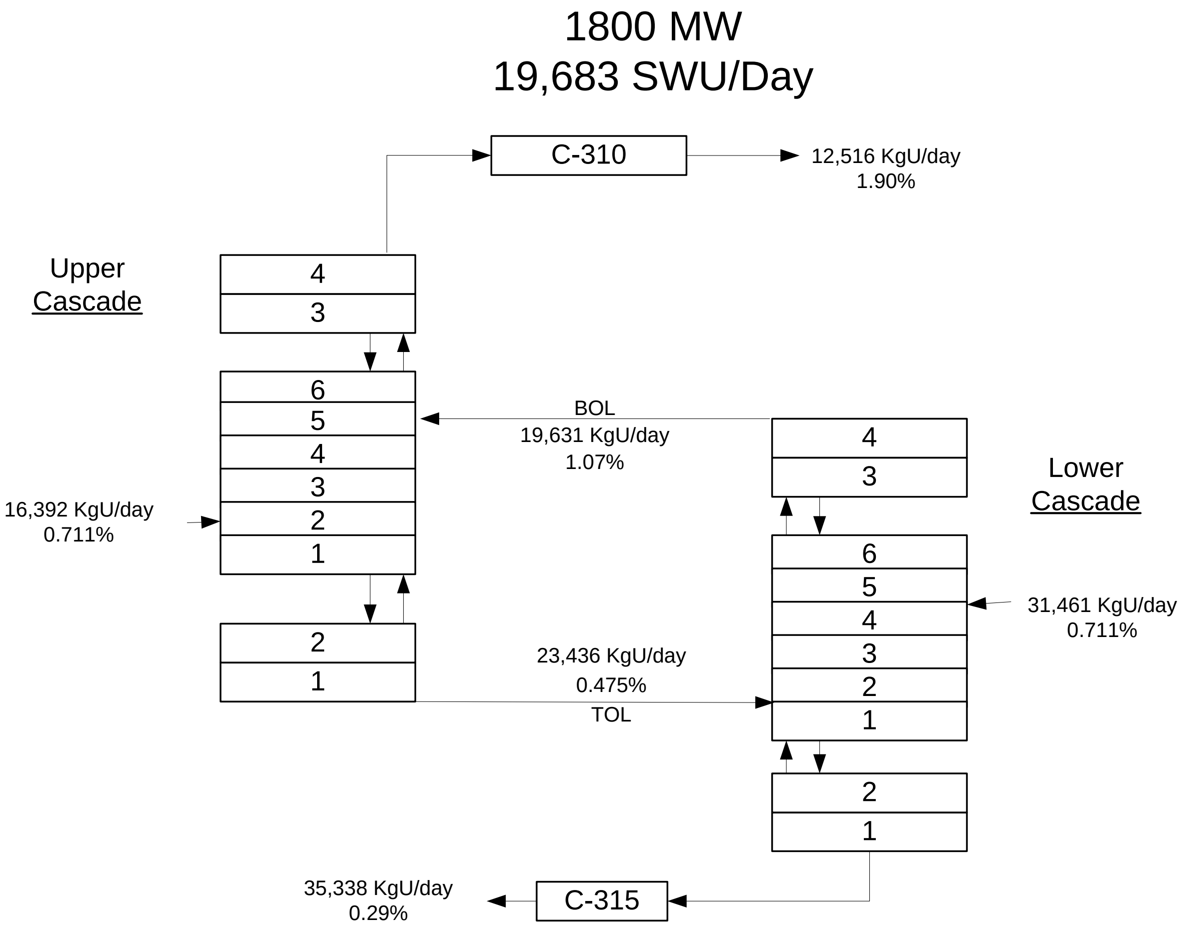


Figure 2-20. Typical Paducah Configuration @ 4.5% Top Product Assay

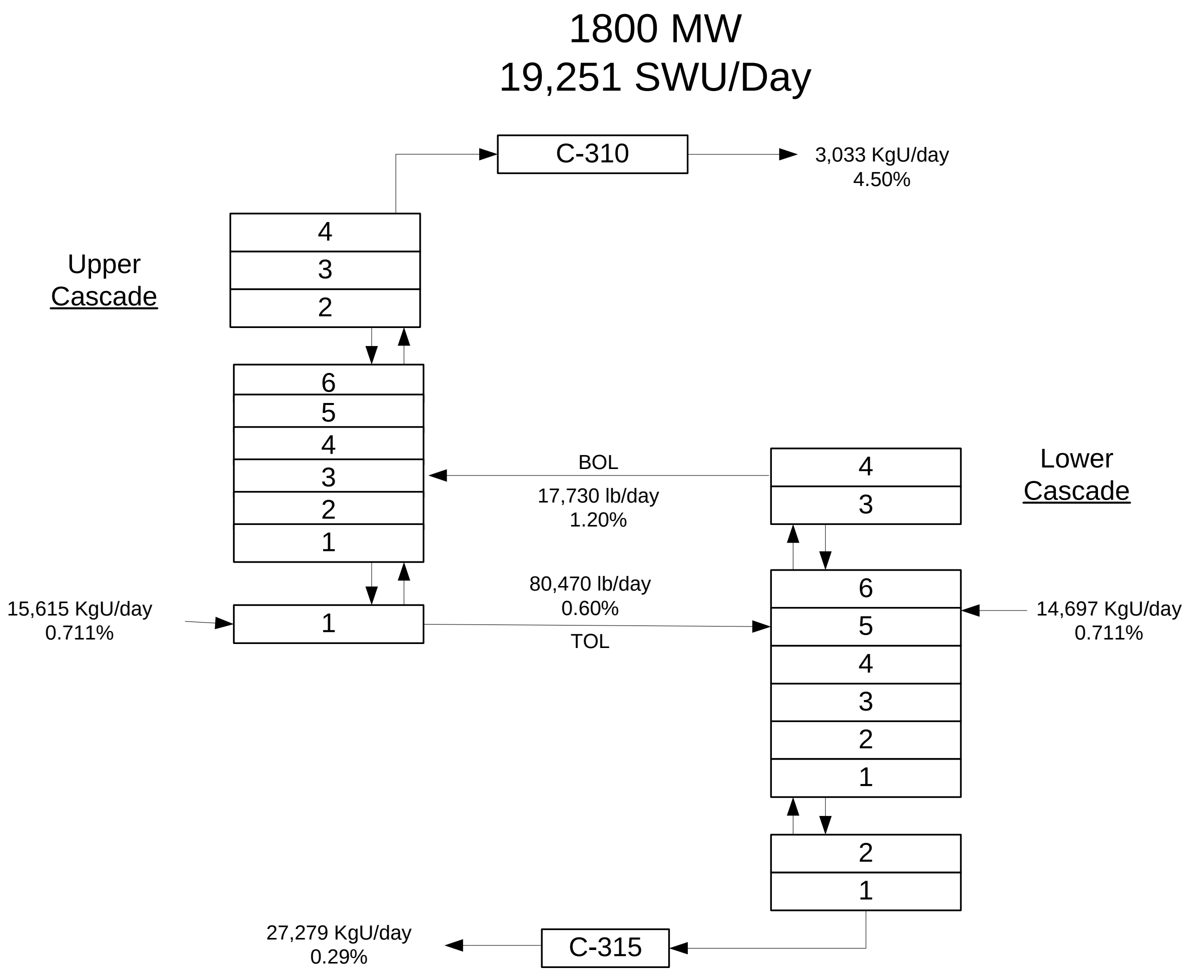


Figure 2-21. Typical Process Building Layout

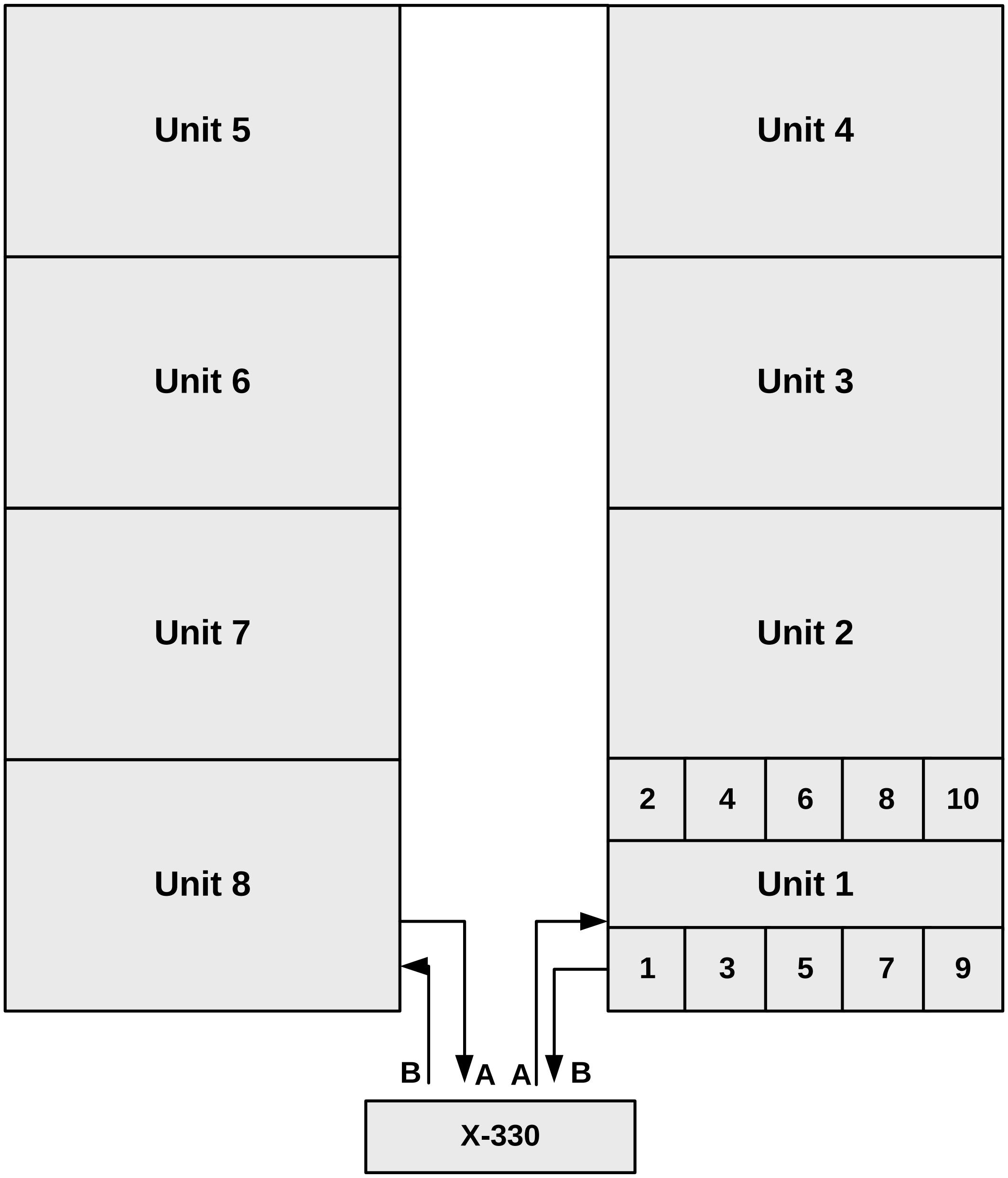
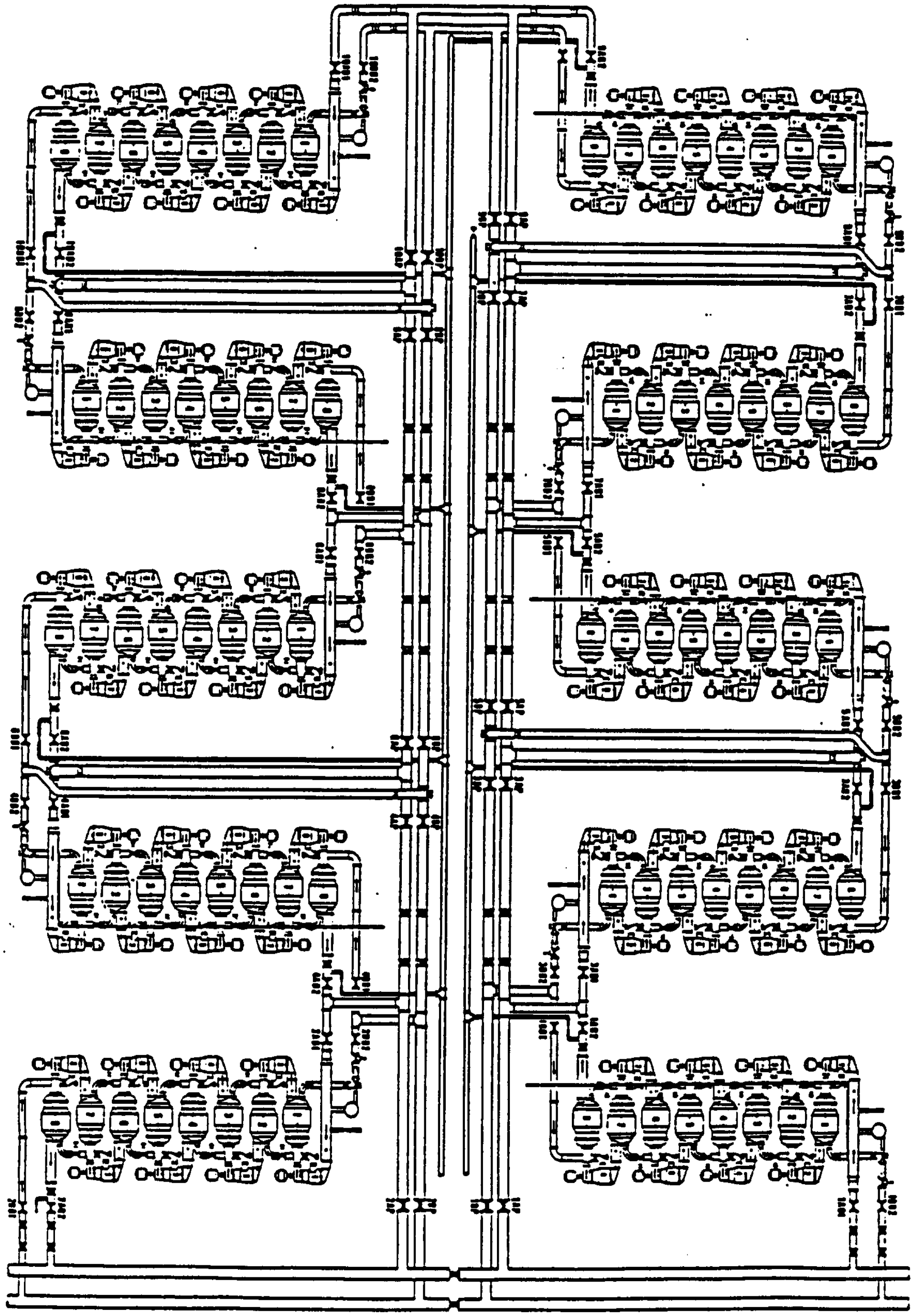


Figure 2-22. Typical Process Unit Configuration



Similarly, the entire cell can be bypassed to connect the previous cell to the next cell without passing the process gas through the isolated cell. The bypass flow path is actually two flow paths, one for the bypassing of the A stream and one for the bypassing of the B stream. The valves are ABP (A stream block valves bypass) and BBP (B stream block valves bypass). See Figure 2-23, “Cell Layout.”

The enriching flow through a cell is “up” through the cell using the A stream flow path, while the depleting flow through the cell is “down” through the cell using the B stream flow path. Thus the A stream flows up from stage 1 through stage 8, and the B stream flows down from stage 8 through stage 1.

The B stream is actually a segmented flow path merging at each stage with the A stream inside the compressor of the next lower numbered stage. That is, the depleted B stream output from a converter (e.g., stage 8) is passed “down” to the middle of the lower numbered stage compressor (e.g., stage 7). This is repeated with each stage as the depleted stream. The purpose of this approach is economy. By reintroducing the depleted output from a stage converter to a lowered number stage compressor, the uranium content in the depleted flow path can be further processed to the enriched stream. By design, the U-235 assay of the B stream that is reintroduced into the lower stage compressor is exactly matched to the U-235 assay of the enriching stream at that stage compressor. See Figure 2-24, “Inter-Stage Flow”, and Figure 2-25, “Separation at Normal Feedpoint.”

With many stages constructing a cell, many cells constructing a unit, and many units constructing a cascade, the control of the equipment is complex. The cascades were designed with a distributed control scheme using a central control station, called Plant Control Facility (PCF) in a supervisory role overseeing several area control rooms in various locations.

Each area control room (ACR) is responsible for many units, cells, and stages. In the ACR, there are controls for the cells in each unit as well as auxiliary support systems associated with each unit. The ACR also controls the systems of piping and valves that interconnect the various units and cells. The ACR is the primary operating location and emergency response location for the cascade.

To assist the area control room, local control centers (LCC) were built to provide local control and additional indicators for each cell, and its associated stages. The LCC contains controls and indications for electrical breakers for valves and compressor motors, stage pressures, cell coolant systems, and sampling connections. See Figure 2-26, “GDP Control Scheme.”

