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MARTIN MARIETTA

Uranium Enrichment Plant Characteristics— A Training Manual For The IAEA

J. M. Whitaker
International Technology Programs Division

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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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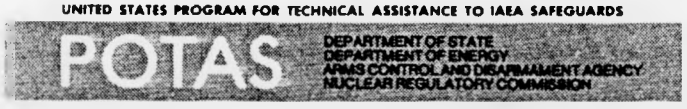

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FOREWARD

This training manual was prepared to compliment a series of training manuals issued by the International Atomic Energy Agency (IAEA) in 1985 to provide organized information on the major types of facilities in the nuclear fuel cycle. The other training manuals in this series are:

Fuel Fabrication Plant
Research Reactor
Critical Assembly
Nuclear Power Plant
Reprocessing Plant

The information in these training manuals was specifically prepared for private study by new inspectors about to undergo training in the Introductory Course on Agency Safeguards (ICAS). The training manuals are intended to give prospective ICAS students the necessary background information needed in the training course. Financial support for this manual was provided by the Program for Technical Assistance to IAEA Safeguards.

I would like to thank members of the International Technology Programs Division of Martin Marietta Energy Systems, Inc., for their contributions in the preparation of this training manual.

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CONTENTS

I. INTRODUCTION

OBJECTIVES

After completing this section, the student should be able to:

1. Relate the scope and level of the material in this manual to his own background and experience.

2. Understand the relationship between this material and the material he will encounter in his training program.

3. Understand how to use this manual effectively along with other manuals in this series to supplement his prior knowledge.

One of the primary objectives of the Safeguards Training Program is to help new inspectors gain knowledge and develop skills that will be required for them to carry out their duties. The formal instructional program for inspectors within the Agency begins with the Introductory Course on Agency Safeguards (or ICAS). Time and resource constraints dictate that this course be devoted specifically to safeguards-related information with the assumption that the students have a basic familiarity with nuclear technology. In some cases, a new inspector's prior experience may have been specialized to the extent that he is unfamiliar with the basic technology of some of the types of nuclear facilities he will be inspecting. In other cases, a student may find it useful to review the English vocabulary for technical terms he may have encountered in another language.

This manual and the five others in this series are intended to provide the student with an overview of the technology involved in the nuclear facility types most often encountered in safeguards inspections. This particular manual addresses uranium enrichment plants. The other manuals consider fuel fabrication plants, research reactors, critical assembly facilities, nuclear power plants, and reprocessing plants.

The primary objective of this training manual is to familiarize an inspector with the basic principles, concepts, structure, and operation of uranium enrichment plants necessary for conducting inspections. Although all existing enrichment methods are discussed, this manual focuses on the gas centrifuge enrichment method because it is the only type of enrichment facility currently under International Atomic Energy Agency (IAEA) safeguards.

Typical plant operating procedures are described and safeguards-relevant features are emphasized.

Part II of the manual provides a discussion of the fundamentals of uranium enrichment. The function of uranium enrichment in the nuclear fuel cycle is discussed, basic separation and cascade theory are presented, current uranium enrichment technologies are described, and the concepts of material balance and separative work are introduced. This discussion is intended to be introductory rather than exhaustive. Example problems are included to illustrate the application of the concepts introduced.

Part III of the manual focuses on the gas centrifuge enrichment technique. The gas centrifuge design history and background are presented, the components and operating parameters of a modern gas centrifuge are described, and the cascade arrangement is explained. Using the fundamental concepts introduced in Part II, equations are developed to compute cascade enrichments and flow rates.

The general features of a typical gas centrifuge enrichment plant are described in Part IV. The major process and support facilities, the process material, the process equipment arrangement, the major on-site nuclear material flows, and the materials accounting system are described.

The specific activities and procedures involved in safeguards activities are not considered in this manual. These are included in the inspectors' training activities in the ICAS and in other follow-on courses.

II. URANIUM ENRICHMENT FUNDAMENTALS

II.A Enrichment and the Nuclear Fuel Cycle

OBJECTIVES

After completing this section, the student should be able to:

1. Identify the isotopes present in natural uranium.

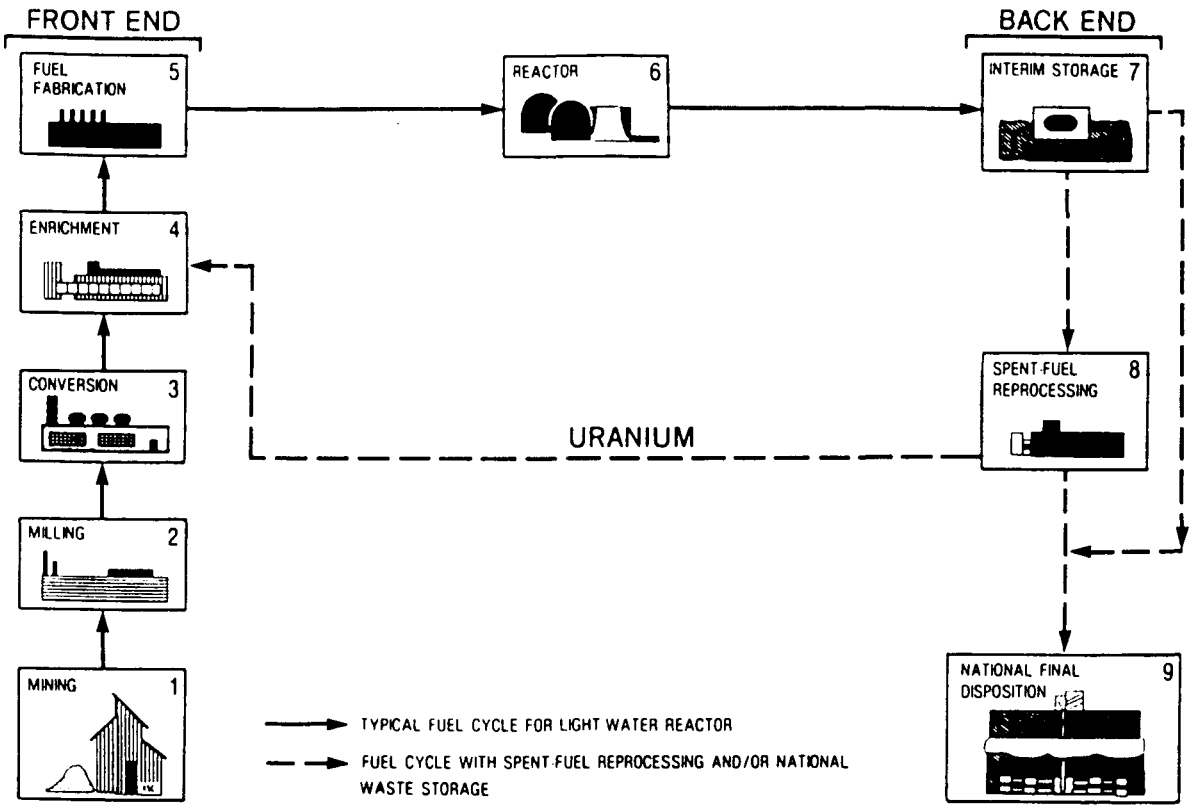
2. Describe the fuel enrichments required in different types of reactors.

3. Understand the function of enrichment in the nuclear fuel cycle.

Uranium as found in nature is called ***natural*** or ***normal*** uranium. Natural uranium is comprised of three isotopes that have mass numbers of 234, 235, and 238. ***Isotopes*** are atoms of the same element that differ from each other only in the number of neutrons contained in their nuclei (i.e., different atomic weights). Even though the chemical and physical properties of isotopes differ only slightly, they behave quite differently in nuclear reactions. Table 1 shows the weight percent of each isotope present in natural uranium. The isotope ^{238}U, the parent of the uranium series, is present in the amount of 99.2846% and is in equilibrium with its great-granddaughter ^{234}U, which is present in the amount of 0.0054%; the principal nuclide utilized in the fission process is ^{235}U, which is present in the amount of 0.71%. Increasing the ^{235}U isotope above its natural concentration of 0.71% is called ***uranium enrichment***. Light water reactor nuclear power plants (i.e., PWRs and BWRs) require fuel enriched to 2 to 5% ^{235}U, and research reactors usually require enrichments ranging from

Table 1. Isotopes present in natural uranium

Isotope	Amount present (wt %)
^{234}U	0.0054
^{235}U	0.71
^{238}U	99.2846



Source: Adapted from *IAEA Bulletin*, Vol. 28, No. 4, winter, International Atomic Energy Agency, Vienna, Austria, 1986, p. 22.

Fig. 1. The nuclear fuel cycle.

20 to greater than 90% ^{235}U. Uranium enriched above natural uranium but less than 20% ^{235}U is called low-enriched uranium (LEU), and uranium enriched to 20% ^{235}U or greater is called highly enriched uranium (HEU). Uranium that has a ^{235}U content less than natural uranium is called depleted uranium.

Isotopic enrichment of ^{235}U takes place at an uranium enrichment plant. Enrichment, however, is only one step in the processing and the use of uranium as a fuel (Fig. 1). To provide feed material to an enrichment plant, uranium must be mined, milled, and converted to the appropriate chemical form used in enrichment operations. In the first step of the fuel cycle, uranium-bearing ore containing small quantities of U_3O_8 (e.g., < 0.2 wt %) is mined. In the milling operation, the uranium is extracted from the ore. The resulting product is a concentrate of uranium oxide known as yellow cake consisting of 70 to 90 wt % U_3O_8. In the conversion plant, the yellow cake is converted to uranium hexafluoride (UF_6), the feed material for most enrichment plants. The yellow cake is first refined to a high purity by

solvent extraction and calcination, and then it is converted to uranium dioxide (UO_2) by hydrogenation. The UO_2 is converted to uranium tetrafluoride (UF_4), called green salt, by reaction with hydrogen fluoride (HF); the UF_4 is then combined with fluorine gas to produce the compound UF_6. This compound is a solid at atmospheric pressure and normal ambient temperatures, but it sublimes to the gaseous phase at relatively low temperatures.

At an enrichment plant the ^{235}U concentration of the UF_6 is altered. The product streams of an enrichment facility are (1) enriched UF_6 and (2) depleted UF_6. The enriched product normally serves as the feed material for a fuel fabrication facility, which chemically and mechanically converts the UF_6 into forms usable in nuclear reactors such as UO_2 or uranium carbide (UC). The depleted product, called tails or waste, is normally stored at the enrichment plant as depleted UF_6; however, it can also be converted and fabricated into a form for use as fertile material in a breeder reactor. For use in nuclear power plants, UO_2 pellets are loaded into alloy tubes, and the tubes are assembled into fuel bundles. These fuel bundles are loaded into a power reactor where the ^{235}U is fissioned with the release of energy in the form of heat. The heat is transformed into electrical energy through steam generators and turbines.

Spent fuel elements removed from the power reactor contain unfissioned ^{235}U, ^{238}U, heavy-element isotopes resulting from neutron irradiation (e.g., plutonium), and a variety of radioactive fission products. Following discharge from the reactor, the spent fuel is placed in on-site interim storage for cooling and to await further disposition. After a sufficient cooling period, the spent fuel elements can be shipped to a spent fuel reprocessing plant, to an off-site interim storage facility, or to a nuclear waste repository. During reprocessing, the residual uranium, plutonium, and fission products are chemically separated. The uranium recovered during reprocessing may be recycled to the isotope enrichment step and then returned to reactor service.

Review Questions for Section II.A

1. What are the isotopes contained in natural uranium?

2. What is uranium enrichment?

3. What is the ^{235}U enrichment range of the fuel required by most nuclear power plants?

4. What is the typical chemical form of uranium when it is mined? When it is processed in an enrichment plant?

II.B Basic Separation and Cascade Theory

OBJECTIVES

After completing this section, the student should be able to:

1. Define the separation element of an enrichment plant.

2. Describe how material throughput affects the arrangement of the separation equipment.

3. Explain why separation elements are combined in series.

The function of a uranium enrichment plant is to increase the concentration of the ^{235}U isotope in the material being processed. Because the chemical and physical properties of isotopes differ only slightly, the separation of isotopes cannot be accomplished using techniques of the kind normally used to purify substances. Isotopic separation has required the development of processes especially designed for this purpose that make efficient use of the small chemical and physical differences among isotopes.

The basic component of an enrichment plant is the separation element. A ***separation element*** (Fig. 2) is a device that separates the incoming feed stream into two outgoing streams: an enriched stream, in which the process material is enriched to some degree in the desired isotope, and a depleted stream that is somewhat depleted in this isotope.

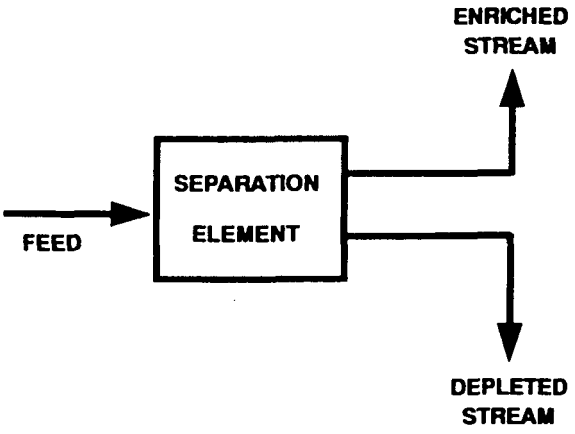


Fig. 2. Basic separation element.

An important feature of a separation element is the ***throughput***, the rate at which feed material can be processed. Some elements can process kilograms of material per minute, while others might process only a few grams per minute. Separation elements are connected in parallel to form ***stages*** to achieve the necessary flow throughput. For separation elements with high throughput (such as the gaseous diffusion diffuser), each stage is comprised of only one

separation element. For separation elements with low throughput (such as the gas centrifuge), each stage is comprised of multiple separation elements.

The degree of separation that can be achieved in a given element or stage is measured by a parameter called the ***separation factor***, α. The magnitude of α is determined by process physics and engineering and varies widely among separation methods. The separation factor is approximately the ratio of the concentration of the enriched stream to the concentration of the depleted stream. (The separation factor is more precisely defined in Sect. III.C.)

$$\alpha = \frac{[\%\ ^{235}U\ /\ (100\ -\ \%\ ^{235}U)]\ \textit{for enriched stream}}{[\%\ ^{235}U\ /\ (100\ -\ \%\ ^{235}U)]\ \textit{for depleted stream}}$$

To achieve useful enrichments, stages are connected in series to form a ***cascade*** (Fig. 3). The feed to a stage is comprised of the enriched stream from the previous stage and the depleted stream from the next stage. The enriched stream withdrawn from the top stage is called the cascade ***product***, and the depleted stream withdrawn from the bottom stage is called the cascade ***tails*** or ***waste***. When the separation factor is very small ($\alpha \sim 1$), only a small degree of enrichment is achieved in a stage. Therefore, the process material must pass through many stages to multiply the separation effect. When the separation factor is large ($\alpha > 1.3$), fewer stages are required to achieve useful enrichments. Figure 4 shows that if the separation factor is 1.004, it takes hundreds of stages to enrich material from 0.71 to 3% ^{235}U; if the separation factor is 1.5, approximately ten stages are required. In designing an enrichment plant, the separation factor and throughput of the selected separation element are used to determine the arrangement of the process equipment.

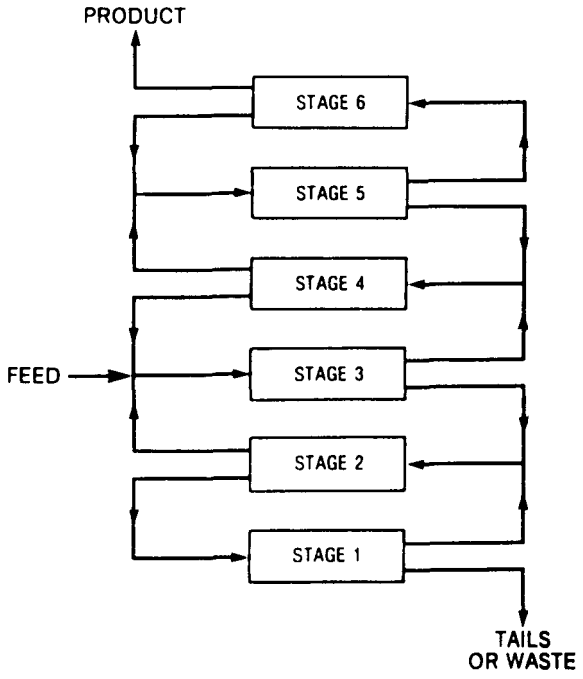


Fig. 3. Stages are connected in series to multiply the separation effect.

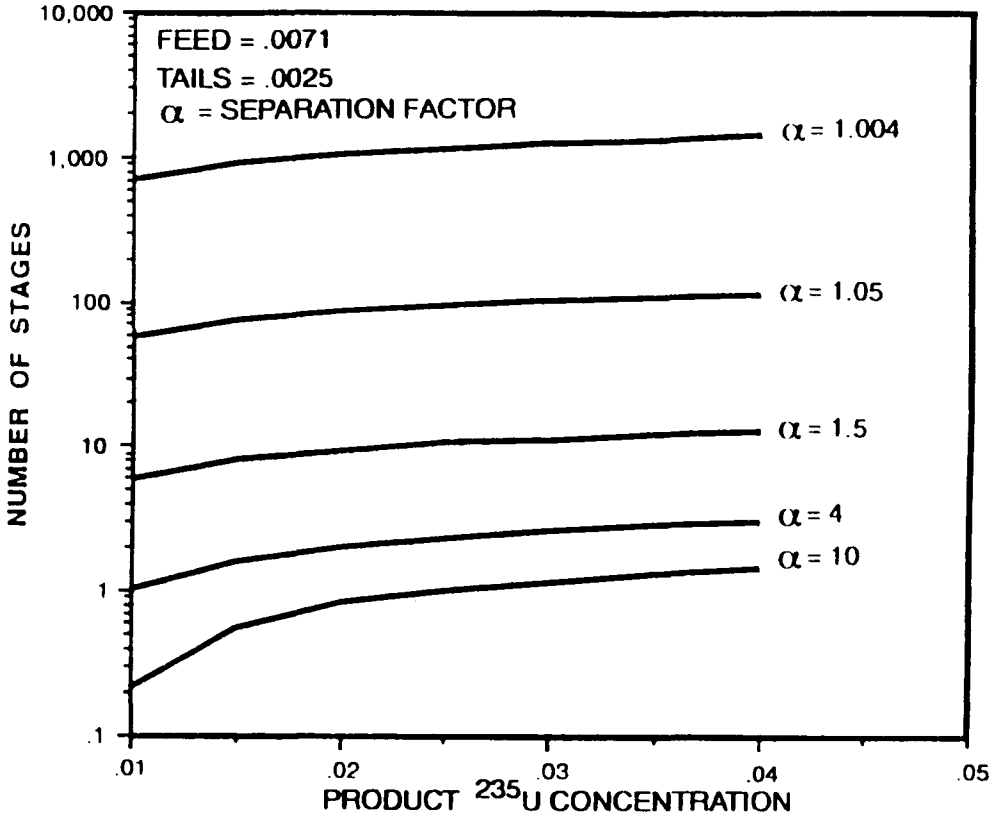


Fig. 4. The number of stages required to provide a desired product concentration increases as the separation factor decreases. (For illustrative purposes, fractional stages are shown in this figure.)

For most enrichment techniques there is a time delay between startup of the cascade and withdrawal of enriched product material. The time required for a cascade to reach its steady-state, designed operating condition is called its ***equilibrium time.*** Initially the entire cascade is filled with feed material at one concentration. Cascade withdrawal valves remain closed while the process material is recycled through the separation elements to increase the initial product concentration from the feed concentration to the desired product concentration (y_P). During this time the cascade is said to be operating in ***total reflux.*** Figure 5 shows that no product material is withdrawn until the concentration gradient is established at time t_1. This time depends on the product and feed concentrations, on the time required for material to pass through a separating element or stage (i.e., stage holdup time), and on the stage separation factor. When the product concentration is achieved, the cascade withdrawal valve is opened slightly and a small flow of product is withdrawn. The product withdrawal rate is gradually increased until the designed withdrawal rate (P) is achieved at time t_3. The cascade is now operating at steady-state. The equilibrium time is defined as the time until the product withdrawal rate reaches approximately half of its asymptotic value (t_2). At time t_2, the area beneath the curve (area 1) equals the area above the curve (area 2) and

the quantity of product material withdrawn from the cascade during the period of t_1 to t_3 is equal to the amount that could be withdrawn if the cascade were operated at steady-state between t_2 and t_3.

The total amount of material required to fill the entire cascade is called the in-process *inventory*. The inventory is highly dependent on process design including the physical state of the uranium-bearing material, equipment volume, and, if the material is in the gaseous phase, its pressure and temperature.

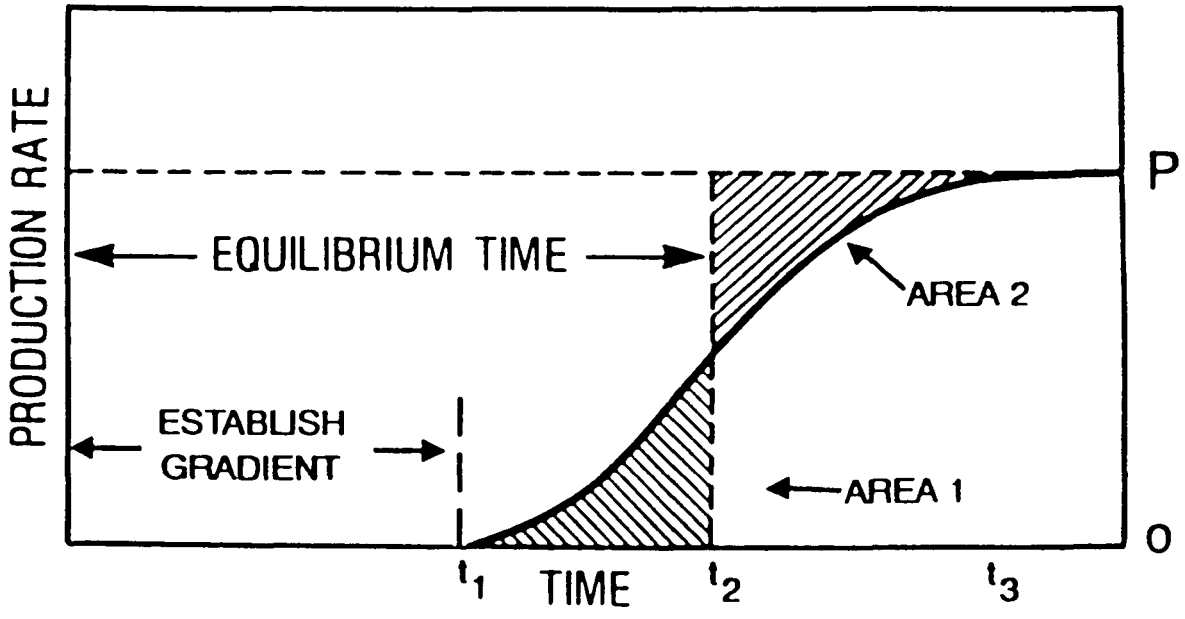


Fig. 5. Cascade equilibrium time.