Figure 2-23. Cell Layout

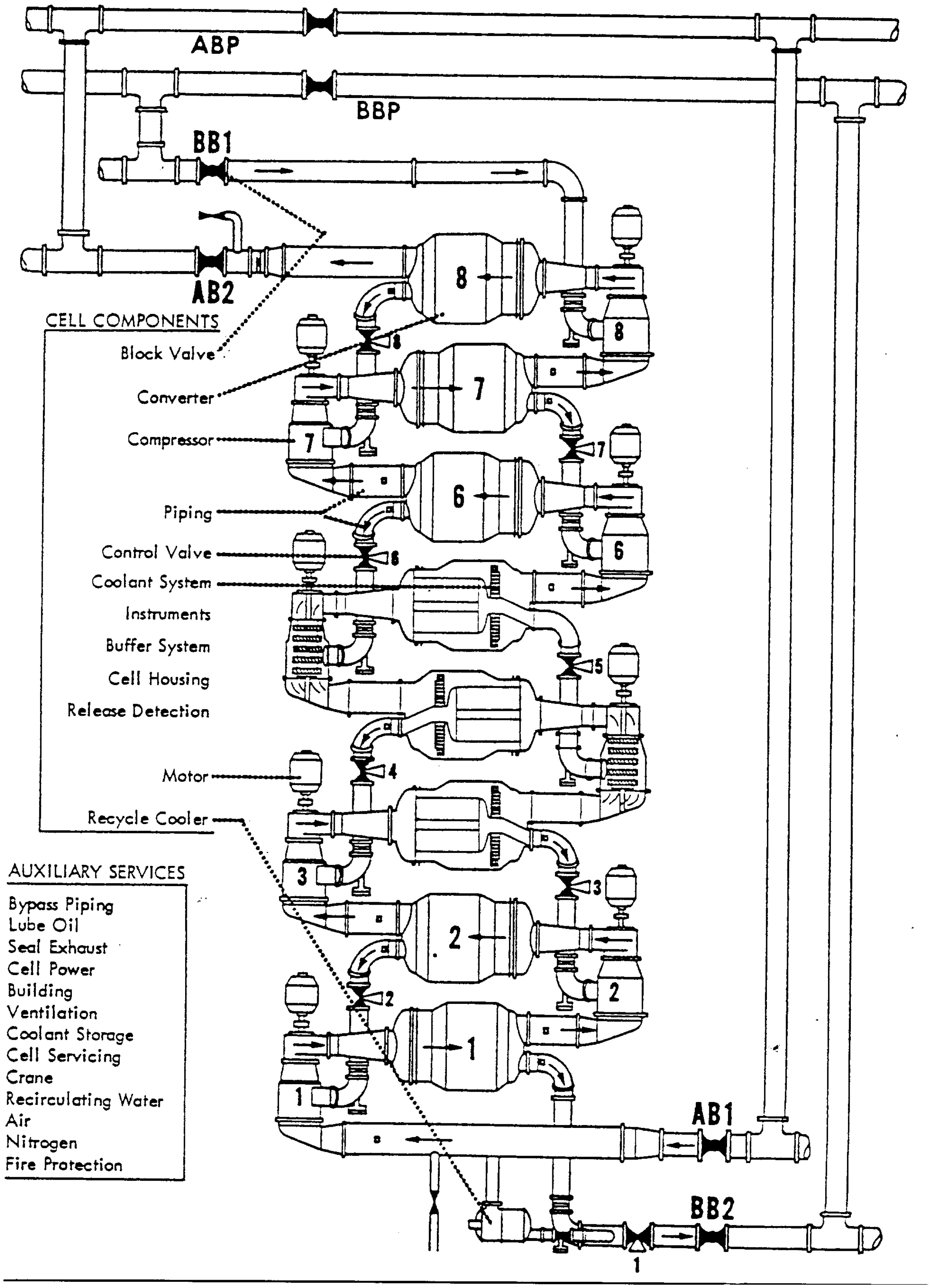


Figure 2-24. Inter-Stage Flow

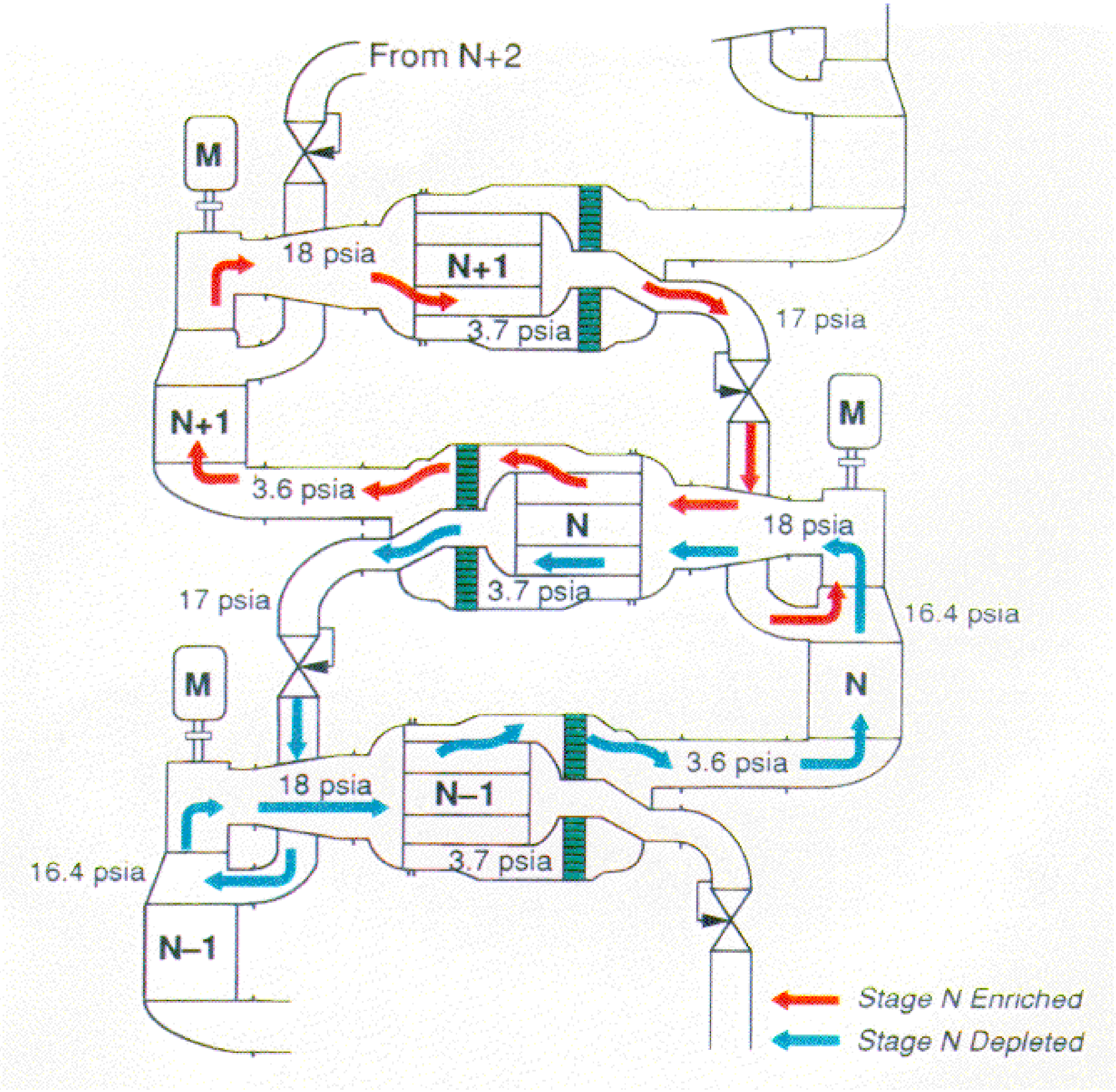


Figure 2-25. Separation at Normal Feedpoint

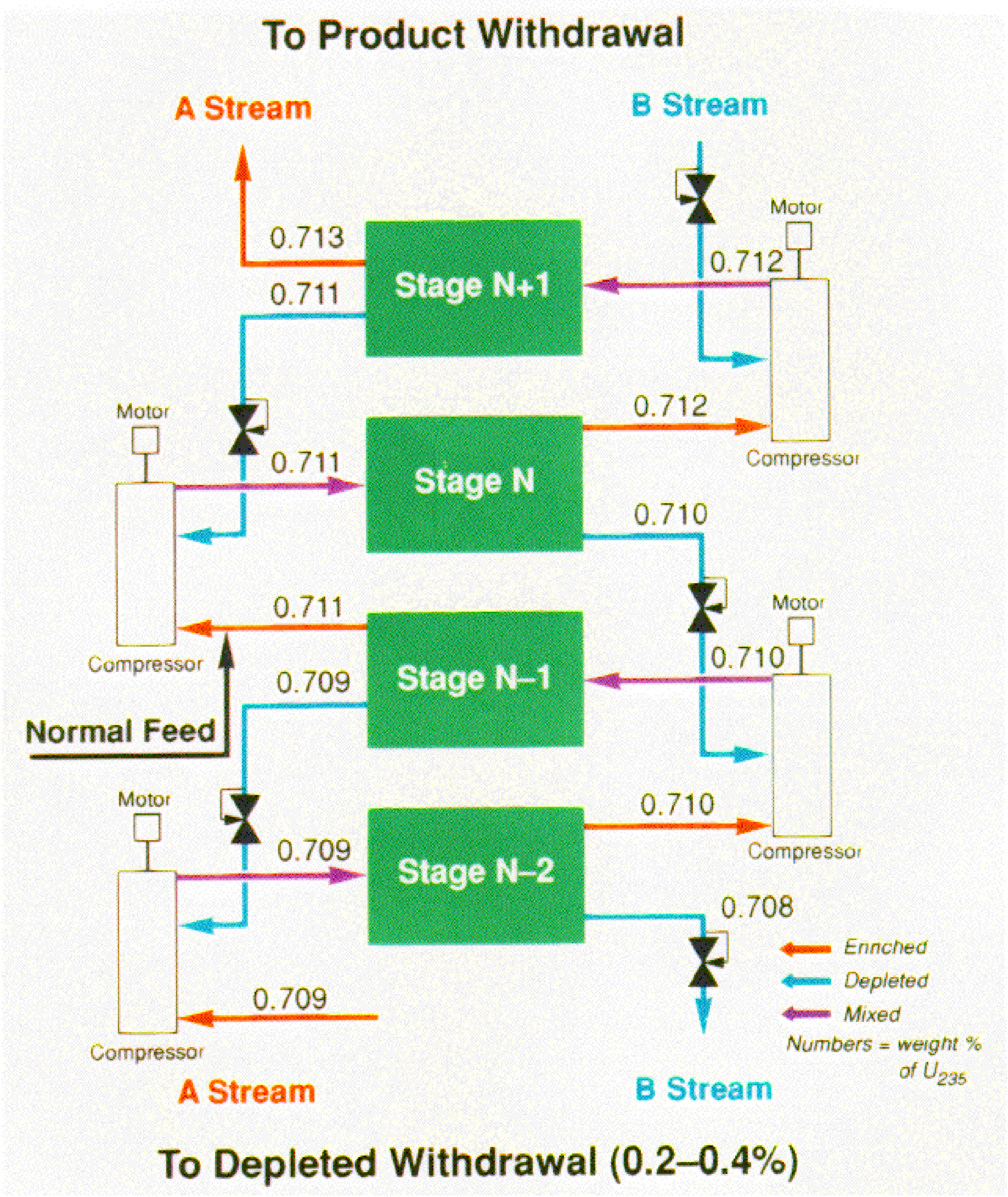
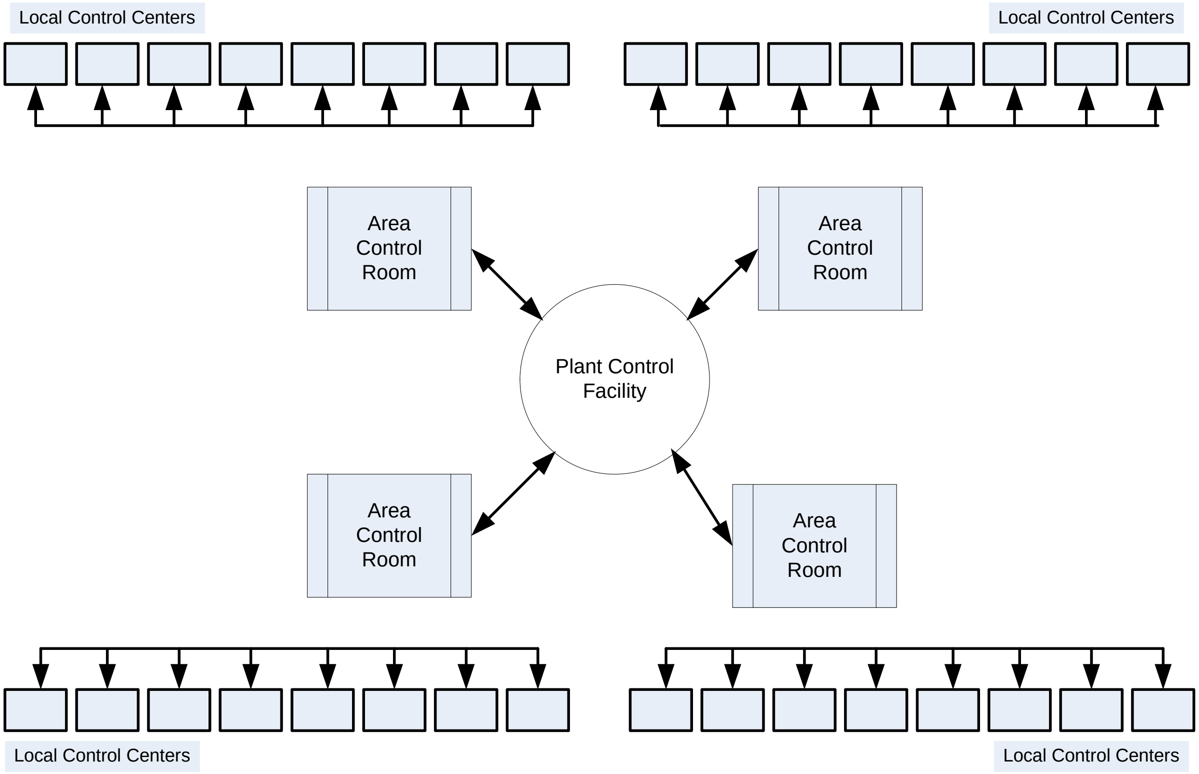


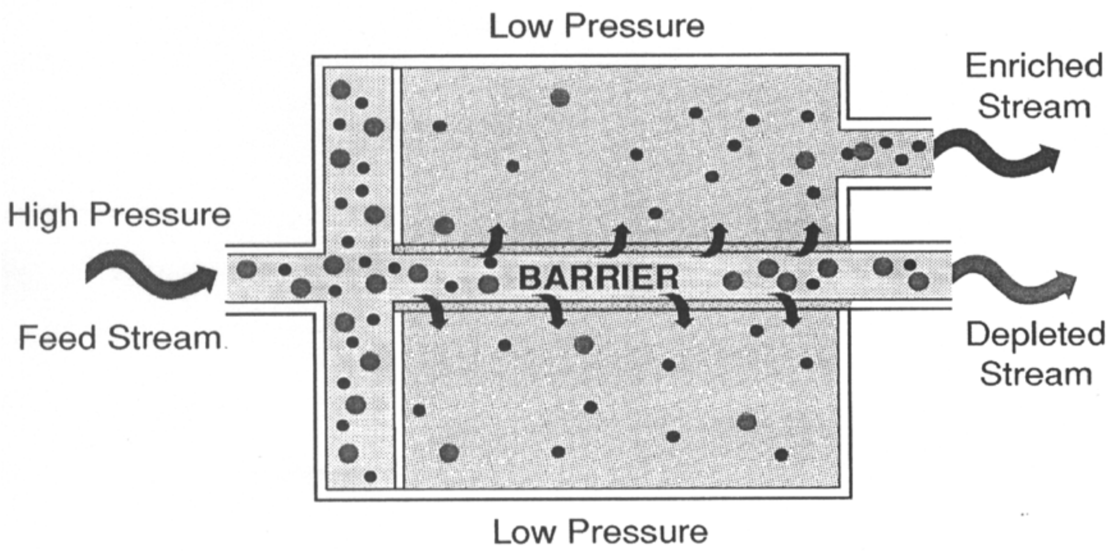
Figure 2-26. GDP Controls Scheme



Components of a Stage

The basic stage configuration is one converter, one compressor, one stage control valve, and associated piping and indications. The primary component of interest is the converter, which is where the enriching process actually occurs. See Figure 2-27, "Gaseous Diffusion Converter."

Figure 2-27. Gaseous Diffusion Converter



Converter

The barrier material is constructed in tubes, many of which are arranged in a tube bundle and installed in a converter. The gas compressor discharges into the converter where a portion of the process gas diffuses through the barrier tube wall and passes on to the next compressor as the "A" stream, which is slightly enriched in the U-235 isotope. The gas that does not diffuse through the barrier material leaves the converter as the "B" stream, which is slightly depleted in the U-235 isotope. The configuration of a motor, compressor, converter, "B" stream control valve, associated piping, and controls is called a stage. See Figure 2-28, "T1A or 0000-Size Converter", and Figure 2-29, "Improved Stage Arrangement."

The gas that enters the converter contains an excess amount of heat imparted to it by the compressor. This heat is removed, and the temperature of the gas is controlled by a gas cooler, which is either in the converter or between the compressor and the converter. There are no moving parts in the converter. All of the converters, compressors, and connecting process gas piping are enclosed in insulated cell housings so that they are at all times surrounded by heated air, which helps to keep the temperature high enough so that no process gas will desublime (plate-out and "freeze").

Compressor

A means must be provided for moving the process gas through the converters and maintaining required pressure differential across the barrier in the converter. This is accomplished by means of gas compressors, one for each converter in the cascade. Both axial flow and centrifugal compressors (or pumps) are utilized for this purpose. Most of the compressors have three pipeline connections, two suction inlets, and one pressure discharge. A compressor gets its suction from the A outlet of the previous stage converter, and mixes it with the flow from the B outlet of the next stage converter. It discharges the gas at a higher pressure into the inlet of the converter to which it is connected.

Axial Flow Compressor

See Figure 2-30, “Axial Flow Gas Compressor,” and Figure 2-31, “000-PEM/CUP Axial Flow Compressor.” The axial flow compressor consists mainly of a rotor, stator, blades, and casing; and is similar in design to an aircraft jet engine. The rotor is a cylindrical metal drum with a shaft through its axis. Blades are attached around the periphery of the rotor, similar to the blades of a fan around its shaft. There are several rows of these blades spaced along the length of the rotor. These can be pictured as a series of fans on the same shaft with spaces between the rows of rotor blades (i.e., for the stator blades).

The stator is cone-shaped shell and fits just outside the tips of the rotor blades. This shape allows for a larger annular opening between the rotor and the stator at the suction end than at the discharge end. Blades that are similar to the rotor blades are placed in rows inside the stator. They may be pictured as fitting between the rows of blades on the rotor.

Figure 2-28. T1A or 0000-Size Converter

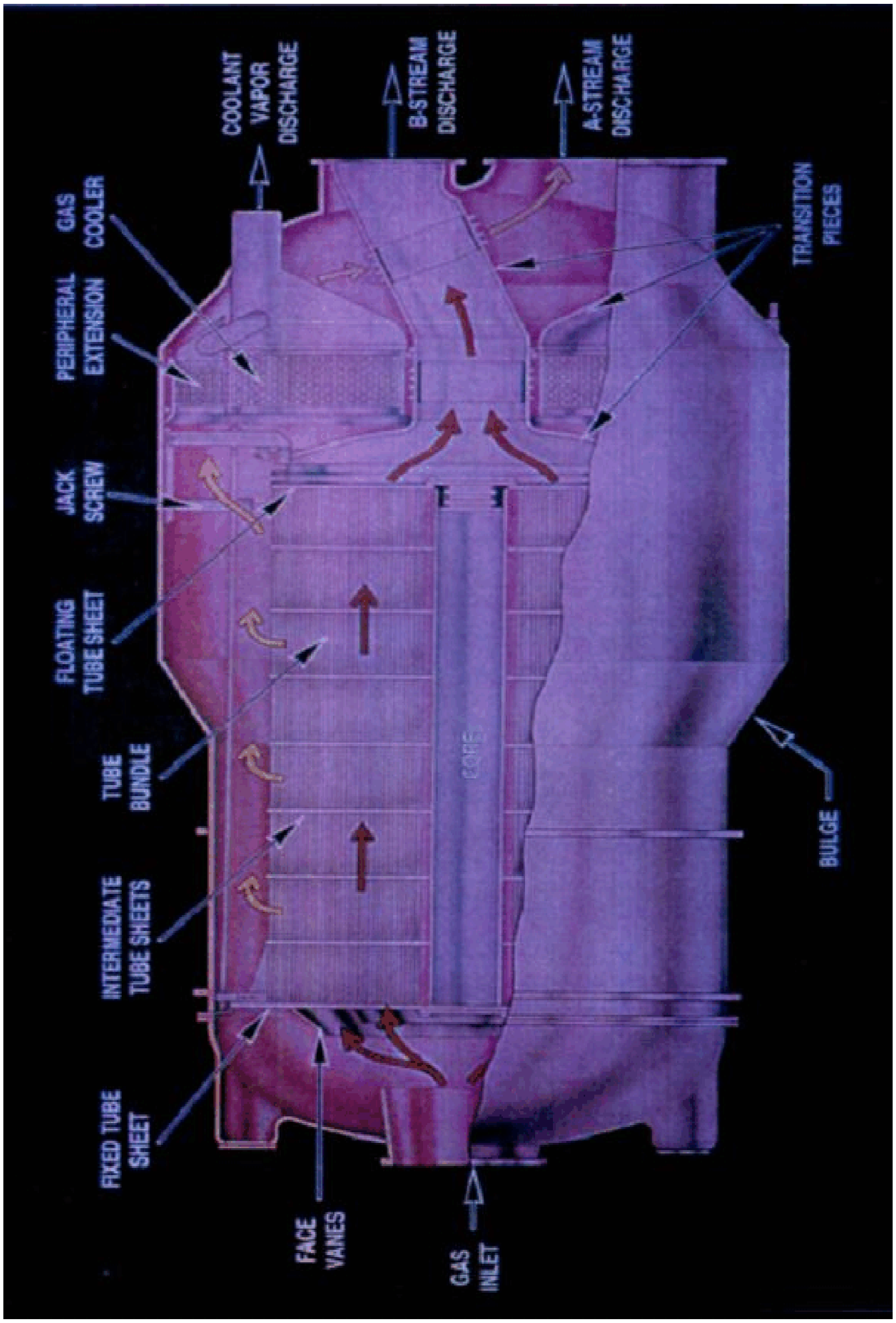


Figure 2-29. Improved Stage Arrangement

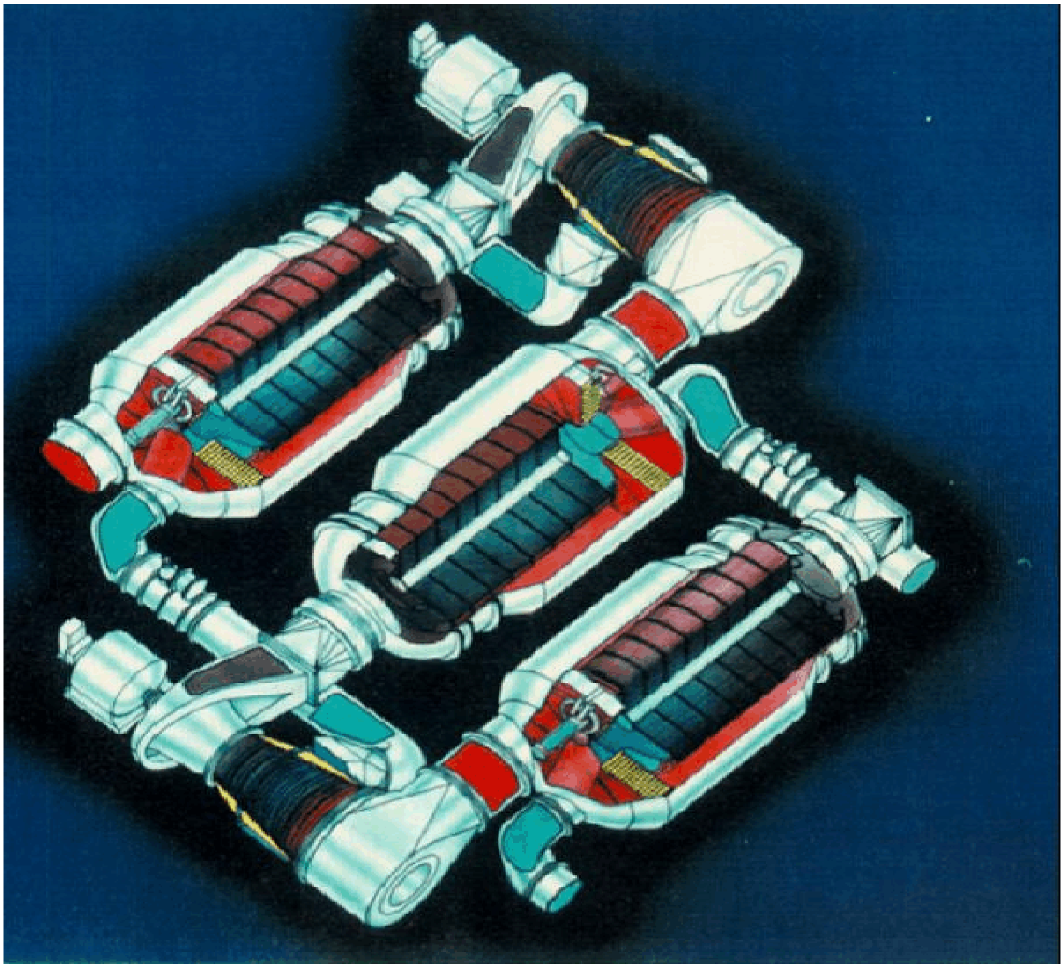


Figure 2-30. Axial Flow Gas Compressor

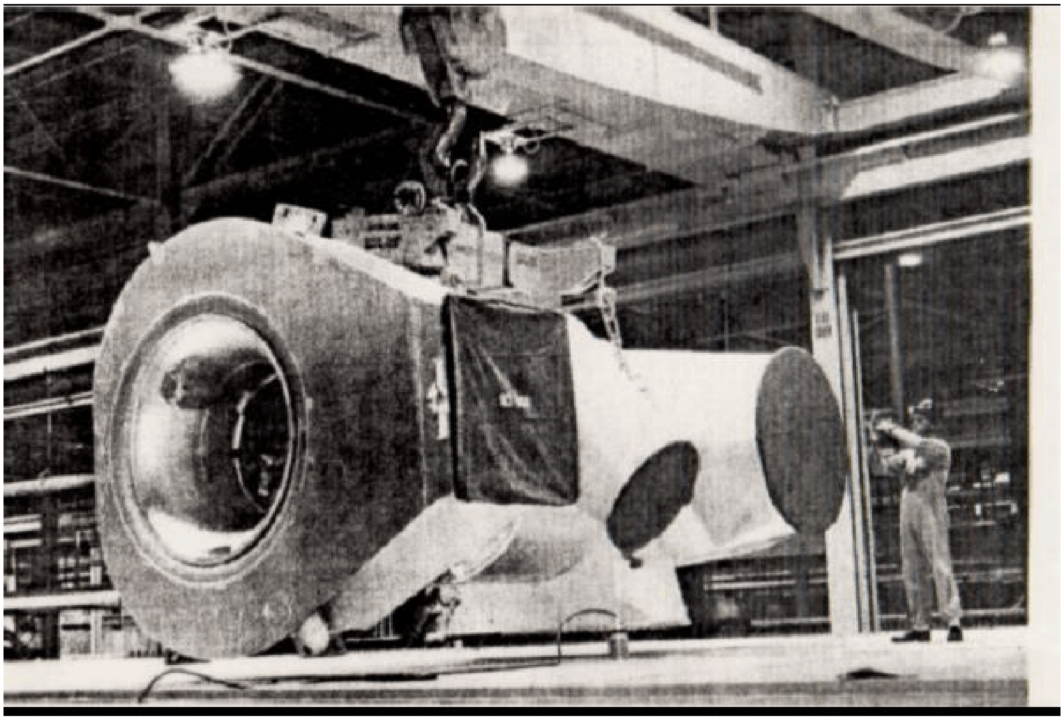
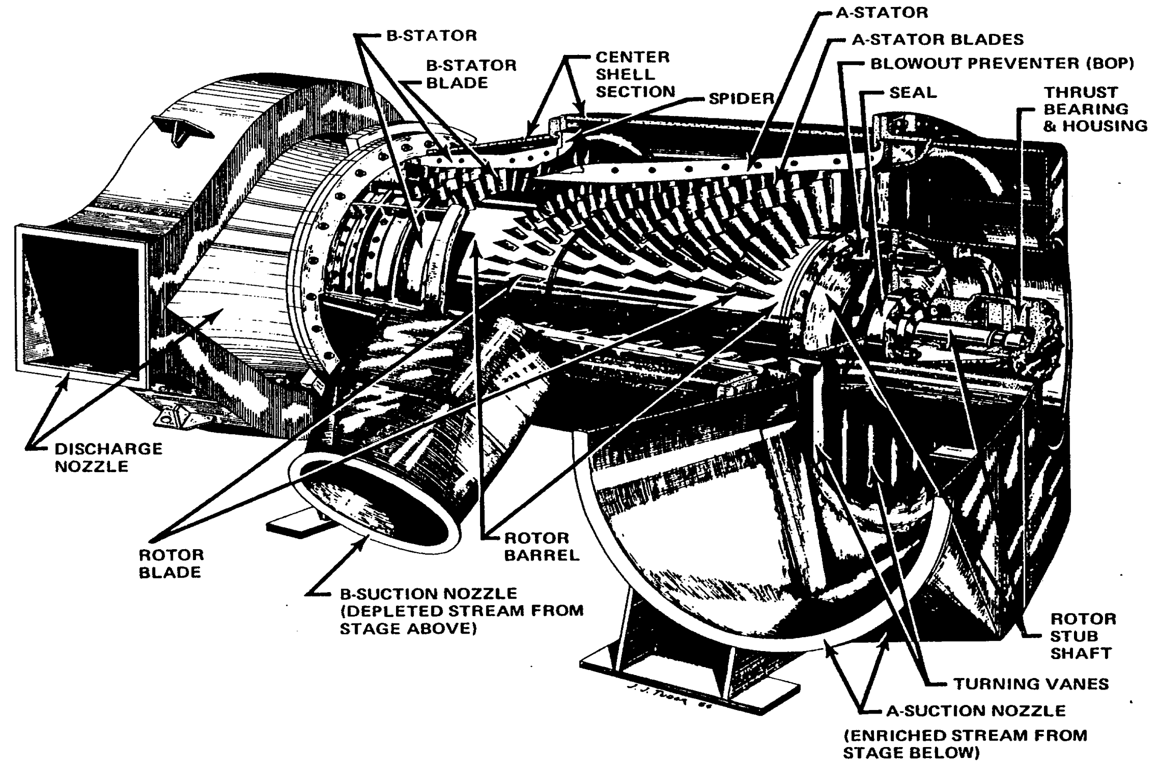


Figure 2-31. 000-PEM/CUP Axial Flow Compressor



Ther

e is a small amount of clearance between the parts of the rotor and the parts of the stator, allowing the rotor to turn freely. As the rotor turns, the gas to be compressed is drawn in at the suction end. Each row of blades progressively builds up the gas pressure, as the gas flows from the large or suction end to the small or discharge end of the compressor. The stator blades act as straighteners and direct the gas at the desired angle into the next row of rotor blades. If there were no stator blades in the compressor, the gas would merely rotate with the rotor.

As previously mentioned the axial flow compressor has two suction inlets, and, thus, two compression stages. All of the gas from both the A and B suction inlets is compressed in the narrower section of the compressor and discharges at the discharge outlet.

The axial flow compressor is called “axial” because the gas flow is parallel to the axis of the rotor. In other words, it has an axial flow of gas.

Centrifugal Compressor

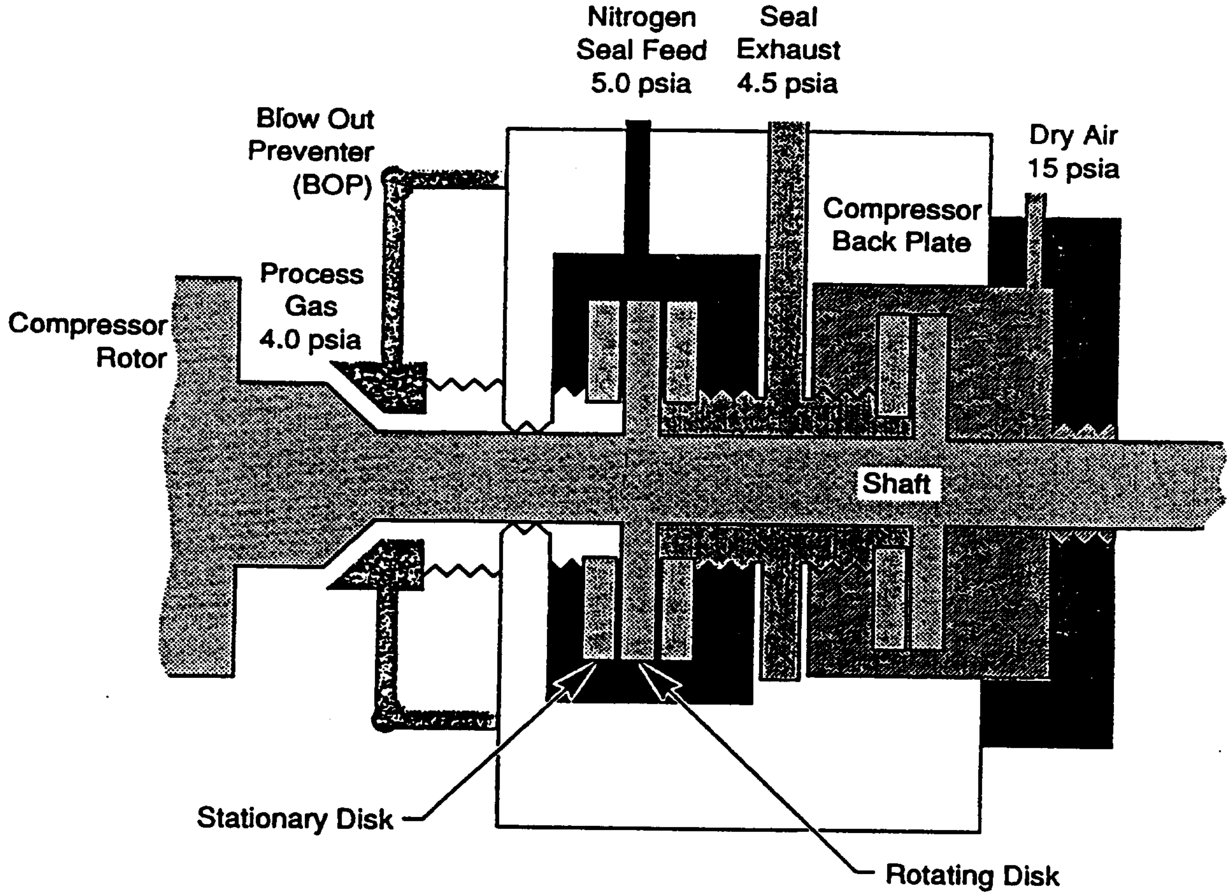
The centrifugal compressor consists mainly of rotating impellers with attached vanes, and a casing. The operational principle of the centrifugal compressor is very similar to that of an ordinary fan blower. Gas admitted to the compressor enters the center of the impeller and is forced centrifugally outward into the discharge passage of the casing. In a manner similar to the axial flow compressor, many of the centrifugal compressors in the plant are actually composed of two stages on the same shaft. These are called two-stage centrifugal compressors. The gas that is discharged from the first section of this type of compressor enters the inlet of the second section or stage, where it is further compressed. In some cases, the B stream of the process gas joins the A stream at the inlet to the second section or stage.

Seals

It is necessary to seal the shafts of both axial and centrifugal compressors where they enter the compressor casings. This prevents the release of UF_6 gas when the process gas pressure is higher and inleakage of air and moisture when the process gas pressure is lower than atmosphere. Ordinary types of packing devices are not satisfactory for this purpose. A special viscous gas seal is used. See Figure 2-32, “Suction End Seal.”

There are three zones of the seal: the process gland, the intermediate gland, and the atmospheric gland. A gland is made up of a stationary flat disc and a rotating flat disc with smooth surfaces and a very small gap maintained by gas pressure. The process gland is the first barrier to the escape of UF_6 from the cascade from around the compressor shaft. This gland seal is maintained by a back pressure of nitrogen seal feed gas applied to the gland gap. If UF_6 does escape the process gland, it travels to the intermediate gland where the seal exhaust system is connected to remove any UF_6 and nitrogen that passes through the intermediate gland seal prior to coming in contact with the atmospheric gland. The atmospheric gland seal is maintained by a back pressure of dry air applied to the gland gap at a significantly higher pressure than the UF_6 that may have escaped from the intermediate gland.

Figure 2-32. Suction End Seal



Motors

Each compressor is powered by a large electric motor connected directly to the shaft of the compressor. All compressor drive motors are three-phase AC induction motors. This type of motor has been selected because of its low original cost, simplicity, reliability, and efficiency. All of the larger motors are equipped with electromagnetic brakes. These brakes are held in the released position while electric power is supplied to the motors. They are applied automatically to quickly stop the motor and compressor rotors after the power is shut off. A large part of the great quantities of power required by the plant is used to operate these motors. The motor and its associated connections are always located outside the cell enclosure. See Figure 2-33, “3300 HP Motor Showing Shaft-Coupling Guard.”

Piping, Flanges, and Valves

Process piping, with its associated flanges, valves, and expansion joints, is the massive transportation system that moves the UF_6 from compressor to converter, cell to cell, and building to building. Process piping varies in size from 3 inches to 54 inches in diameter. UF_6 piping is nickel-plated internally to reduce corrosion. In addition, piping is also used for support and utility systems. Figure 2-34 gives the approximate miles of piping at the Portsmouth GDP.

Process piping is heated either by routing the piping through heated enclosures or by steam tracing and insulation where heated housings are not practical to maintain the UF_6 in a gaseous state.

Connecting pipe headers called interbuilding tie lines are used to move UF_6 between buildings. These lines vary in length from a few hundred feet to several thousand feet and are evaluated to clear obstacles such as roadways. Housings that enclose the tie lines are steam-heated to prevent UF_6 freeze out.

Cell block valves and bypass valves are normally fully opened or closed and are only operated when equipment is taken off-stream or placed on-stream. Block valves are also occasionally used to control flow by pinching, or partially closing, the valve. Expansion joints are provided at appropriate locations to allow for thermal expansion and small misalignment of process piping.

Figure 2-33. 3300 HP Motor Showing Shaft-Coupling Guard

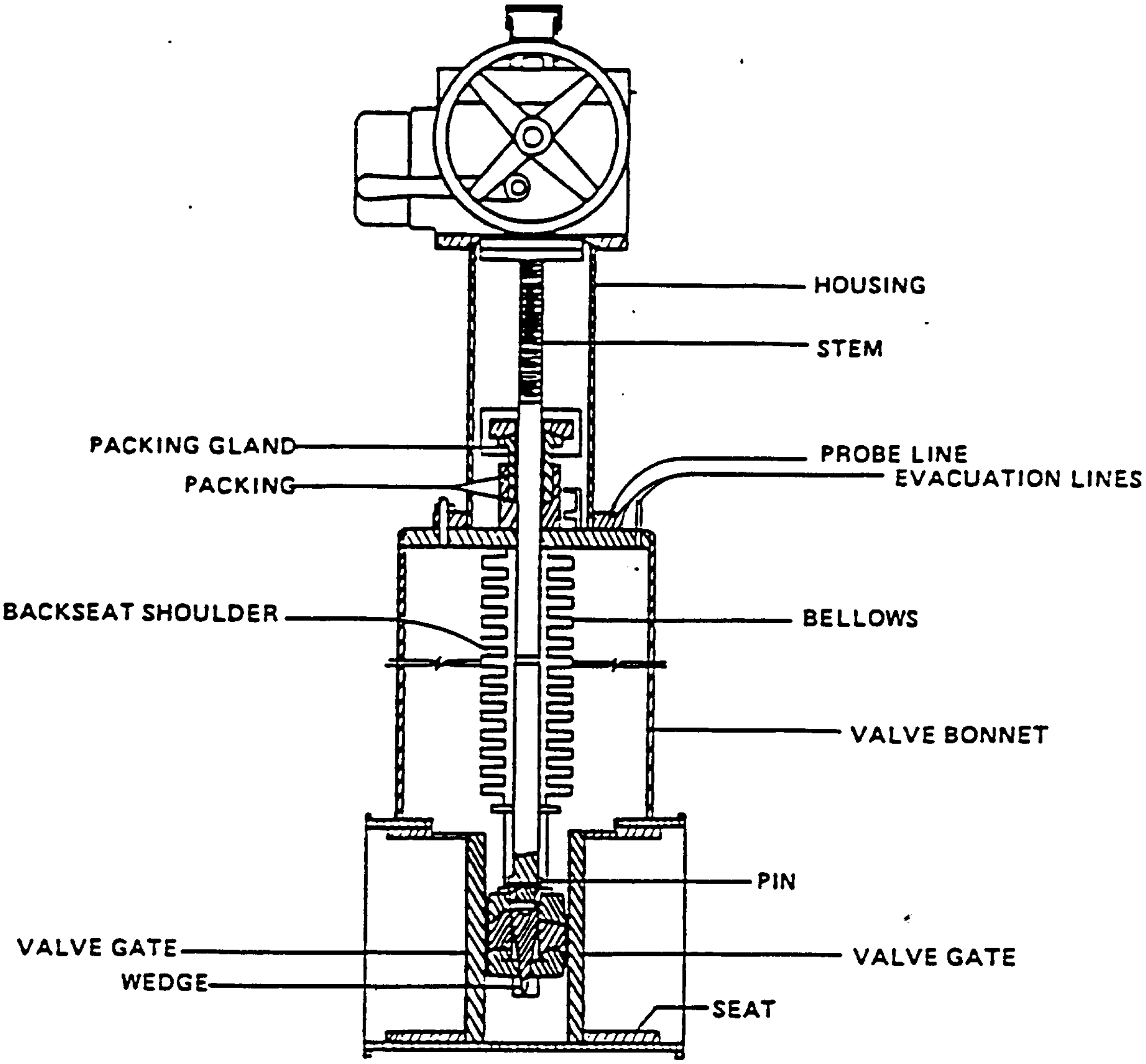
Figure 2-34. Miles of Piping in the Portsmouth Cascade

▸	COOLANT	43
▸	LUBRICATING OIL	69
▸	DRY AIR	47
▸	NITROGEN	62
▸	SEAL EXHAUST	38
▸	RECIRCULATING COOLING WATER	16
▸	PROCESS GAS (UF_6)	40
	TOTAL MILES	315

Cell Block Valves

As stated before, the function of the block valves in the system is to isolate cells or other major UF_6 containing process equipment, allowing the equipment to be taken out of service for repairs. The primary cell block valves in the system are large dual disk gate valves equipped with motor operators that allow the associated valves on a cell to be operated rapidly and in unison from a single push button when placing a cell on-stream or off-stream. Motor operated valve (MOV) closure time is dependent upon valve size. Large (> 30 inches) MOVs have a travel time of approximately three minutes, while smaller MOVs typically travel within two and one-half minutes. Figure 2-35, “Crane G-17 Process Block Valve,” shows the components of a block valve.

Figure 2-35. Crane G-17 Process Block Valve



Stage Control Valve

A stage control valve automatically controls the process gas pressure in the converter. It operates as a throttling or back pressure valve. By its physical shape, as shown in Figure 2-36, “Stage Control Valve,” cannot operate as an isolation valve. When the control valve closes, the pressure of the process gas is increased. When it opens, the process gas pressure is decreased. The stage control valve can provide a maximum 3% to 10% change in process gas pressure depending upon its location in the cascade. Each stage control valve is controlled by an individual pressure indicator controller (PIC) on the local control panel. They can be operated in automatic or manual mode but are normally placed on automatic to maintain the proper pressure for cell gradient purposes. Stage control valve closure time can range from 15 seconds to 25 seconds depending on the differences in the controllers in the buildings.

Control Instrument System

The primary methods of system control are configuration and pressure. The configuration is set by placing cells on and off stream accounting for significant changes in the cascade performance and significant emergency response efforts. More routine controls and emergency response are handled by controlling pressures at all locations in the cascade. The control means, stage control valves discussed above, are controlled by the stage pressure control system. The controls for the system are equipped with audible and visible alarms that will warn the operator when an undesirable or dangerous condition exists in the system. The stage pressure control system senses the B stream pressure from the B outlet of the converter in order to properly position the stage control valve to maintain the desired pressure in the B stream return to the previous stage compressor. The B outlet pressure from the converter is processed and compared to a set Pressure Level Index (PLI) which is calculated and inputted based on cascade configuration and overall through-put needs of the cascade. The resultant comparison signal is sent to the stage control valve as a positioning signal to maintain the desired B-stream pressure of that stage. This pressure control is accomplished individually for every stage in the cascade. Figure 2-37, “Stage Pressure Control,” is representative of a typical stage pressure control system.

Figure 2-36. Stage Control Valve

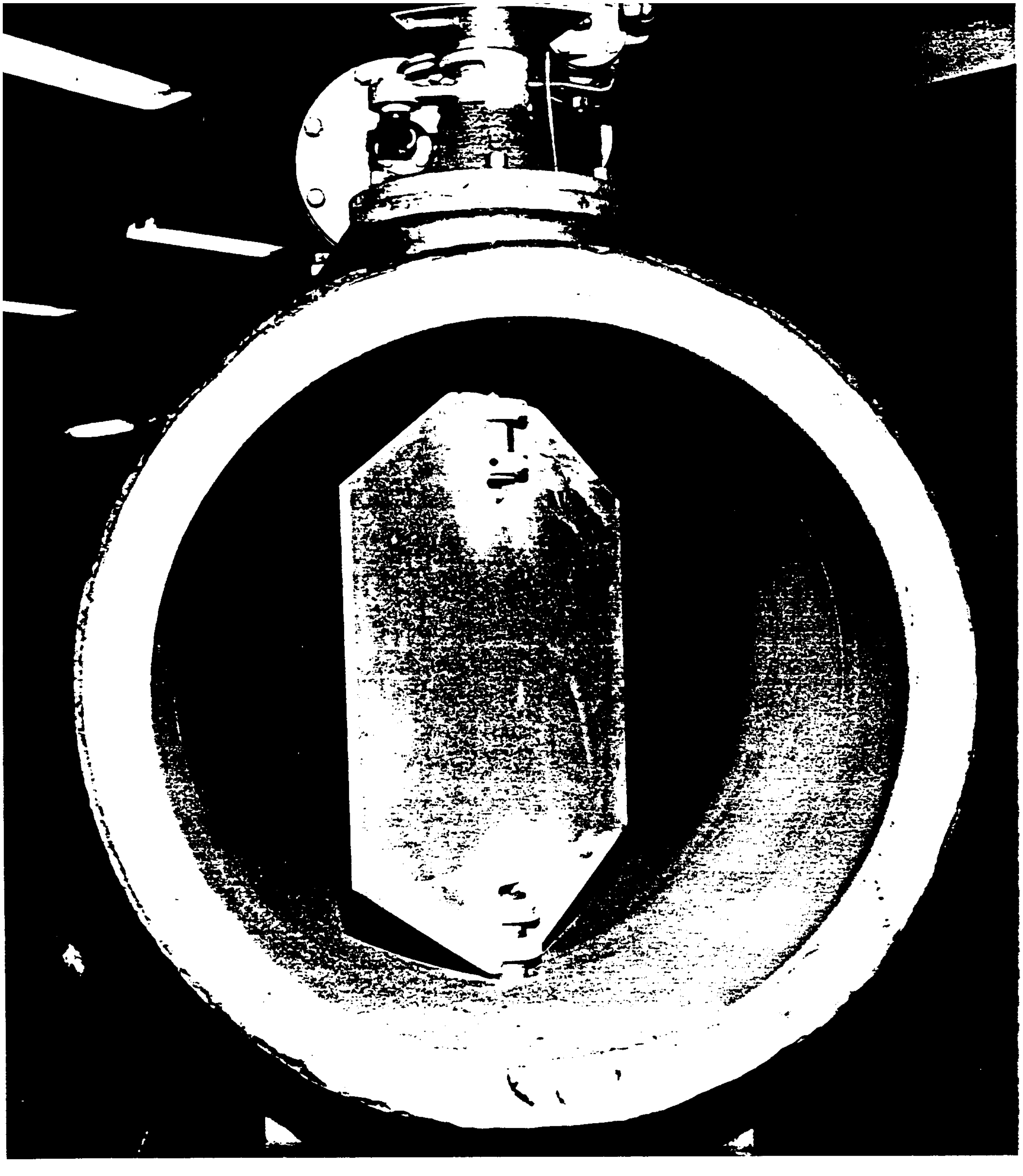
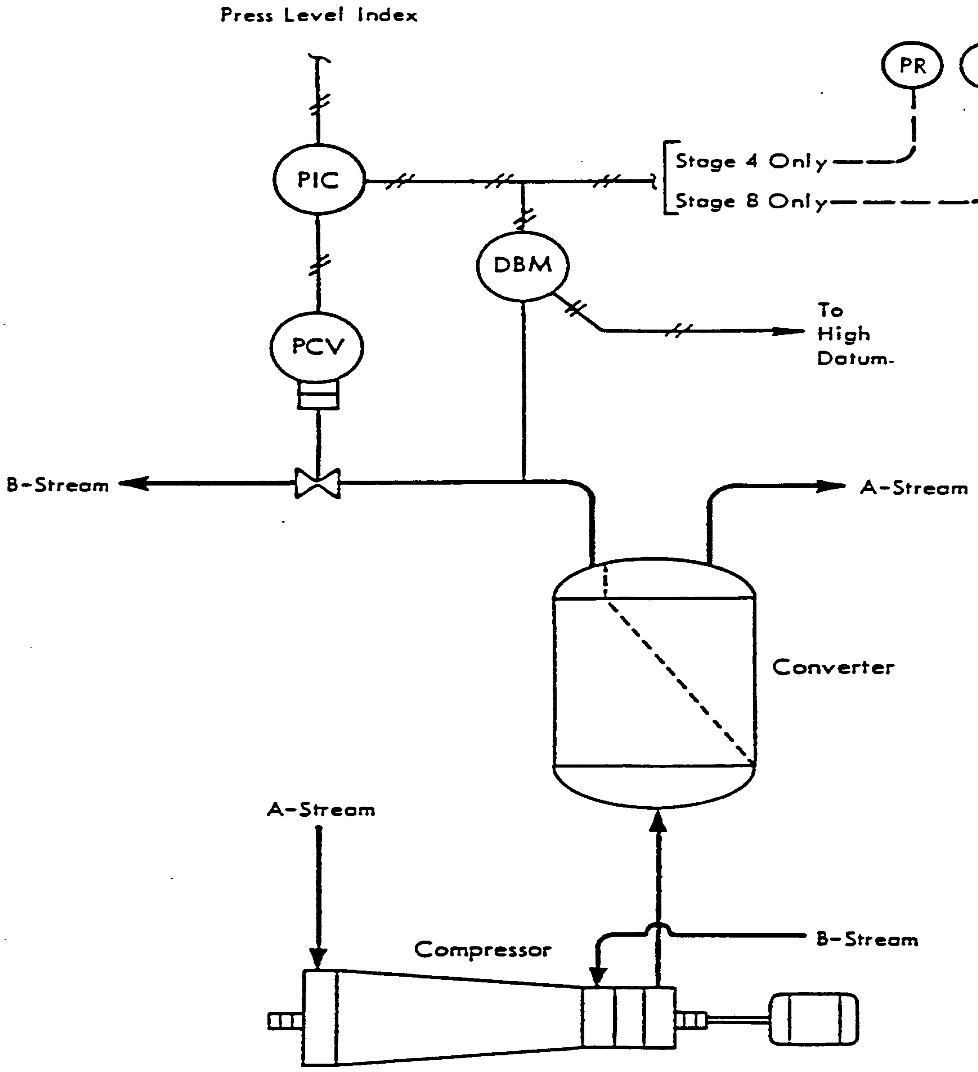


Figure 2-37. Stage Pressure Control



Self-Check Questions 2-3 ✓

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

1. A schematic representation of an efficient cascade is usually drawn with a diamond shape. What does this shape illustrate?

2. What determines the required length of the cascade (number of stages)?

3. What is a cell?

4. What constitutes a unit and how does it constitute a cascade?

5. A cascade is operated under several large divisions called what?

6. What are the "A" and "B" streams?

7. Provide a brief description of the following valves.

   AB1 and AB2.

   BB1 and BB2.

   ABP and BBP

8. If given stages 1 through 8, how does the A stream and B stream flow?

9. What are area control rooms (ACR)?

10. What are local control centers (LCC)?

11. What are the components of a stage?

12. What are converters, compressors, and connecting process gas piping enclosed in to keep the temperature high enough so that no process gas will condense or desublime (freeze)?

13. What piece of equipment must be provided for moving the process gas through the converter and to maintain required pressure differential across the barrier in the converter?

14. What makes up an axial flow compressor?

15. What do stator blades do in the compressor?

16. What are three zones of a seal and what purpose do they serve?

17. What is the purpose of connecting pipe headers?

18. If a stage control valve is opened more due to a need to slightly lower the pressure on the B stream outlet from a converter, what happens to the pressure at the B stream inlet of the compressor of the previous stage?

19. What happens to the A stream inlet of that same compressor?

20. What happens to the output of the compressor?

Coolant System (FREON)

The purpose of the cell coolant system is to remove unwanted heat from the cell using a cooling coil that is internal to the converter A stream outlet chamber. This cooling is important to the proper operation of the barrier material and the compressor. Maintaining the proper temperature increases the performance of the barrier and the lifetime of the compressor.

The coolant medium is a refrigerant, FREON R-114. The coolant system is designed to operate by natural circulation with the cooling coil in the converter vaporizing the heavier liquid coolant. The vapor has a lower density, and, therefore, rises. The coolant vapor collects in a condenser at an elevation high above the converter. The condenser is cooled by water, thus condensing the vapor into a heavier liquid form of the coolant. This cooled, liquid coolant flows back to the cooling coil in the converter helping to push the vapor out. Figure 2-38, "Cell FREON System," illustrates a typical FREON system.

The choice of FREON R-114 was originally based upon its high thermal conductivity, high thermal capacity, and good phase change characteristics over a wide range of temperatures and pressures. See Figure 2-39, "Vapor Pressure of FREON-114 30°F - 180°F."

Coolant and Barrier Gas Hazards

Small quantities of dichlorotetrafluoroethane (R-114) coolant are always present in the process stream, and larger quantities may be introduced at any time if a leak of R-114 should develop in the process gas coolers. Also, limited quantities of fluorine and chlorine trifluoride are used as cell treatment gases in the cascade. Mixtures of F_2, ClF_3, and R-114 are explosive in certain concentrations if an ignition source is available, such as friction heat created by rubbing equipment from some compressor failures. The areas of most concern are in the purge cascade or in off-stream cells where an explosion may release UF_6. Explosions can be produced when ClF_3 comes in contact with materials containing carbon and hydrogen, such as hydrocarbon oil or grease.

Freezer–Sublimer System

The freezer–sublimer system is designed to provide for nuclear criticality safe storage of UF_6 in key locations in the cascade process. In cascade units with large equipment and high through-put, there is a periodic need to "hold up" some UF_6 to reduce the workload on equipment further up the A stream. For example, when there is a need to reduce power consumption in the cascade, UF_6 can be diverted to a freezer–sublimer instead of pushing it up the A stream which consumes power. When the reduced power need has passed, then the UF_6 can be removed from the freezer–sublimer and placed back in the A stream.

Figure 2-38. Cell FREON System

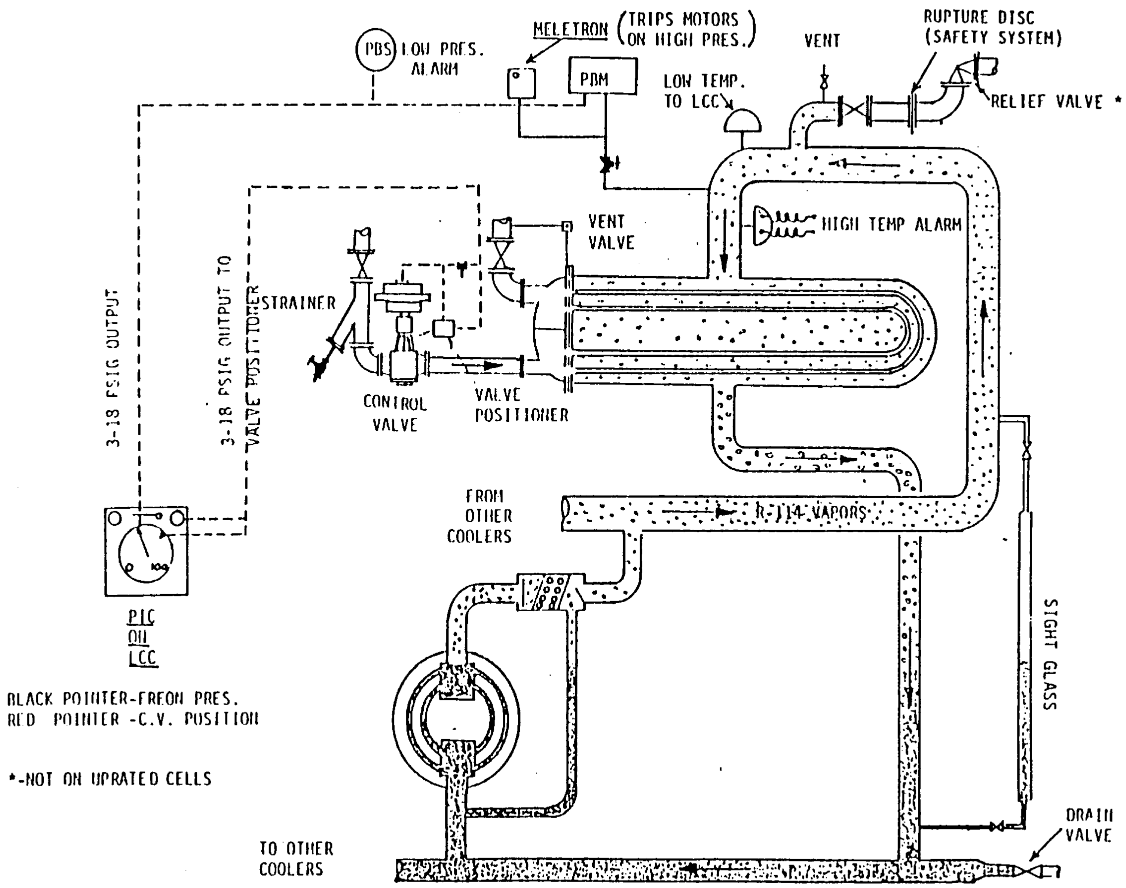
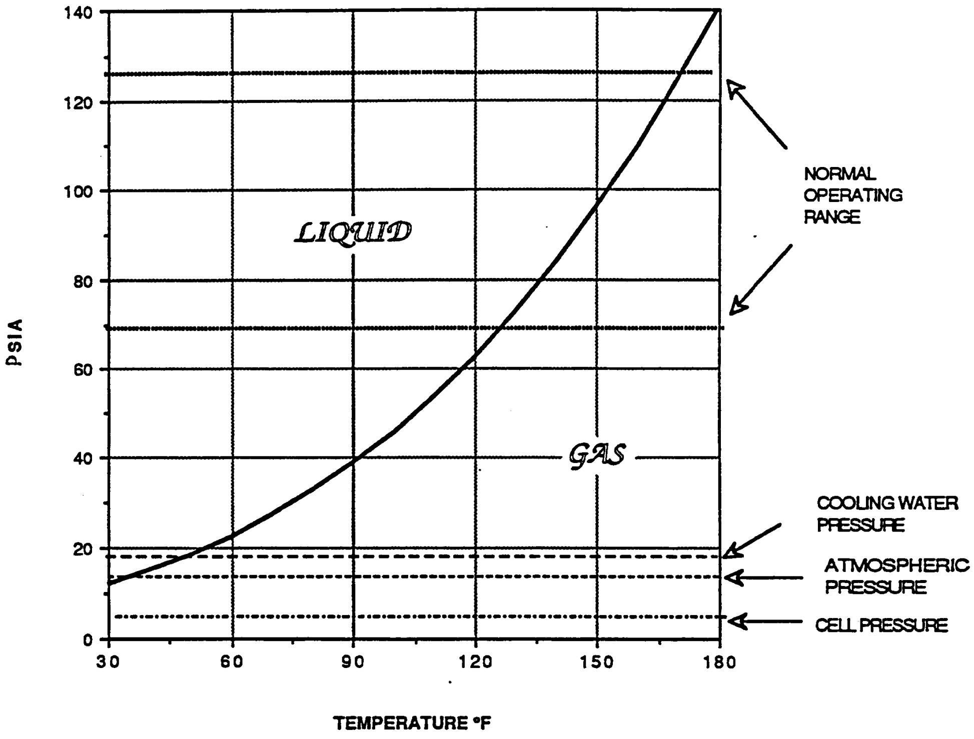


Figure 2-39. Vapor Pressure of FREON-114 30°F - 180°F



The freezer–sublimer is designed to take the UF_6 from the B stream and "freeze" it to the solid phase until such time it is needed for return to the A stream. To return the UF_6 to the A stream, it is sublimed to the gas phase and moved into the A stream. The freezer–sublimer has a weight indicating and limiting system (loadcells) to ensure that safe mass and configuration concerns for nuclear criticality safety are always met.