Review Questions for Section II.B

1. What is the basic component of an enrichment plant?

2. Why are separation elements connected in series? in parallel?

3. Can material at the desired product enrichment be withdrawn from a cascade immediately after startup?

II.C Uranium Enrichment Technologies

OBJECTIVES

After completing this section, the student should be able to:

1. Describe uranium enrichment processes that are in commercial use or in advanced degrees of development.

2. Explain the advantages and disadvantages of each uranium enrichment process.

During the twentieth century many techniques for enriching uranium have been investigated. Table 2 lists the uranium enrichment processes that are either in commercial use or subject to intense research and development for possible use in future large-scale production facilities. These processes include gaseous diffusion, gas centrifugation, nozzle separation, the vortex tube process, chemical exchange, ion exchange, atomic vapor laser isotope separation (AVLIS), and molecular laser isotope separation (MLIS). This section provides a brief description of each process followed by a comparison of the processes.

Table 2. Uranium enrichment processes in commercial use or subject to intense research and development

Process	Enrichment principle
Gaseous diffusion	Diffusion
Gas centrifugation	Density gradient
Separation nozzle	Density gradient
Vortex tube process	Density gradient
Chemical exchange	Chemical equilibrium
Ion exchange	Chemical equilibrium
Atomic vapor laser isotope separation	Photoexcitation
Molecular laser isotope separation	Photoexcitation

Gaseous Diffusion

The gaseous diffusion separation process depends on the separation effect arising from molecular effusion (i.e., the flow of gas through small orifices). When a mixture of gas molecules is confined in a vessel and is in thermal equilibrium with its surroundings, the average thermal velocity of the lighter molecules is greater than that of the heavier molecules to maintain a constant kinetic energy. Therefore, the molecules of the lighter gas strike the vessel walls more frequently (relative to its concentration) than the molecules of the heavier gas. If the walls of the container are porous with holes large enough to permit the escape of individual molecules, but sufficiently small so that bulk flow of the gas is prevented, then the lighter molecules escape more readily than the heavier ones. The escaped gas is then enriched with respect to the lighter component of the mixture.

The basic unit of the gaseous diffusion process is the gaseous diffusion diffuser (commonly known as a converter) (Fig. 6). Compressed UF_6 feed gas is made to flow inside a porous membrane or barrier tube. Approximately one-half of the gas passes through the barrier into a region of lower pressure. This gas is enriched in the component of lower molecular weight (^{235}U) and is sent to the next diffuser. The gas that does not pass through the barrier is depleted with respect to ^{235}U and is sent back to the previous diffuser. Upon leaving the diffusion chamber, the enriched and depleted streams have to be recompressed to the barrier high-side pressure to make up for the frictional losses.

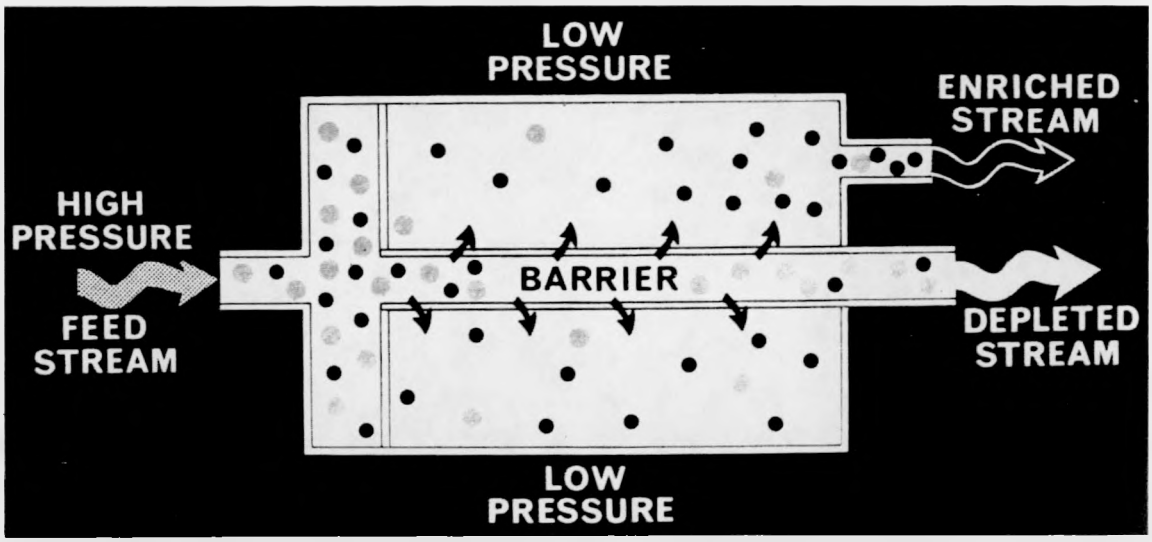


Fig. 6. Gaseous diffusion diffuser.

Gas Centrifugation

The gas centrifuge separation process uses the principle of centrifugal force to create a density gradient in a gas containing components of different molecular weights. Centrifugal force causes the heavier molecules to move closer to the outer wall of the centrifuge than the lighter molecules. The gas centrifuge is essentially a hollow, vertical cylinder (i.e., rotor) that is spun about its axis at a high angular velocity inside an evacuated casing (Fig. 7). Gaseous UF_6 is fed into the rotor and accelerates to approximately the angular speed of the rotor. Centrifugal force causes the heavier $^{238}UF_6$ molecules to move closer to the wall of the rotor and produces partial separation of the ^{235}U and ^{238}U isotopes. This separative effect is increased by an axial countercurrent flow of gas within the centrifuge that moves the enriched and depleted streams to opposite ends of the rotor. The introduction of feed gas and the withdrawal of enriched and depleted streams are accomplished by means of stationary tubes at the axis of the rotor; stationary scoops at the ends of the rotor extend into the rotating gas. The countercurrent circulation may be induced by the mechanical action of the unshielded scoop or by temperature differences between the ends of the rotor. The rotor, driven by an electric motor, is supported at the top by a magnetic bearing and at the bottom by a needle bearing.

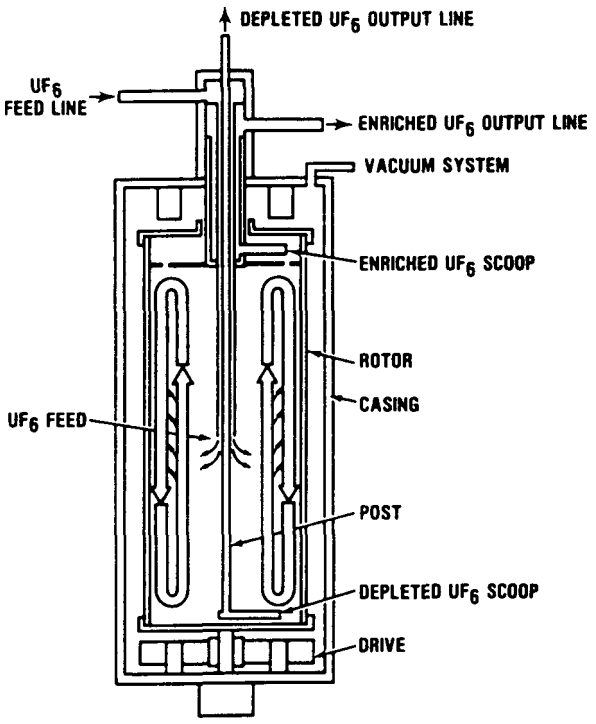


Fig. 7. Schematic diagram of a gas centrifuge.

Separation Nozzle

The nozzle process is based on the centrifugal effect obtained by pumping a gas containing two components of differing molecular weights through a nozzle into an evacuated volume bounded by a curved surface. To use the separation nozzle process for uranium enrichment, a mixture of gaseous UF_6 and hydrogen (H_2) is compressed and then directed

along a curved wall at high velocity (Fig. 8). The UF_6 gas is mixed with lighter H_2 gas to achieve the high velocities that are required. The heavier ^{238}U-bearing molecules move out to the wall relative to those containing ^{235}U. At the end of the deflection, the gas jet is split by a knife edge into a light fraction and a heavy fraction which are withdrawn separately.

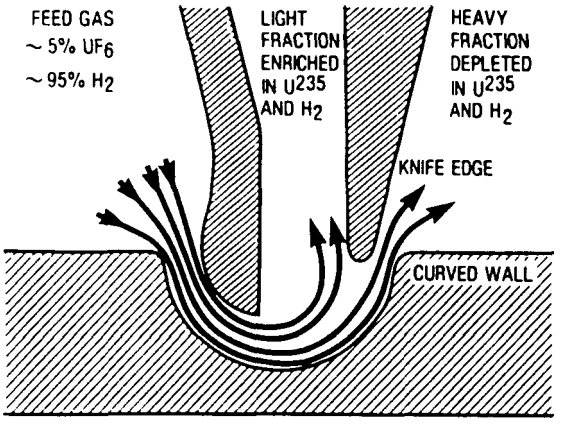


Fig. 8. Separation nozzle process.

Vortex Tube Process

The vortex tube process is an aerodynamic separation method, developed by South Africa, that depends upon establishing a pressure gradient, as does the gas centrifuge. This process is also referred to as a stationary-wall centrifuge. In the vortex tube process, feed gas (a mixture of 1 to 2% UF_6 and 98 to 99% H_2) is compressed and tangentially enters the vortex tube, traveling at a velocity close to the speed of sound, through nozzles or holes (Fig. 9). This tangential injection of gas results in a spiral or vortex motion within the tube, and two streams are withdrawn at opposite ends. In general, the spiral swirling flow decays downstream of the feed inlet because of friction of the wall. This particular design shows a tapered inside diameter that is intended to reduce the decay in the swirling flow as the fluid moves away from the tangential inlet stream.

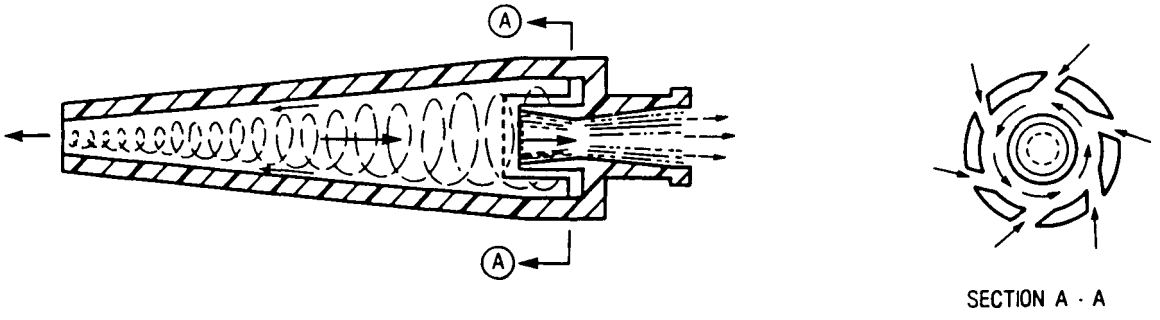


Fig. 9. Vortex tube separation principle, showing a cross section of a tangential end-drive tapered vortex tube (from Wikdahl patent).

Chemical and Ion Exchange

France has developed a chemical exchange enrichment process called "CHEMEX." The process is based on the isotopic effect obtained from the equilibrium exchange reaction between trivalent uranium (U_{III}) and tetravalent uranium (U_{IV}). Immiscible liquid phases (i.e., aqueous and organic) are counter-currently contacted in pulsed columns giving the cascading effect of thousands of separation stages (Fig. 10). In these columns the heavier aqueous solution is fed in the top of the column, while the lighter organic phase is fed into the bottom of the column. A rapid reciprocating motion is applied to the contents of the column, which leads to efficient and intimate contact of the two phases. Separation is achieved because ^{235}U prefers the U_{IV} state (residing in an organic phase) and ^{238}U prefers the U_{III} state (residing in an aqueous phase). After passing through the column, the enriched and depleted streams must be chemically treated so that they can be recirculated through the column (refluxed) or sent to another column for additional enrichment.

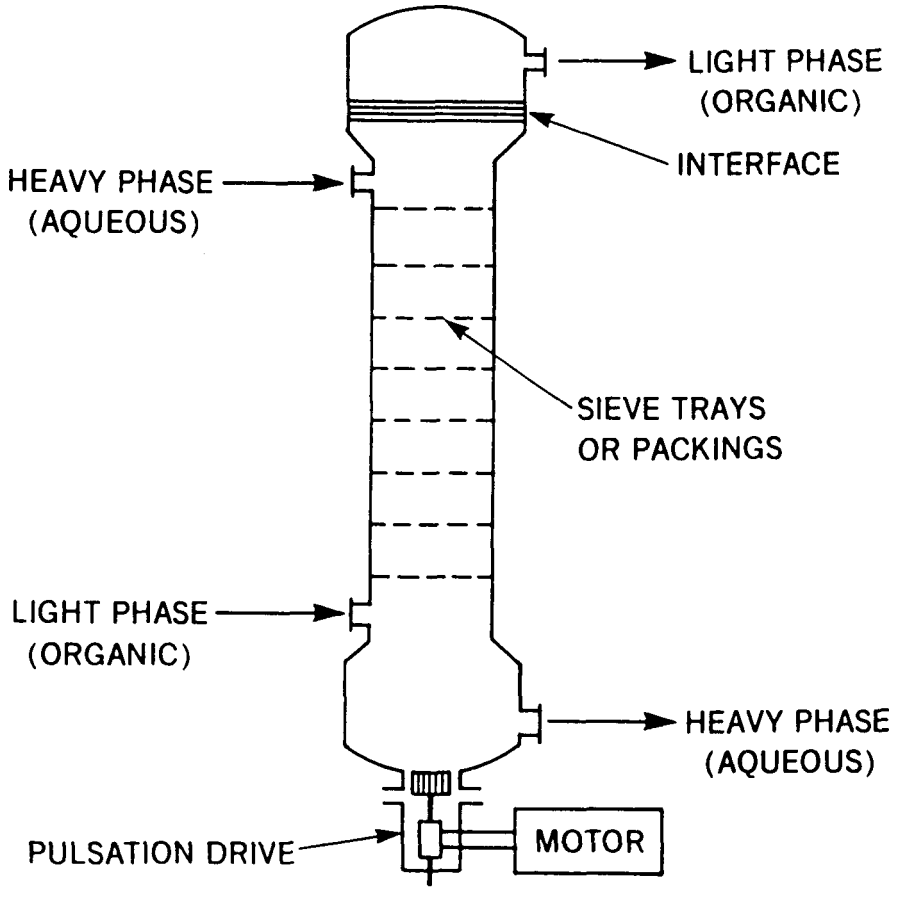


Fig. 10. Chemical exchange process.

The Asahi Chemical Industry Company of Japan has developed an analogous process based on uranium valence states of U_{IV} and hexavalent uranium (U_{VI}). The process uses a cylindrical enrichment column packed with a fine spherical adsorbent (ion-exchange resin). When an acidic uranium solution flows through the adsorbent-packed column, U_{VI} ions are selectively removed from the solution and retained by the adsorbent (as a "fixed phase"), while U_{IV} ions in the solution (as a "moving phase") flow between the adsorbent spheres (Fig. 11). The adsorbent must have a very high ion-exchange rate to allow achievement of isotope equilibrium within a short time. The isotope exchange equilibria are thus established between the fixed phase and the moving phase throughout the enrichment column.

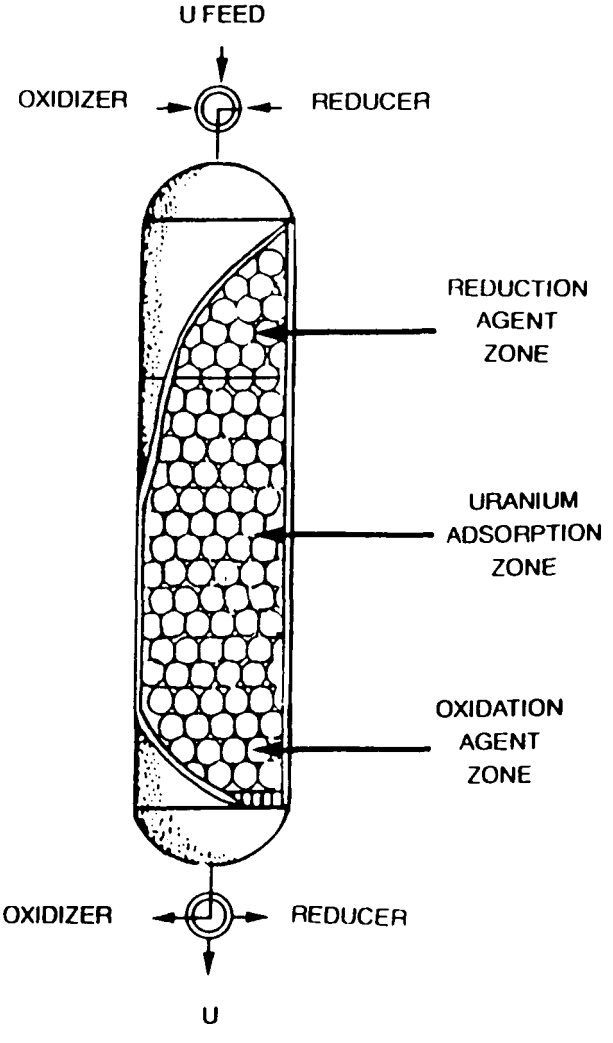


Fig. 11. Ion exchange process.

Atomic Vapor Laser Isotope Separation

The AVLIS technique is based on the fact that the electron energy states of the uranium atom are very precisely defined and depend on the mass of the nucleus. These energies give rise to light absorption characteristics that are unique to each isotope. The process material for AVLIS is uranium vapor. Figure 12 is an illustration of how one isotope (^{235}U) can be selected for photo-ionization and extraction to the exclusion of the other (^{238}U) by proper tuning of a laser system. When the laser light illuminates the uranium vapor, the ^{235}U vapor absorbs the light, but ^{238}U does not. The now excited ^{235}U ejects an electron thus becoming a positively charged atom or ion, which is deflected by an electromagnetic field to the product collector. The ^{238}U remains uncharged and passes through the collector section to the tails collector.

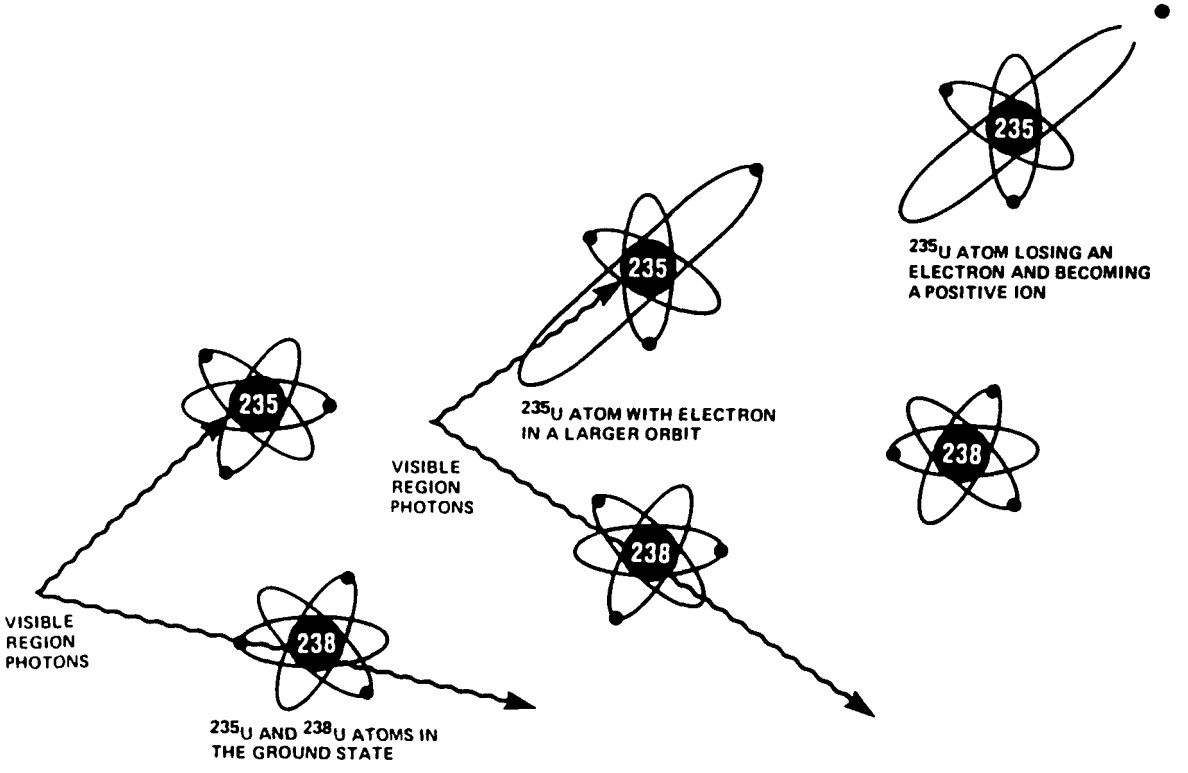


Fig. 12. Atomic vapor laser isotope separation process.

Molecular Laser Isotope Separation

Uranium in the UF_6 molecule is at the center of an octahedron; the six fluorine atoms are equally spaced at the corners (Fig. 13). In the MLIS process, the $^{235}UF_6$ is selectively excited with an infrared laser. The absorption of one or more infrared photons by the UF_6 results in a broadening and red shift of the vibrational absorption spectra. An increase in the ultraviolet absorption cross section of the excited $^{235}UF_6$ results in the preferential dissociation of the excited molecules to $^{235}UF_5$ when illuminated with an ultraviolet laser. Once the dissociation of the UF_6 takes place, the $^{235}UF_5$ can be collected as a powder on a product collector.

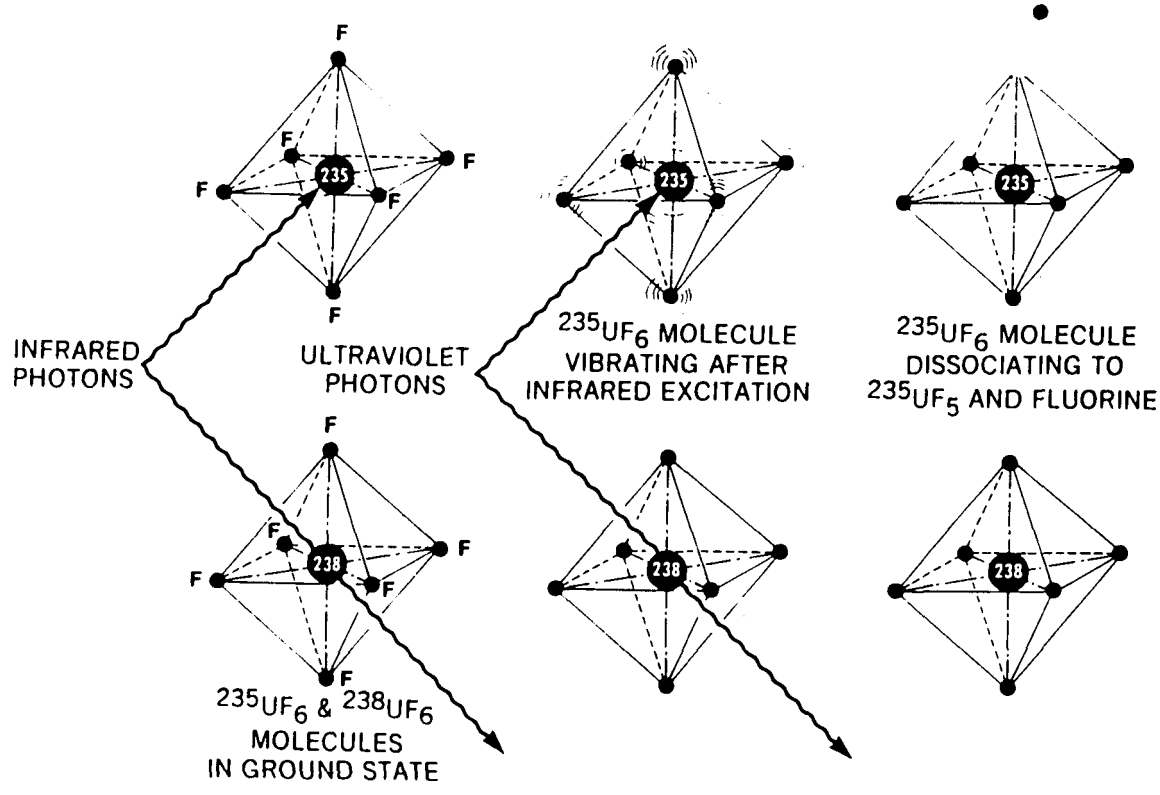


Fig. 13. Molecular laser isotope separation process.

Comparison of Processes

Major factors important to the selection of a uranium enrichment process include the separation factor (how many stages), throughput (how many equipment units per stage), in-process inventory, equilibrium time, energy requirement, capital costs, and operating costs. The ideal enrichment process would have a very high separation factor, a high throughput,

a small in-process inventory, low energy consumption, low capital costs, and low operating costs. The perfect process does not exist, however, and tradeoffs among these factors must be accepted.

Comparisons of some of the more important parameters of the enrichment processes just described are provided in Table 3. The gaseous diffusion process, the first commercial-scale process developed, remains the standard of comparison. Relative to other enrichment methods, the gaseous diffusion process has a very high energy consumption (and consequently high operating costs), a small stage separation factor (which implies many stages), a large in-process inventory of UF_6, and stage units with high throughput. By contrast, the gas centrifuge process has a low energy consumption, stage separation factors that are moderate to high, a very small in-process inventory of UF_6, and equipment units with low flow throughput.

Table 3. Comparison of the enrichment processes

Process	Separation factor	Number of stages[a]	Number of equipment units[a]	Equilibrium time	Throughput	Specific inventory (kg U/ SWU/year)	Specific energy consumption (kWh/SWU)
Gaseous diffusion	1.004	1300 - 1400	1300 - 1400	10 - 40 days	High	~ 0.1 - 0.3	2400
Gas centrifuge	> 1.3	< 20	Thousands	< 1 hour	Low	~ 0.0005	100
Separation nozzle	1.015	~ 700	~ 700	1 - 2 days	High	0.002	4000
Vortex tube process	1.03	1500 - 1800	< 100	~ 1 day	High	0.003	3500
Chemical exchange	1.0026	~ 2000	10s of columns	> 150 days	High	1.1	360
Ion exchange	1.001	6000 - 7000	Several columns	20 - 90 days	High	0.1 - 0.4	140
AVLIS	2 - 6	< 2	< 2	Very short	Mod.	Low	150
MLIS	2 - 6	< 2	< 2	Very short	Mod.	Low	150

[a]Approximate number of stages and equipment units for plants designed for LEU production.

As of 1990, the mix of production capacity on the world market is: gaseous diffusion (69.6%), gas centrifuge (29.7%), and the vortex tube process (0.7%). The locations of existing commercial enrichment plants are listed in Table 4 and are shown in Fig. 14. While the laser isotope separation technologies, as well as the chemical and ion-exchange processes, are indeed very promising and are being intensely investigated, they are still under development. Currently there are no known firm plans to build commercial enrichment facilities based on any of these processes.

Table 4. Locations of existing commercial enrichment plants

Nation or group	Location	Enrichment process	Completion date	Capacity (tonne/year)
China	Lanzhou	Gaseous diffusion	1960s and currently being updated	300
EURODIF	Tricastin, France	Gaseous diffusion	1982	10,800
URENCO	Almelo, The Netherlands	Centrifuge	1980-continuing	1,400
	Capenhurst, United Kingdom	Centrifuge	1980-continuing	1,000
	Gronau (Federal Republic of Germany)	Centrifuge	1985-continuing	500
Japan	Ningyo Toge[a]	Centrifuge	1988	200
South Africa	Valindaba[b]	Vortex tube	1989	300
U.S.	Paducah, Kentucky	Gaseous diffusion	1950s	11,300
	Portsmouth, Ohio	Gaseous diffusion	1950s	8,300
U.S.S.R.	Siberia	Centrifuge	1960s-continuing	10,000
	Siberia	Gaseous diffusion	1950s	Unknown

[a]Demonstration plant.

[b]Semicommercial plant.

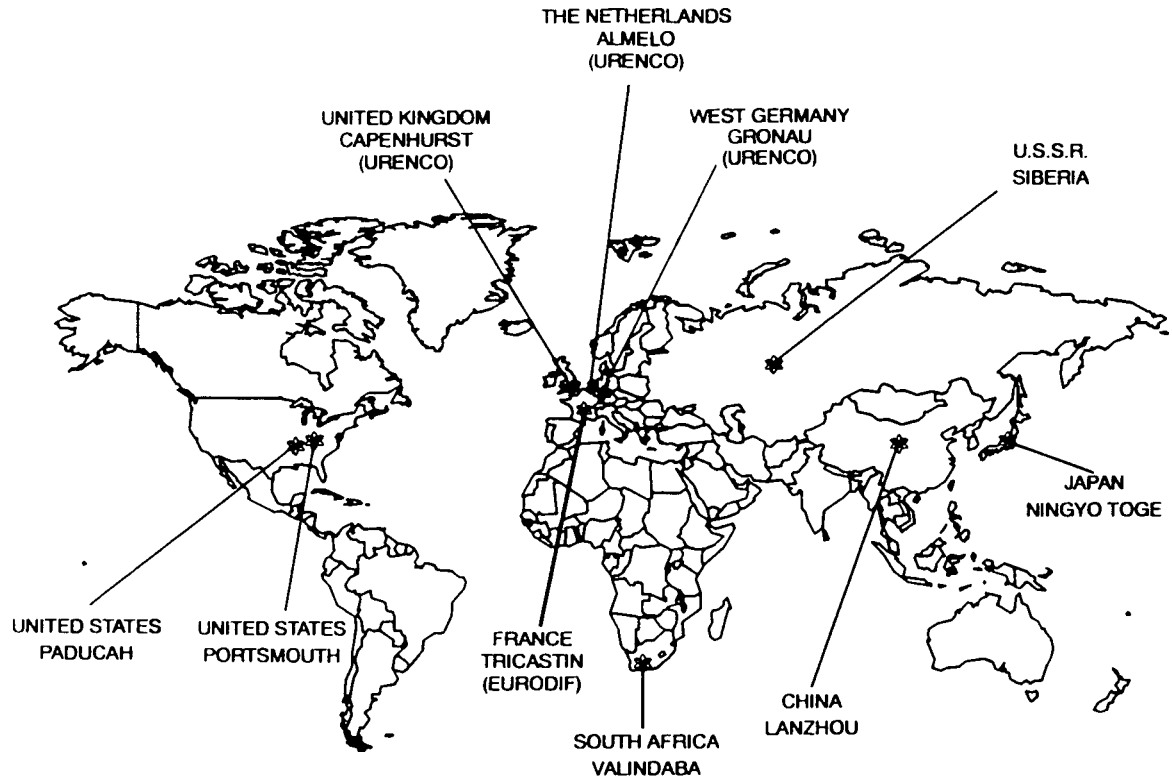


Fig. 14. Location of commercial uranium enrichment facilities.

Review Questions for Section II.C

1. What are some of the uranium enrichment processes that have been developed?

2. What is the most prevalent process used for enriching uranium?

3. What are desirable characteristics of an enrichment process?

4. How does the gas centrifuge enrichment process compare with the other enrichment processes (i.e., advantages versus disadvantages)?

II.D Material Balance and Separative Capacity

OBJECTIVES

After completing this section, the student should be able to:

1. Describe the material balance concept for the external streams of a cascade.

2. Describe the importance of separative work.

3. Calculate material and separative work balances for a cascade.

A simple cascade (or three-stream cascade) divides a feed stream into two streams—one enriched and one depleted in the desired component with respect to the feed composition. Figure 15 shows a schematic diagram of a simple cascade and introduces the nomenclature. The mass flow rates of the product, feed, and waste (tails) streams are identified as P, F, and W, respectively. The ^{235}U content, or concentration, of each stream is identified as y_P, x_F, and x_W, respectively. These concentrations can be expressed in terms of the weight (or mass) fraction of each component or the atom fraction of each component. Because the atomic weights of ^{235}U and ^{238}U are close, for practical applications atom fractions and weight fractions can be used interchangeably for cascade calculations.

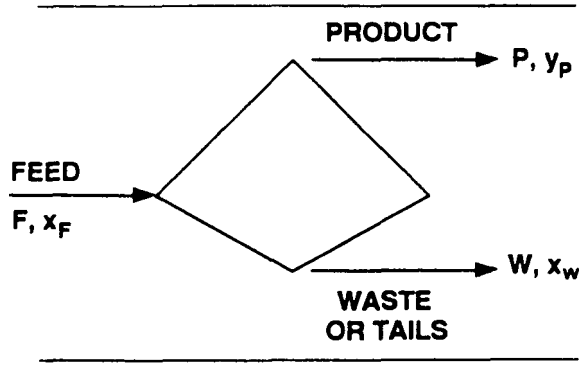


Fig. 15. Simple cascade.

Material Balance

During the enrichment process the total quantity of uranium remains constant even though the concentrations of the product and tails streams are different from the feed stream concentration. In other words, "what goes in must come out."[1] Thus the total quantity of

[1]In an actual enriching process, very small quantities of uranium are consumed as deposits in the process equipment.

uranium [Eq. (1)] and the total quantity of each isotope [Eq. (2)] contained in the feed, product, and tails streams must balance. These balance equations apply to the separation element, stage, or cascade regardless of the enrichment method used.

$$\textit{Uranium balance:} \qquad F = P + W \,. \tag{1}$$

$$^{235}U \textit{ balance:} \qquad F(x_F) = P(y_P) + W(x_W) \,. \tag{2}$$

These equations can be rearranged and solved to obtain the feed per unit product ratio [Eq. (3)].

$$\frac{F}{P} = \frac{y_P - x_W}{x_F - x_W} \,. \tag{3}$$

Problem 1: How much natural uranium is required to produce 1 kg/hour of 3% enriched product material if the tails concentration is 0.25%?

Solution: The required mass flow rate for the feed stream can be calculated using Eq. (3).

$$\frac{F}{1 \text{ kg U/hour}} = \frac{0.03 - 0.0025}{0.0071 - 0.0025} = 5.98$$

or, 5.98 kg U/hour of natural feed is required.

(Note that the ^{235}U concentrations are always expressed in decimal form; e.g., 3% is 0.03.)

In addition, the mass flow rate of the tails stream can be calculated using Eq. (1).

5.98 kg U/hour = 1 kg U/hour + W

or, 4.98 kg U/hour of 0.25% tails will be generated.

Separative Capacity

Separative capacity is the best descriptive measure of a separation element, cascade, or plant's capability to enrich uranium. The importance of the concept of separative capacity lies in the fact that it is a good measure of the effort (e.g., energy consumption) required to perform a separation task. Many of the design parameters of an enrichment plant that affect the initial capital cost are proportional to the plant's separative capacity, and the annual operating costs are proportional to the amount of separative work done per year. For example, in a gaseous diffusion plant, the total flow rate, the total compressor capacity, the total power consumption, and the total barrier area are proportional to the separative capacity of the facility. For a gas centrifuge plant, the number of gas centrifuges (of a particular design) required in a plant is proportional to the plant separative capacity.

Separative work is customarily measured in separative work units (SWU). The separative work can be calculated in units of kg SWU or, simply, SWU when the product, feed, and tails streams are given in kg U (not kg UF_6). The separative capacity is the amount of separative work produced in a given time period and is computed by constructing a value balance of the input and output streams. Equation (4) is used to calculate the separative work (ΔU in units of SWU) required to produce the resulting product and tails streams. The value function V(x) used in Eq. (4) is described in the next section.

$$\Delta U = PV(y_P) + WV(x_W) - FV(x_F) \; . \tag{4}$$

Value Function

The value function was developed in the 1940s and is a function of the ^{235}U concentration, x, in the uranium. The standard form of the value function is given in Eq. (5).

$$V(x) = (2x - 1) \ln\left(\frac{x}{1 - x}\right) . \tag{5}$$

Value is an abstract property of a quantity of uranium that is independent of cost and price. There is no physical interpretation to value of uranium. The value of the output streams increases when isotopes are separated because work is done to effect the separation. The magnitude of the separation task can be characterized by the overall increase in value of the final materials compared with the starting material.

The value function V(x) is plotted in Fig. 16. It is nonlinear and has the property that V(0) and V(1) are infinite. It can also be concluded from this figure that value is lost when two samples of uranium with unequal concentrations of ^{235}U are mixed. Let a chord (i.e., a straight line) connect the V(a) and V(b) of two samples of uranium bearing concentrations a and b, respectively, in ^{235}U. If the amounts of each sample are equal, for example, the concentration of the blend will be at the midpoint of the chord. Notice that for any pair of concentrations, a and b, every point on the V(x) curve lies below the corresponding point on the chord indicating that the value has decreased relative to the average value of the samples prior to mixing.

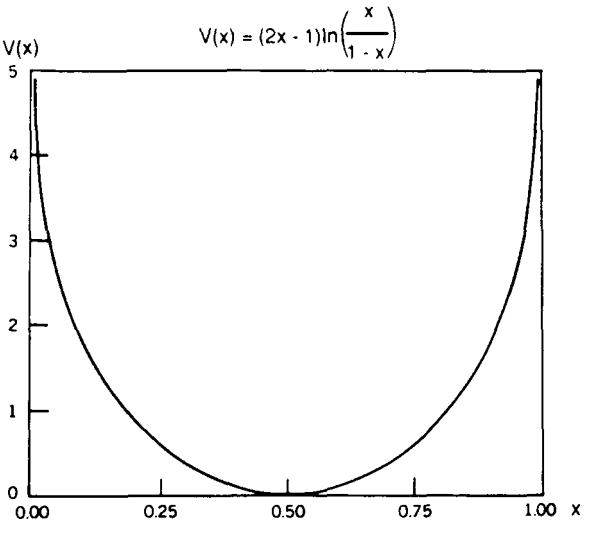


Fig. 16. The value function.

The value function for any ^{235}U enrichment can be calculated using Eq. (5).

Problem 2: What is the value function for (a) natural uranium, (b) 3% ^{235}U enriched product material, and (c) 0.25% ^{235}U depleted tails material?

Solution: Using Eq. (5), the ^{235}U concentration is substituted (in decimal form) for x as follows:

$$\text{a. } V(0.0071) = [2(0.0071) - 1] \ln \frac{0.0071}{(1 - 0.0071)} = 4.870$$

$$\text{b. } V(0.03) = [2(0.03) - 1] \ln \frac{0.03}{(1 - 0.03)} = 3.268$$

$$\text{c. } V(0.0025) = [2(0.0025) - 1] \ln \frac{0.0025}{(1 - 0.0025)} = 5.959$$

The significance of value is its usefulness to form balances and to compute separative work as demonstrated in Problem 3.

Now that the value function has been discussed, let us solve separative work problem.

Problem 3: How much separative work is required to accomplish the separation task identified in Problem 1?

Solution: The separative work is calculated using Eq. (4). Substituting the flow rates and enrichments from Problem 1 yields:

$$\Delta U = 1\ V(0.03) + 4.98\ V(0.0025) - 5.98\ V(0.0071).$$

(Note that the flow rates are provided in kg U.) Substituting the values calculated in Problem 2 yields:

$$\Delta U = 1\ (3.268) + 4.98\ (5.959) - 5.98\ (4.870) = 3.821\ \text{SWU}.$$

Thus, 3.821 SWU are required to produce 1 kg U of 3% enriched product from 5.98 kg U natural uranium with a tails concentration of 0.25%.

Listed below are some rules of thumb regarding separative work. The quantities shown are dependent on exact product and tails concentrations. Based on a 0.25% ^{235}U tails concentration, it takes approximately:

100,000 SWU to fuel a 1000-MWe light-water reactor for one year's operation,

4 SWU to produce 1 kg of LEU (3%) from ~ 6 kg of natural uranium, and

200 SWU to produce 1 kg of HEU (90%) from ~ 200 kg of natural uranium.

Review Questions for Section II.D

1. What are the fundamental material balance equations?

2. What are the customary units used to measure separative capacity?

3. Does the value function provide the cost incurred during uranium enrichment?

III. GAS CENTRIFUGE ENRICHMENT PROCESS

IIIA Design History and Background

OBJECTIVES

After completing this section, the student should be able to:

1. Understand the history of isotope separation technology.

2. Describe the trend towards commercialization of the gas centrifuge enrichment process.

The general principles on which many of the uranium enrichment methods of current interest are based were first recognized in the early parts of the twentieth century. Following the discovery of radioactivity at the turn of the century, the existence of isotopes was recognized, and the word "isotope" was coined by Soddy (England) in 1913. In 1919 Aston and Lindemann (England) identified four distinct principles on which separation of isotopes could be based: distillation, diffusion, density (gravitational or centrifugal fields), and electromagnetic methods.

Laboratory experiments on several specific methods of isotope separation were carried out in the 1920s and 1930s. This included work on gaseous diffusion by Aston, who separated neon isotopes in a single stage in 1920, and later by Hertz (Germany), who used a 24-stage cascade to separate neon isotopes in 1932 and soon thereafter separated isotopes of hydrogen, nitrogen, and carbon. Hertz also used gaseous diffusion to separate neon isotopes in 1934. Laboratory experiments on thermal diffusion were conducted in the 1930s, most notably by Clausius and Dickel (Germany), who built the first thermal diffusion column in 1938. Thermal diffusion arises when a mixture is subjected to a temperature gradient leading to partial separation of the components. Beams (United States) developed the first convection-free vacuum gas centrifuge in 1934 and soon thereafter used it to separate chlorine isotopes. From the earliest days of work with isotopes, the electromagnetic method of separation and detection has been widely used in laboratories (universally). Mass spectrometer instruments developed by Thompson, Aston, Dempster, Nier, and others were used for research. By the late 1930s Lawrence (United States) had developed the forerunner of the calutron, the cyclotron, a device used for accelerating charged particles to high energy for physics research.

Attempts at development of industrial-scale processes did not occur until the rush to build the atomic bomb during World War II. The need for large amounts of ^{235}U stimulated intense research and development efforts by Germany, England, and the United States on methods suitable for uranium isotope separation.

In Germany, initial emphasis was placed on the liquid thermal diffusion process. Beginning in 1941 attention centered on the gas centrifuge process. Subsequently, progress was made on centrifuge machine design, but the effort was greatly hampered by Allied bombing, and the process was not taken beyond a very small pilot scale.

In the United Kingdom, the gaseous diffusion process was being developed for large-scale separation of ^{235}U under the British Tube Alloys Directorate Project. By the end of 1943, U.S. and British scientists and engineers were freely sharing information on the gaseous diffusion process, and the decision to build a large-scale plant in the United States had already been made. Early British work on the gas centrifuge had been dropped in 1940 in favor of the centrifuge effort under way in the United States.

In the United States, under the Manhattan Project, virtually every possible process known at the time was considered and evaluated. Preliminary research was conducted on many processes. Four processes were carried through or beyond the large pilot stage: gaseous diffusion, thermal diffusion, electromagnetic, and gas centrifugation. Beams first separated uranium isotopes using experimental centrifuge machines in 1940. However, a number of technical disadvantages associated with gas centrifuge were discovered and, after the gaseous diffusion process proved reliable in 1944, work on the centrifuge process was suspended. Nevertheless, the basic theory had been developed.

Development of the gas centrifuge continued following the conclusion of the war, and several major breakthroughs in machine size, speed, and efficiency made centrifugation an attractive process for uranium enrichment. One such development (in the early 1950s) was the novel bearing design which replaced the conventional oil bearings with pivot and magnetic bearings. These bearings hold the rotating shaft in suspension and dampen vibrations. In addition, new high-strength, light-weight materials were created to handle the severe mechanical stresses generated in the outer wall. These new construction materials and bearings allowed the centrifuges to spin at extremely high speeds.

It was not until the 1970s that the gas centrifuge enrichment process began to challenge the dominance of gaseous diffusion. Perhaps the most significant difference between these processes is the power usage. A centrifuge plant requires only about 5% of

the power needed for a diffusion plant to perform an equivalent separative task. Other advantages that make the gas centrifuge process more competitive than gaseous diffusion include smaller floor space requirements, the capability to expand the plant capacity in small increments, and the flexibility to design and operate a cascade or module of cascades for a specified product enrichment.

Review Questions for Section III.A

1. When was the existence of isotopes first recognized?

2. What stimulated worldwide efforts to develop an industrial-scale uranium enrichment process?

3. What factors make the gas centrifuge enrichment process more attractive than the gaseous diffusion process?

III.B Modern Gas Centrifuge

OBJECTIVES

After completing this section, the student should be able to:

1. Identify the major components of a gas centrifuge.

2. Describe the operating characteristics of a gas centrifuge.

A gas centrifuge is essentially a hollow, vertical cylinder that is spun about its axis at a high angular velocity (Fig. 17). For the centrifuge detailed in the figure, the enriched stream is withdrawn from the top of the rotor and the depleted stream is withdrawn from the bottom of the rotor. Depending on the centrifuge model, the flow may be reversed. The principal parts of a centrifuge include:

1. center post and scoops;
2. rotor, baffle, and end caps;
3. molecular pump;
4. top and bottom suspension systems;
5. electric motor; and
6. casing.