Unit Lube Oil System

Lubricating oil is used in the cascade to lubricate compressor bearings, compressor motor bearings, and provide a source for hydraulic operating oil for the stage control valves. There is a lube oil system for each unit in the cascade that supplies all the stages in the cells in that unit. The oil system operates as a gravity supply system with the pressure in the supply header being provided by a supply tank located high above the elevation of the compressors and motors. The oil that passes through the compressors and motors returns via a return header to a drain tank. Oil in the drain tank is pumped up to the supply tank by oil transfer pumps operating in automatic. See Figure 2-40, "Typical GDP Lube Oil System."

Lubrication Oil System Hazards

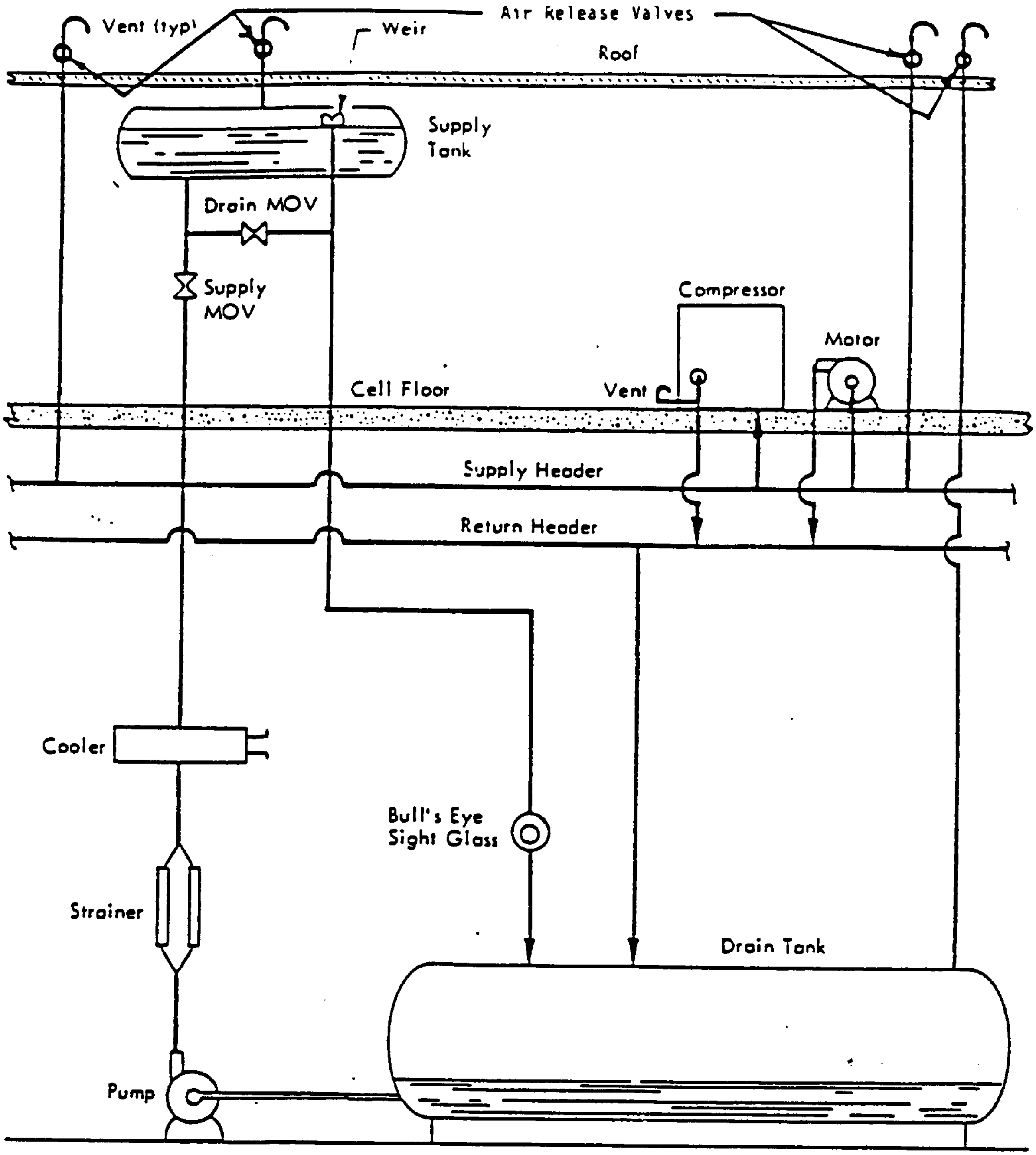
The enrichment facilities at Paducah and Portsmouth have extensive lubrication oil systems. The oil in these systems constitutes a serious and unavoidable fire and explosion hazard. Explosions could occur as a result of over pressure of isolated equipment, the ignition of explosive gas mixtures, or exothermic reactions.

A lube oil fire occurred at the Paducah Gaseous Diffusion Plant in 1956. A major fire was discovered in the C-310 Purge and Product Building. The investigation indicated that the fire originated at a withdrawal compressor position. The compressor was operating at beyond-atmospheric pressure when the shaft seal failed. The seal failure resulted in the escape of process gas and a small quantity of F_2, which reacted vigorously with lube oil on the compressor surface. The resulting fire burned with an intense heat, which caused the lube oil supply line to the compressor bearing to rupture. The intense heat, together with the additional supply of fuel from the ruptured oil line, caused the fire to grow very rapidly to a size sufficient to ignite the roof.

In December 1998, a fire occurred at the Portsmouth Gaseous Diffusion Plant. The fire occurred in a gaseous purge system cell which is used to remove extraneous gases from the processing system. The fire was likely caused by a mechanical failure in a compressor which led to overheating through friction. Friction, resulting from rubbing of compressor parts, is believed to have generated enough heat to reach the melting point of aluminum. The molten aluminum then chemically reacted with the UF_6 process gas generating additional heat. As the cell continued to operate onstream, additional UF_6 was available to feed the reaction and spread it to other stages. At least one gas cooler eventually ruptured releasing R-114 coolant into the cell. The release and expansion of the coolant into the cell increased the cell pressure and generated additional heat as aluminum chemically reacted with the coolant. The high temperatures and potentially elevated pressure led to the destruction of the converter tube bundles and breach of the cell boundary.

The possibility of fires occurring in the compression and/or liquefaction withdrawal system is high because of the presence of lube oil against a possible ignition source (hot compressor bearing). However, new safety systems have been designed since the Paducah fire, which should prevent such incidents. Fires should be prevented in the future by compressor shutdown systems if high bearing temperatures are detected.

Figure 2-40. Typical GDP Lube Oil System



Furthermore, if the lube oil supply is disrupted due to a fire, compressor vibration accelerometers would be triggered by the resultant compressor vibration and the compressor would be shut down, avoiding a release of UF_6.

Ventilation System

The heat load generated by the gaseous diffusion process is enormous. The GDPs consume vast amounts of electricity. For example, the Portsmouth GDP operated at 1900 MW, and the Paducah GDP can operate at up to 3000 MW with much of this energy resulting in heat generation from the compression of UF_6 in the cascade process. Although the process is completely inside cell housings, these housings are not insulated. Thus, the roughly 290°F cascade temperatures heat the building beyond what could be handled through ambient heat loss. The ventilation system is provided to rapidly change the air in the building on a continuous basis as a form of heat removal. The system draws in outside air with supply fans on the first floor (operating floor). These supply fans discharge to the second floor (cell floor). Figure 2-41 shows a typical process building ventilation system.

Building exhaust fans take a suction on the cell floor at each stage compressor motor and exhaust the hot air to the outside atmosphere through an exhaust duct up the side of the building. See Figure 2-42.

Figure 2-41. Typical Process Building Ventilation System

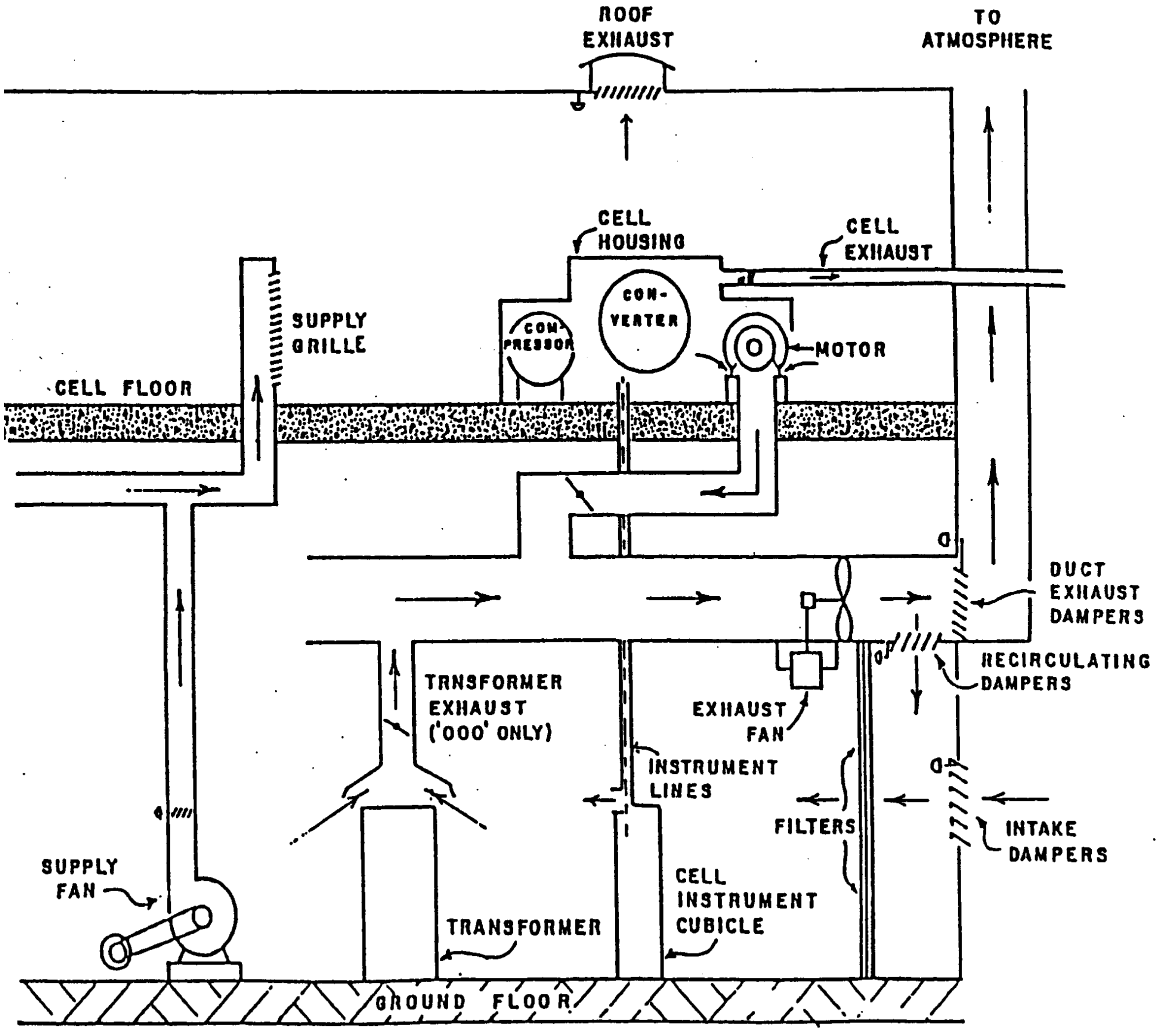
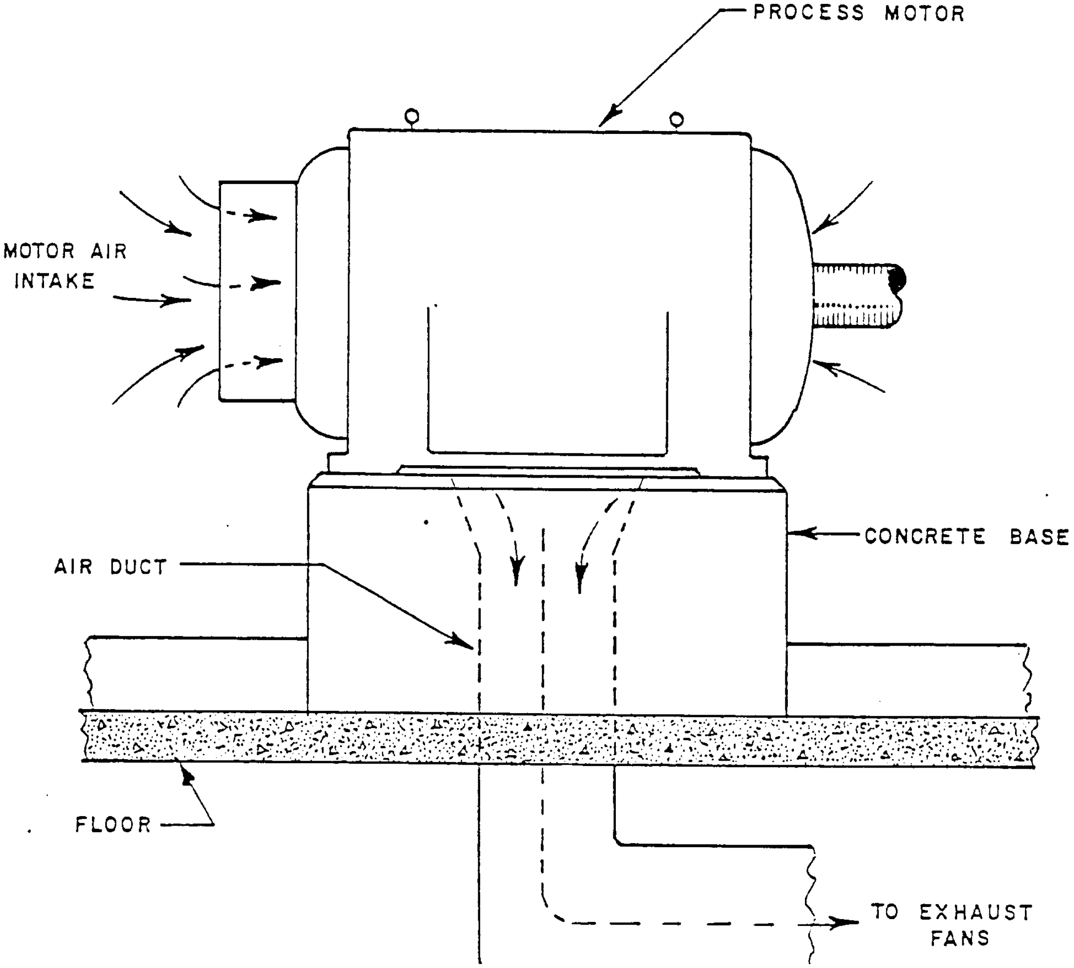


Figure 2-42. Process Motor Air Flow



Self-Check Questions 2-4

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

1. What is the purpose of the cell coolant system and why is it important?

2. Why was FREON R-114 the original choice for a coolant medium?

3. How could mixtures of F_2, ClF_3, and R-114 be considered hazardous?

4. Where are the areas of most concern where an explosion may release UF_6?

5. What is the purpose of the freezer–sublimer system and give an example of when it could be used?

6. Why is lubricating oil used in the cascade?

7. What hazards are associated with lubrication oil systems?

8. What is the purpose of a ventilation system in a gaseous diffusion facility?

STEP 4 - TAILS CONDENSATION AND WITHDRAWAL

All enrichment processes produce two uranium streams: an enriched stream with > 0.711% U-235 and a stream of depleted uranium (DU) with < 0.711% U-235. DU is a “byproduct” of enrichment. In the gaseous diffusion and centrifuge processes, the depleted stream is in the form of depleted uranium hexafluoride (DUF_6 or UF_6 tails).

The UF_6 tails, which are depleted in U-235, are continuously withdrawn from the diffusion cascade through heated piping to the tails withdrawal facility. The UF_6 gas is compressed and condensed as liquid UF_6 and drained as a hot liquid at above atmospheric pressure into 10- or 14-ton tails storage cylinders. Usually, thinner-walled 48G cylinders are used for DU. The filled tails cylinders are weighed and moved outside the building where they are permitted to cool at ambient conditions until their contents are solidified, taking at least five days. The cooling process leaves the cylinders at a substantial vacuum (typically < 5 psia). These cylinders are then transported to long-term storage yards.

The typical assay of the tails material is between 0.2% and 0.4%. The actual tails assay that is chosen is a programmed value based upon the economics of the optimum match of cascade configuration, cost of normal feed (0.711% assay), cost of power, operating pressures, and enriched product market price.

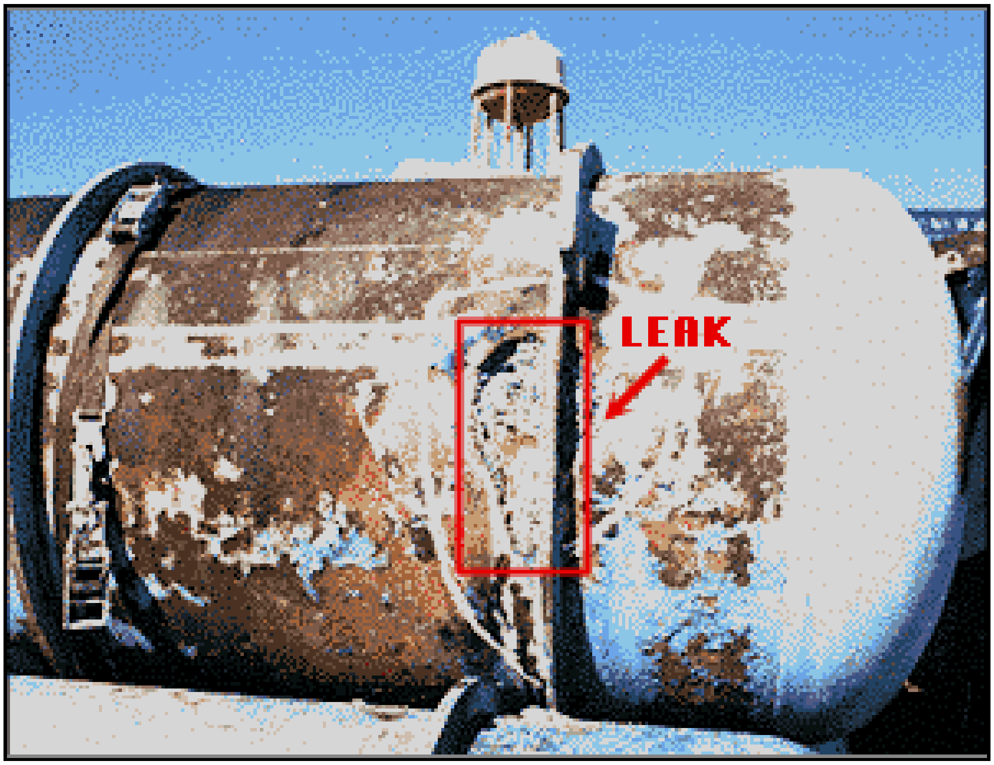
DU is considered a source material under NRC regulations. At the present time, there is only limited reuse of DU, and, consequently, most DU is probably a waste and would be treated with disposal in mind. If DU is considered a waste, the NRC would categorize it as LLW, and it may require a special disposal site. NRC licensees must address DU tails disposition with specific plans for actions, including setting aside funds.

Module 7 provides more information on DU management and disposition.

STEP 5 - TAILS STORAGE

Tails material is typically stored in 14-ton cylinders, stacked two-high on large concrete pads, called storage yards. Cylinder integrity is periodically inspected for signs of visual damage. The DOE experience with tails cylinder storage shows that cylinder integrity is maintained for decades at a vacuum. This experience also shows that the cylinders rust from general corrosion of the outside surface. See Figure 2-43, “DU Cylinder Breach.”

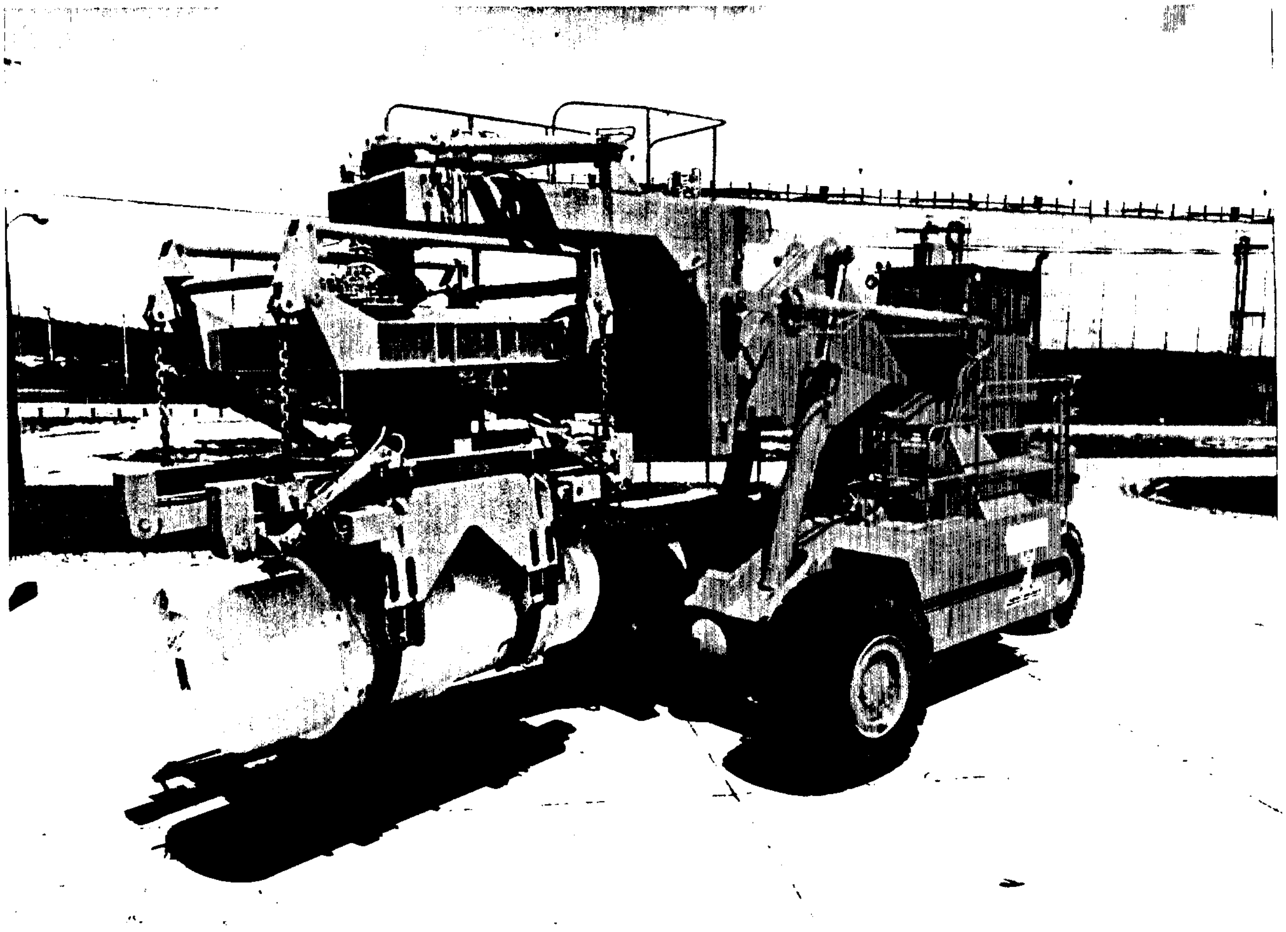
Figure 2-43. DU Cylinder Breach (48G cylinder)



Cylinder Leak

Cylinder movements and stacking are accomplished with large capacity mobile equipment specifically designed to safely handle the large 14-ton and 10-ton cylinders filled with solid UF_6. Mobile equipment is not permitted by the Technical Safety Requirements (TSR) to be used to transport liquid UF_6 cylinders. See Figure 2-44, "Raygo–Wagner Cylinder Handler/Stacker."

Figure 2-44. Raygo–Wagner Cylinder Handler/Stacker



Self-Check Questions 2-5 ✓

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

1. What form(s) of UF_6 make(s) up tail material and what size cylinders are used for tails storage?

2. What is the typical assay of tails material?

3. How is actual tails assay chosen?

4. What size cylinders are typically used for tails storage?

5. How are cylinder movements and stacking accomplished?

6. Is mobile equipment used to transport liquid UF_6 cylinders?

STEP 6 - PRODUCT CONDENSATION AND WITHDRAWAL

At Paducah, UF_6 product in the gaseous state is removed from the enrichment cascade through heated piping to the product withdrawal facilities where it is further compressed to a pressure of approximately 30 psia and cooled for condensation to the liquid phase. The liquid UF_6 is then drained into 10-ton product cylinders (usually designated as 40X). The filled cylinders are transported outside the building on an air-powered scale cart, lifted by a 20-ton bridge crane, and moved to a cool-down area adjacent to the building. After the UF_6 has solidified, gaseous contaminants may be removed by venting through chemical traps. Cylinders containing solidified UF_6 product used as feed by the Portsmouth Plant are transported and shipped. At Portsmouth, 10-ton product cylinders used to fill enriching services contracts are transported for sampling and then their UF_6 contents are transferred to smaller cylinders for shipping. The smaller cylinders contain 2.5 tons of UF_6 and are designated as 30B. All product cylinders containing UF_6 at $\geq$ 1% U-235 are shipped in protective packages called "overpacks." See Figure 2-45, “Centrifugal Compression Product Withdrawal System at Portsmouth.”

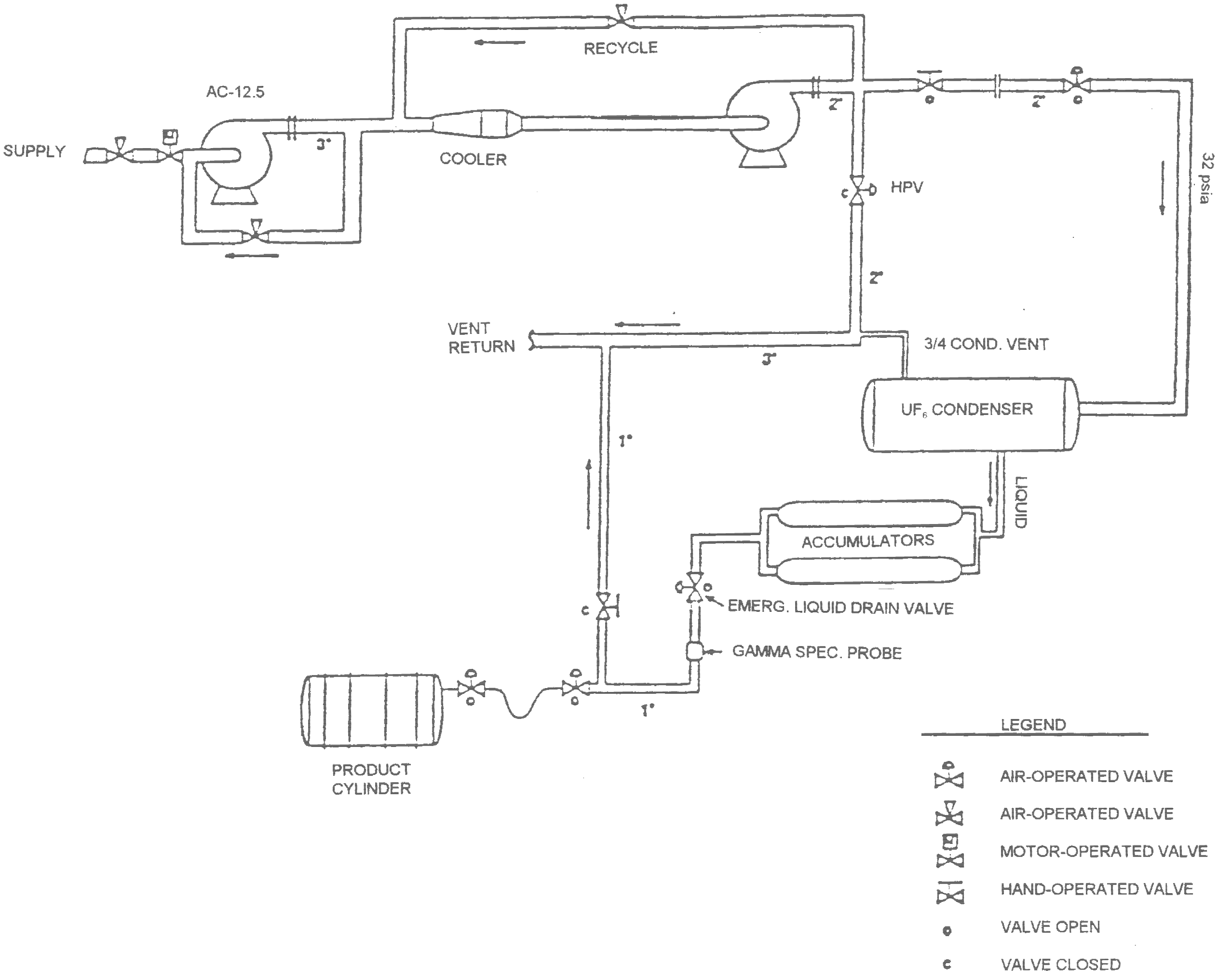
The assay of the contents of all product cylinders can be determined by laboratory analysis of a UF_6 sample collected by an automatic sampler during cylinder filling operations or other approved methods, such as in-line mass spectrometers.

Accumulators are located in the liquid withdrawal line to provide storage of liquid UF_6 during withdrawal interruptions. Each withdrawal loop has its own accumulator, separated from other withdrawal loops by double valves with buffers to prevent mixing of materials of different assays between the withdrawal loops. The size of these accumulators determines the maximum allowable assay that may be withdrawn through that loop.

To ensure compliance with the accumulator assay limitations, administrative controls require frequent, periodic laboratory-analysis verification of continuous mass-spectrometer assay determination and physical lockout of withdrawal header valves.

Laboratory analysis of the new assay material is performed before condensing is started by circulating the new assay for 30 minutes prior to pulling the sample from the withdrawal station sample manifold. When a preliminary sample result is received, condensing is started, but the filling of the cylinder is not started until the assay is confirmed by laboratory analysis. The gamma assay spectrometers cannot be used for this purpose because they are not reliable until flow of liquid UF_6 to the cylinder has started.

Figure 2-45. Centrifugal Compression Product Withdrawal System at Portsmouth



STEP 7 - PRODUCT STORAGE

The 10-ton product (48X) cylinders that are used for the withdrawals from the cascade are not used for delivery of product to enrichment customers. The 10-ton cylinder provides an efficient way to store finished product material until such time as sampling and transfer to 2.5-ton (30B) customer cylinders is necessary.

The 2.5-ton cylinder (30B) is the standard for transporting enriched uranium, nationally and internationally. This means that the contents of a 10-ton cylinder must be transferred to four 2.5-ton customer cylinders. This also provides the opportunity to confirm assay and purity of the product by sampling prior to filling customer cylinders. These actions are completed in the Product Sampling and Transfer Station. The 10-ton cylinder is placed in an autoclave, heated, and liquefied for transfer to the customer cylinders. Figure 2-46, “Portsmouth Product Sampling and Transfer Station.”

Once again, the cylinders containing liquid UF_6 must be cooled for five days to allow sufficient time to ensure that the contents have solidified prior to shipment. Handling cylinders with the potential for liquid UF_6 contents can only be accomplished with qualified overhead cranes and qualified lifting equipment designed with redundant features. Figure 2-47, “Lifting Fixture for Cylinders Filled with Liquid UF_6.”

Those cylinders shipped to be liquid-sampled are placed in containment-type autoclaves and heated to convert the UF_6 from solid to liquid. Liquid samples are withdrawn for analyses to ensure conformance with the enriching services contract. The liquid UF_6 can be transferred to customer-owned cylinders, which are cooled at ambient temperature to convert the contents to a solid at sub-atmospheric pressure and shipped. The empty product cylinders are removed from the autoclave, weighed, and cooled prior to return to the product withdrawal facility for refilling.

Figure 2-46. Portsmouth Product Sampling and Transfer Station

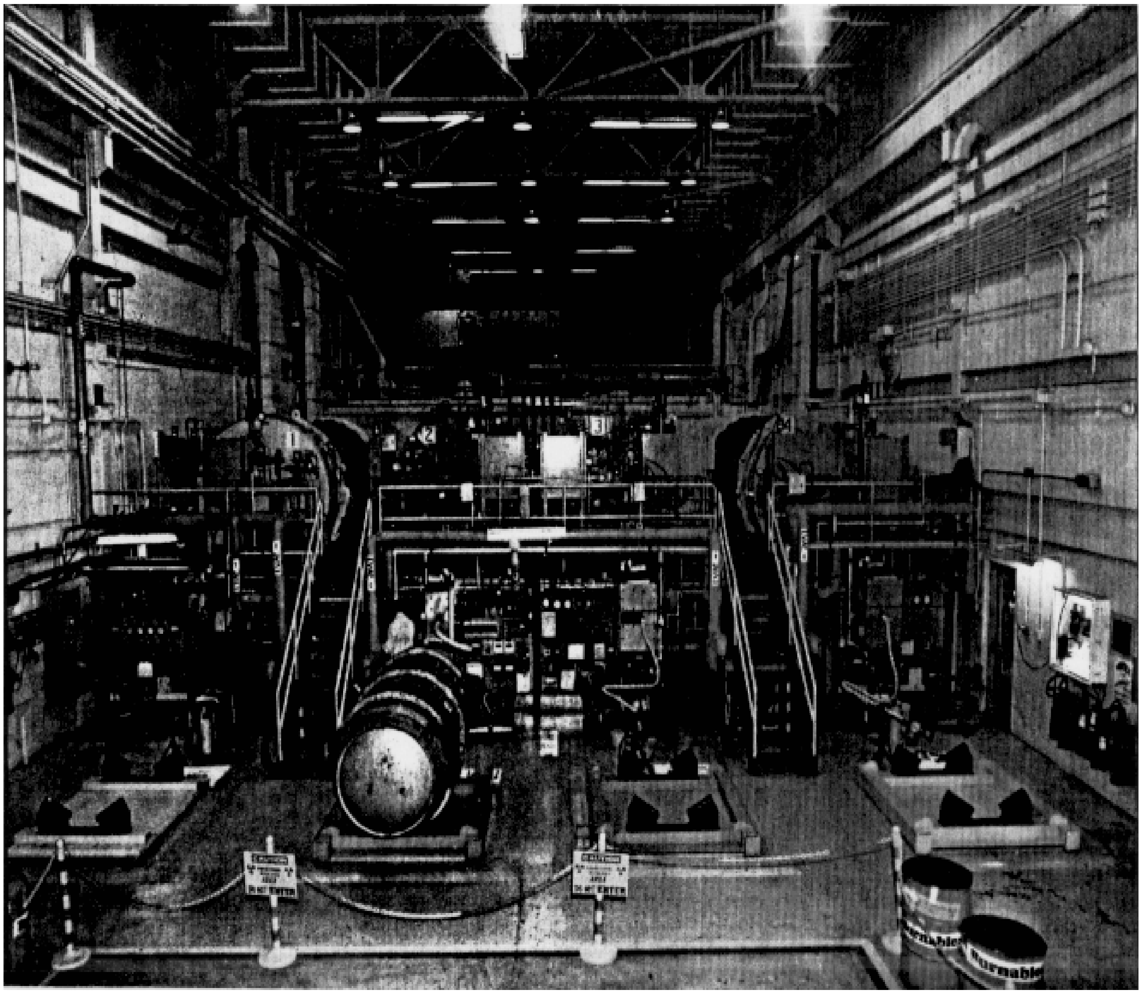
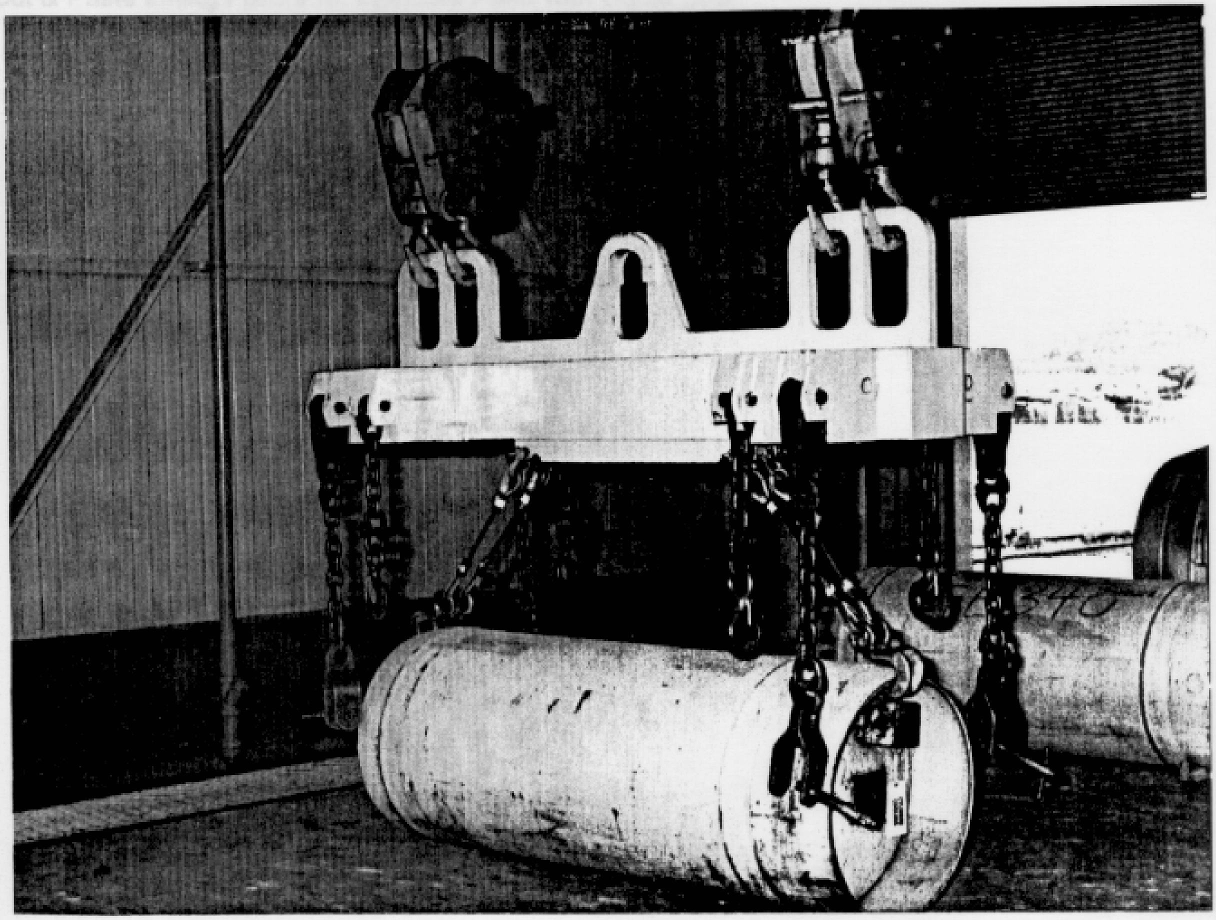


Figure 2-47. Lifting Fixture for Cylinders Filled with Liquid UF_6



XII-8

STEP 8 - PRODUCT SHIPPING

Once the customer cylinder contents have cooled for five days, shipment off-site can take place. Customer cylinders are loaded into special transport housings called “overpacks” on a flatbed tractor-trailer. These overpacks provide additional transport protection for the cylinders as well as an additional barrier to the potential spread of contamination should contamination leach from the metal surfaces of the cylinder.

These special nuclear material shipments are made over approved roadways and by approved methods in accordance with Department of Transportation and NRC regulations. Each shipment includes the documents that fully describe the contents, associated hazards, and instructions in the event of an accident. The shipments of enriched uranium are made to licensed nuclear fuel fabrication facilities.

Self-Check Questions 2-6

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

1. What four sizes of cylinders are mostly used for transferring UF_6 in GDP operations? What are their typical designations and contents?

2. What are two methods that could be used to assay the contents of product cylinders?

3. Why are accumulators located in the liquid withdrawal line?

4. To ensure compliance with accumulator assay limitations, what should administrative controls require?

5. Laboratory analysis of new assay materials is performed before condensing is started by circulating the new assay for _______________ minutes prior to pulling the sample from the withdrawal station sample manifold.

6. What size cylinders are used for product withdrawal from the cascade?

7. What size cylinders are used for transfer of product to customers?

8. What is the purpose of overpacks?

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

NRC Regulation

The NRC oversees operation of two gaseous diffusion plant~~s~~, the Paducah GDP located at Paducah, Kentucky and the Portsmouth GDP located in Piketon, Ohio. The plants are operated by the United States Enrichment Corporation under lease with the U.S. Department of Energy. The Portsmouth GDP was in full operation until June 2001. It is now in “cold standby.” Some sampling and transferring functions continue.

The Energy Policy Act of 1992 established USEC and authorized NRC to regulate the radiological and operational health and safety aspects of the gaseous diffusion plants.

10 CFR Part 76: Certification of Gaseous Diffusion Plants

In accordance with that Act, NRC promulgated regulations for the gaseous diffusion plants in 10 CFR Part 76 in September 1994. NRC certified that the plants met the requirements in Part 76 in late 1996. After certification, the two plants came under NRC regulation on March 3, 1997. Table 2-1, “10 CFR Part 76 - Certification of Gaseous Diffusion Plants,” provides a brief description of each subpart within 10 CFR Part 76.

New provisions for gaseous diffusion are in Subsection B, Part 76.45, and Subsection C, Part 76.68. Recent amendments processed under Part 76.45 include HAUP for the Paducah Plant and Cold Traps for the Portsmouth plant. See Module 6 for more discussions about regulations.

Table 2-1. 10 CFR Part 76 - Certification of Gaseous Diffusion Plants

Subpart	Description
A - General Provisions	Provides the purpose, scope, and general approach to managing the regulatory environment and communication of the gaseous diffusion plants.
B - Application	Sets the certification application procedure and contents as well as setting the annual renewal requirements.
Part 76.45	Permits amendments to certificates, establishing a formal process for proposed new or modified activities. The amendment application should contain sufficient information for the NRC to make findings of compliance or acceptability in same manner as required for original certificate.
C - Certification	Sets the additional regulatory requirements from other Parts, describes the issuance, denial, expiration, and termination of certificates, describes the procedure for plant changes, and post issuance procedures.
Part 76.68	Covers plant changes. Requires safety analysis, SAR update that demonstrates no undue risk to public. The changes may not decrease the effectiveness of the plant's safety, safeguards, and security programs or may not involve a change in certificate of compliance or approved compliance plan.
D - Safety	Describes the use and transfer of radioactive materials, sets the scope of accident assessment, technical safety requirements, criticality accident requirements, emergency planning, quality assurance, and training.
E - Safeguards and Security	Sets the specific requirements for physical security, special nuclear material accountability and control, and protection of certain information.
F - Reports and Inspections	Describes the event reporting and NRC inspection processes.
G - Enforcement	Sets the scope of violations and penalties allowed under law for enforcement of GDP regulations purposes.

Self-Check Questions 2-7 ✓

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:

barrier
blades
block
cell housings
compressors
configuration
centrifugal
converter
corrosion
feed
FREON R-114
freezer–sublimer
headers
heat
motor
oil
parallel
process gland
rotor
seal
size
stage
stage control
stator
subatmospheric
UF_6
ventilation

1. The number of separative work units required to enrich a given amount of uranium is dependent on the enrichment of the final product, the tails assay, and the ____________________ enrichment.

2. The basic______________________ configuration is one converter, one compressor, one stage control valve, and associated piping and indications.

3. A means must be provided for moving the process gas through the converters and maintaining required pressure differential across the barrier in the converter. This is accomplished by means of gas________________, one for each converter in the cascade.

4. The ___________________ material is constructed in tubes, many of which are arranged in a tube bundle and installed in a converter.

5. The gas that enters the ______________ contains an excess amount of heat imparted to it by the compressor.

6. All of the converters, compressors, and connecting process gas piping are enclosed in insulated ____________________ so that they are at all times surrounded by heated air, which helps to keep the temperature high enough so that no process gas will condense or sublimate.

7. The axial flow compressor consists mainly of a rotor, ____________________, blades, and casing.

8. The____________________ is a cylindrical metal drum with a shaft through its axis.

9. The stator is cone-shaped and fits just outside the tips of the rotor__________________.

10. The axial flow compressor is called “axial” because the gas flow is__________________ to the axis of the rotor.

11. The _________________ compressor consists mainly of rotating wheels or impellers with attached vanes, and a casing.

12. It is necessary to_____________________ the shafts of both axial and centrifugal compressors where they enter the compressor casings.

13. The____________________ is the first barrier to the escape of UF_6 from the cascade from around the compressor shaft.

14. The ____________________ and its associated connections are always located outside the cell enclosure.

15. Process piping, with its associated flanges, valves, and expansion joints, is the massive transportation system that moves the ______________________ from compressor to converter, cell to cell, and building to building.

16. UF_6 piping is nickel-plated internally to reduce_______________________.

17. Connecting pipe ______________________ called interbuilding tie lines are used to move UF_6 between buildings.

18. The function of the____________________ valves in the system is to isolate cells or other major UF_6 containing process equipment, allowing the equipment to be taken out of service for repairs.

19. Motor operated valve (MOV) closure time is dependent upon valve_________________.

20. A ___________________ valve automatically controls the process gas pressure in the converter. It operates as a throttling or back pressure valve.

21. The primary methods of system control are_____________________ and pressure.

22. The purpose of the cell coolant system is to remove unwanted ____________________ from the cell using a cooling coil that is internal to the converter A-stream outlet chamber.

23. The coolant medium is a refrigerant called_________________________.

24. The___________________ system is designed to be a nuclear criticality safe storage of UF_6 in key locations in the cascade process.

25. Lubricating _____________________ is used in the cascade to lubricate compressor bearings, compressor motor bearings, and provide a source for hydraulic operating oil for the stage control valves.

26. The____________________ system is provided to rapidly change the air in the building on a continuous basis as a form of heat removal.

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:

2.1.3 Identify the uses of gaseous diffusion in industry and the required production amounts of uranium hexafluoride.

INDUSTRIAL USE OF THE GASEOUS DIFFUSION PROCESS WORLD-WIDE AND RELATED PRODUCTION AMOUNTS OF URANIUM HEXAFLUORIDE

Gaseous diffusion is a uranium enrichment process based on the difference in rates at which uranium isotopes in the form of gaseous uranium hexafluoride diffuse through a porous barrier.
At gaseous diffusion plants (GDPs), UF_6 is heated and the gas introduced into the enrichment process stream. The process steadily enriches the amount of desired uranium-235. The enriched UF_6 is then shipped to a fuel fabrication facility.

United States: Portsmouth and Paducah Gaseous Diffusion Plants

Gaseous diffusion currently is the only enrichment process used in the United States. Three plants, the Oak Ridge Gaseous Diffusion Plant (ORGDP), the Paducah, Kentucky plant, and the Portsmouth GDP were built in the 1940s and 1950s to utilize an integrated three-plant operation. A full scale gaseous diffusion plant was operated in Oak Ridge, Tennessee, from August 1945 until 1985. The Paducah GDP was constructed in 1951 to 1954. The Portsmouth GDP located in Piketon, Ohio, was built in 1953 to 1956.

The three gaseous diffusion plants' output was nearly all highly enriched uranium for the weapons program between 1946 and 1964. The plants also produced low-enriched uranium to be used as production reactor fuel during this period. In the integrated mode, Paducah enriched uranium to about 2% for use as feed to the other two plants. Oak Ridge was used to enrich the uranium-235 up to 93%, and Portsmouth enriched uranium-235 to a "top product" up to over 97%.

The United States' total production of highly enriched uranium from 1945 to 1992 was 994 metric tons. The ORGDP, later known as the K-25 site, produced 483 metric tons of highly enriched uranium. Highly enriched uranium production began in 1945 and terminated in 1964. The site was placed on standby in 1985 and shut down in 1987. The Portsmouth GDP produced 511 metric tons of highly enriched uranium. Portsmouth began producing highly enriched uranium in 1956 and stopped production in 1992. The Paducah plant is still operational; the Portsmouth GDP was placed in “cold standby” in June 2001, although some transferring and sampling operations continue.

In 1992, Congress passed the Energy Policy Act, and, under its provisions, uranium enrichment operations at the Portsmouth and Paducah plants were leased by the DOE to the newly created USEC. USEC, which became a private corporation in 1998, continues to operate the plants, although DOE has retained the responsibility for managing the environmental legacy left from prior operations.

The Paducah Gaseous Diffusion Plant consists of a diffusion cascade and extensive support facilities. The cascade is housed in four buildings, covering a total of about 75 acres (Rogers and Jett 1989). The plant has provided an enriched feed stream to the Portsmouth GDP and previously provided a similar stream to the ORGDP before it was shut down. Hazardous, nonhazardous, and radioactive wastes have been generated and disposed of as a result of plant operations.

Extensive support facilities include a steam plant, four electrical switchyards, four sets of cooling towers, a recovery and decontamination building, a water treatment plant, a cooling water blowdown treatment facility, maintenance facilities, and two active landfills.

HAUP

USEC pursued certification for higher assay enrichment through its initiative of the Higher Assay Upgrade Project (HAUP). Prior to HAUP, the Paducah GDP enriched uranium at less than 1% up to 2.75% of its licensed limit. The material was then shipped to the Portsmouth GDP for final enrichment. The HAUP approval on March 19, 2001, and subsequent NRC licensing allows the Paducah GDP to enrich to the 4% to 5% levels required by nuclear power plants.

To enrich uranium at Paducah to the levels required by nuclear power plants requires that the Paducah product be re-circulated into the cascade to effectively increase the number of enrichment stages. In addition to the modifications for re-feeding, the HAUP included approximately 20 other physical plant modifications. Existing plant controls were examined to determine if they were adequate for safe operation at the higher assay or if additional controls would be required.

Cascade Operations

The Portsmouth GDP cascade is housed in three buildings covering a total of about 166 acres. The principal site process at Portsmouth has been the separation of uranium isotopes through gaseous diffusion process. Support operations included the feed and withdrawal of material from the primary process, treatment of water for both potable and cooling purposes, steam generation for heating purposes, decontamination of equipment removed from the plant for maintenance or replacement, recovery of uranium from various waste materials, and treatment of industrial wastes.

In addition to normal assay UF_6 utilized feed cylinders, the Portsmouth GDP has utilized a second source of feed, an enriched product up to 2% assay uranium-235 from Paducah. This feed material is received by cylinder and goes through the same processes as described previously for the other feed materials.

A third source (rarely used) of feed came from UF_6 tails material withdrawn from the gaseous diffusion cascades with uranium-235 assay above the currently programmed tails assay. This material, which was in 14-ton thin-walled (48Y) cylinders, was transported from the tails storage area to a feed vaporization facility. The cylinders were weighed, inspected visually, pressure checked, and placed in steam-heated containment-type autoclaves for vaporization and feeding to the cascade. When emptied, these cylinders were transported to the tails withdrawal facility for filling with depleted tails material for long-term storage. See Figure 2-48.

Figure 2-48. Feed Cylinders

48Y cylinders contain approximately 12,500 kg of uranium hexafluoride

Figure 2-49 shows the Paducah feed handling facility. Feed cylinders are moved by rail and trucks, and lifted by cranes into the autoclaves.