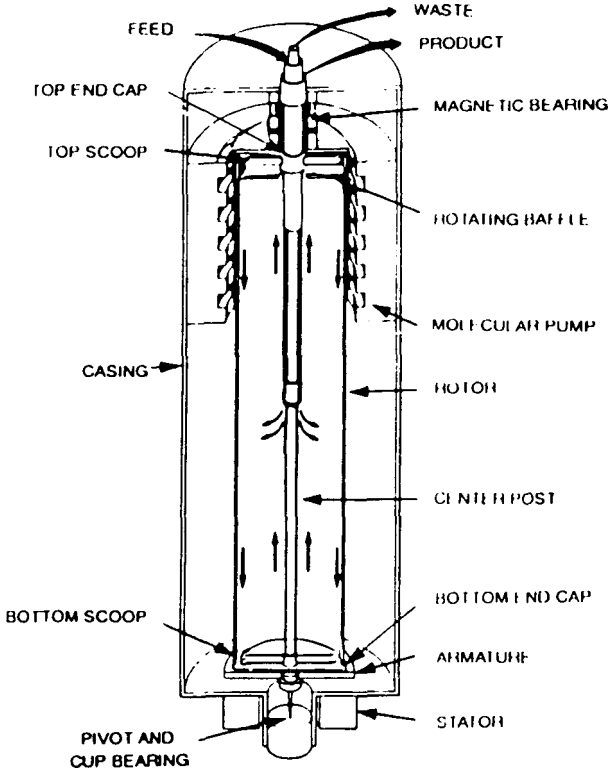


Fig. 17. Modern gas centrifuge.

The gaseous UF_6 feed, enriched, and depleted streams are introduced and withdrawn through a three-chambered stationary center post. The post penetrates into the centrifuge through an axial hole in the top end cap. The feed stream is introduced at a constant rate into the rotor through the center post. The enriched and depleted fractions are withdrawn at opposite ends of the rotor through stationary scoops that extend into the spinning gas. The scoop at one end also introduces aerodynamic drag which induces a circulatory countercurrent UF_6 gas flow.

The rotating components include the rotor, baffle, and end caps (top and bottom). The rotor is a thin-walled cylinder that is rotated inside the casing. It has a thickness of 12 mm or less and a diameter of 75 to 400 mm. The baffle is disc shaped and has holes to allow the gas to leak from the main rotor cavity into the area near the scoop. A baffle is needed at one end to keep the scoop from imposing a vertical flow that would counteract the circulatory flow generated by the scoop at the other end. The rotor is sealed at the top and bottom with disc-shaped end caps. The caps are especially designed to fit the ends of the rotor so that the UF_6 cannot escape from the rotor.

A molecular pump is used to maintain a low pressure between the rotor and the casing. Trace amounts of gas may leak from the interior of the rotor through the small annular gap around the stationary central post at the top of the centrifuge. This gas is confined to the cavity above the rotor by a close-fitting, spiral-grooved sleeve which serves as a very efficient pump. The cavity above the rotor is evacuated by an external vacuum system.

The top and bottom suspension systems serve several functions: (1) reliably support the rotor at full speed, (2) control the rotor at startup and run-down speeds, and (3) allow the rotor to rotate about its center of mass. The suspension consists of an oil-lubricated pivot and cup bearing at the bottom of the rotor and a magnetic bearing at the top of the rotor. The rotor spins about a thin, flexible steel needle that rotates in a hardened depression in a metallic plate at the base of the centrifuge. The bottom bearing assembly includes a mechanism for damping lateral and axial rotor vibrations. The magnetic bearing supports and centers the top end of the rotor without touching the rotating components. It provides some lift to relieve the load on the bottom bearing and dampens vibration by providing radial stabilizing forces.

The rotor is driven by an electric motor. The armature is a flat, hardened steel plate attached to the bottom of the rotor. The stator is fed by an alternator at a frequency synchronous with the rotor speed.

The outer casing provides a vacuum-tight enclosure for the rotor to minimize the drag on the rotating parts. This reduces the power consumption resulting from gas friction when the rotor is spinning. In addition, the casing must be leakproof and provide a physical barrier for protection from flying debris in the event of a machine failure. It is important to the operation of the plant that the failure of one machine does not cause the failure of adjacent machines.

Separative Capacity

The separative capacity of a gas centrifuge is greatly influenced by its rotational speed and the length of the rotor. Separative capacity is proportional to the rotor length and increases rapidly with rotor speed. The basic objective in designing a centrifuge is to produce the fastest and longest rotor possible at the lowest price.

The peripheral speed of the rotor is limited by the strength-to-density ratio of the rotor construction materials. The very high rotational speed of the centrifuge causes mechanical stresses in the outer wall. Aluminum alloys and stainless steels are capable of rotor peripheral speeds slightly in excess of 400 m/s. Peripheral speeds can exceed 500 m/s using maraging steels (strong, low-carbon steels which contain up to 25% nickel). Even higher speeds can be achieved using glass-fiber and carbon-fiber composites. The choice of materials suitable for centrifuge components is limited, however, because the UF_6 process gas (described in Sect. IV.B) is extremely corrosive.

The length of the rotor is limited by rotor dynamics. The rotor must be carefully balanced and damped to prevent wobbling and vibration. Major factors affecting the rotor dynamics include the straightness of the rotor, the uniformity of the wall, and the durability of the bottom bearing. Another concern with centrifuges that have a large length-to-diameter ratio is the problem of bringing them to operating speed. During acceleration, the rotor must transverse critical speeds at which severe vibrations can occur. Unless the vibration can be controlled by the use of damping bearings in the rotor suspension system, a centrifuge rotor might destroy itself while passing through the resonant speeds.

The physical size and separative capacity of gas centrifuges vary. European and Japanese centrifuges are relatively small (25 cm in diameter and 2 to 4 m long) and have separative capacities in the range of 5 to 30 SWU/year. The U.S.-designed centrifuges are substantially larger and have separative capacities up to 10 times larger.

Review Questions for Section III.B

1. What are the major components of a gas centrifuge?

2. What is the separative capacity of a gas centrifuge related to?

III.C Gas Centrifuge Cascade

OBJECTIVES

After completing this section, the student should be able to:

1. Describe a centrifuge cascade.

2. Compute the number of stages and stage concentrations to achieve a desired concentration span in a simple cascade.

3. Compute the material flow rate for each stage of a simple cascade and the number of centrifuges required per stage.

The capacity of a single gas centrifuge is limited (in terms both of separation factor and throughput) by mechanical considerations and, in the general case, is insufficient to accomplish low-enriched uranium production. Therefore, centrifuges are connected in series to achieve the desired concentration range and are connected in parallel to provide the desired material flow rate. Figure 18 illustrates the series and parallel arrangement of centrifuges in a cascade. The stages between the points where the feed is introduced and the product is withdrawn are called the "enriching stages" or more simply the "enricher." The stages between the points where the feed is introduced and the depleted stream is withdrawn are called the "stripping stages" or the "stripper."

Series Connections

The number of stages that are connected in series to form a cascade depends on the desired ^{235}U concentration of the feed, product, and tails streams and on the magnitude of the stage separation factor. To illustrate cascade arrangement, let us design a simple gas centrifuge cascade to produce nominal 3% product material and 0.25% tails material from natural feed. (These represent typical feed, product, and tails ^{235}U concentrations of a uranium enrichment plant supporting light-water reactor fuel production.) A separation factor of 1.5 is used for the example cascade.

In defining the separation factor, it is convenient to utilize the convention of abundance ratio to represent the ratio of the desired isotope concentration to the concentration of the nondesired isotope (i.e., the ^{235}U concentration divided by the ^{238}U

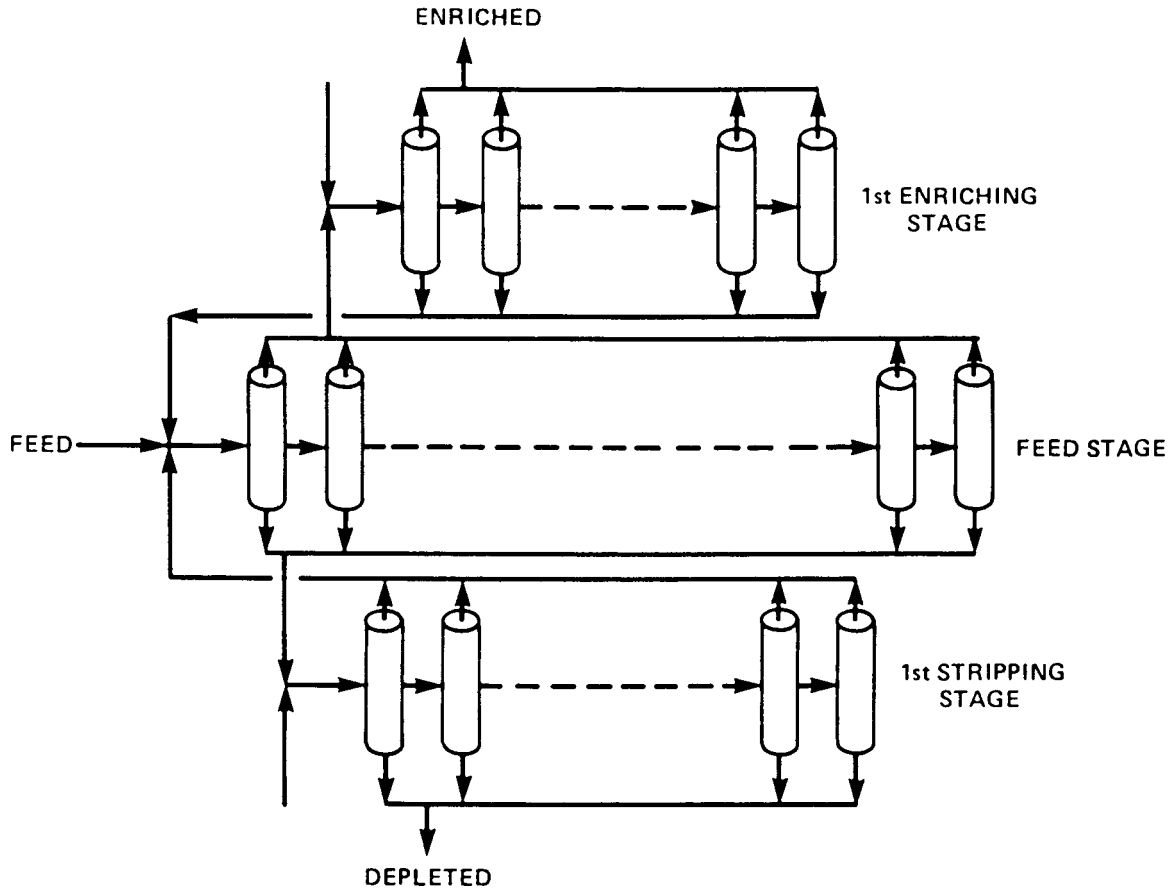


Fig. 18. Centrifuge cascade.

concentration). Because ^{235}U and ^{238}U are the dominate isotopes present, the ^{238}U concentration is approximated by one minus the ^{235}U concentration. Using the nomenclature introduced in Sect. II.D, the relevant abundance ratios are defined as:

$$R_{x_P} \equiv \frac{x_P}{1 - x_P} ,$$

$$R_{y_P} \equiv \frac{y_P}{1 - y_P} ,$$

$$R_{x_W} \equiv \frac{x_W}{1 - x_W} .$$

In terms of abundance ratios, the stage separation factor (α) is defined as

$$\alpha = \frac{R_{y_P}}{R_{x_W}} ,$$

which can be expressed as

$$\alpha = \left(\frac{R_{y_P}}{R_{x_F}}\right)\left(\frac{R_{x_F}}{R_{x_W}}\right) = (\alpha_E)\,(\alpha_S) .$$

In this form, the first term represents the enriching factor α_E (the degree of separation between the feed and the product) and the second term, the stripping factor α_S (the degree of separation between the feed and the tails). If the product and tails abundance ratios for the two separation factors (α_E and α_S) are replaced by the relationships from the definitions above and if the resulting expressions are solved for the product and tails concentrations, y_P and x_W, respectively, the following expressions result:

$$y_P = \frac{\alpha_E R_{x_F}}{(1 + \alpha_E R_{x_F})} , \tag{6a}$$

$$x_W = \frac{R_{x_F}}{(\alpha_S + R_{x_F})} . \tag{6b}$$

To illustrate the degree of separation that occurs in a single stage, let us calculate the enrichments of the product and tails streams of the feed stage in our centrifuge cascade. For calculational purposes, it is assumed that the separation is symmetric in an individual centrifuge. That is, the degree of enriching (α_E) is equivalent to the degree of stripping (α_S). Assuming symmetrical separation and α of 1.5, both α_E and α_S are $(1.5)^{1/2}$.

$$y_P = \frac{\sqrt{1.5}\left(\frac{0.0071}{1 - 0.0071}\right)}{1 + \sqrt{1.5}\left(\frac{0.0071}{1 - 0.0071}\right)} = 0.0087 ,$$

$$x_W = \frac{\left(\frac{0.0071}{1 - 0.0071}\right)}{\sqrt{1.5} + \left(\frac{0.0071}{1 - 0.0071}\right)} = 0.0058 .$$

In a single gas centrifuge with a separation factor of 1.5, natural feed (with a ^{235}U concentration of 0.71%) will be enriched to 0.87% and stripped to 0.58%.

Equation (6a) can be used to calculate the product enrichment of each successive enriching stage of our cascade; Eq. (6b) can be used to calculate the tails concentration of each stripping stage. As shown in Fig. 19, 11 stages are required to achieve the desired concentration span. Using natural feed material, the product concentration of the cascade is 2.87% ^{235}U, and the tails concentration is 0.259% ^{235}U.

Stages are cascaded so that the enriched stream of a stage is introduced as feed material to the next stage and the depleted stream is introduced as feed material to the previous stage. In other words, the feed material to a specific stage is composed of enriched material from the previous stage and depleted material from the next stage. With this arrangement only streams of identical isotopic concentrations are blended, which minimizes separative work losses resulting from mixing streams of differing concentrations. The enriched stream concentration from a stage matches the feed stream concentration to the next stage, and the depleted stream concentration matches the feed stream concentration to the previous stage.

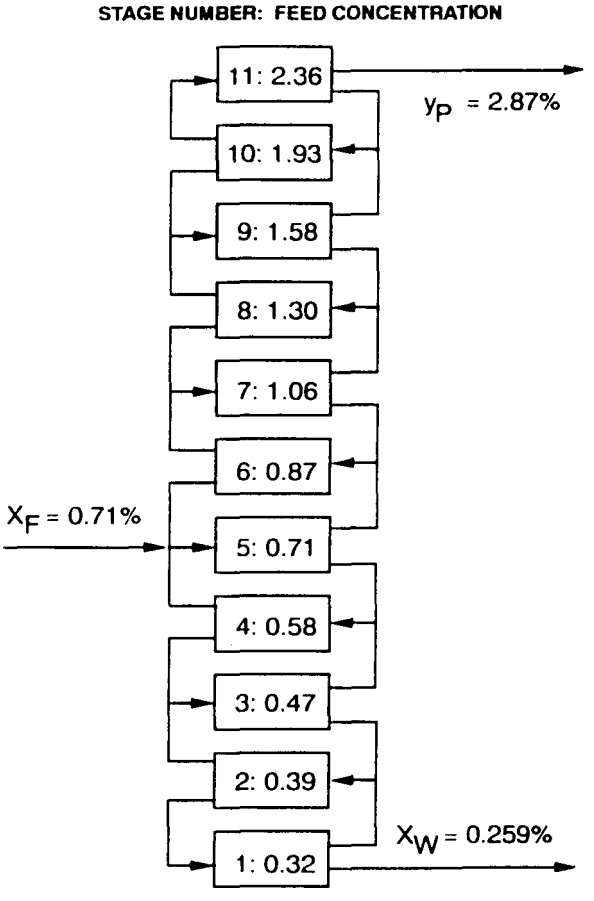


Fig. 19. Stage enrichments for a gas centrifuge cascade with a separation factor of 1.5.

Parallel Connections

The number of centrifuges that are connected in parallel in each stage depends on the desired product withdrawal rate from the cascade and the throughput of the individual centrifuges. Each centrifuge connected in parallel has the same values for the feed stream rate and concentration, enriched stream rate and concentration, and depleted stream rate and concentration. A typical throughput for a modern gas centrifuge is 0.02 g U/s or 1.728 kg U /day.

The material flow rates (and the number of centrifuges connected in parallel) are different for each stage to ensure that the streams between stages match concentrations. The material feed rate to a specific stage is dependent on the separation factor, the isotopic concentrations of the streams, and the flow rates of the exiting streams. Equations (7a) and (7b) are simplified equations for calculating the feed flow rates in the enriching and stripping sections, respectively.

In the enriching section,

$$F_{Stage} = P_{Stage}\left(\frac{\alpha_E + 1}{\alpha_E - 1}\right)\left(\frac{y_P - x_F}{x_F\,(1 - x_F)}\right). \qquad (7a)$$

In the stripping section,

$$F_{Stage} = W_{Stage}\left(\frac{\alpha_S + 1}{\alpha_S - 1}\right)\left(\frac{x_F - x_W}{x_F\,(1 - x_F)}\right). \qquad (7b)$$

To illustrate the difference in flow rates between stages, let us calculate the flow rate and determine how many centrifuges are required for each stage of our example centrifuge cascade. The first step is to establish the quantity of material to be withdrawn from the cascade. Let us assume that the desired cascade product withdrawal rate is 80 kg U/day. Knowing that the desired product rate for the top stage (stage 11) is 80 kg U/day and the feed and product concentrations are 2.357% and 2.87%, respectively, the required feed flow rate to the top stage can be calculated from Eq. (7a) as follows:

$$F_{Top\ stage} = 80\ \frac{kg\ U}{day}\left(\frac{\sqrt{1.5} + 1}{\sqrt{1.5} - 1}\right)\left(\frac{0.0287 - 0.02357}{0.02357\,(1 - 0.02357)}\right) = 177\ \frac{kg\ U}{day}.$$

To achieve a product withdrawal rate of 80 kg U/day, the required feed flow rate for stage 11 is 177 kg U/day. The number of centrifuges required to be connected in parallel in stage 11 is calculated by dividing the desired material flow rate by the centrifuge throughput.

$$\frac{177\ kg\ U/day}{1.728\ kg\ U/day/centrifuge} = 102\ centrifuges\ .$$

A total of 102 centrifuges must be connected in parallel in stage 11 to carry a material flow rate of 177 kg U/day. Figure 20 shows the basic arrangement of our cascade, and lists the feed flow rate and number of centrifuges required for each stage. The cascade is composed of 7896 centrifuges arranged in 11 stages. Because the amount of material fed into each stage is different, the width of each stage (i.e., number of centrifuges in parallel) is different. Note that the feed stage to the cascade (stage 5) has the largest material flow rate and, therefore, has the greatest number of centrifuges connected in parallel. One additional point: all individual centrifuges in a cascade are physically identical. From visual observation, one cannot distinguish the isotopic concentrations or flow rate of the process gas contained within a centrifuge, stage, or cascade.

The remaining operating parameters of the example cascade can be defined using the material balance equations in Sect. II.D. The cascade feed and tails flow rates can be calculated using Eqs. (3) and (1) by substituting the desired product withdrawal rate for the cascade and calculated cascade product and tails concentrations:

$$F_{Cascade} = 80\ \frac{kg\ U}{day}\left(\frac{0.0287 - 0.00259)}{0.0071 - 0.00259)}\right) = 463\ \frac{kg\ U}{day}\ ,$$

$$W_{Cascade} = 463\ \frac{kg\ U}{day} - 80\ \frac{kg\ U}{day} = 383\ \frac{kg\ U}{day}\ .$$

The separative work is computed using Eq. (4):

$$\begin{aligned}\Delta U &= 80\ V(0.0287) + 383\ V(0.00259) - 463\ V(0.0071)\\ &= 80\ (3.319) + 383\ (5.923) - 463\ (4.870)\\ &= 279\ SWU/day,\ or\ \sim\ 102{,}000\ SWU/year\ .\end{aligned}$$

Stage number	Feed concentration (% ^{235}U)	Feed flow rate (kg U/day)	Number of centrifuges
11	2.36	177	102
10	1.93	392	227
9	1.58	654	379
8	1.30	974	564
7	1.06	1365	790
6	0.87	1843	1066
5	0.71	2428	1405
4	0.58	2115	1224
3	0.47	1733	1003
2	0.39	1266	733
1	0.32	697	403
		Total	7896

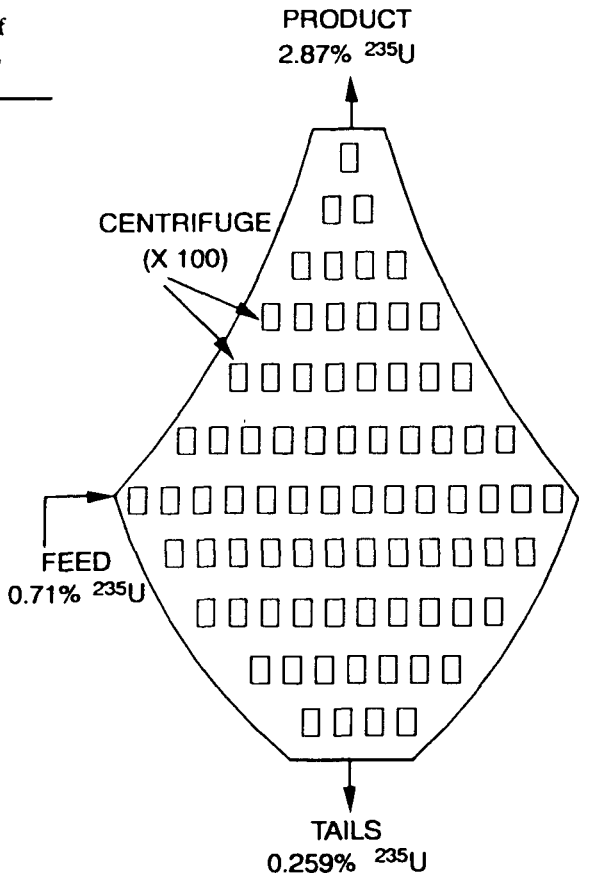


Fig. 20. Basic cascade arrangement.

The average separative work of an individual centrifuge is approximated by dividing the separative work of the cascade by the number of centrifuges.

$$\frac{102{,}000\ SWU/year}{7{,}896\ centrifuges} = 12.9\ \frac{SWU/year}{centrifuge}\ .$$

The equations for flow rates and stage concentrations presented in this section assume a simple three-stream cascade in which streams of differing isotopic concentration are never mixed together. In practice, cascades may have more than one feed point as well as more than one product withdrawal point, and some separative work losses are sustained due to mixing. In addition, operating centrifuges differ slightly in manufacturing characteristics or

operating conditions and therefore may differ slightly in flow rates or composition. Great care is taken to minimize differences between centrifuges during the design and manufacturing so that the concentrations of the enriched and depleted streams withdrawn from individual centrifuges connected in parallel match.

A plant designed for the production of 100,000 SWU/year can be arranged as a single high-throughput cascade or as multiple low-throughput cascades connected in parallel. The plant, in either arrangement, contains the same number of stages to span a desired enrichment range. However, each stage in the single high-throughput cascade is comprised of hundreds to thousands of centrifuges. This cascade arrangement has the advantage that the random failure of a few centrifuges does not affect the overall cascade performance. The disadvantage, however, is that one large cascade does not permit production flexibility. In practice, the 100,000-SWU/year plant would be composed of a number of small cascades operating in parallel. The individual stages of these small cascades are comprised of tens to hundreds of machines. If each small cascade is identical and produces the same product and tails concentrations as the described single large cascade, the sum of the outputs from each small cascade is equivalent to the output of the single large cascade. The advantages of multiple parallel cascades are easier maintenance (e.g., a single cascade can be taken off-stream for repairs) and production flexibility (e.g., a variety of product enrichments can be produced). The disadvantage is that the failure of several machines may affect cascade performance. In practice, the operational flexibility of a multiple cascade plant far outweighs the disadvantage of reduced cascade performance due to failed machines.