Figure 2-49. Paducah Feed Handling Facility

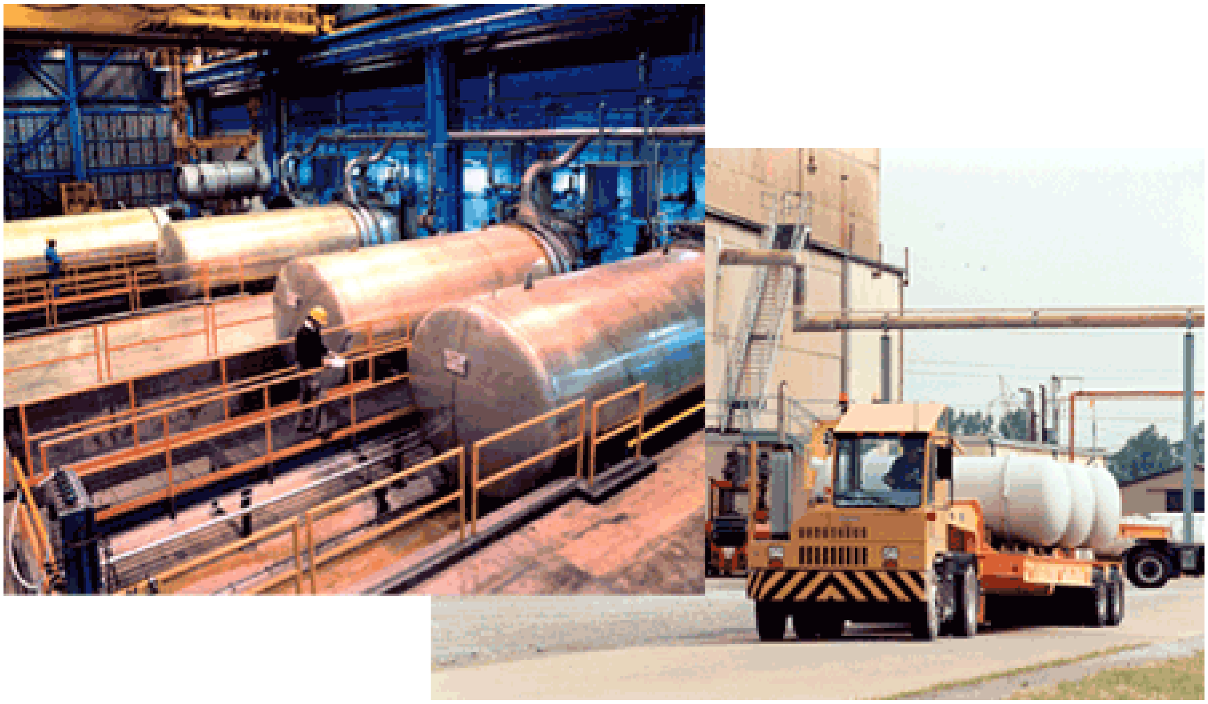


Figure 2-50, “Paducah in Conjunction with Portsmouth,” also helps to demonstrate how the two plants have operated together in the past. For example, the output of the Paducah cascade was a second input to the Portsmouth cascade, along with the normal feed. The endpoint product for the customer came from the Portsmouth output.

The Paducah GDP has operated as two enrichment cascades in an overlap arrangement that could be set up to provide a “shorter” cascade with higher through-put (lower % assay) or a “longer” cascade with a higher enrichment (% assay) output (lower through-put). See Figure 2-51.

Note: The Portsmouth GDP is currently in standby mode.

Figure 2-50. Paducah in Conjunction with Portsmouth

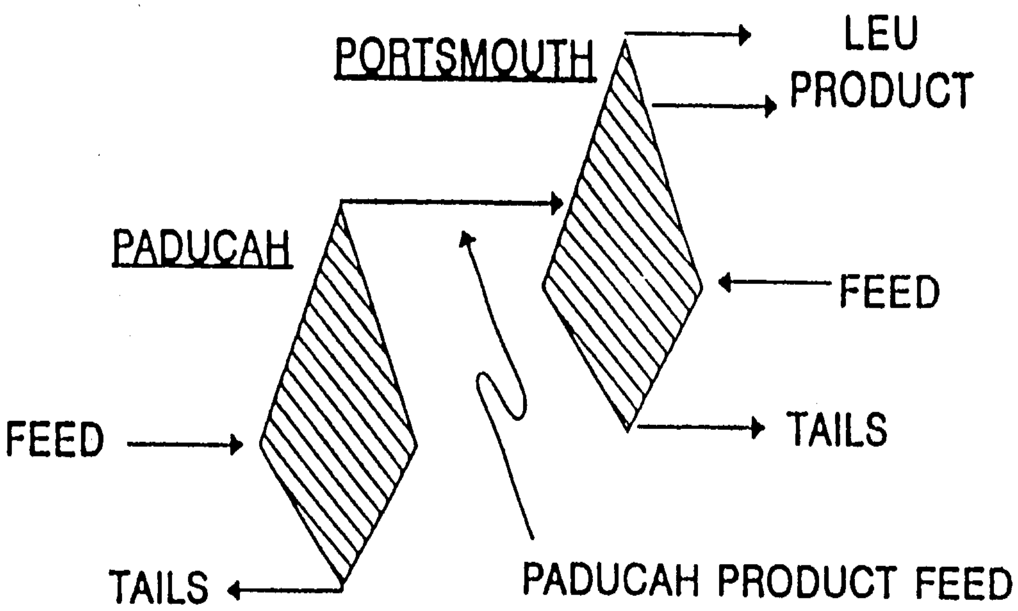
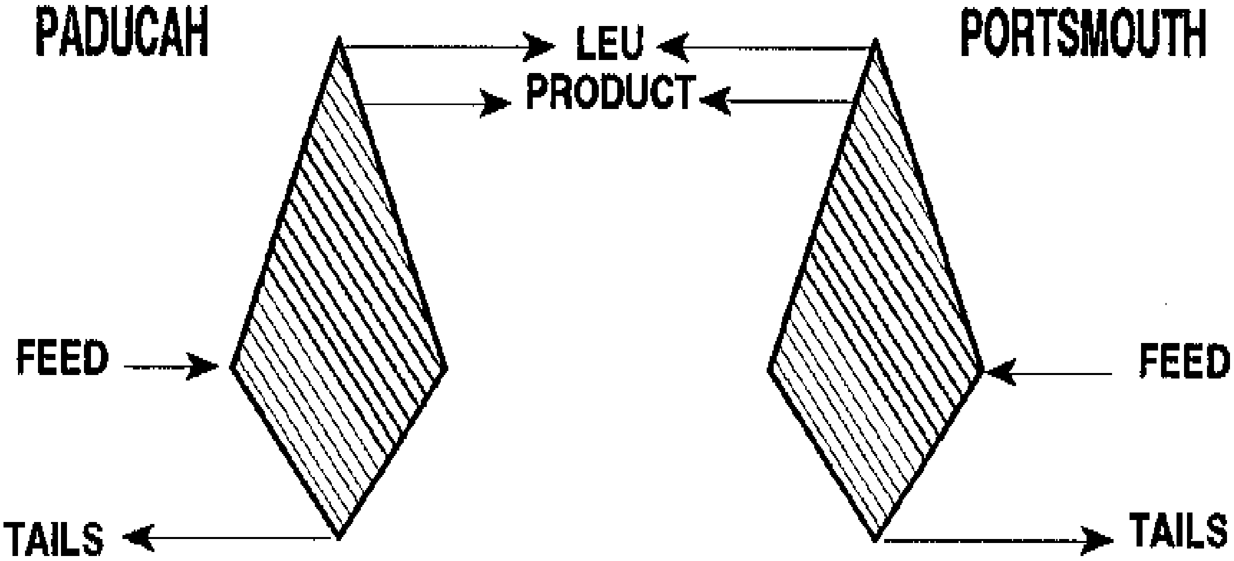


Figure 2-51. Higher Assay Improvements



Tails Storage Tails material is typically stored in 14-ton cylinders, stacked two-high on large concrete or gravel pads, called storage yards. Cylinder integrity is periodically inspected for signs of visual damage. The DOE experience with tails cylinder storage shows that cylinder integrity is maintained for decades at a vacuum. This experience also shows that the cylinders rust from general corrosion of the outside surface. See Figures 2-52 and 2-53, "Portsmouth Depleted Cylinder Storage Yard."

Cylinder movements and stacking are accomplished with large capacity mobile equipment specifically designed to safely handle the large 14-ton and 10-ton cylinders filled with solid $UF_{6.}$ Mobile equipment is not permitted by the Technical Safety Requirements (TSR) to be used to transport liquid UF_6 cylinders. Look back to Figure 2-44, Raygo–Wagner Cylinder Handler/Stacker page 2-70.

DUF_6

The DOE has title to most of the DUF_6 in the United States. Thousands of aging DUF_6 cylinders are stored at DOE facilities at Paducah, Kentucky; Piketon, Ohio; and the East Tennessee Technology Park, formerly ORGDP, in Oak Ridge, Tennessee. These large quantities and the reactive and corrosive properties of DUF_6 are main sources of perceived environmental, safety and health hazards and potential liability for the DOE. In addition, the costs for maintaining the cylinders and storage yards have prompted the DOE to search for alternative approaches to DU disposition. One of these approaches is conversion to other more stable forms, such as U_3O_8, UO_2, or metal, before storage, reuse, or disposal. DU reuse options include DU technology applications (solar cells, thermoelectric devices, or catalysts); re-enrichment by another process; breeder, MOX fuel, or energy reuse; or shielding applications.

Shielding is the only alternative where an application and market currently exist and regulatory and economic issues appear to be manageable. In fact, shielding could handle all existing DU. The NRC regulates SNF (spent nuclear fuel) shielded casks, but no licenses or applications containing significant quantities of DU currently exist.

Module 7 provides more information on DU disposition.

Figure 2-52. Portsmouth Depleted Cylinder Storage Yard. Source: Portsmouth Tour

Figure 2-53. Aerial View of Depleted Cylinder Storage Yard. Source: Portsmouth Tour

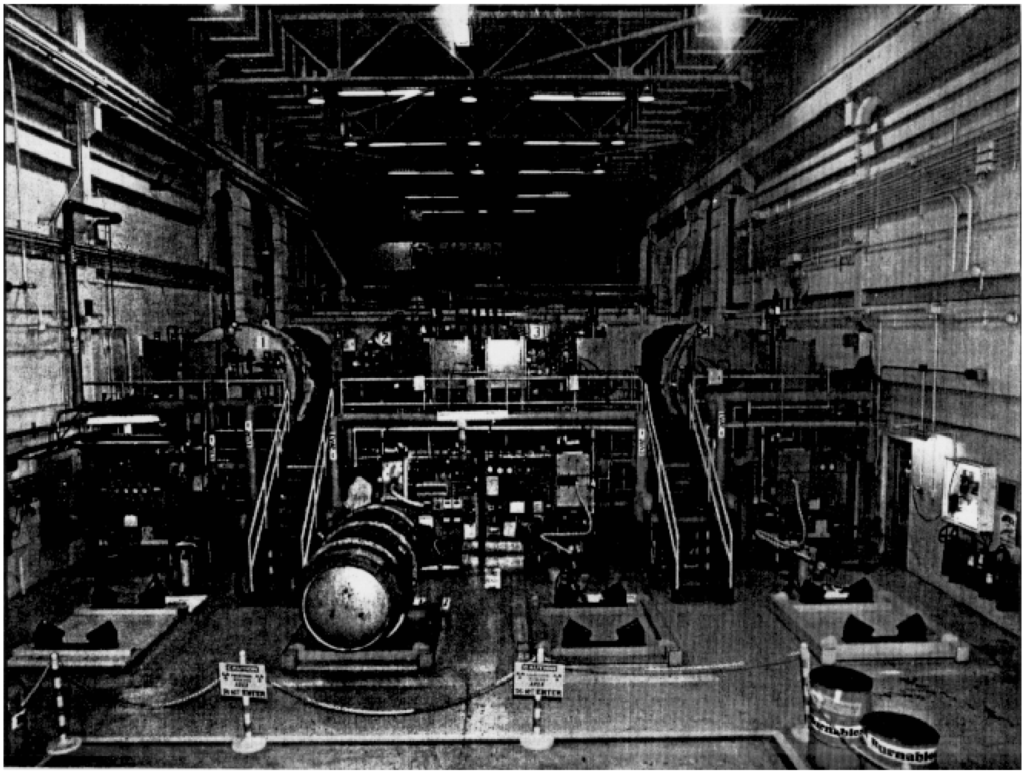
Product Condensation and Withdrawal

As stated in Step 6 at Paducah, UF_6 product in the gaseous state is removed from the enrichment cascade through heated piping to the product withdrawal facilities where it is further compressed to a pressure of approximately 30 psia and cooled for condensation to the liquid phase. The liquid UF_6 is then drained into 10-ton product cylinders. The filled cylinders are transported outside the building on an air-powered scale cart, lifted by a 20-ton bridge crane, and moved to a cool-down area adjacent to the building. After the UF_6 has solidified, gaseous contaminants may be removed by venting through chemical traps. Cylinders containing solidified UF_6 product have been used as feed by Portsmouth then transported and shipped. At Portsmouth, 10-ton product cylinders (48Xs) that fill enriching services contracts are transported for sampling and then their contents transferred to smaller customer cylinders (30Bs) for shipping.

Product Storage

The 10-ton cylinder provides an efficient way to store finished product material until such time as sampling and transfer to 2.5-ton customer cylinders is necessary. Sampling is done to confirm the assay and the purity of the product before filling the customer's cylinders and preparing for shipment. See Figure 2-54, “Portsmouth Product Sampling and Transfer Station.”

Figure 2-54. Portsmouth Product Sampling and Transfer Station



United States: Oak Ridge Gaseous Diffusion Plant

Until the summer of 1985, the primary mission of the ORGDP was enrichment of UF_6 in the uranium-235 isotope for use as a fuel in nuclear reactors. In August 1985, the gaseous diffusion process of ORGDP was placed in a "ready standby" mode because of declining demands for enriched uranium. Since that time, the decision was made in 1987 to permanently shut down the gaseous diffusion cascade. Waste management activities at ORGDP are increasing. Although the enrichment operations at ORGDP are shut down, some waste streams are being generated, and wastes now in storage will require disposal in the future. Low-level radioactive wastes from other DOE-Oak Ridge Office (ORO) sites are now being placed in interim storage facilities in ORGDP buildings until the final disposition strategy is devised. Also, beginning in 1987 polychlorinated biphenyl (PCB) wastes contaminated with uranium began arriving from other DOE-ORO sites began arriving for future incineration in the K-1435 Toxic Substances Control Act (TSCA) incinerator.

DOE awarded a contract for the environmental cleanup of its ORGDP to a team led by BNFL, Inc., the American subsidiary of British Nuclear Fuels Limited (BNFL). Under the U.S. $238 million contract, BNFL, Inc. has begun decontamination and decommissioning of three large enrichment facilities at ORGDP, and making the floor space available for commercial use as part of the East Tennessee Technology Park, formerly the ORGDP/K-25 Site.

A significant factor in the choice of BNFL, Inc. was BNFL’s successful decommissioning of its Capenhurst GDP, a smaller plant but similar in design and layout to the three American GDPs. The Capenhurst GDP was closed for economic reasons in 1982 and decommissioning commenced. It is one of the largest plants to be decommissioned and has been a pioneering recycling project. BNFL removed 160,000 tons of material. More than 99% is being decontaminated and made available for unrestricted use. Some 7,000 tons of metal have already been resold. BNFL also has been involved in other major DOE environmental and waste management projects at former defense sites.

France: Eurodif

France has successfully marketed its nuclear wares and services throughout Europe, Asia, China, and the United States. It is firmly committed to nuclear power at home, where it has admitted to having "no gas, no oil, no coal, and no choice."

Brief Profiles of Major Nuclear Power Generators

In 1946, the Commissariat ê lEnergie Atomique (CEA) assumed responsibility for promoting the use of nuclear energy in France. That same year, Electricite de France (EdF) was created by nationalizing more than 1,500 electricity producing and distribution companies. In 1956, the French government directed EdF to build the first commercial versions of the prototype, natural uranium-fueled, graphite-moderated, gas-cooled reactors that the CEA had already developed. However, in 1969, EdF switched to LWRs fueled by enriched uranium and supplied by French reactor vendor Framatome, and the government undertook to establish a nuclear program technically independent of the United States. In 1981, Framatome terminated its licensing agreements with Westinghouse, the American reactor designer and vendor.

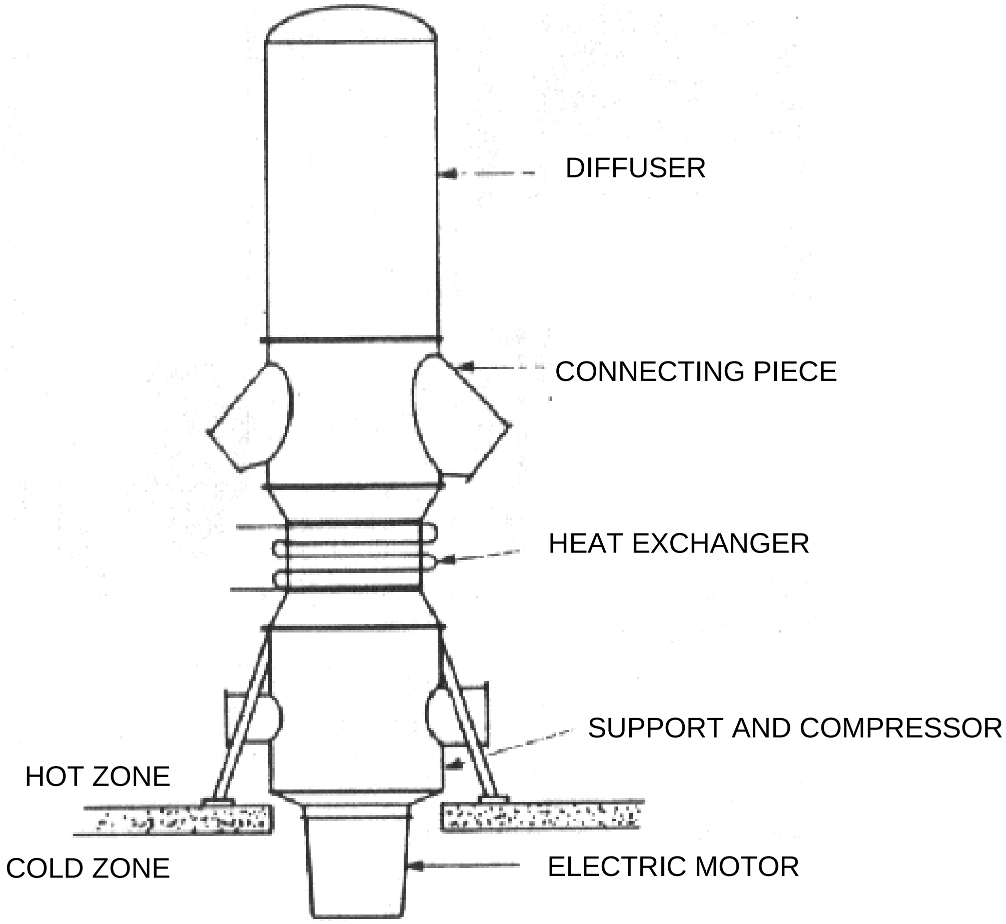
Today, no other country relies so much on nuclear power for its domestic electricity. By the end of 1992, 56 operating reactors were producing 72.9 percent of the nation's electricity. Moreover, a report published in 1993 by the French Ministry of Industry showed a base production cost of 0.24 to 0.26 French Francs per kilowatt hour of nuclear electricity (including research and development, waste management, and plant decommissioning expenses), compared to 0.29 to 0.35 for coal-fired electricity and 0.29 to 0.36 for gas-fired electricity.

Through various subsidiaries and partnerships, the French company AREVA has significant control of the nuclear fuel cycle: mining, ore conversion into UF_6, fuel fabrication into LWR fuel, MOX fuel fabrication, reprocessing, and waste conditioning. AREVA also operates gaseous diffusion enrichment facilities in a consortium with Spain, Italy, and Belgium, called Eurodif. Eurodif is a corporation formed and administered under French law, although its ownership is held over a broad international base.

French Gaseous Diffusion Stage Layout

The French stage design of the Eurodif gaseous diffusion plant represents a good example of a vertical configuration (see Figures 2-55 and 2-56) giving a compact assembly. The assembly is mounted on a base slab that separates the lower cold zone, where the electrical drive motors are located, from the upper hot zone that contains the other components resting on a support piece also serving to house the compressor. The compressor is a vertical multistage axial-flow type with an overhung rotor. The heat exchanger is placed at the low-pressure intake of the compressor, that is, on the diffused stream outlet from the diffuser.

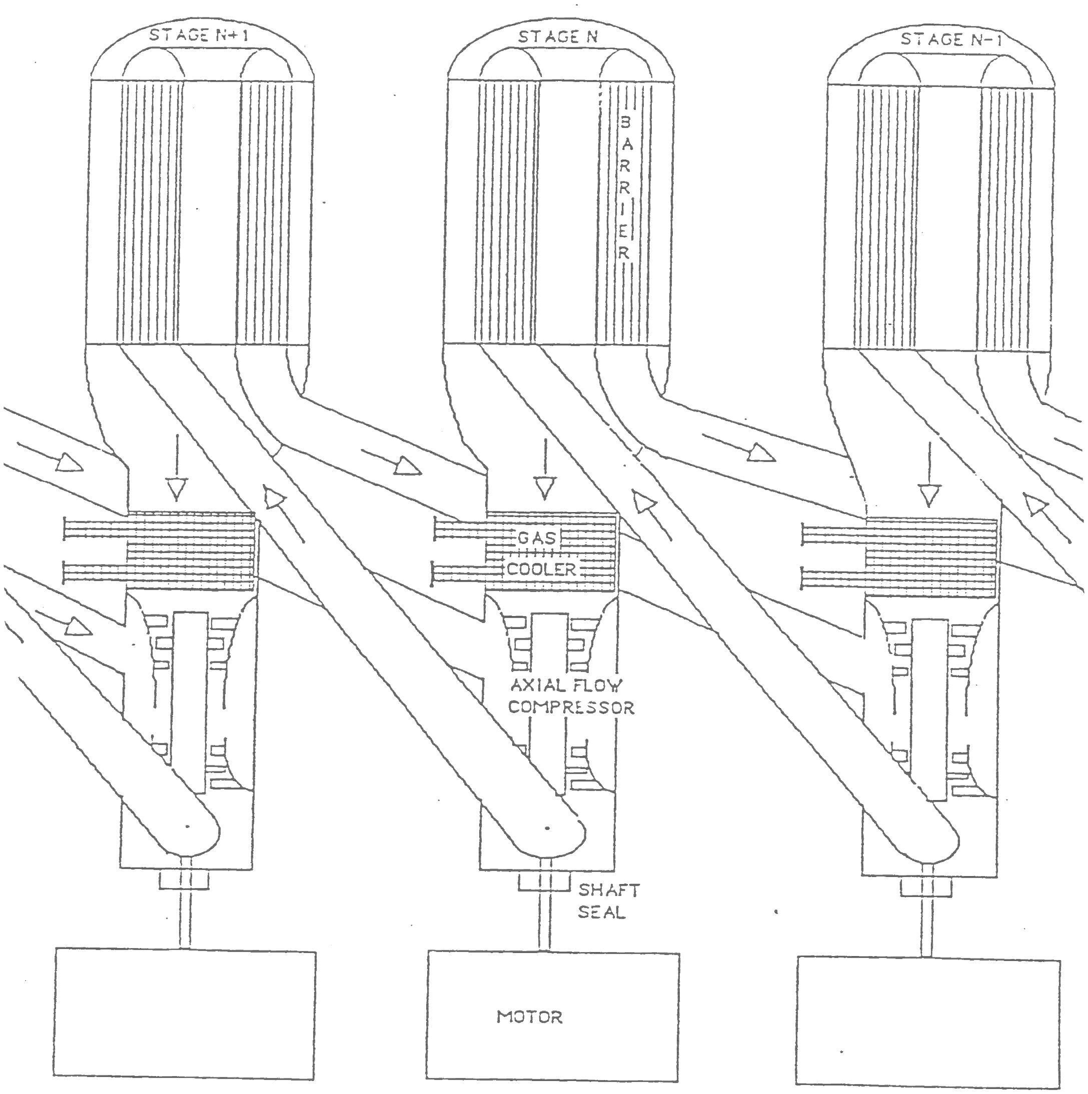
Figure 2-55. Diagram of Eurodif Vertical Stage Assembly



The high pressure (HP) gas feeds to the insides of the barrier tubes at the same height as the output on the diffuser housing. The gas is forced upwards into a number of barrier tubes and out through their upper parts into an annular space that channels it to a remaining second set of tubes through which it then travels downward. Less tubes are needed for the descending than for the ascending gas since the gas flow internal to the tubes becomes progressively less. The gas remaining in the tubes after the descending pass is the medium pressure (MP) depleted fraction that then exits the diffuser. The other half, which has passed through the barrier, is the enriched fraction and is collected in the unit's central space, which is kept at a reduced base pressure (BP). The enriched fraction then passes through the heat exchanger and into the low pressure suction of the compressor.

The Eurodif configuration has 20 stages in each cell (see Figures 2-55 and 2-56). It uses 1400 stages to produce low-enriched uranium, that is, up to ~5% uranium-235. The cascade is comprised of three stage sizes: 0.6, 1.5, and 3.3 Mega Watt electric (MWe).

Figure 2-56. Several Stages at the Eurodif Plant



France: Pierrelatte

Research on uranium isotope separation by gaseous diffusion began in 1953. A gaseous diffusion plant for defense purposes has been in full operation at Pierrelatte since March 1967. The construction of the 4-cascade plant at Pierrelatte started in 1961 and the plant has been in full operation since March 1967 producing highly enriched uranium. The area covered by the four buildings is about 220,000 m^2.

The product enrichment assays attained in the four buildings are, from bottom to top, about 2%, 7%, 25%, and over 90%. The plant separative capacity is generally reported as 400 tonne (400,000) SWU per year. Since 1967, the complete plant has been operated with an onstream efficiency over 98%. The compressors of the larger stages are of the single stage centrifugal type. The stage and cascade components are built from aluminum alloys, stainless steel, and copper alloys.

Beginning in the fall of 1984, the plant was shifted into seasonal mode of operation in which the cascade is shut down for 5 months (November through March) and then restarted and operated for 7 months (April through October). It was shut down in the late 1990s.

Eurodif: Tricastin

The Eurodif George Besse gaseous diffusion plant at nearby Tricastin was completed in 1982 for the purpose of producing low enriched uranium for power reactors (Figure 2-56). The Tricastin GDP consists of four main process buildings having a total combined floor area of 179,000 m^2 and a total separative capacity of 10,800 tonne SWU per year. The plant has two large cooling towers that provide process cooling water and the Tricastin nuclear power station consists of four 930-MWe nuclear reactors. Although not part of the Eurodif plant proper, this power station, owned and operated by the Electricite de France (EdF), was built to provide dedicated power and process steam to the Eurodif plant.

The process technology of the Eurodif plant was developed by, and is owned and licensed by, France’s Commissariat a l’Energie Atomique (CEA). The plant cascade consists of a total of 1400 stages arranged into 70 cells with 20 stages per cell. There are three stage sizes in the plant: 0.6, 1.6, and 3.3 MWe. When operated at its full nominal capacity, the plant consumes about 3000 MW of electrical power, equating to an energy use of roughly 26 billion kWh/year or 2400 kWh/SWU produced.

DU Storage/ Conversion in France

Eurodif is transitioning to gas centrifuge enrichment over the next ten years and plans to shut down the gaseous diffusion process. The gas centrifuge plant will have a capacity equal to the existing GDP (10.8 million SWU/yr) but will only consume about 100 MWe of electricity, a savings of 96%.

The depleted uranium from the Eurodif Tricastin plant has a residual U-235 content of 0.2% to 0.3% in the chemical form of UF_6.

For long-term storage or disposal, the depleted UF_6 is required to be converted to a less reactive chemical form such as UF_4, U_3O_8, and UO_2. France's nuclear fuel company AREVA considers the depleted uranium to be a usable raw material rather than a waste product and is going forward with plans to store nearly 200,000 metric tons of depleted uranium for possible future use. At Cogema's Pierrelatte facility, the UF_6 is converted to the chemically more stable form of U_3O_8. It is then transported by rail to the site of the former uranium recovery facility of Besines-sur-Gartempe near Limoges and stored as a powder in steel containers.

Re-enrichment

According to the nuclear industry, changes in the market or new enrichment technologies might allow for an economical recovery of the residual U-235. Recovery of residual U-235 is, in fact, taking place outside of the U.S. Depleted uranium from the European uranium enricher Urenco and others was enriched up to 0.7% or so in Russia. This UF_6 material was returned to Urenco and used in the GC facilities and re-enriched. However, operating costs depend on enrichment and uranium market conditions. Tails upgrading may not make economic sense given current market conditions of a tightening enrichment market and higher operating costs.

Re-enrichment could be an option for the management of the U.S. DOE depleted uranium stockpile. Roughly 30% of the DOE inventory has a relatively high tails assay in the 0.3–0.4% range, and a relatively low-cost enrichment process in the U.S., such as a centrifuge plant, would make this option viable. However, for re-enrichment, the maximum net reduction is only 5–10% of the total existing DU and would require processing most or all of the existing DU. Some interest currently exists in re-enrichment due to the present high price of uranium.

Iraq: Tarmiya and Ash Sharqat

By 1982, the Iraqis had begun to explore electromagnetic isotope separation at Tuwaitha, which eventually became the principal focus of nuclear research in that country. Baghdad was said to be confident that its scientific establishment had the necessary skills and technology to master the extremely difficult discipline of nuclear enrichment. By the early 1980s, the Iraqis had begun to explore a variety of nuclear enrichment processes: gas centrifuge, gaseous diffusion, chemical enrichment, and laser isotope separation. Initially, much time, money, and effort went into gaseous diffusion. This route was abandoned when some of the technical problems proved insurmountable. Also, it is reported that Saddam Hussein's agents were having trouble trying to buy essential equipment on the open market, much of which had been embargoed by the West. Looking at the lists of items acquired, they appear, nevertheless, to have been remarkably successful.

Starting in the late 1980s, Iraqi scientists began working on centrifuge enrichment as a possible alternative or a source of LEU for electromagnetic isotope separation (EMIS). They had hoped to achieve a production output of about 15 kg of 93% weapons-grade uranium per year at each of the EMIS production units that they intended to build. Originally, the gaseous diffusion elements would have provided low-enriched uranium as a feedstock for the EMIS plants, dramatically increasing highly enriched uranium (HEU) production. The Tarmiya complex on the Tigris river (built by a Yugoslavian firm, Federal Directorate of Supply and Procurement) and its “twin” at Ash Sharqat, several hundred kilometers to the north of Baghdad, were designated to support industrial-scale EMIS production. While there were numerous problems of a technical nature, both plants together, ultimately, could have produced between 25 and 100 kg of weapons-grade HEU a year had they operated successfully. This would have given Iraq the capacity to build up to four atomic bombs per year.

A small plutonium separation program was started in the mid-1970s. Following contact with SNIA-Techint of Italy, a radiochemical laboratory was set up in Baghdad for research on fuel processing. This facility was eventually able to separate small quantities of plutonium, again, contrary to the NPT safeguard agreement.

Currently, there are no nuclear programs in Iraq.

China: Lanzhou Chengdu

Plans to build a gaseous diffusion enrichment plant in Lanzhou, China, began in 1957. A hexafluoride plant came into operation in 1963 and the enrichment plant began operation in 1964. The enrichment plant has been enlarged and new equipment has been developed. A second gaseous diffusion plant was built at Chengdu in the 1970s. The two plants have a reported capacity of 500,000 SWUs per year. Additional Chinese enrichment capacity is being provided by centrifuge plants built in conjunction with the Russians.

Russia: Sverdlovsk

The closed city of Sverdlovsk-45, currently Lesnoy, was established in 1947 as a home to the Plant 418 – an electromagnetic separation (calutron) facility to produce HEU. An industrial-scale separation facility, SU-20, was completed at the Plant 418 simultaneously with the Soviet first gaseous diffusion plant D-1 in Sverdlovsk-44 under the Soviet Regime. Initially, the SU-20 facility was used to increase the level of enrichment of uranium received from the D-1 plant from 70% to 90% uranium-235. Improvements in the gaseous diffusion technology subsequently eliminated the need in electromagnetic separation of uranium isotopes and the SU-20 facility was redirected to enrich non-uranium isotopes.

In the late 1950s, a portion of the Plant 418 was adopted to house a nuclear warhead assembly/disassembly facility–the Combine "Electrochimpribor." The Combine was established to duplicate the Electro-Mechanical Plant "Avangard" in Arzamas-16 in assembling physics packages and nuclear warheads. Eventually, it has become Russia’s largest warhead assembly complex. The production complex is supported by two large national warhead stockpile storage sites, the nearest of which is located approximately 10 km west of the main production area. Gaseous diffusion was phased out in the early 1960s in favor of centrifuge enrichment. Some gaseous diffusion capacity is still used as a first stage to centrifuges to eliminate chemical impurities.

Russia: Angarsk

The Angarsk Electrolyzing and Chemical Combine (AEKhK) was established in the late 1950s to produce enriched uranium for the former Soviet nuclear program. The gaseous diffusion plant in Angarsk attained its full capacity in 1964 and, at the time, was believed to be the most efficient of the existing Soviet enrichment facilities.

The enrichment plant in Angarsk has never produced HEU. Instead, its partially enriched uranium product was probably sent to other Russian enrichment facilities to produce HEU. At present, the Combine that now employs centrifuge technology accounts for 8% of Russia’s enrichment capacity. In addition, the complex operates one of Russia’s two large conversion facilities producing UF_6, the feed material for enrichment facilities.

Russia now uses gas centrifuges for enrichment but maintains some GDP facilities in standby mode.

Large-Scale Operating Enrichment Plants

The most common types of enrichment facilities with production capacity in the world market are gaseous diffusion and gas centrifuge. Including pilot and demonstration facilities that serve at a commercial capacity, the ratio of those operating enrichment facilities was gaseous diffusion at 57% and gas centrifuge at 43%. A summary of the large-scale operating gaseous diffusion enrichment plants is provide in Table 2-2.

Table 2-2. Summary of Large-Scale Operating Gaseous Diffusion Plants

Nation/ Group	Location	Completion Date	Capacity (tonne SWU/Year)
United States	Paducah, Kentucky *Portsmouth/Piketon, Ohio	1950s Upgraded in 1970s	11,300 8,300
Eurodif	Pierrelatte, France* Tricastin, France**	 1982	400 10,800
China	Lanzhou Chengdu	1960s 1970s	300 200
Russia	Urals and Siberia*	1950s	20,000

* Placed in “cold standby”, shutdown or decommissioned.
** Tricastin is located near Pierrelatte.

Self-Check Questions 2-8 ✓

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

1. What are the locations and operating status of the two gaseous diffusion plants in the United States?

2. Which gaseous diffusion plant has produced feed material for other gaseous diffusion plants?

3. Who operates the Paducah and Portsmouth plants?

4. Who is responsible for managing the environmental legacy left from prior operations at the two plants?

5. What overseas corporation operates gaseous diffusion enrichment facilities in a consortium with Spain, Italy, and Belgium?

6. Eurodif gaseous diffusion plant represents a good example of this type of configuration.

7. In the Eurodif configuration, approximately how many stages are in each cell?

8. The Pierrelatte facility in France has a separative capacity that is generally reported as how many tonne SWU per year?

9. The Eurodif Tricastin gaseous diffusion plant has what separative capacity per year?

10. Besides the United States and the Eurodif consortium, what other countries have enriched uranium via gaseous diffusion?

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:

2.1.4 Identify the hazards and safety concerns for the gaseous diffusion process, including major incidents.

HAZARDS AND SAFETY CONCERNS

The primary concern of the systems analyzed in the gaseous diffusion process is atmospheric releases of UF_6, HF, and F_2. UF6 in the liquid phase presents the greatest potential hazards because it is pressurized and violently flashes upon a loss of confinement (e.g., a leak). This produces a relatively large source term. Upon loss of confinement (e.g. a leak). Smaller releases can occur when it is in the gaseous state. A release of solid UF_6 will not contaminate the environment, except in the immediate area, due to the low vapor pressure of the solid material. UF6 reacts with water to produce HF; HF can also be released from tanks on site. More than one-half of all major UF_6 releases have occurred at the pigtail connection between the piping manifolds and the cylinders. Thus, special emphasis is placed on their design and durability.

Basic Categories of Hazards Associated with Gaseous Diffusion Plants

In December 1994, a Memorandum of Understanding (MOU) between the DOE’s Office of Environment, Safety and Health (now part of The Office of Health, Safety, and Security) and the United States Department of Labor's Occupational Safety and Health Administration (OSHA) was put in place to delineate the areas of responsibility of each agency at the gaseous diffusion plants owned by DOE and leased by the USEC. The MOU also describes generally the efforts of the agencies to assure worker protection, and provides procedures for coordination of activities between DOE and OSHA.

Initially, both DOE and OSHA had jurisdiction over radiological safety and health at the portions of the gaseous diffusion plants leased by the USEC. A coordinated interagency effort minimizes potential gaps in the protection of workers and, at the same time, avoids possible conflicting requirements.

The MOU defines four basic categories of hazards that are associated with the gaseous diffusion plants:

A. Industrial safety hazards due to the plant's physical condition or its operations

B. Health hazards due to chemical and toxicological exposures associated with non-radioactive materials

C. Health hazards due to potential exposure associated with radioactive materials

D. Radiation hazards to the general public and the environment

OSHA regulates the hazards listed in categories A, B, and C. DOE and/or NRC regulate the hazards listed in categories C, and D.

The Energy Policy Act also required the NRC to establish standards for the regulation of the gaseous diffusion plants leased by the USEC by October 24, 1994, in order to protect the public health and safety from radiological hazards and to provide for the common defense and security. After these standards were promulgated, the USEC was required to apply at least annually for a certificate of compliance with these standards.

NRC assumed regulatory jurisdiction of the gaseous diffusion plants in 1997 and the leased portions of the facilities transferred to USEC. At that time, NRC and OSHA entered into an MOU that describes the authorities of NRC and OSHA in implementing the Energy Policy Act of 1992. This provision on occupational safety and health hazards at the gaseous diffusion plants covers inspection, investigation, enforcement, and other regulations relating to such hazards.

Potential Hazards

The following potential hazards could occur at a gaseous diffusion facility:

- UF_6 releases can occur at pigtail connectors, manifolds, and cylinder valves, and as the result of dropping cylinders filled with liquid UF_6.

- The potential for releases of UF_6 to the atmosphere exists at the following: feed, autoclaves, withdrawal stations, cylinder-to-cylinder transfer autoclaves, sampling autoclaves, and during cylinder transport.

- Liquid releases of UF_6 can occur at the feed, withdrawal, cylinder sampling, and cylinder-to-cylinder transfer facilities.

- The potential exists for UF_6 reaction with H_2O in the autoclaves, resulting in formation of HF and UO_2F_2 and an increase in pressure.

- All cells in the enrichment cascade above 1% assay contain sufficient uranium-235 to present a criticality hazard.

- UF_6 reacting with water, wet air, or oil results in the formation of UO_2F_2 and HF.

- Inleakage of lube oil could cause the formation of a solid mass of uranium compound large enough to become critical.

- Inleakage of wet air results in the formation of UO_2F_2 deposits on the barrier and interior surfaces.

- Criticality during the removal of equipment could affect maintenance, operating, and supervisory personnel.

- Exothermic reactions could result in uranium compound deposits (for example, UF_4 might be formed by the heat of friction caused by compressor rubbing).

- Exothermic reactions could result in friction heat and melting of aluminum (that is, molten Al will react with UF_6, resulting in an explosion, intense heat, and the formation of a uranium solid).

- Workers could be exposed to uranium deposit treatment gases (ClF_3 and F_2).

- UF_6 cylinders may be stacked to form a critical mass and geometry.

Risks of Handling UF_6 Cylinders

The risks in UF_6 handling and storage are due primarily to operator error. Equipment failure will also be a risk but to a lesser extent. Examples of these risks are:

- Dropping a liquid-filled UF_6 cylinder (operator error or equipment failure).

- Moving a liquid-filled UF_6 cylinder while the cylinder is still connected to the feed, withdrawal, or autoclave manifold (operator error).

- Handling a liquid-filled UF_6 cylinder with straddle carrier (operator error).

- Moving a UF_6 cylinder with mobile equipment prior to the UF_6 solidifying (operator error).

- Operator using an uncertified pigtail, which could result in rupture (operator error and equipment failure).
- Operator not leak testing pigtails after hookup (operator error).
- Expansion joint failure in liquid withdrawal facilities (equipment failure).
- Failure of Safety Systems to perform as designed (equipment failure).
- Stacking UF_6 cylinders to form a critical mass and geometry (operator error).

Coolant and Deposit Treatment Gas Hazards

Small quantities of dichlorotetrafluoroethane (R-114) coolant are always present in the process stream, and larger quantities may be introduced at any time if a large leak of R-114 should develop in the process gas coolers. Also, limited quantities of fluorine and chlorine trifluoride are used as cell treatment gases in the cascade. Mixtures of F_2, ClF_3, and R-114 are explosive in certain concentrations if an ignition source is available, such as friction heat created by rubbing equipment from some compressor failures. The areas of most concern are in the purge cascade or in off-stream cells where an explosion may release UF_6. Explosions can also be produced when ClF_3 comes in contact with materials containing carbon and hydrogen, such as hydrocarbon oil or grease.

Lubrication Oil System Hazards

The enrichment facilities at Paducah and Portsmouth have extensive lubrication oil systems. The oil in these systems constitutes a serious and unavoidable fire hazard. Fires and explosions could occur as a result of over pressure of isolated equipment, the ignition of flammable materials and explosive gas mixtures, or exothermic reactions.

A lube oil fire of this type occurred at the Paducah GDP in 1956. A major fire was discovered in the C-310 Purge and Product Building. The investigation indicated that the fire originated at a withdrawal compressor position. The compressor was operating at beyond-atmospheric pressure when the shaft seal failed. The seal failure resulted in the escape of process gas and a small quantity of F_2, which reacted vigorously with lube oil on the compressor surface. The resulting fire burned with an intense heat, which caused the lube oil supply line to the compressor bearing to rupture. The intense heat, together with the additional supply of fuel from the ruptured oil line, caused the fire to grow very rapidly to a size sufficient to ignite the roof.

The possibility of fires occurring in the compression and/or liquefaction withdrawal system is high because of the lube oil presence and possible ignition source (hot compressor bearing). In December 1998, a fire occurred at the Portsmouth GDP. The fire occurred in a gaseous purge system cell which is used to remove extraneous gases from the processing system. The fire was likely caused by a mechanical failure in a compressor which led to overheating through friction. Friction, resulting from rubbing of compressor parts, is believed to have generated enough heat to reach the melting point of aluminum. The molten aluminum then chemically reacted with the UF_6 process gas generating additional heat. As the cell continued to operate onstream, additional UF_6 was available to feed the reaction and spread it to other stages. At least one gas cooler eventually ruptured releasing R-114 coolant into the cell. The release and expansion of the coolant into the cell increased the cell pressure and generated additional heat as aluminum chemically reacted with the coolant. The high temperatures and potentially elevated pressure led to the destruction of the converter tube bundles and breach of the cell boundary.

Administrative and Engineering Controls/ Preventive Measures

The following administrative and engineering controls should be considered for preventive measures:

- Pigtails are preshaped, certified, and tagged after testing.

- Permanent cylinder valve shielding protrudes past the ends of large cylinders (2.5-ton, 10-ton, and 14-ton), and screw-on caps are installed on 5.5-in., 8-in., and 12-in. cylinders prior to movement.

- Cylinders receive minimum handling while the UF_6 is in the liquid state.

- Autoclaves are designed and constructed to contain the contents of a UF_6 cylinder in the event of any major release from the cylinder, provided the autoclave's water content (condensate and steam) is less than the maximum limit.

- A pressure relief system is installed in each autoclave, consisting of a rupture disk and a pressure relief valve to vent excess reaction products (HF and UO_2F_2).

- Administrative controls entail the use of chained and locked valves to reduce the possibility of misvalving to a withdrawal point other than the one intended.

- To reduce the probability of a criticality, temperatures and pressures are maintained at values to prevent solidification of UF_6 and moderators are excluded.

- The cascade is maintained in a leaktight condition, preventing the intake of wet air.

- Radiation monitoring is conducted throughout the cascade to locate any accumulation of solid uranium masses or deposits.

- In plant areas where uranium solutions or compounds are processed or stored, additional criticality controls are employed, including geometry and batch control, uranium concentration limitations, and other administrative controls.

- The UF_6 inventory and assay in any cell is insufficient to form an unmoderated critical mass, even if all the UF_6 is solidified and concentrated in one stage of the cell.

- During maintenance and equipment removal, all equipment should be covered with plastic sheeting to protect the uranium compounds from loss, protect the maintenance personnel at the scene, and prevent water from entering the equipment.

- All processes should be analyzed by the nuclear criticality safety staff before approval.

- Administrative requirements for assay monitoring and verification dictate that withdrawals be made into the proper cylinders to reduce the probability of a criticality.

- Independent safety reviews should be conducted on a periodic basis.

Table 2-3 shows a listing of potential hazards requiring administrative controls for prevention.

Table 2-3. Potential Hazards Requiring Administrative Controls for Prevention

Potential Hazards	Administrative Controls
Cylinder valve failure during filling or movement	Cylinder valve inspection and controlled movement of cylinders
Pigtail failure during filling	Pigtail inspection
Pigtail gasket failure during filling	Pigtail inspection and use of new gasket
Inadvertent UF_6 release during maintenance	Radiation work permits and purging
Failure of the UF_6 outleakage detectors to detect UF_6 release	Post watch
Uncontrolled movement of cylinder, resulting in liquid UF_6 release	Restrictions governing lifting, lifting over other cylinders, and proximity
Movement of cylinder during filling	Use of locking device
Failure of safety system or design feature following either maintenance or system failure	Verification of system operability
Hydraulic rupture of a frozen line during reheating of the line	Control of heating
Egress from mezzanine area	Restriction of access during cylinder change operation

Gaseous diffusion plants are designed, for economic reasons, to be run continuously for periods of several years. Process equipment and components are highly reliable. A GDP comprises both pressure systems and vacuum systems, driven by large compressors (pumps). The most common problems are associated with vibrations leading to pump and valve leakages and even failure.

The primary hazard (radiological and toxicological) in the GDP is exposure of operating personnel to a major release of UF_6 from the process equipment. Low-level/chronic radiation exposure of operating personnel is possible in certain phases of the process, such as in feed and withdrawal areas, full and empty cylinder handling, and during process maintenance activities.

Most of the chemical compounds encountered in GDPs are Class "D" (primarily uranium hexafluoride and uranyl fluoride). However, due to the reaction of UF_6 with the internal equipment surfaces, some Class "W" compounds are present on the internal surfaces of the process equipment with the associated uranium decay products.

Note: Various chemical compounds are classified in 10 CFR Part 20 into one of three groups according to the rate in which they are cleared from the respiratory system.

Class D - 0 to 10 days
Class W - 10 to 100 days
Class Y - more than 100 days

In addition, contaminants introduced with the UF_6 feed will be present in various concentrations. In general, any contaminant of higher molecular weight than uranium (for example, transuranics) will concentrate at or slightly below the UF_6 feed point. Those contaminants with molecular weight lower than that of uranium (for example, technetium) will travel up the diffusion cascade and concentrate at the UF_6 "front" (the break point between UF_6 and low-density gases such as O_2 and N_2). While the lighter contaminants will concentrate at the higher-enrichment section (top end) of the gaseous diffusion process, some of the material will deposit on internal surfaces at much lower concentrations throughout the process system. In general, the presence of uranium decay products or fission products poses no significant hazard while confined within the process equipment. The primary hazard occurs when the equipment is opened and removed for maintenance or replacement.

Operations utilizing uranium hexafluoride will not generally present a hazard from penetrating radiation, except in the handling of empty UF_6 cylinders (especially the newly emptied) and the maintenance and decontamination of process equipment. Newly emptied cylinders contain uranium decay products and lack the implicit shielding provided by the UF_6. Consequently, the beta–gamma fields are higher as compared to full cylinders. However, internal exposures may be of significant concern from the standpoint of both acute and chronic exposures.

Note: The following discussion is from a health hazard evaluation conducted by the National Institute for Occupational Safety and Health (NIOSH) between November 1996 and February 1997 at the Portsmouth Gaseous Diffusion Plant.

Major sources of radiation exposures at Portsmouth are low energy photons from ^{235}U, thorium (^{231}Th and ^{234}Th), beta particles from protactinium (^{234m}Pa), and Bremsstrahlung radiation produced by the beta particles from uranium daughters and technetium (^{99}Tc). Other potential sources within this category but with limited exposure potential to the workforce include high energy photons from calibration sources of cesium (^{137}Cs), radium (^{226}Ra), and cobalt (^{60}Co), and machine-generated x-rays at tube potentials ranging from 70 to 200 kilovolts (kV). Bremsstrahlung refers to the secondary photon radiation associated with the deceleration of charge particles (electrons) passing through matter. Very low levels of gamma and Bremsstrahlung radiation (0.2 to 0.1 microsieverts per hour, μSv/hr) are found throughout the process buildings. The highest levels (up to 50 μSv/hr) can be found in UF_6 feed cylinder handling areas. Technetium-99 is a beta-emitting fission product introduced into the Portsmouth cascade from reprocessed spent reactor fuel, referred to as recycled uranium (RU). As previously mentioned, it concentrates near the top end of the enrichment process because it is lighter in relation to the uranium isotopes.

The minor sources of radiation exposures at Portsmouth are from trace amounts of the transuranic elements neptunium (^{237}Np) and plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu). These are introduced into the enrichment process through RU. Additionally, RU contains trace amounts of uranium isotopes not found in nature, such as ^{232}U and ^{236}U. The radiological impact of these impurities is negligible in many cases. However, chemical processes that concentrate these radionuclides may require that certain radiological controls be employed. These exposures would become more common if the United States were to resume RU processing at these facilities.

Neutrons at GDPs can be produced from a fission or spontaneous fission of the uranium isotopes. Neutrons can also be produced by reactions between alpha particles emitted by uranium isotopes (primarily ^{234}U) with bonded fluorine atoms.

It is clear from the physical nature and characteristics of uranium and uranium compounds that neutron exposures are most likely to occur in areas where uranium is stored (cylinder yards) or routinely handled (feed and withdrawal areas), and in areas where uranium forms deposits within the cascade. The point at which this exposure becomes a radiological concern depends on several factors, including: neutron production/generation rates, enrichment, neutron moderation factors, (e.g., inadvertent introduction of water) geometry, deposit size, detection capabilities, time of exposure, and distance from a source.

A slow buildup of uranium material within the cascade causes a slight increase in the production of neutrons. If the buildup continues without intervention, the “growing” deposit may lead to a critical or super-critical event, particularly if a moderator is added or introduced inadvertently. This phenomenon of a slow build-up of uranium material that approaches criticality has been termed by the gaseous diffusion industry as a slow cooker. In essence, a “slow cooker” is a mass of uranium in where there is a multiplication of neutrons but at a rate below the critical threshold. Slow cookers are directly associated with uranium deposits which have routinely occurred at Portsmouth since the plant’s inception.

The danger associated with this phenomenon varies with the location, size, and type of deposit formed within the cascade. In general, the number of neutrons produced is proportional to the amount of uranium and the degree of enrichment. For example, an equal number of neutrons can be produced with either a large amount of low-enriched or natural uranium (^{238}U) or a small amount of highly enriched uranium (^{235}U). The energy of the produced neutron is proportional to the percent of enrichment. Highly enriched uranium will result in more energetic neutrons. The potential neutron dose (including photon exposures) from of an unknown or unidentified slow cooker depends on the time of exposure, distance from the source, and the number and energy of the incident neutrons interacting with the target material (tissue).

Slow cookers remain fixed relative to the movements of the workers within the process buildings, thereby making it very difficult to link a particular worker’s dose to a specific deposit. The dynamic nature of slow cookers makes them difficult to characterize and detect. For example, they can remain stable in size, producing a chronic low-level radiation field obscured by adjacent radiation fields, and may go undetected for long periods of time. Or they may continue to build and produce an ever increasing radiation field until they are identified, characterized, and removed from the cascade. This removal action could be completed remotely by chemical treatments or by physically removing the uranium from the cascade. Table 2-4 highlights some of the potential hazards, by type, present in all steps of the gaseous diffusion process.