Review Questions for Section III.C

1. Why are centrifuges connected in series?

2. Why are centrifuges connected in parallel to form stages?

3. Are the centrifuges located at the product end of the cascade physically different from those at the tails end?

4. What stage in a simple cascade contains the most centrifuges?

5. What are the advantages of using multiple small cascades connected in parallel?

IV. GAS CENTRIFUGE ENRICHMENT PLANT DESCRIPTION

IV.A Facility Layout

OBJECTIVES

After completing this section, the student should be able to:

1. Identify the support facilities required for a gas centrifuge enrichment plant.

2. Describe the material flows between the process buildings and support facilities of a centrifuge plant.

3. Understand the forms and concentrations of the nuclear material flows between process and support areas.

The operation of a gas centrifuge enrichment plant requires many process and support facilities and involves a variety of nuclear materials flows. Figure 21 is a layout of a typical gas centrifuge enrichment plant showing the process and support facilities and depicting material flows between these areas. Included are:

1. weighing and sampling areas,
2. cylinder storage areas,
3. feed and withdrawal areas,
4. cascade halls,
5. analytical laboratory,
6. decontamination and maintenance areas, and
7. scrap recovery and waste treatment areas.

Major nuclear material flows at a gas centrifuge enrichment facility include receipt of UF_6 feed material on-site, transfer of feed material from UF_6 cylinders to the process system, transfer of enriched and depleted process gas to product and tails cylinders, and shipment of product cylinders off-site (Fig. 22). Minor material flows include sample transfers to the analytical laboratory, process equipment transfers for decontamination and repair, and waste transfers to the scrap recovery and waste treatment areas (Figs. 23 and 24). It should be noted that not all identified flows or areas will exist at every centrifuge facility.

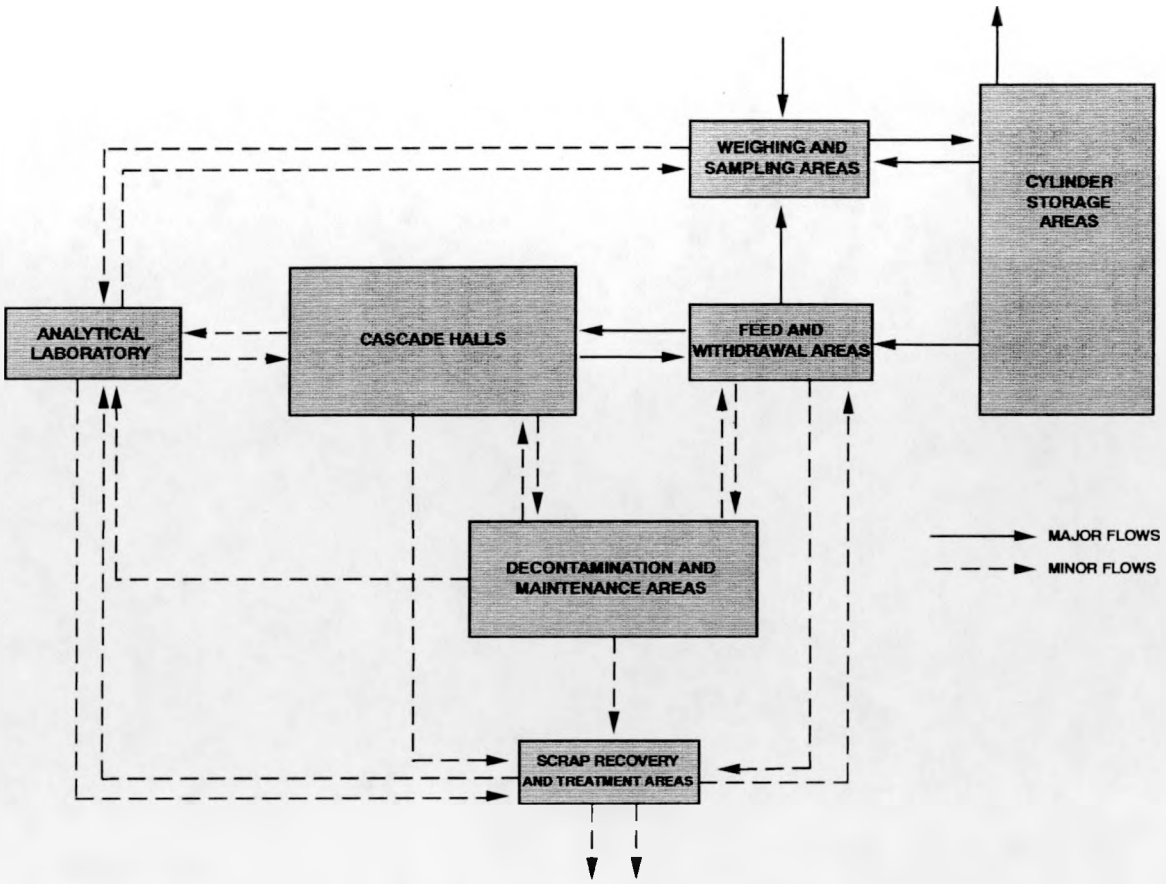


Fig. 21. Process and support facilities at a typical gas centrifuge enrichment plant.

Weighing and Sampling Areas

In the weighing and sampling areas, UF_6 cylinders are weighed and sampled to establish nuclear materials accountability values and to verify customer product specifications. Full and empty UF_6 cylinders are weighed prior to being transferred to the cylinder storage areas. Samples are withdrawn from full cylinders (generally product and feed) and sent to the analytical laboratory for destructive analysis. Also, the UF_6 from several cylinders of varying enrichment may be blended in this area to customize the product concentration.

Cylinder Storage Areas

A single centrifuge plant may have multiple storage areas (both indoors and outdoors) for its on-site cylinder inventory. The cylinder inventory supporting the major UF_6 flows

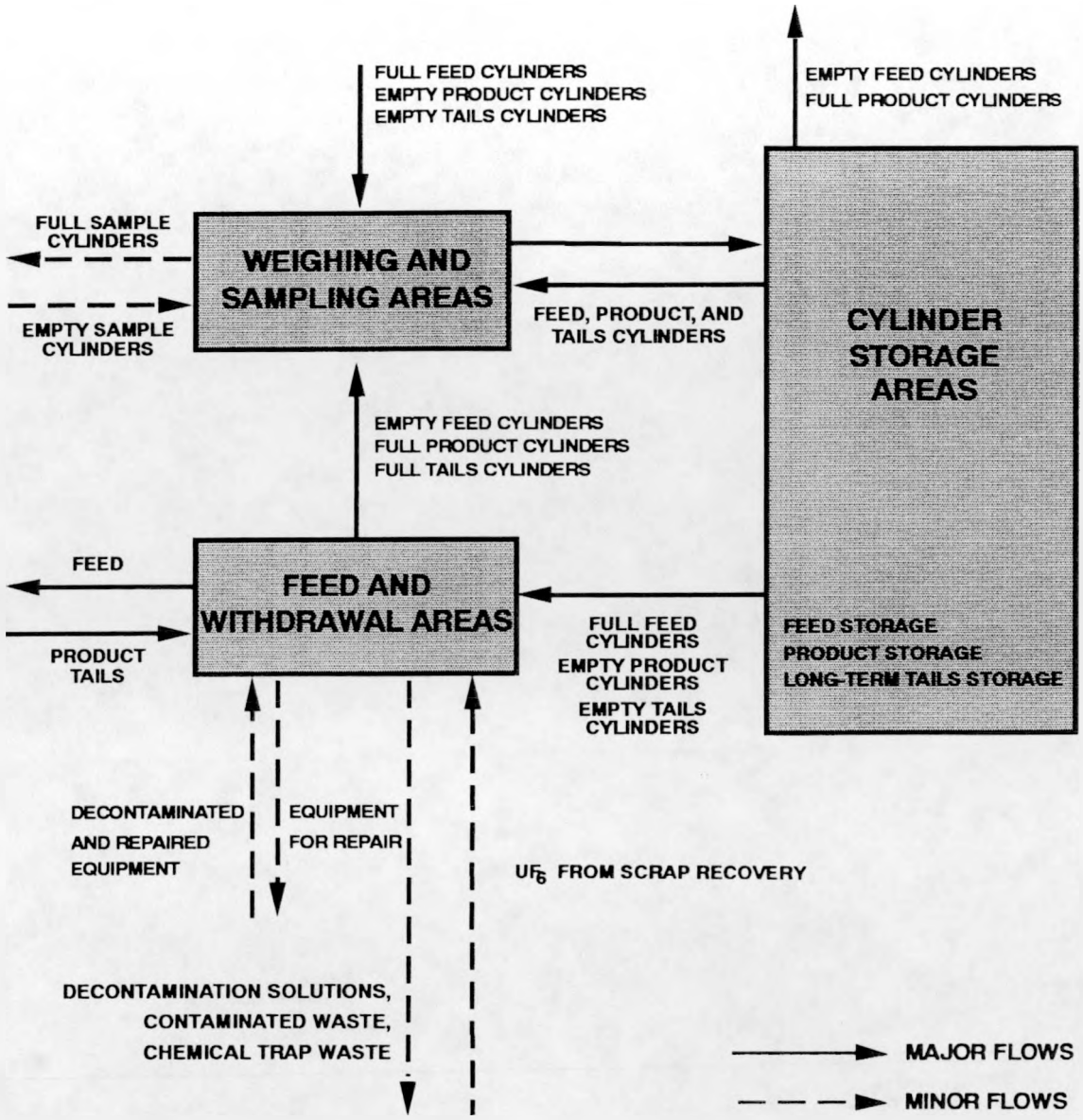


Figure 22. Major nuclear material flows at a typical gas centrifuge enrichment plant.

consists of (1) full feed cylinders waiting to be fed to the process; (2) empty feed cylinders awaiting shipment off-site; (3) empty product and tails cylinders for filling; (4) full product cylinders for further processing (e.g., blending or rebatching), storage, or shipment off-site; and (5) full tails cylinders which generally remain in an outdoor cylinder yard at the plant for long-term storage. Full feed, product, and tails cylinders contain UF_6 in the solid state. The empty product and tails cylinders are usually clean (i.e., contain no residual uranium or

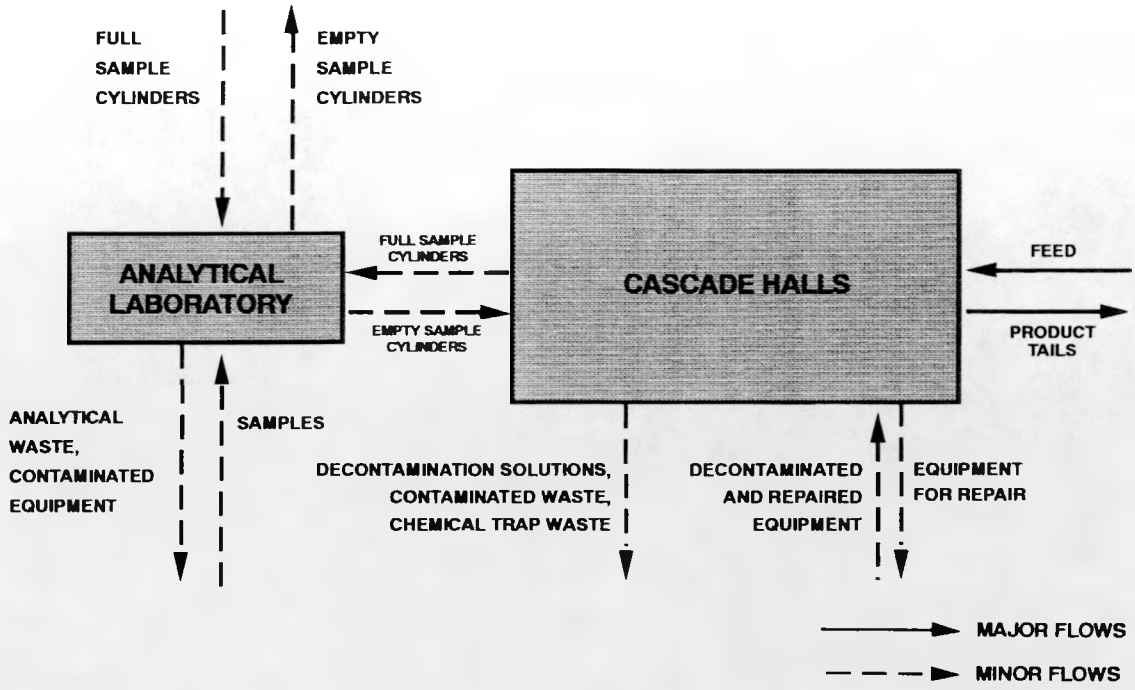


Figure 23. Minor nuclear material flows at a typical gas centrifuge enrichment plant.

contaminants). The empty feed cylinders, however, contain a residual amount of UF_6 and nonvolatile reaction products of uranium called ***heels***. Heels material is present because it is not practical to completely empty the UF_6 from a cylinder during the feeding process.

Feed and Withdrawal Areas

In the feed area, cylinders containing feed material are placed in heating stations where they are heated to convert the UF_6 from solid to gas. The gaseous UF_6 passes through piping to a pressure-reduction station and is withdrawn into pipes leading into the cascade halls. The pressure-reduction station and the piping leading to it are heated to prevent the gaseous UF_6 from cooling and solidifying in the pipes and valves. Heating is not required downstream from this station because the UF_6 is at low pressures and remains gaseous at ambient temperatures.

In the withdrawal areas, cylinders are filled with the product and tails material. After the enriched and depleted streams leave the cascades, they are collected in desublimers where the gas solidifies. When full, the desublimers are heated and the UF_6 is transferred, either as a gas or liquid (depending on the system), to empty cylinders where it solidifies. At some

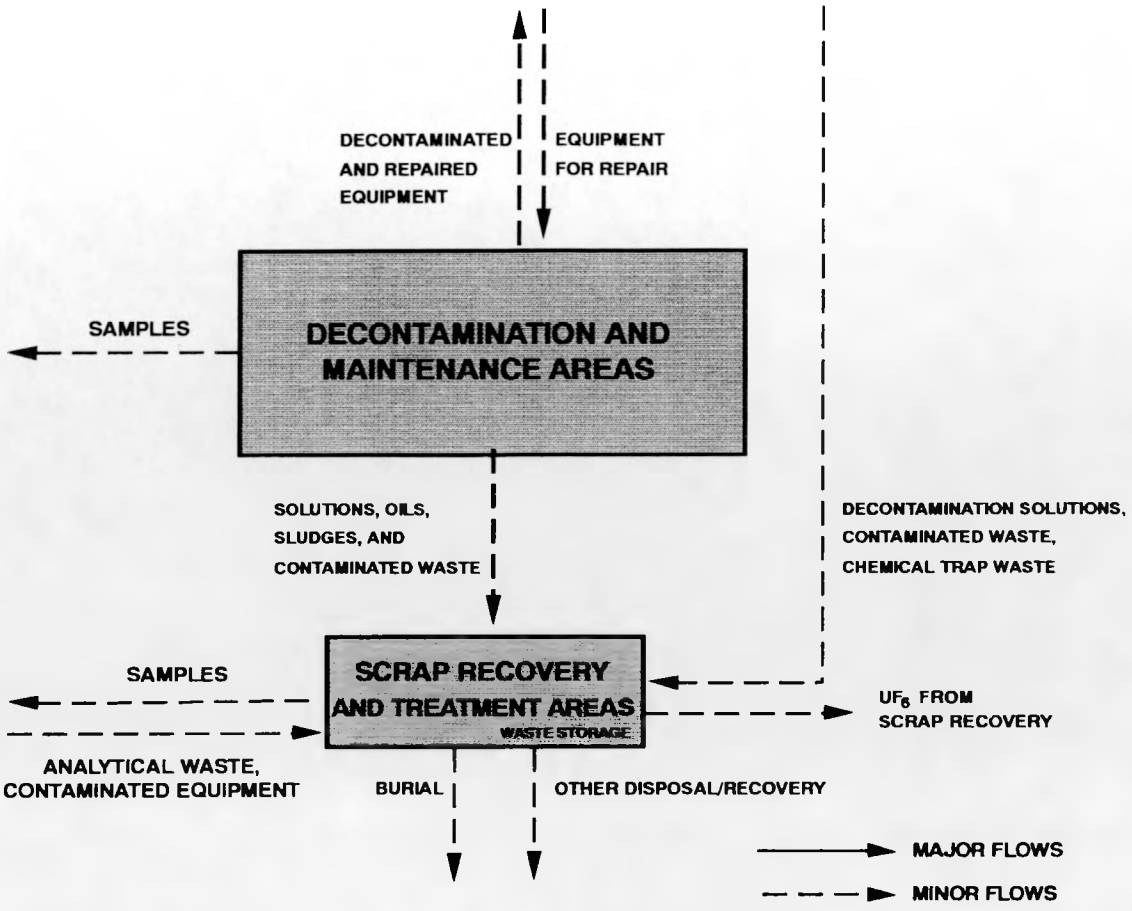


Figure 24. Minor nuclear material flows at a typical gas centrifuge enrichment plant.

facilities, a compressor system may be used instead of desublimers to collect the product and/or tails material.

Cascade Halls

The cascade halls contain the centrifuge machines arranged in cascades. Each hall may house a number of cascades connected in parallel. Feed material is transferred to the cascade halls from the feed stations in process header piping. Likewise, enriched and depleted process material is transferred separately from the cascades to the desublimer stations in product and tails header piping. Because the process gas remains at low pressures in the cascade header piping and centrifuge machines, it is not necessary to heat the cascade hall process system to keep the UF_6 in the gas-phase. Because a parallel grouping of cascades

can be operated independently to produce a specific product enrichment, separate product desublimer stations may service a single cascade hall.

Analytical Laboratory

The analytical laboratory provides on-site capability to destructively analyze process and waste materials. Standard analyses performed on a sample include: (1) the determination of the uranium concentration by the gravimetric method, (2) the determination of the isotopic abundances and ^{235}U content by gas-phase mass spectrometry, and (3) the determination of impurity content by a variety of techniques. Samples that may require analyses include UF_6 samples from feed, product, and tails cylinders; process gas samples from the cascades; and other uranium-bearing samples from scrap materials.

Decontamination and Maintenance Areas

The decontamination and maintenance areas provide facilities where plant equipment that has been in contact with UF_6 (e.g., containers, pumps, and valves) is stored, disassembled, decontaminated, repaired, and tested as needed. Other operational materials that have been in contact with UF_6 (e.g., vacuum pump oil) may also be decontaminated prior to further use or disposition. Only small quantities of uranium are contained in these areas.

Scrap Recovery and Waste Treatment Areas

The scrap recovery and waste treatment areas serve as the collection and processing point for all scrap and waste streams. Scrap and waste materials from all areas in the plant are collected and stored until recovery or disposal occurs. Typical materials include contaminated burnable and nonburnable wastes; alumina and/or sodium fluoride from chemical traps; decontamination solutions, other solutions, oils, and sludges from the decontamination and maintenance areas; and samples and analytical wastes from the analytical laboratory.

Summarized in Table 4 are the form, containment, and enrichment of the process material contained in each of the typical areas described for a gas centrifuge enrichment plant.

Table 4. Process material form, containment, and enrichments

Building or areas	Form	Enrichment
Weighing and sampling	Solid, liquid, and gaseous UF_6 in cylinders	Feed, product, or tails
Cylinder storage	Solid UF_6 in cylinders	Feed, product, or tails
Feed and withdrawal	Solid, liquid, and gaseous UF_6 in desublimers and cylinders	Feed, product, or tails
Cascade halls	Gaseous UF_6 in process piping and centrifuges	All enrichments ranging from tails to product
Analytical laboratory	Solid and liquid solutions	All enrichments ranging from tails to product
Decontamination and maintenance	Wide variety of solid uranyl compounds and solutions	All enrichments ranging from tails to product
Scrap recovery and waste treatment	Solids and solutions	All enrichments ranging from tails to product

Review Questions for Section IV.A

1. What process and support facilities would you expect to see at a gas centrifuge enrichment facility?

2. What are the major nuclear material flows at a gas centrifuge enrichment plant? What are typical minor nuclear material flows?

3. What is the form of the process material when it is in the cascade hall?

IV.B Process Material

OBJECTIVES

After completing this section, the student should be able to:

1. Describe the physical, chemical, and toxic properties of UF_6.

2. Identify the advantages of using UF_6 as a process gas.

3. Understand the safety concerns associated with handling UF_6.

As described in Sect. II.C, uranium isotope separation using the gas centrifuge enrichment technique relies on the difference in the mass of the $^{235}UF_6$ and $^{238}UF_6$ molecules that are mixed together in the process gas. The advantages of UF_6 as a process gas for uranium enrichment are (1) the difference in mass between the $^{235}UF_6$ and $^{238}UF_6$ molecules is due entirely to the uranium isotopes because fluorine has only one natural isotope, (2) UF_6 exists in a gaseous form at practical operating temperatures and pressures, and (3) UF_6 has a single molecular structure so it is easy to produce at high purity levels. The disadvantages of UF_6 are that it is very reactive chemically and highly corrosive. Its use in uranium enrichment requires special materials of construction, entails special operating techniques, and places limitations on operating temperatures and pressures.

Physical Properties

At room temperature, UF_6 is a colorless, high-molecular-weight solid with significant vapor pressure. This statement immediately implies that one will not be handed a bag containing UF_6 or a bottle of liquid UF_6 but rather will probably receive UF_6 as a condensed solid contained in a metal or Teflon tube sealed by a valve or clamp.

As indicated in the phase diagram of pure UF_6 (Fig. 25), the sublimation temperature of UF_6 is below the triple point. The ***sublimation temperature*** is the lowest temperature at which the vapor pressure of the solid equals atmospheric pressure. When UF_6 is in equilibrium at atmospheric pressure, solid UF_6 sublimes directly to the gaseous state without passing through the liquid state. The ***triple point*** is the temperature and pressure at which solid, liquid, and vapor exist in equilibrium. To handle UF_6 as liquid, the pressure must be above 0.15 MPa (1137.5 torr) and the temperature must be above 64°C. Thus, any liquid process (e.g., feed cylinder heating, product cylinder liquid filling) will be subject to leakage

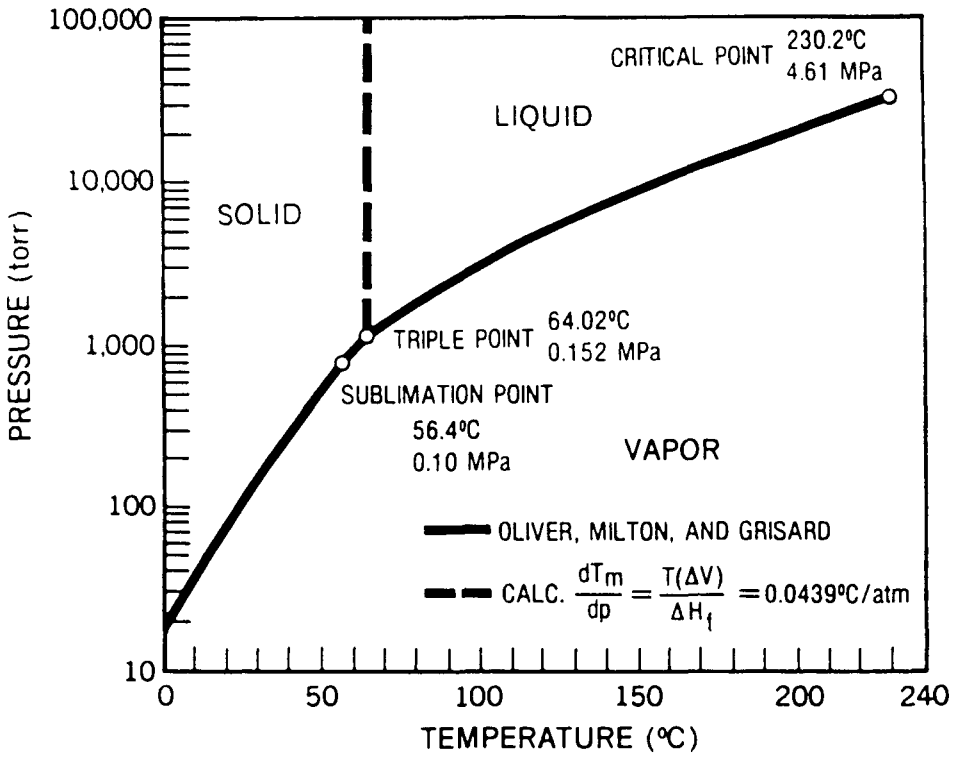


Fig. 25. UF_6 phase diagram.

of the UF_6 to the atmosphere if equipment is breached. Transfer below 0.15 MPa or below 64°C involves the formation of the gas through sublimation and desublimation of the gas to a solid on a cooled surface. The ***critical point*** is the temperature and pressure above which liquid and vapor are indistinguishable.

The physical characteristics and phase-change conditions of UF_6 are summarized in Tables 5 and 6. The large difference in density between solid and liquid UF_6 has implications for filling UF_6 cylinders. Sufficient space must be maintained in a UF_6 container to provide for liquid expansion for the temperature range over which the liquid is to be heated. Particular attention must be paid to the fill limits of containers when UF_6 is desublimed as solid, liquid filled in layers, or liquid filled at lower than normal temperatures. When the contents are liquified for removal, the volume required for liquid UF_6 at 100°C is 50% greater than the volume of UF_6 in the solid state. If this difference in volume is not accounted for, the cylinder may rupture when it is heated.

Table 5. Physical characteristics of UF_6

Physical State	Appearance	Density
Solid	White	5.09 g/cm^3 @ 20°C
Liquid	Clear	3.40 g/cm^3 @ 100°C
Gas	Colorless	

Table 6. Phase-change conditions of UF_6

Sublimation point	56.4°C @ 0.10 MPa (760 torr)
Triple point	64.02°C @ 0.152 MPa (1,137.5 torr)
Critical point	230.2°C @ 4.61 MPa (34,600 torr)

Chemical Properties

UF_6 is a stable chemical if contained in a scrupulously clean system. It is also a mild fluorinating agent that reacts vigorously with many chemicals that might be encountered. UF_6 reacts chemically with water, ether, and alcohol forming soluble reaction products. It reacts with most organic compounds, glass, rubber, and many metals. UF_6 does not react with oxygen, nitrogen, hydrogen, or dry air at room temperature. UF_6 is relatively inert to clean and dry aluminum, copper, nickel, Monel, and Teflon; thus these materials can be exposed to UF_6 without excessive corrosion.

The most common UF_6 reaction is with water, which is commonly present in moist air and on the interior surfaces of metal containments previously exposed to moist air. UF_6 reacts with the water vapor to form solid uranyl fluoride (UO_2F_2) and toxic hydrogen fluoride (HF) gas. The inner surfaces of metals used to contain UF_6 may be coated with oxides and hydroxides with which UF_6 will react at rates that depend on temperature. UF_6 can also react with pure metal. Possible reaction products include UF_5, U_2F_9, and UF_4. Finally, UF_6 reacts with many other chemicals that might be encountered during its transport through metal components such as grease, organic chemicals introduced during manufacturing, or solvents used to clean the metal.

The chemical reactions of UF_6 are a very important aspect of uranium enrichment because these reactions lead to the loss of process material. These losses are usually defined as corrosion and consumption losses. ***Corrosion*** losses are due to the reaction of UF_6 with the metal within which it is contained. Materials resistant to corrosion include stainless steel, aluminum, aluminum alloys, nickel, and alloys containing greater than 60% nickel. ***Consumption*** losses are due to all mechanisms such as the reaction of UF_6 with surface impurities, water, organic compounds, and inorganic materials, as well as metal corrosion. Consumption is affected by several variables including temperature, UF_6 pressure, prior exposure of the equipment to air or other gases, the environment of this exposure (e.g., dry or wet gas), and the interior surface areas.

Toxic Properties

UF_6 as a gas is a moderately toxic material, partly because uranium is a heavy-metal poison and partly because its reaction with water in the respiratory system produces the irritating and burning hydrofluoric acid. When released to the atmosphere, gaseous UF_6 quickly reacts with atmospheric moisture to form a visible white cloud consisting of HF gas and particulate UO_2F_2, which tends to settle on surfaces. The corrosive properties of UF_6 and HF are such that exposure to a severe release can result in skin burns and temporary lung impairment. Like most heavy-metal compounds, water-soluble uranium compounds such as UO_2F_2 are toxic to the kidneys when inhaled or ingested in large quantities. Fortunately, uranium has a very short biological half-life of ~ 15 days and is rapidly eliminated from the body by kidney action.

Exposure to UF_6 is also a radiological concern because UF_6 is an alpha, beta, and gamma-ray emitter. Alpha particles resulting from the primary disintegration of uranium present no external radiation problem because they do not penetrate the skin. However, the decay products of uranium found in process piping and UF_6 cylinders include isotopes that emit mildly penetrating beta rays and highly penetrating gamma rays. The UF_6 cylinders are the greatest radiological concern because they contain a large quantity of UF_6. In addition, the nonvolatile materials concentrate in the cylinder heels. Ironically, the radiation level emanating from a full cylinder may be less than that from an empty cylinder with a heel because the decay products are dispersed through the UF_6 in a full cylinder and are shielded to some extent. Radiation exposures of employees working around UF_6 cylinders are easily controlled at very low levels through conventional distance-time limitations.

Safety Guidelines

The implications of the properties of UF_6 can be summarized in terms of the following rules:

1. UF_6 should not be exposed to moisture; it should be handled in a sealed system (preferably a metal system) having vacuum capability to aid in transfers. Liquid transfers are possible in a system that can be operated above ~ 0.152 MPa (1137.5 torr) and 64°C.

2. In the event of a release, UF_6 or its reaction products should not be inhaled because they are toxic.

3. It is extremely important that UF_6 cylinders not be overfilled because the volume required for liquid UF_6 is greater than the volume required for solid UF_6.

4. UF_6 cylinders should not be connected directly to vacuum pumps because of the possibility for hydrocarbon oil to contaminate the cylinder. Liquid UF_6 and organic materials, other than fluoroplastics, can react violently.

UF_6 can be handled safely by careful attention to the suggested precautions.

Review Questions for Section IV.B

1. What characteristics make UF_6 attractive for use as a process gas?

2. What are the physical characteristics of UF_6 in the solid, liquid, and gaseous states?

3. What is the most common UF_6 reaction?

4. What are the chemical and radiological concerns with UF_6?

5. What safety precautions does an enrichment plant operator follow in handling UF_6?

IV.C Cascade Enrichment

OBJECTIVES

After completing this section, the student should be able to:

1. Describe the piping arrangements in a gas centrifuge cascade and cascade hall.

2. Describe the typical operations in a cascade hall.

Process Equipment

The actual work of enriching the UF_6 gas occurs in the cascade halls of the centrifuge enrichment plant. The major process equipment found in every cascade hall includes the centrifuge machines and the process piping. Most cascade halls also contain machine-cooling water pipes (to control the temperature in the centrifuges), vacuum lines (to evacuate and to maintain the vacuum in the centrifuge casings), and plant support systems (e.g., fire water pipes; heating, ventilation, and air conditioning pipes). Some cascade halls may contain the vacuum pumps and chemical traps of the centrifuge casing evacuation system and sampling lines for an automated process monitoring system.

During facility startup, portable UF_6 feed and/or withdrawal carts may be used in the cascade halls to evacuate the cascades and to fill the cascades with UF_6. This permits the cascade to be operated in the recycle mode to achieve its designed product enrichment before UF_6 is introduced to the process system through the feed and withdrawal system. In addition, these portable carts can be used for cascade maintenance activities and to independently operate a cascade in the throughput mode. The equipment on a feed cart includes a cylinder heating enclosure, air heater and blower, temperature sensor, vacuum pump, chemical trap, pressure sensors, piping, and valving. The equipment on a withdrawal cart includes a cold trap, refrigerant unit, evacuation pump, chemical trap, pressure gages, and connectors. The carts are typically mounted on wheels and are equipped with interfaces to the building's electrical and instrument air systems.

Cascade Arrangement

In practice, the cascades in a centrifuge plant are arranged to balance performance efficiency and operational flexibility. To produce a product flow rate that is practical for withdrawal, several cascades with identical arrangements are connected in parallel to form production units. Each cascade of a production unit contains a few thousand (or less) centrifuges, receives the same feed concentration, and produces the same product and tails concentrations. The current commercial centrifuge enrichment plants contain multiple production units, each comprised of less than ten cascades. Production units may be operated independently to provide a quantity of material at a specific product enrichment or in parallel to increase the throughput at that product enrichment (Fig. 26). The advantages of production units include the capability (1) to produce enrichment revenue before the entire plant is completely operational, (2) to produce a variety of product enrichments to meet customer product specifications, and (3) to enrich recycled material (i.e., UF_6 from reprocessed uranium) separately. In addition, the size of the plant can be tailored to meet current and future market needs.

Process Piping

The process gas transferred to the cascades halls from the feed area is contained in primary feed pipes at low pressures. Multiple feed pipes may be present to supply material at different concentrations to separate production units or set of production units (one pipe may be used to feed all of the production units if the feed material is of the same concentration and purity). The unit feed header pipe is connected to the cascade feed header pipes for each of the parallel cascades in that production unit. Here the gas pressure is further reduced to achieve cascade operating pressure.

The feed gas to the cascade enters the feed stage header and is distributed to each centrifuge in the stage. After processing, the enriched gas from each centrifuge in the feed stage enters the stage product header; simultaneously, the depleted gas from each feed stage centrifuge enters the stage tails header (Fig. 27). The stage product header becomes the feed header for the next stage in the cascade; the stage tails header becomes the feed header for the previous stage. The gas is similarly processed through the enriching and stripping stages to achieve the desired concentration range. The product header of the top stage in the cascade is the cascade product header and empties into the unit product header; the tails header of the bottom stage is the cascade tails header and empties into the unit tails header.

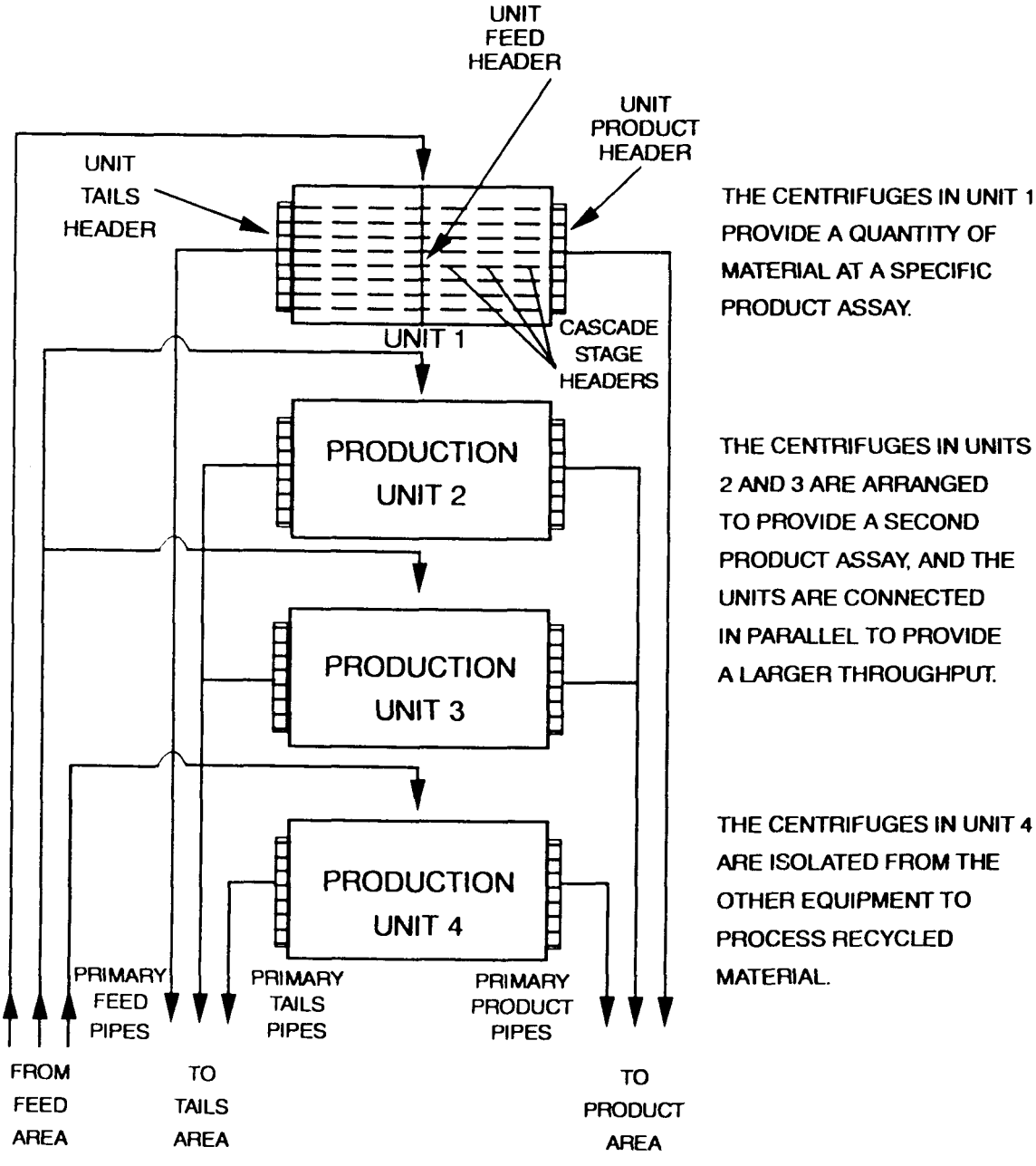


Fig. 26. Schematic illustrating how production units can be operated independently or in parallel. Each unit contains multiple cascades connected in parallel.

The material in the unit headers is transferred directly to the withdrawal areas through primary product and tails withdrawal pipes. (If the product and tails concentrations for the production units are identical, there may be only one primary product pipe and one primary tails pipe.)

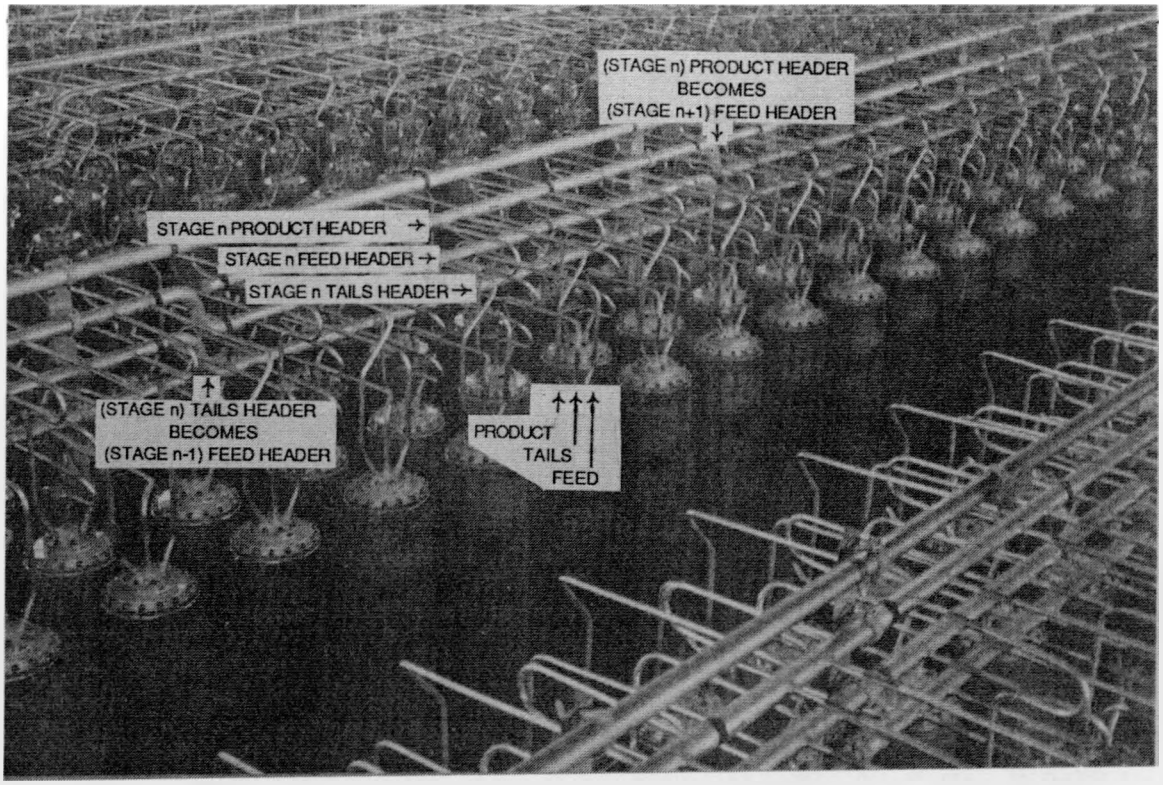


Fig. 27. Stage header piping in centrifuge cascade.

Each cascade contains two additional piping-structure components of safeguards interest. First are the evacuation and sampling ports. These ports are used to evacuate the process system before operation begins, to remove process samples from the cascade while it is operating, and to remove process gas prior to maintenance activities. The cascade feed header port can also be used to fill the cascade with process gas. Depending on the design of the cascade, only one port may be present on each header or there may be multiple ports throughout the cascade to permit the withdrawal of samples from individual stages. Second is the cascade recycle line that joins the cascade product and tails headers to the feed header. With proper setting of the header pipe valves, the cascade can run indefinitely on the same process gas by continuously recycling it. The recycle mode of operation is generally used to permit a cascade to reach the design product and tails concentrations (e.g., initial startup or restart following maintenance) before the cascade output is introduced to the process system and when the cascade is in standby mode.

Cascade Hall Operations

When entering the cascade halls, what would one expect to see? Assuming that the cascade halls are fully operational and no maintenance or construction work is occurring, one would see parallel rows of centrifuges with stage header piping, casing evacuation piping, and utility piping running parallel to the rows. Unit header pipes (feed, product, and tails) run perpendicular to the end of each row. If the centrifuge casing evacuation system is located in the cascade hall, one would also see vacuum pumps and chemical traps at the ends of the rows of centrifuges. If not, evacuation headers would be located with the other unit header pipes. One would not expect to see personnel, UF_6 cylinders, portable feed and withdrawal carts, or any other process or maintenance equipment. One might also observe failed centrifuges (with crimped process piping) that were left in place after failure. No manual operations, except occasional inspections and process sampling, are routinely performed in a completed cascade hall.

Review Questions for Section IV.C

1. Describe the flow path of UF_6 gas from the moment it enters a production unit feed header until it leaves the unit product header.

2. Describe personnel operations performed in a fully operational cascade hall.

3. How many product enrichments can be produced in an enrichment plant composed of 100 cascades (assuming product is removed only at the top of the cascade)? How many enrichments can be produced if all 100 cascades are connected in parallel?

IV.D UF_6 Cylinder Handling

OBJECTIVES

After completing this section, the student should be able to:

1. Describe the cylinders used to store and transport UF_6.

2. Explain the typical UF_6 operations in an enrichment plant.

3. Understand the techniques and activities involved in feeding and withdrawing UF_6 from the process.

The UF_6 at a gas centrifuge enrichment plant is contained in internationally standardized UF_6 cylinders when it is not being processed in the piping or centrifuges of the process system. These cylinders are used for on-site long-term storage and to transport the process material to and from the site and between on-site facilities. Figure 28 depicts the UF_6 handling operations in an enrichment plant.

Full feed cylinders are brought on-site, weighed, inspected, liquid sampled (optional), and placed in a storage area. When it is time for the contents of a full feed cylinder to be fed into the process, the cylinder is moved from the storage area to the feed area, placed in a heating station, and heated to convert the cylinder contents from solid to gas. The gaseous UF_6 is then transferred through piping to the cascade halls for processing. Simultaneously, enriched and depleted process gas streams are withdrawn from the cascades into separate desublimers where the material solidifies. The desublimers are subsequently heated to transfer the material to product and tails UF_6 cylinders. The tails cylinders containing the depleted material are weighed and then moved to an on-site storage yard for long-term storage. The product cylinders containing the enriched material are weighed, liquid sampled, possibly blended or rebatched, and then transferred to a storage area to await shipment off-site.