Table 2-4. Gaseous Diffusion Hazards by Type

Type of Hazard	Hazard Descriptions
Chemical and Chemical Reaction Hazards	• UF_6 reacts explosively with organic material to form fluorinated compounds and HF • HF and F_2 releases from fluorine generation and feed processes • UF_6 reacts with H_2O or wet air to form highly corrosive and toxic HF • H_2 formation within process stream • Contaminants introduced with the UF_6 feed (for example, transuranics and Tc) • Potential UF_6 reaction with H_2O in autoclave, resulting in formation of HF and UO_2F_2 and a resultant increase in pressure • Exothermic reactions resulting in uranium compound deposits (for example, UF_4) • Exposure of workers to uranium deposit treatment gases (for example, ClF_3 and F_2)
Physical/ Mechanical Hazards	• Normal industrial mechanical hazards during maintenance of heavy industrial/chemical processing plants--lifts, falls, heat, etc. • Use of cranes/hoists to move cylinders and process equipment • Normal electrical hazards of high-voltage switch yards and 13.8-kV process power • Autoclave steam pressure hazards • Equipment vibrations leading to pump and valve leakages, and resultant blade failures and potential missiles • Blade release melts into system; FREON gets into cascade • UF_6 reacts with internal surfaces of process equipment, resulting in uranium compounds (including any RU contaminants, such as technetium), which are a potential hazard during maintenance operations

Table 2-4. Gaseous Diffusion Hazards by Type (Continued)

Type of Hazard	Hazard Descriptions
Radiological/ Criticality Hazards	• Liquid and/or solid UF_6 can become critical • Potential for UF_6 to solidify within the cascade due to either abnormally low temperature and/or wet air entering the cascade and forming solid UO_2F_2 • High gamma radiation from handling empty and newly emptied cylinders, and the maintenance and decontamination of process equipment • Low-level alpha radiation from uranium oxide contamination • Stacking UF_6 cylinders to form a critical mass and geometry • Uranium-235 assays greater than 1% present a criticality hazard • Neutron exposures are most likely to occur in areas where uranium is stored (cylinder yards) or routinely handled (feed and withdrawal areas) and in areas where uranium forms deposits within the cascade. • Sources of radiation exposures are low energy photons from ^{235}U, thorium (^{231}Th and ^{234}Th), beta particles from protactinium(^{234m}Pa) and Bremsstrahlung radiation produced by the beta particles from uranium daughters and technetium (^{99}Tc) • Limited exposure potential to the workforce include high energy photons from calibration sources of cesium (^{137}Cs), radium (^{226}Ra), and cobalt (^{60}Co), and machine-generated x-rays at tube potentials ranging from 70 to 200 kilovolts (kV) • Trace amounts of the transuranic elements neptunium (^{237}Np) and plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu)
Fire and Explosives Hazards	• HF/F_2 releases at process feed and fluorine generation operations • Flammable solvents used in decontamination and recovery operations • ClF_3 conditioning gas reacts with FREON to form H_2 during cleaning • H_2O cannot be used to fight fires in process area • Lube oil fires • F_2 reacts explosively with coolant R-114 • ClF_3 reacts explosively with materials containing carbon and hydrogen (for example, hydrocarbon oil or grease) • Exothermic reactions resulting in friction heat and melting of aluminum (for example, molten Al reacts explosively with UF_6)
Environmental and Natural Disasters	• Seismic activities and tornadoes (disruption of confinement systems)

Operation of the uranium enrichment facility at Paducah, requires the use of materials that, if not contained, have the potential for adverse health effects to humans. Some of these materials (for example, UF_6, HF, and NH_3) are directly involved in operating processes. Others (for example, chlorine, natural gas, and gasoline) are used in auxiliary support processes.

Non-Radioactive Chemicals Used in Enrichment Process

With the possible exception of the calutron process, all enrichment facilities are chemical plants. These facilities use a variety of different chemicals, some hazardous and some not so hazardous.

Hazardous non-radioactive chemicals common to enrichment facilities are anhydrous hydrogen fluoride (HF), ammonia (NH_3), chlorine (Cl), fluorine (F_2), sulfur dioxide (SO_2), nitric acid (HNO_3), and hydrochloric acid (HCl). These have the potential to affect the safe handling of licensed radioactive materials. The quantities of these chemicals vary from process to process. Many of the hazards are addressed by training operators and emergency response personnel.

Hydrogen Fluoride (HF) and Fluorine (F_2)

Anhydrous HF is used for the production of fluorine. Fluorine is used for cascade equipment maintenance operations such as uranium deposit removal. Neither fluorine nor HF alone constitutes a fire or explosion hazard, because both chemicals are nonflammable, but F_2, and HF in some cases, will promote ignition (sometimes violent) in contact with wood or other organic materials. There is also a latent fire or explosion hazard due to the possible generation of hydrogen in containers, piping, and equipment used in handling and storage of F_2 or HF. Containers for F_2 or HF should never be heated; they should be protected from direct sunshine and stored in a location where temperatures below 100^oF can be maintained.

Containers of volatile liquids should never be filled completely, in order to allow for liquid expansion as temperature rises. No water, dilute acid, or other liquids should ever be added to a steel container used for F_2 or HF. A container reclosed after such contamination is likely to rupture with extreme violence.

Hydrogen fluoride is used in F_2 production, with a maximum of 30,000 pound (lb) (Portsmouth) and 36,000 lb (Paducah) in inventory at any time. The worst accident scenario would be a tank rupture with an instantaneous release of approximately 36,000 lb of anhydrous HF.

To address this concern, HF is no longer stored in bulk quantities. The "HF tank farms" have been shut down.

A more credible event would be pipe or valve failure with a postulated release of 160 lb of HF. In this case, the probability is greater, but the risk level is lower due to the greatly reduced source term.

Ammonia (NH_3)

Ammonia is used at both Paducah and Portsmouth. Four cylinders are manifolded together to provide 150 lb of anhydrous NH_3 when full. The worst-case scenario would involve the release of 600 lb of ammonia into the building via a manifold or valve breakage, with subsequent exposure of 10 to 20 employees to possibly lethal concentrations of ammonia gas. However the risk level is considered low due to the use of trained staff and the low probability of multiple failures.

Chlorine (Cl_2)

Chlorine is used for algae and bacteria control in the process recirculating water system. Chlorine is fed into the recirculating water system from 2,000-lb cylinders. The worst-case scenario with any reasonable probability of occurrence would involve the release of the entire contents of a 2,000-lb cylinder due to either rupture or valve failure. Rough dispersion estimates used to estimate downwind concentrations indicate no off-site hazards. On-site hazards resulting in serious injuries appear possible. The resultant risk level associated with this scenario is low due to the low initiating frequency of the event and trained staff.

Chlorine Trifluoride (ClF_3)

Chlorine trifluoride is used as a drying agent and for recovering uranium deposits. The worst-case scenario for ClF_3 would involve a valve breakage with the potential release of as much as 1,000 to 2,000 lb of ClF_3. Rough dispersion estimates indicate no off-site hazards, but some serious onsite injuries appear possible. Chlorine trifluoride reacts violently with water, organic matter, glass, asbestos, sand, chlorofluorocarbons, acids, alkalies, halogens, salts, and metal oxides, as well as many other materials. The risk level of this event is considered low due to the low frequency of valve breakage and the use of trained staff.

Radioactive Chemicals

In many respects, the greatest potential hazard present at the Portsmouth and Paducah facilities is the hazardous chemicals used in the uranium enrichment processes and ancillary support activities. Over 600 separate chemicals have been identified at the two facilities from a review of the hazardous materials control systems of these two sites. These reviews were conducted as part of safety analysis reviews (SARs) to identify the presence of materials that would have the potential—due to their innate hazardous properties (for example, toxicity, reactivity, flammability, etc.), quantity stored, and location—to cause significant health and safety impacts if released to the environment in an uncontrolled manner.

Only five of the chemical hazards identified were determined to have accident scenarios that could involve multiple fatalities and at the same time have any real potential for occurrence. The risk assessments for even these five show low or extremely low risks associated with the events described; individual discussions for four of these (HF, Cl_2, NH_3, and ClF_3) are similar to their non-radioactive chemical effects, discussed previously, and are not repeated on the following pages.

Uranium Hexafluoride (UF_6)

UF_6 poses potential health risks for three primary reasons:

- Uranium is radioactive and can therefore increase the likelihood of cancer in exposed individuals.
- Uranium is a heavy metal that can have toxic effects (primarily on the kidneys) if it enters the bloodstream through ingestion or inhalation.
- UF_6 can react with moisture in the air to produce HF, a corrosive gas that can damage the lungs if inhaled.
- HF can also penetrate the skin. In addition to severe burns, it can react with calcium affecting bones and the electrolyte balance (the latter can result in cardiac effects).

Ingestion or inhalation of uranium or HF gas can only occur if a cylinder leaks. Cylinders are inspected regularly for leaks and other damage, and appropriate actions are taken if necessary.

Exposure to radiation in the vicinity of full and empty cylinders (especially newly emptied cylinders) is the primary direct exposure mechanism; however, administrative controls reduce the possibility and level of exposure, particularly around newly emptied cylinders.

In addition to the radiological and chemical health risks associated with depleted UF_6 cylinders, there are also risks of industrial accidents and transportation-related accidents during handling, storage, or transport of depleted UF_6.

An accident analysis of all GDP facilities with regard to UF_6 releases has been done (FSAR-ORGDP, K/D-5050); a facility safety analysis report specifically for the Paducah Gaseous Diffusion Plant was published in April 1985 (KY-734, Sections 4 and 5). The most credible accident at a GDP would involve the dropping and rupture of a UF_6 cylinder containing 28,000 lb of liquid UF_6.

The results of the SAR suggest that there is some probability of a significant offsite hazard from a very large UF_6 release. Onsite, the plant population is at some risk, especially those located downwind of the release. Provided that personnel are not trapped, they would not be expected to remain in the plume, and evacuation of the affected area would greatly mitigate the consequences and emergency. In any event, whether cylinder rupture or operator error, it is assumed that reasonable reaction by other operators would occur, and that safety systems and emergency responders would react, thus mitigating the consequences and making the relative risk low to extremely low to individuals both on- and off-site.

A review of the SARs indicates that the only scenarios to have the potential for significant health impacts are a catastrophic failure of the main HF storage tanks (currently unused and empty) or a massive release of UF_6. The list of events in Table 2-5 provides a summary of the accident scenarios, risk assessments, and other relevant information for chemical hazards that might have significant impacts on health and safety at a large GDP.

Table 2-5. Potential Hazards with Significant Health or Safety Impacts at a Large GDP

System/ Material	Source Term, Release Quantity	Initiating Events Scenario	Existing Controls (Physical and/or Administrative)
Ammonia	300 lb	Manifold failure	Employee training Operating procedures Emergency response
Anhydrous hydrogen fluoride	1,260 lb	HF vaporizer release	Design features Equipment inspection Employee training Operating procedures Emergency response
Anhydrous hydrogen fluoride	* Maximum spill from HF tank, 30,000 lb, cylinders: 160 lb	Rupture of two main tanks	Design features Equipment inspection Employee training Emergency response
Fluorine	240 lb	Rupture of outside line	Employee training Operating procedures Emergency response
Sulfur dioxide	2,000 lb	Rupture of 1-ton cylinder	Employee training Operating procedures Emergency response
Uranium hexafluoride	28,000 lb	Dropping and rupturing a cylinder inside the building	Administrative controls Design features Employee training Operating procedures Inspection of cylinders Emergency response
Uranium hexafluoride	28,000 lb	Dropping and rupturing a cylinder outside the building	Administrative controls Design features Employee training Operating procedures Inspection of cylinders Emergency response

* This is unlikely to occur, as all HF is supplied to the system with #850 bottles.

Confinement

In uranium enrichment, confinement is provided by the equipment, which is highly leak tight as a design requirement. Secondary confinement consists of the cells housing the most sensitive systems, or the building itself, so that in the event of an accidental release, UF_6 is kept to a minimum.

The primary concern of the GDP is atmospheric releases of UF_6, HF, and UO_2F_2. The probability of massive releases is greater when UF_6 is in the liquid state and smaller when UF_6 is in the gaseous state. This is because the release rate from a confinement breach will be much higher in a liquid release due to self-pressurization, and the UF_6 will flash to a gaseous state very quickly at ambient temperatures and pressures. In systems utilizing gaseous UF_6, the gas pressures rarely exceed 30 psia and are usually subatmospheric; the amount of material in the equipment is thus relatively small. Contamination spread from a breach of a vessel containing solid UF_6 will generally be limited to the immediate area, as a result of the low vapor pressure of the solid UF_6 mass. Any release will be due to the slow reaction of moist air with the surface of the solid UF_6, sublimation of UF_6 to the gaseous state, or combinations thereof.

Typical confinement materials, such as stainless steel and copper, retain their long-term integrity by virtue of the immediate formation of a passive, impervious, protective fluoride layer when first contacted by uranium hexafluoride, which prevents further corrosion and thinning of the confinement.

Processing facilities are designed to a high degree of leaktightness, particularly where hexafluoride is under reduced pressure, in order to prevent the ingress of moisture and the formation of solid UO_2F_2 and related compounds, which could build up and cause blockages, equipment malfunctions, or (if enriched) criticality.

It is those two requirements—that is, to contain UF_6 within a plant and to keep air and moisture out—which tend to dominate most of the tasks performed in enrichment plants.

Operating the cascade at below atmospheric pressure has prevented the release of large quantities of UF_6. (Large releases have occurred from UF_6 storage cylinders.) Releases to date have been from 0.25-inch instrument lines, seal cavities, cells with insufficient UF_6 negatives (<1 ppm of UF_6 in an area), sample purging, and the purge cascade vent stream. Table 2-6 is a summary of UF_6 releases from 1961 through 1978.

Table 2-6. Summary of UF_6 Releases: 1961 Through 1978

Site and Incident #	Location	Date	Description	kg U Released
Oak Ridge Gaseous Diffusion Plant-1	Laboratory Development Feed Vaporization	11/61	Cylinder valve failure	193*
2	Liquid Feed Sampling	5/69	Pigtail evacuation with cylinder valve open - operator error	7*
3	Feed Vaporization	12/70	Pigtail connection leak - operator error	153*
4	Test Loop Feed Vaporization	4/71	Pigtail connection failed	11*
5	Liquid Product Transfer	9/75	Cylinder failure resulting from explosive UF_6 oil reaction	6
Paducah Gaseous Diffusion Plant-1	Feed Vaporization	11/60	Hydraulic rupture of cylinder - operator error	5,467*
2	Tails Storage	3/66	Liquid cylinder dropped and ruptured cylinder wall - operator error	8
3	Sampling	1/71	Broken pigtail - operator error	15*
4	Tails Withdrawal	1/78	Rubbing compressor - UF_6/R-114 reaction	9
Portsmouth Gaseous Diffusion Plant-1	Tails Withdrawal	11/60	Pigtail failure	92
2	Feed Vaporization	7/65	Pigtail rupture	14*

Table 2-6. Summary of UF_6 Releases: 1961 Through 1978 (Continued)

Site and Incident #	Location	Date	Description	kg U Released
3	Tails Withdrawal	7/69	Cylinder valve would not close	460
4	Feed Vaporization	12/70	Pigtail leak	12*
5	Sampling	5/73	Cylinder valve would not close	45*
6	High-Assay Sampling	11/75	Pigtail connection leak	11*
7	Transfer Bay	9/76	Pigtail connection leak	65*
8	Transfer Autoclave	12/77	Cylinder valve thread leak	6*
9	Feed Vaporization	12/77	Pigtail connection leak	8*
10	Sampling	3/78	Cylinder connection leak - operator error	6*
11	Liquid Cylinder Storage	3/78	Cylinder rupture from straddle carrier drop	5,926
12	Tails Withdrawal	10/78	Cylinder valve broke as result of transport while connected - operator error	561

*Autoclave incidents

Nuclear Criticality Safety

According to safety analysis reports, the radiation levels found in normal GDP operations do not present any immediate danger to life and health for plant personnel or the public; however, because of the range of uranium-235 enrichment involved, nuclear criticality safety is a major concern of uranium enrichment facilities. The analyses of criticality potential at the Paducah and Portsmouth GDPs show that the risks associated with inadvertent criticality are low to extremely low.

Formerly, the maximum uranium enrichment produced and stored at the Portsmouth GDP was 98% uranium-235. As of FY 1999, all HEU has been removed from the Portsmouth plant. The bulk of the uranium inventory within the process equipment is in the form of gaseous UF_6, a phase that will not sustain a critical reaction at any mass, geometry, or enrichment level. Other phases of UF_6, that is, liquid or solid, can become critical. The probability exists for UF_6 to solidify within the cascade due to either abnormally low temperature conditions or wet air entering the cascade and forming solid UO_2F_2.

Note: The inleakage of lube oil into the UF_6 system could cause the formation of a solid mass of uranium compound large enough to become critical with moderation by additional oil. However, the deposit would probably restrict flow, alerting operating personnel to the problem, and the deposit would be removed before a critical mass accumulated.

Although criticality incidents are considered to be of low or extremely low probability, analyses revealed that limited hazards exist for personnel outside in the immediate vicinity of the incident. In general, if an accidental excursion were to occur, the likelihood of one or two fatalities accompanied by a few cases of radiation sickness would be high for personnel in the immediate area. It is conceivable that as many as eight fatalities (from a maintenance or firefighting crew) could result, but it is very unlikely.

Criticality alarms will not prevent an incident; however, employees will be alerted to the need to evacuate and/or not to enter the facility. The alarm system will initiate evacuation from the building and should reduce the dose received by personnel in the immediate area.

A criticality can be considered a local event. Because of the confinement provided by the process buildings, there would be no significant immediate radiological effects resulting from exposure to fission products formed during a criticality event.

There are primarily two hazard identification systems in place in the GDP. The first is the UF_6 Release Detection System, which is constructed of detectors that sense a change in the conductivity of air based on the presence of UF_6 and/or HF.

The second system is the Criticality Alarm System, which is constructed of redundant detectors that sense specific areas for the presence of neutrons or gamma rays that could result from a criticality event. Both systems have alarm features to warn personnel to take action. (See Figure 2-57)

Figure 2-57. Criticality Detector Cluster


RemRad
MODEL GCM-850
GAMMA CRITICALITY MONITOR
NRC
NUCLEAR RESEARCH CORPORATION
WARRINGTON, PA. USA

Self-Check Questions 2-9

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

1. What is the primary concern of the systems analyzed in the gaseous diffusion process?

2. The probability of massive releases is greater when UF_6 is in a (solid, liquid, or gaseous) state?

3. Where is the most vulnerable equipment in the UF_6 feed, withdrawal, sampling, handling, and cylinder storage operations?

4. Place a "Y" for "Yes" or an "N" for "No" if liquid releases of UF_6 can occur in the following areas in the gaseous diffusion facility:

   __ Feed

   __ Withdrawal

   __ Cylinder sampling

   __ Cylinder-to-cylinder transfer facilities

5. The potential exists for UF_6 reaction with H_2O in the autoclaves, resulting in formation of ___________________ and ___________________ and an increase in pressure.

6. True or False. Inleakage of lube oil could cause the formation of a solid mass of uranium compound large enough to become critical.

7. True or False. Exothermic reactions could result in friction heat and melting of aluminum.

8. What uranium deposit treatment gases could workers be exposed to during enrichment operations?

9. The risks in UF_6 handling and storage is due primarily to _______________________ .

10. Give three examples of operator error in handling and storing UF_6 cylinders.

11. Mixtures of F_2, ClF_3, and R-114 are explosive in certain concentrations if an ignition source is available, such as friction heat created by rubbing equipment from some compressor failures. The areas of most concern are in the ____________________ cascade or in ____ ________________ where an explosion may release UF_6. Explosions are also produced when ClF_3 comes in contact with materials containing _____________and hydrogen.

12. The possibility of fires occurring in the compression and/or liquefaction withdrawal system is high because of the____________________ presence and possible ignition source (hot compressor bearing).

13. To reduce the probability of a criticality, temperatures and pressures are maintained at values to prevent_______________________ of UF_6.

14. Radiation ______________________ is conducted throughout the cascade to locate any accumulation of solid uranium mass.

15. During maintenance and equipment removal, all equipment should be covered with ______________________ sheeting to protect the uranium compounds from loss, protect the maintenance personnel at the scene, and prevent water from entering the equipment.

16. In general, any contaminant of higher molecular weight than uranium (for example, transuranics) will concentrate at or slightly___________________ the UF_6 feed point. Those contaminants with molecular weight lower than that of uranium (for example, technetium) will travel__________________ the diffusion cascade and concentrate at the UF_6 "front" (the break point between UF_6 and low-density gases such as O_2 and N_2).

17. In general, the presence of uranium decay products or fission products poses no significant hazard while confined within the process equipment. The primary hazard occurs when the equipment is ______________________ and removed for maintenance or replacement.

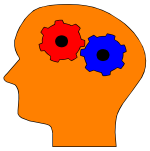
18. Operations utilizing uranium hexafluoride will not generally present a hazard from penetrating radiation, except in the handling of ______________________ cylinders and the maintenance and decontamination of process equipment. However, internal exposures may be of significant concern from the standpoint of both acute and chronic exposures.

19. What are some examples of materials that may be used in auxiliary support processes that could have adverse health effects on humans?

20. How are chlorine trifluoride, hydrogen fluoride and fluorine used in the gaseous diffusion process? What are some of the hazards associated with their use? List two substances that chlorine trifluoride can react with to produce a violent reaction.

21. What are the three primary reasons why UF_6 poses a potential health risk?

Activity 2 - United States Enrichment Corporation's Facilities



Purpose: The purpose of this activity is to access the United States Enrichment Corporation's World Wide Web site to review background information and facts about both the Paducah and Portsmouth Gaseous Diffusion Plant sites as well as take an electronic tour of each site.

Instructions: Complete the activity questions and take the electronic tours for Paducah and Portsmouth by using the following steps:

1. Through your internet provider, access the USEC World Wide Web address by keying in: www.usec.com
2. Select Uranium Enrichment, then Gaseous Diffusion.
3. Select the Paducah and Portsmouth site information.
4. Review background and facts information for each site and answer activity questions.
5. Take an electronic tour for each site and answer the remaining activity questions.

Answers are located in the answer key section of the Trainee Guide.

1. Review the plant history of the Paducah Gaseous Diffusion Plant. When did the following events occur?

Event:	**Date:**
First production cells go “onstream.”	
Plant shifts from military mission to commercial application to supply enriched uranium to electric utilities operating nuclear power plants.	
Energy Policy Act creates USEC to take over government’s uranium enrichment enterprise.	
USEC assumes responsibility for the Paducah and Portsmouth uranium enrichment plants.	

Event:	**Date:**
NRC grants certificates of compliance for USEC’s two enrichment plants.	
Regulatory oversight of enrichment plants officially transfers from DOE to NRC.	

2. How many process buildings are at the Paducah site?

   How many enrichment stages?

3. How many process buildings are at the Portsmouth site?

   How many enrichment stages?

4. Access the Paducah electronic tour. The following questions are each related to a specific tour section which is noted at the beginning of each question. Note: Not all sections have a question, however, you are encouraged to view each section. Answers are located in the answer key section of the Trainee Guide.

   a. The Central Control Center. In addition to the Shift Superintendent and his staff monitoring plant functions around the clock, what other center is based here?

   b. The Process Buildings. The four enrichment process buildings are each supported by what?

   c. The Product Withdrawal Facility. What happens to enriched UF_6 at the Product Withdrawal Facility?

d. Cooling Towers. What is the purpose of the cooling towers and how many gallons of water are lost each day through steam-off from the cooling towers?

5. Access the Portsmouth electronic tour. The following questions are each related to a specific tour section which is noted at the beginning of each question. Note: Not all sections have a question, however, you are encouraged to view each section. Answers are located in the answer key section of the Trainee Guide.

   a. Delivery of Slightly Enriched Uranium. The Paducah Tiger rail cars deliver slightly enriched UF_6 from the Paducah Gaseous Diffusion Plant in Kentucky to which facility at the Portsmouth Plant?

   b. Production Feed Cylinder. What happens to production feed cylinders?

   c. Process Cell. What are the components that make up process cells?

   d. Withdrawing Product. Product is withdrawn from the cascade in 10-ton USEC-owned cylinders. The product is then transferred into what size customer-owned cylinders?

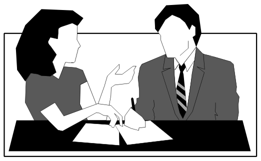
   e. Product Preparation Shipping Facility. Approximately how many customer cylinders are filled each year at the Portsmouth site?

   f. Control Room Instrumentation. Which level (upper or bottom) instrumentation of the Control Room provides power operations monitoring and control of the switchyards?

g. Control Room Instrumentation. Which level (upper or bottom) instrumentation of the Control Room provides monitoring and control instrumentation for portions of the process buildings?

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

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



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:

- NRC regulation of enrichment facilities
- Gaseous Diffusion:
  - UF$_6$ Feed Storage
  - Tails Storage
  - Feed Supply Autoclave
  - Product Condensation and Withdrawal
  - Enrichment Cascade
  - Product Storage
  - Tails Condensation and Withdrawal
  - Product Shipping
- Gaseous Diffusion Hazards and Accident Prevention
- Sampling and Measurement in Gaseous Diffusion facilities

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

III. As a Regulator:

- What have been the most recent problems at the gaseous diffusion plants?
- What are the administrative and engineering controls used at the gaseous diffusion plants? Tell me how administrative controls and engineering controls are effective or not effective.
- What documentation would you recommend that I review before I visit the gaseous diffusion plants?

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 SUMMARY

The enrichment process in the United States is a necessary part of the fuel cycle and therefore the nuclear industry. This process is mature yet represents a complex process with chemical and radiological component hazards. These hazards are similar to other chemical processing industry hazards, except for the complexity that arises from the accompanying radiological aspect.

The enrichment process used for over 60 years in the United States is the gaseous diffusion process. This process takes naturally occurring uranium in the form of UF_6 gas, and through molecular diffusion, increases the percent of uranium-235 present in the gas. This higher assay is advantageous to the nuclear power plant fuel designs.

The GDP feed process takes solid UF_6 in cylinders, heats it to a liquid, and sends the vapor that forms from the heated liquid to the cascade. The cascade is the series of thousands of stages (converter, compressor, control valve) that incrementally raise the uranium-235 assay until the desired enrichment is achieved. The more stages, the more enrichment. When the desired enrichment is met, the UF_6 gas is withdrawn and compressed to a liquid for filling a product cylinder. Once the full cylinder is cooled for five days, it is transferred to the product sampling and transfer facility. Here, the enriched solid UF_6 is heated once more to sample (to meet customer specifications) and transfer to smaller customer-owned cylinders. Once cooled to a solid (another five days), the product is ready for shipment to the customer's choice of nuclear fuel fabricators.

The GDP process is energy-intensive. A single stage can require up to a 3300 HP motor to drive the compressor for moving the heavy UF_6 gas from stage to stage. With thousands of stages, the power usage is enormous. This level of energy present in the cascades adds to the complexity of the operation and the associated hazards. Portsmouth GDP used up to 1900 MW and Paducah GDP used up to 3000 MW of electricity. Because of this level of energy use, the cost of nuclear fuel is influenced by the enrichment process.

Although centrifuge enrichment is the primary process internationally, the gaseous diffusion process remains the primary means of enrichment in the United States. As centrifuge plants are built128 domestically, it is likely GDP operations will be reduced or even curtailed completely.

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