Cylinder Names

Cylinder sizes and names (i.e., model numbers) are relatively standard across the UF_6-handling industry. The most commonly used cylinders for UF_6 containment and transport are the 30-in.-diam (Model 30B, 2.5-ton) cylinders for low-enriched product, 48-in.-diam

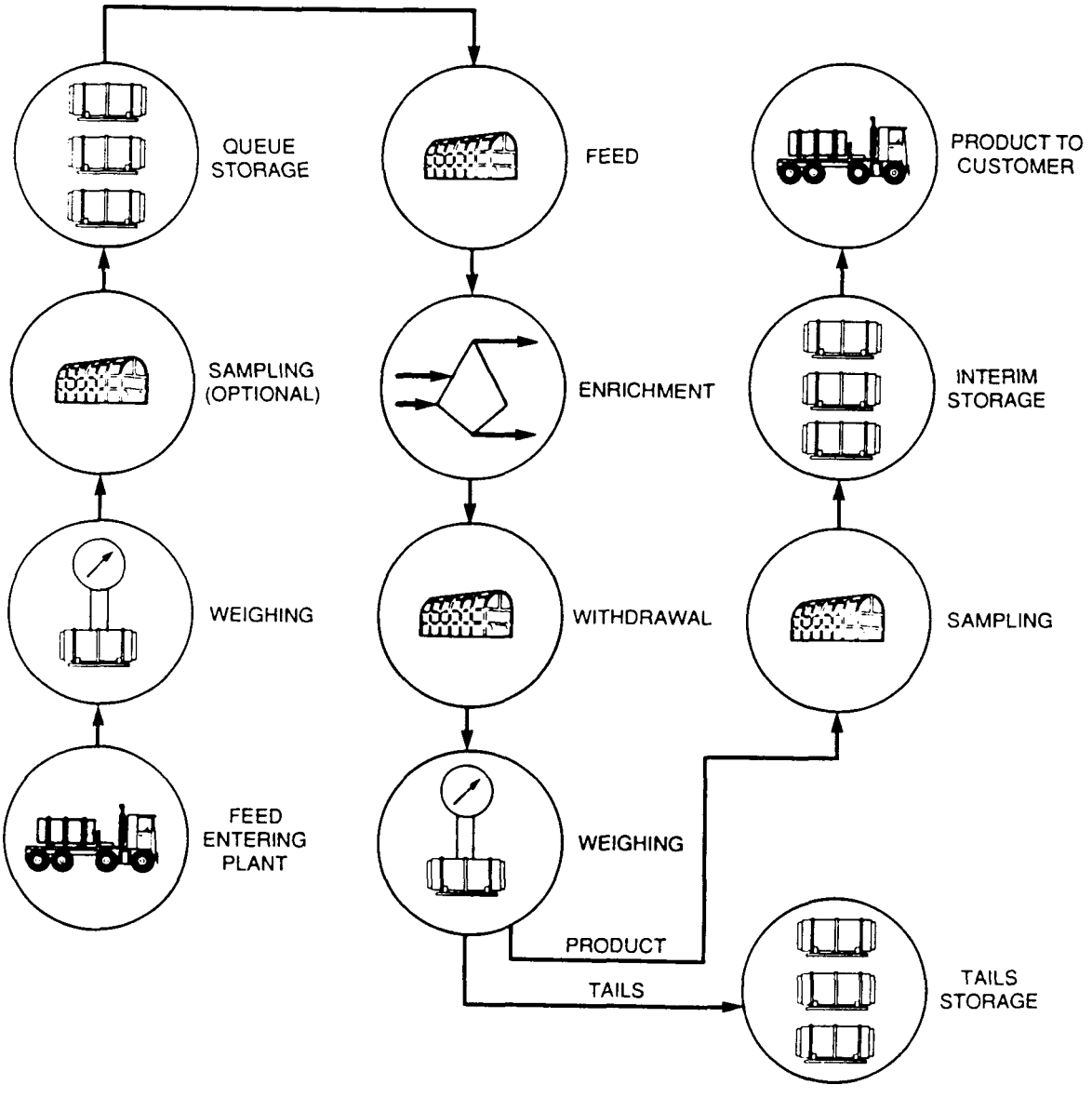


Fig. 28. UF_6 operations in an enrichment plant.

(Models 48X and 48Y, 10- and 14-ton) cylinders for natural feed, and 48-in.-diam, thin-wall (Model 48G, 14-ton) cylinders for long-term tails storage. The Models 48X and 48Y cylinders are sometimes used for on-site containment of low-enriched product, although enriched material is usually shipped in Model 30B cylinders. General data on these cylinders are provided in Table 7.

Table 7. General data on feed, product, and tails cylinders

	Cylinder model			
	30B	48X	48Y	48G
Basic material of construction	Steel	Steel	Steel	Steel
Maximum isotopic content	5.0%[a] ^{235}U	4.5%[a] ^{235}U	4.5%[a] ^{235}U	1.0% ^{235}U
Nominal diameter: cm (in.)	76.2 (30)	121.9 (48)	121.9 (48)	121.9 (48)
Nominal length: cm (in.)	205.7 (81)	307.3 (121)	381 (150)	370.8 (146)
Wall thickness: cm (in.)	1.27 (0.5)	1.59 (0.625)	1.59 (0.625)	0.79 (0.31)
Nominal tare weight: kg (lb)	635 (1,400)	2,041 (4,500)	2,359 (5,200)	1,179 (2,600)
Maximum net weight: kg (lb)	2,277 (5,020)	9,539 (21,030)	12,501 (27,560)	12,701 (28,000)
Nominal gross weight: kg (lb)	2,912 (6,420)	11,580 (25,530)	14,860 (32,760)	13,880 (30,600)

[a] ^{235}U maximum with moderation control.

The basic material of construction for these cylinders is steel. The maximum isotopic content limit for 30B cylinders is 5% ^{235}U; for 48X and 48Y cylinders, 4.5% ^{235}U; and for 48G cylinders, 1.0% ^{235}U. The maximum permissible enrichment levels stated for the 30B, 48X, and 48Y cylinders apply to UF_6 with a minimum purity of 99.5%, which provides moderation control. The ***tare weight*** refers to the weight of an empty, clean cylinder; the ***gross weight*** is the weight of a cylinder filled with UF_6; and the ***net weight*** is the difference between the gross weight and the tare weight (i.e., the weight of the UF_6 contained in the cylinder).

Model 1S and Model 2S cylinders are the most commonly used cylinders for collecting liquid UF_6 samples and for transporting UF_6 samples. General data on these cylinders are provided in Table 8. These cylinders are of nickel construction and are approved to contain a maximum net UF_6 weight of 0.45 kg and 2.2 kg, respectively, at any enrichment level.

Cylinder Movement and Storage

Cylinders of UF_6 are shipped on-site and off-site by rail or by truck. Cylinders containing UF_6 enriched to greater than 1% ^{235}U must be shipped in protective shipping packages (Fig. 29). Centrifuge facilities have a variety of on-site cylinder-handling capabilities to unload incoming cylinders and load outgoing cylinders as well as for moving cylinders within the facility. These capabilities include forklifts, cranes, and specialized cylinder-handling

Table 8. General data sample cylinders

	Cylinder model	
	1S	2S
Basic material of construction	Nickel	Nickel
Maximum isotopic content	100% ^{235}U	100% ^{235}U
Nominal diameter: cm (in.)	3.8 (1.5)	8.9 (3.5)
Nominal length: cm (in.)	27.9 (11)	29.2 (11.5)
Wall thickness: cm (in.)	0.16 (0.063)	0.28 (0.112)
Nominal tare weight: kg (lb)	0.79 (1.75)	1.91 (4.2)
Maximum net weight: kg (lb)	0.45 (1.00)	2.22 (4.9)
Nominal gross weight: kg (lb)	1.25 (2.75)	4.13 (9.1)

machinery (Figs. 30 and 31). Because of the hazards associated with moving cylinders of liquid UF_6, movement and operations involving large cylinders containing liquid material are kept to a minimum. The UF_6 in these cylinders is allowed to cool and solidify before the cylinders are placed in storage or shipped off-site. Solidification of liquid UF_6 under ambient building conditions requires approximately 5 days for a 48-in. cylinder and 3 days for a 30-in. cylinder.

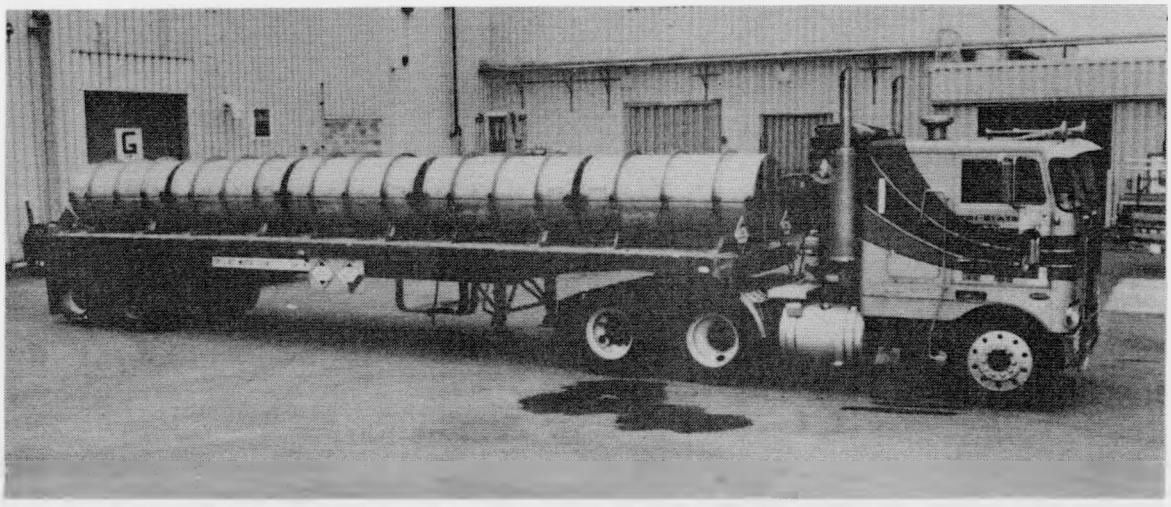


Fig. 29. Truck shipment of five 2 1/2-ton UF_6 cylinders in protective shipping packages.

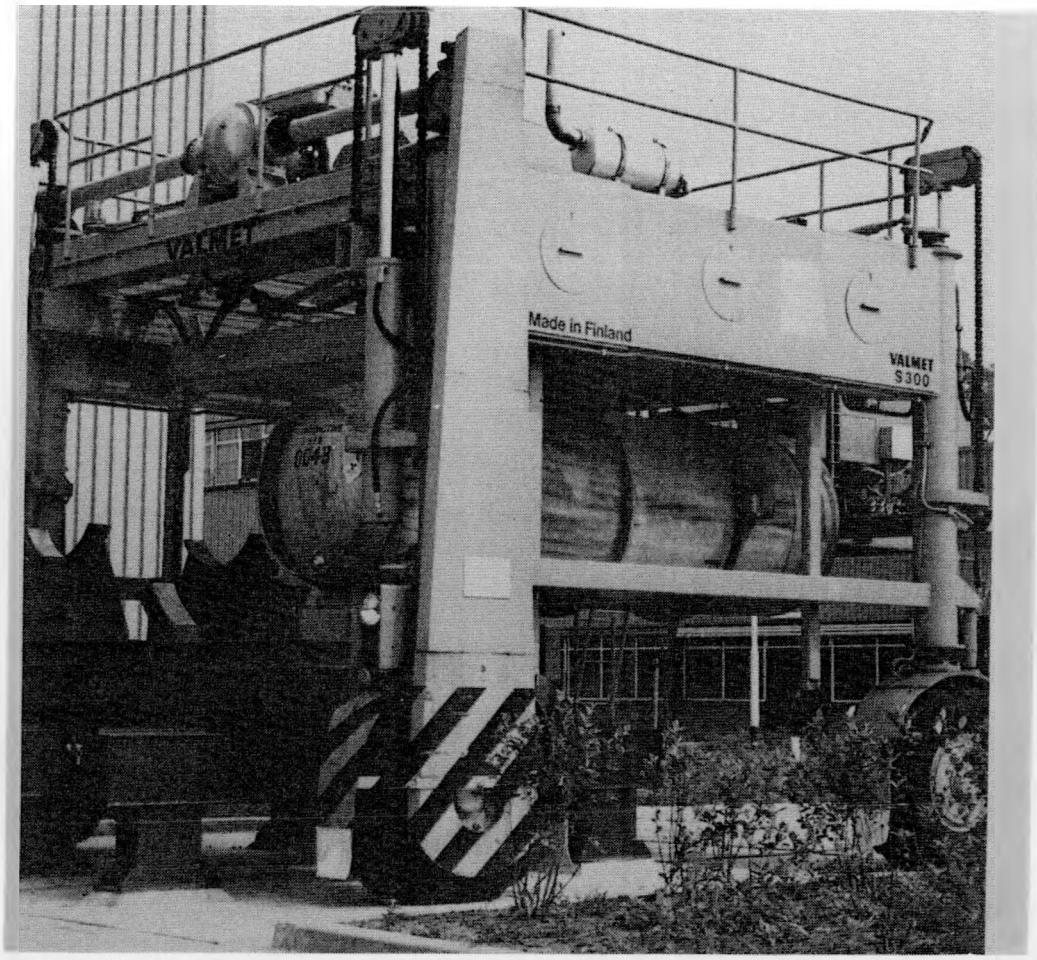


Fig. 30. Urenco on-site feed cylinder transporter.

The common practice is to store cylinders of natural UF_6 horizontally and in a single layer or tier. No special storage configuration is required for criticality safety. Spacing of arrays is generally dictated by the accessibility of the cylinder-handling equipment. Depending upon the feed source and operating philosophy of the enrichment plant operator, the facility will maintain a stockpile of feed cylinders. Because tails material remains on-site in long-term storage, tails cylinders are packed in tighter storage arrays to conserve space. Sufficient clearance must be provided, however, so that the tails cylinders are visually accessible for periodic monitoring of their physical condition as well as for inventory-taking purposes. At some facilities, tails cylinders are stacked in the storage yards (Fig. 32). Enriched material is stored in cylinders of suitable geometry and/or with suitable moderation control.

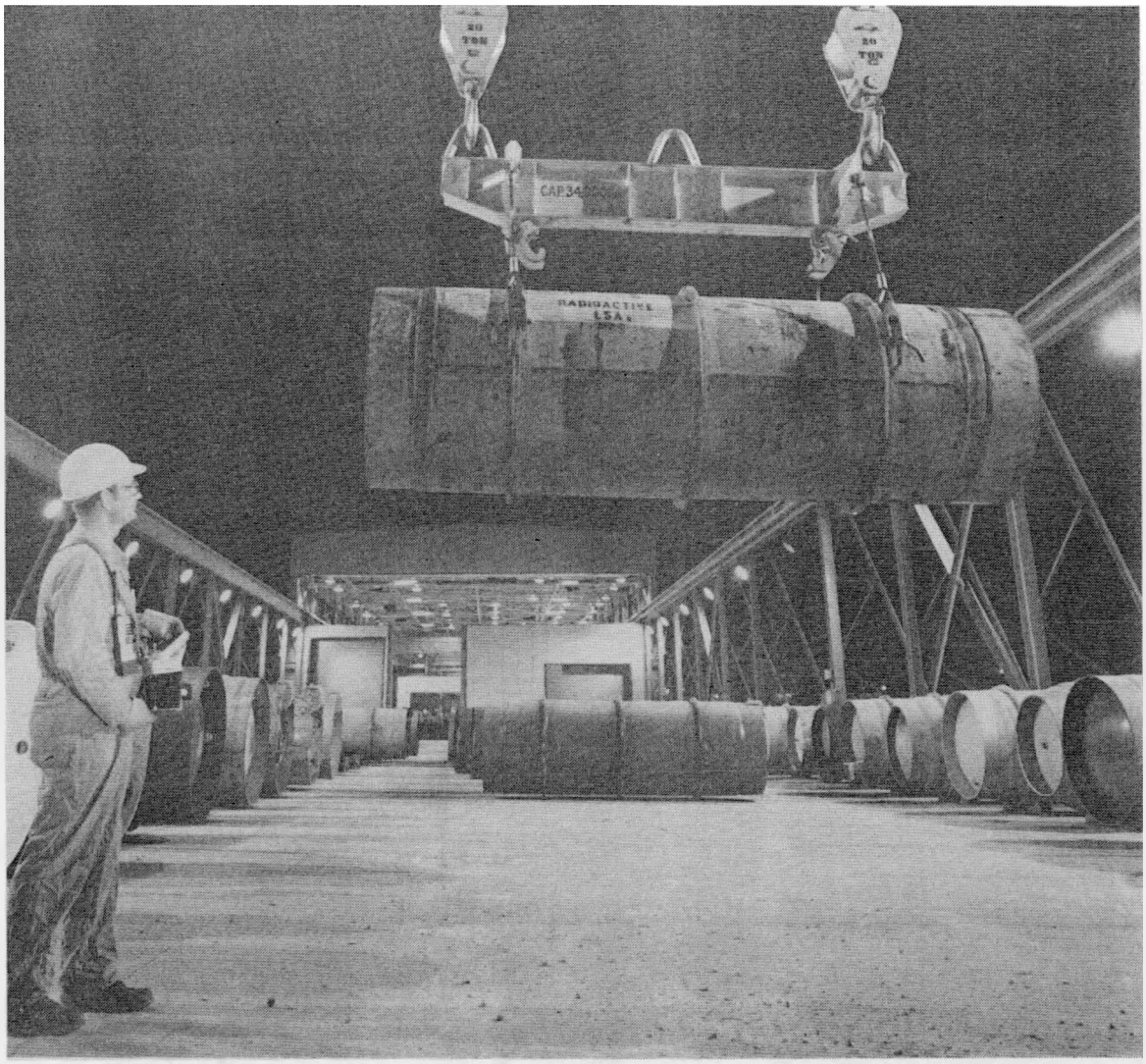


Fig. 31. Overhead double-hook crane moving a 14-ton cylinder.

To illustrate the number of UF_6 cylinders that are received and shipped from a centrifuge plant, consider a 1-million-SWU/year facility. Each year the contents of approximately 200 Model 48Y feed cylinders are fed into the process. During the same period, 190 Model 30B product cylinders and 170 Model 48G tails cylinders are filled. If cylinder shipments occur weekly, approximately four feed cylinders are brought on-site, four product cylinders are shipped off-site, and three tails cylinders are moved to long-term storage each week. In addition to these full cylinder movements, shipments of empty feed cylinders and receipts of empty product and tails cylinders also occur.

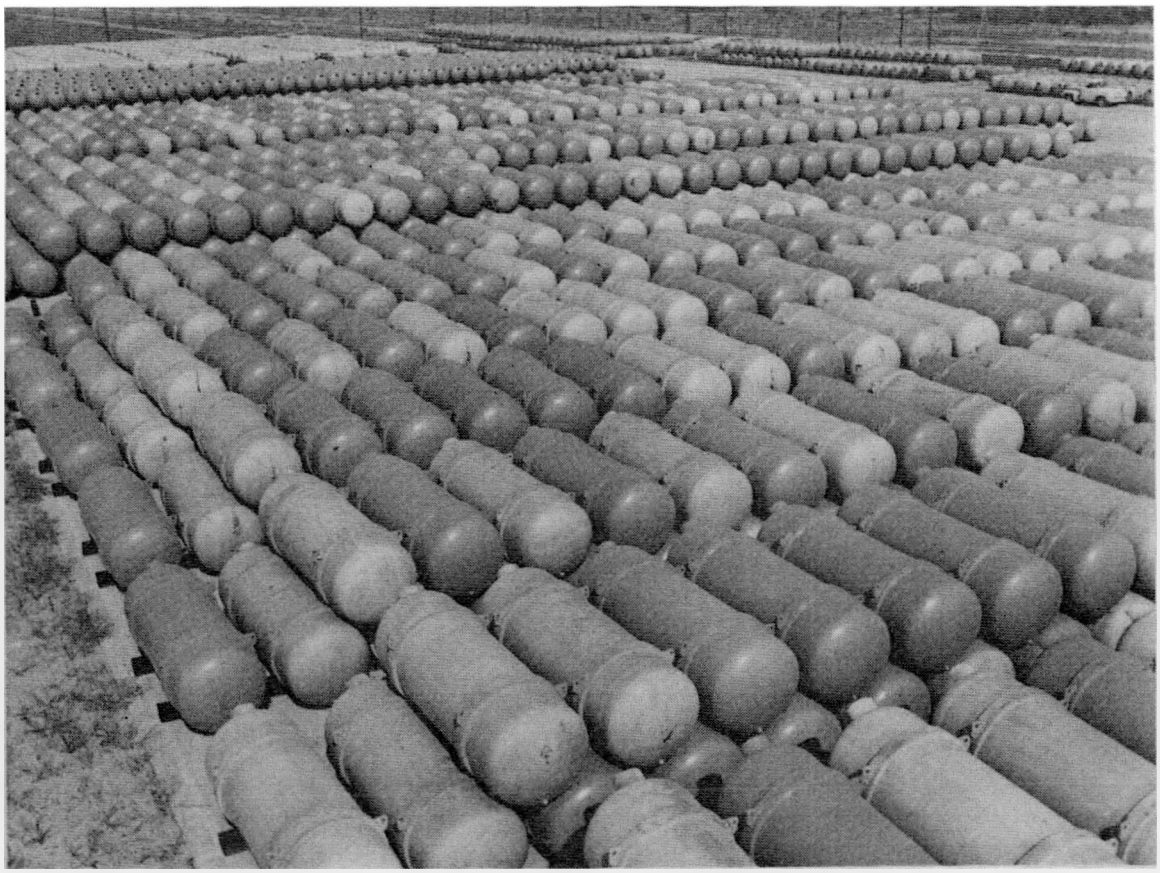


Fig. 32. Long-term tails cylinder storage yard.

Cylinder Weighing

Accurate measurements of UF_6 cylinders are required to account for the quantity of process material being fed to and withdrawn from the cascades. These data are important to both materials accounting and operations personnel. All UF_6 cylinders are weighed (1) when they are received on-site, (2) after being filled or emptied, and (3) after they are sampled (or after material is removed for any other reason).

The quantity of UF_6 feed material introduced into the process is the difference between the feed cylinder weights before and after feeding. The weight of the cylinder after feeding consists of the empty cylinder weight and the weight of the remaining heel material. An acceptable heel weight for a 48-in. feed cylinder is 23 kg or less. Likewise, the net weight of UF_6 product or tails material is the difference between the weights of the product or tails cylinder before and after filling. If recycled product cylinders are being filled, they may contain a heel quantity of material remaining from the previous cylinder evacuation. An acceptable heel weight for a 30-in. product cylinder is 11 kg or less.

A variety of scales exist for weighing the different types of UF_6 cylinders. Two and a half-ton, 10-ton, and 14-ton cylinders are weighed on load-cell scales or platform scales (Fig. 33). These scales are capable of indicating a difference as small as 1 kg even with loads up to 14,000 kg. The smaller sample cylinders can be weighed on laboratory scales such as an equal-arm balance with even greater measurement accuracy.

To ensure continuous accuracy of the weight measurements, scale calibration and operating procedures are developed and implemented by the facility operator. Operating procedures provide for the proper and consistent use of the scales for weighing UF_6 cylinders and establish the requirements for control checks and scale calibration. Scales are calibrated

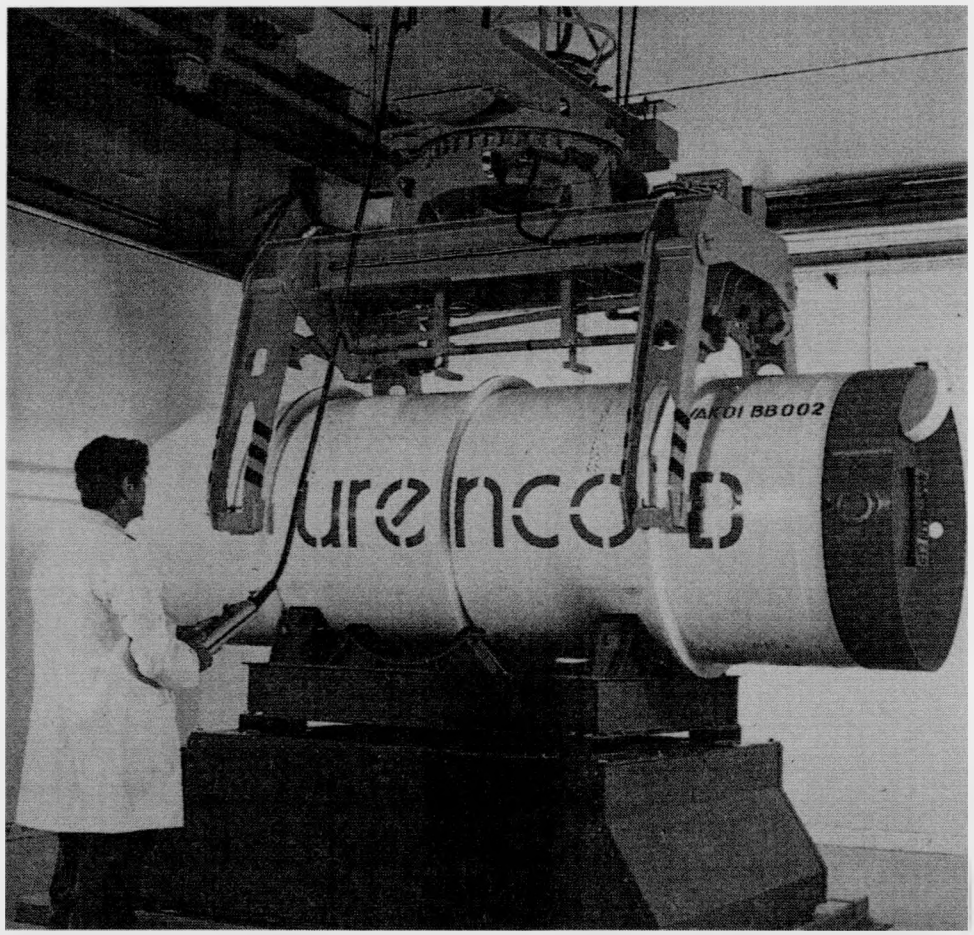


Fig. 33. Platform scale.

on a routine basis and at other times as the need arises (e.g., when the control checks do not meet established criteria) with standards traceable to a national or international standards organization. To ensure that the scales are functioning properly between calibrations, check weights that are the same size and weight as the typical empty and full production cylinders are weighed.

Cylinder Sampling and Blending

Sampling of UF_6 cylinders is necessary to ascertain the chemical purity (i.e., percent uranium) and the isotopic concentration (i.e., weight percent ^{235}U) of the process material. These data are used (1) to determine if the material meets the feed and product specifications and (2) to quantify the nuclear material contained in the cylinder for materials accounting. To establish the quantity of uranium contained in a cylinder, the net weight of UF_6 is multiplied by the percent uranium; the quantity of ^{235}U is determined by multiplying the uranium weight by the weight percent ^{235}U. UF_6 feed cylinders may be sampled upon receipt into the enrichment plant. Product cylinders are sampled after being filled. Tails cylinders are usually not subject to sampling because they remain on-site in long-term storage.

The most representative sample of the UF_6 in a cylinder is a sample withdrawn from the liquid phase after the cylinder contents are completely homogenized. Because impurities concentrate in the vapor, gas-phase samples cannot be used to determine the chemical purity of the UF_6. The UF_6 contained in a cylinder may be stratified because of cooling of the UF_6 between intermittent fillings of the cylinder and/or heel material may be present in the cylinder prior to filling. The cylinder is heated to homogenize the contents which are mixed by thermal action of the liquid. Homogenization requires approximately 8 hours for a 30-in. cylinder and 12 hours for a 48-in. cylinder. A liquid sample is withdrawn into a sample cylinder and is solidified with liquid nitrogen (Fig. 34). The sample cylinder is then weighed and transferred to the analytical laboratory for subsampling and analysis. The parent cylinder is removed from the heating station and placed in a storage area for cooling.

The enrichment requested by the customer cannot always be precisely obtained directly from the cascades. To achieve the desired enrichment, two containers with UF_6 enriched to different levels are heated in autoclaves and their contents transferred and blended in a third cylinder. Sampling of the new product cylinder occurs after the blending operation.

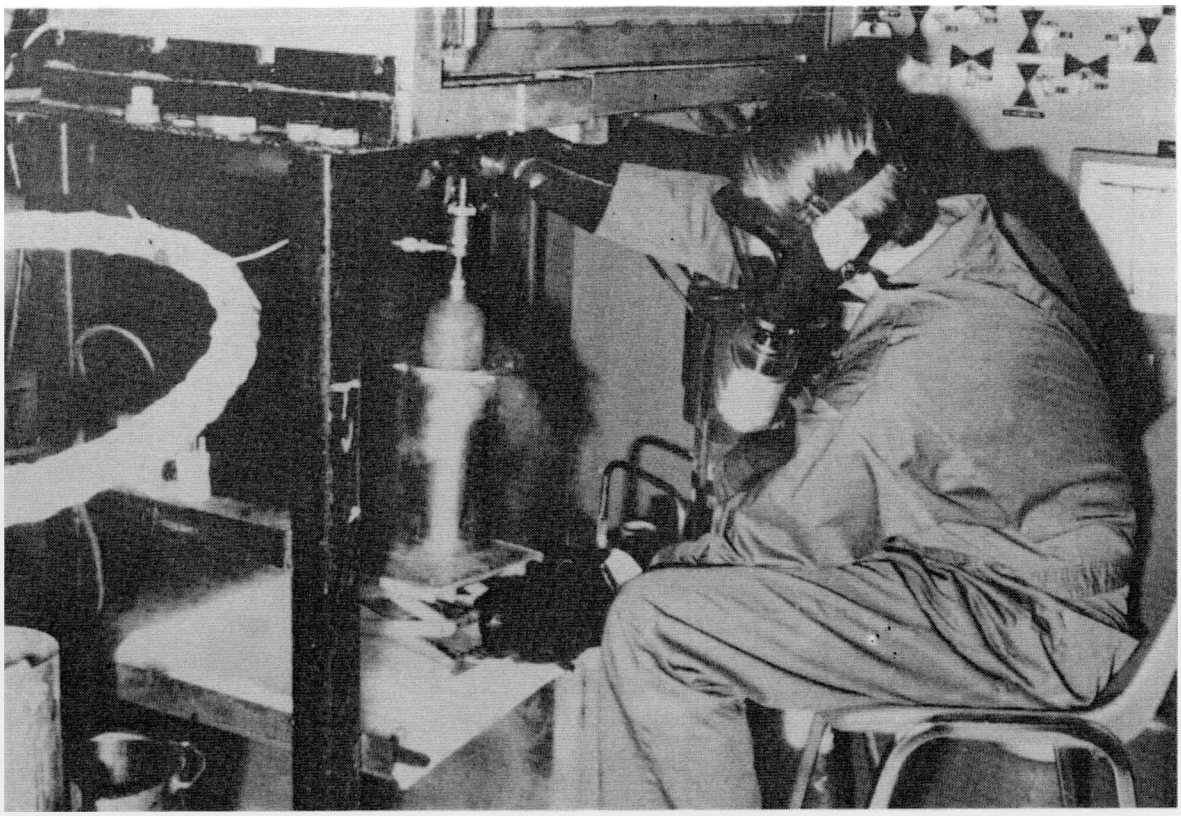


Fig. 34. Pulling a 2S sample at an autoclave.

Cylinder Heating

Cylinders are heated to convert their UF_6 contents from solid to liquid for sampling or from solid to gas for feeding into the process. Before heating a cylinder of UF_6, the cylinder is inspected for any physical defects, weighed to ensure that it adheres to fill limits, and cold-pressure checked for light gas contaminants. The cylinder is then transferred to a containment-type autoclave. A ***containment autoclave*** is a steam or electrically heated pressure vessel, of sufficient structural strength and with the necessary instrumentation, for sensing and confining any inadvertent UF_6 release that might occur from a cylinder when UF_6 is being heated, fed, or transferred.

Once the cylinder has been placed in the autoclave, it is connected to the feed or sampling system. All connections are leak-tested, the cylinder valve is opened, and the containment autoclave is closed and locked before the cylinder is heated. When heat in the containment autoclave is applied to a cylinder, the cylinder pressure is monitored continuously so that an automatic shutdown can be performed if an abnormal sequence or an abnormally high cylinder pressure is observed. Instrumentation is present to quickly indicate an inadvertent UF_6 release. As additional safety factors, the autoclaves have redundant isolation

valves, and the amount of water allowed to be present in the autoclave (if steam heated) is controlled.

Cylinder Feeding

The function of the feed system is to convert the solid UF_6 in a cylinder to a gas and to transfer the gas to the centrifuge cascades for processing. To maintain a continuous feed rate to the cascades, the feed system contains a number of autoclaves in parallel (Fig. 35). Once the UF_6 cylinder has been placed and positioned in the containment autoclave, the low-molecular-weight contaminant gases (e.g., HF and air) contained in the cylinder are withdrawn through a series of desublimers and chemical traps.

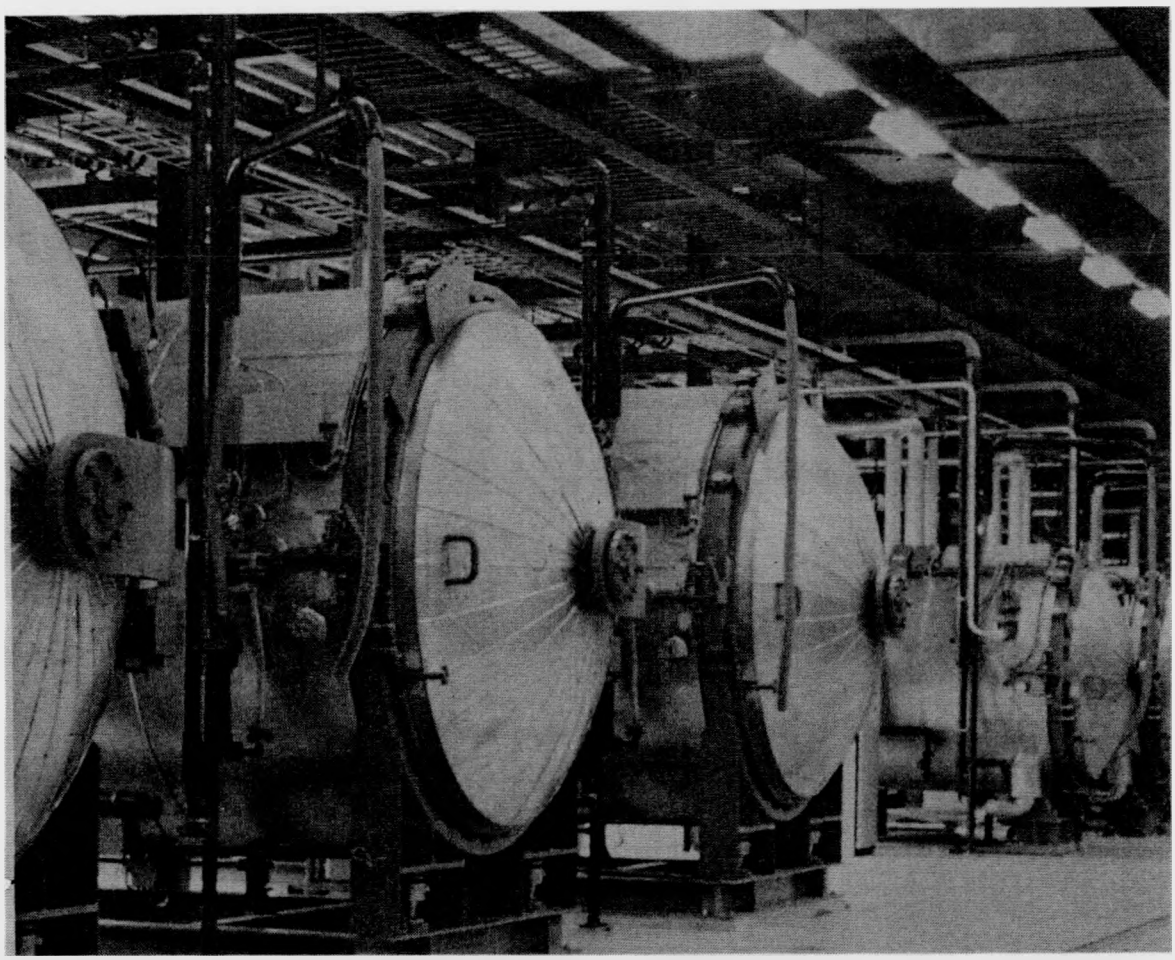


Fig. 35. Steam autoclaves for UF_6 feeding.

The feed cylinder is heated to convert the UF_6 from a solid to a gas. For rapid transfer, the cylinder is heated to a temperature greater than the triple point of UF_6 so that the solid UF_6 melts into a liquid and then evaporates into a gas. For slower transfer, the cylinder may be heated to a temperature less than the triple point and the solid UF_6 sublimes directly into a gas. The UF_6 gas, from either transfer technique, is fed into a hold-up drum (i.e., surge tank). The hold-up drum serves as a buffer to enable the operator to maintain a continuous gas flow during cylinder changeovers and feed system process upsets. After leaving the hold-up drum, the gas may flow into a mixing drum that provides the capability of mixing UF_6 gas from several autoclaves before feeding the gas to the cascade. The gas is fed into the process system at the point where the feed concentration matches the cascade concentration. When the cylinder is nearing empty, a constant feed rate can no longer be maintained. Alternative evacuation procedures are then used to minimize the residual quantity of material that remains in the cylinder.

Cylinder Filling

The function of the UF_6 withdrawal system is to collect the enriched and depleted gaseous UF_6 streams from the cascades, to remove the light gas impurities, and to transfer the remaining material to product and tails cylinders. Product and tails concentrations can be adjusted by varying the withdrawal rates or by changing the withdrawal points from the cascade. Two techniques can be used for collecting and transferring UF_6 gas to the product and tails cylinders: desublimation or compression.

In the ***desublimation*** technique, gaseous UF_6 flows through a desublimer where it desublimes on the cooled walls and internal elements. To maintain a continuous withdrawal rate, multiple desublimers are connected in parallel (Fig. 36). When one desublimer is filled, the gas flowing from the cascades is diverted to the next empty desublimer. The contents of the full desublimer are then transferred to an empty cylinder as either a liquid or a gas. For liquid transfer, the desublimer is heated to a temperature greater than the triple point. The solid UF_6 melts into a liquid, drains into the cylinder that is cooled by air or water, and solidifies. Liquid UF_6 in product and tails cylinders requires from 3 to 5 days to solidify at ambient temperatures. For a gas transfer system, the desublimer is heated to a temperature less than the triple point. The UF_6 sublimes from a solid to a gas, is transferred to the cylinder, and sublimes on the cold walls of the cylinder. In either technique, the product and tails cylinders being filled are positioned on scales to prevent overfilling.

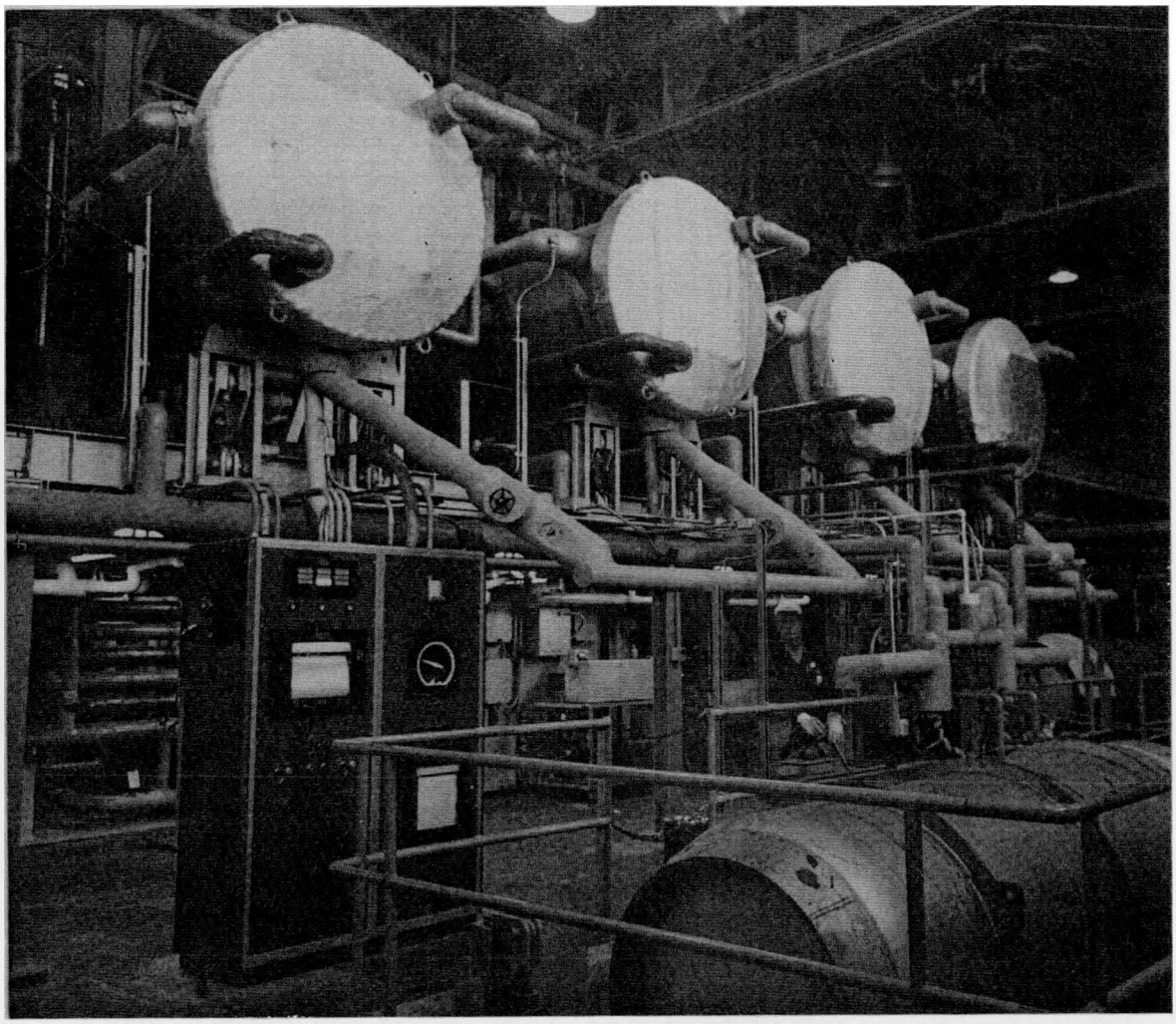


Fig. 36. Desublimers for UF_6 removal.

In the *compression* technique, the UF_6 gas is compressed and cooled by a series of compressors and interstage coolers to increase the UF_6 pressure and decrease the gas temperature. The gaseous UF_6 can be compressed to a point below or above the triple point such that the material is collected as either a gas or liquid, respectively. For a gas transfer system, the gaseous UF_6 is routed to an empty cylinder where the gas sublimes on the cold walls of the cylinder which can be cooled by air or water. If the compressed gas is liquefied in the condenser, it is drained through accumulators into empty cylinders where it cools and solidifies. The accumulators serve as a buffer and can store UF_6 during steady-state flow disruptions (e.g., cylinder changes).

Review Questions for Section IV.D

1. What is the state of UF_6 when it is shipped?

2. How much material is contained in typical feed, product, and tails cylinders?

3. What is a containment autoclave used for?

4. What is the function of the feed system?

5. What activities are involved in feeding a cylinder?

6. How are product and tails cylinders filled?

7. What operations are performed on a feed cylinder when it arrives on-site?

8. How do you determine the quantity of process material fed to or withdrawn from the process?

IV.E Materials Accounting Records

OBJECTIVES

After completing this section, the student should be able to:

1. Describe the key elements of facility nuclear materials accounting consisting of record keeping, accounting reports, and measurement assurance.

2. Explain material balance area (MBA) structure and activities associated with physical inventory taking and material balance closure.

3. Identify measurement techniques used by the facility operator for material balance activities.

Nuclear Materials Accountability

A centrifuge enrichment plant operator needs to establish an effective nuclear materials accounting system to ensure efficient operation; to satisfy health, safety, and safeguards requirements; and to fulfill contractual obligations. Nuclear materials accounting refers to those activities performed to establish (1) the quantities of nuclear material present within defined areas and (2) the changes in quantities of nuclear material occurring within a defined period of time. Key elements of nuclear materials accounting include record keeping (and reporting, as necessary), inventory taking, measurements, verification of the accuracy of the accounting data (including auditing and measurement control programs), and evaluation of inventory differences.

Material Balance Area Structure

The starting point for a nuclear materials accountability system is the MBA structure and the account structure within an MBA. Each facility develops an MBA and account structure that is tailored to its organization and facility operations. The generic MBA structure for safeguards at centrifuge enrichment facilities is two MBAs: a process MBA and a storage MBA. The MBA structure is chosen so that:

1. the quantity of nuclear material in each transfer into or out of each MBA can be determined; and

2. the physical inventory of nuclear material in each MBA can be determined when necessary, in accordance with specified procedures.

Following these guidelines, the storage MBA is generally defined to include all UF_6 cylinders not attached to the process system. The process MBA has been defined to include the process system, UF_6 cylinders attached to the process system, the decontamination and maintenance operations, and the scrap recovery and waste treatment operations. The analytical laboratory and the weighing and sampling areas may belong to either MBA or may belong to a separate MBA. As stated previously, each facility develops an MBA and account structure tailored to meets its specific needs.

The storage MBA inventory is composed of items (i.e., UF_6 cylinders). Items resident in this MBA are stored, shipped to other facilities, and transferred to the process MBA. Rebatching, blending, and cylinder sampling that may be performed in this area would be the only activities that would change the accountability records for an item in residence.

The process MBA inventory is composed of process, scrap, and waste materials contained in a variety of configurations. The inventory is contained in the process system, decontamination solution containers, chemical traps, removed process equipment, and a variety of containers for scrap and waste materials. The magnitude of this inventory is constantly changing. Removals from this MBA are generally limited to transfers of UF_6 in cylinders to the storage MBA, scrap and waste materials shipped to another facility for recovery and/or disposal, and measured discards that are disposed of to the environment.

Records and Reports

Source documentation, records, and reports are generated whenever nuclear material passes through a key measurement point. A ***key measurement point*** is a location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. Key measurement points include, but are not limited to, the input and output streams of each MBA (including measured discards) and the storage items in each MBA. Flow key measurement points are identified for all nuclear material transfers between MBAs and facilities, for nuclear material category changes, and for rebatching and blending operations. Inventory key measurement points are identified for all material types on the facility inventory.

The source documents are the data records from which the change and inventory records and reports are prepared. Source documents include weight tickets, elemental and isotopic concentration reports from the analytical laboratory, shipping papers, inventory lists, nuclear material transfer forms, accountability procedures, and explanatory reports. The records include nuclear material transaction journals and ledgers. The reports include inventory change and material balance reports and physical inventory listings.

Inventory and Material Balance Closure

Material balance closures are performed at most centrifuge enrichment facilities on an annual basis and involve the determination of the actual inventory in each MBA and the comparison of this inventory to the facility's book inventory. The result of a material balance closure is a statement of "material unaccounted for" (MUF), that is, the difference between the book inventory (beginning inventory + receipts - shipments) and the actual inventory. If this difference falls within the calculated uncertainty limits for the material balance, the material balance is accepted; if not, the difference requires resolution. Most enrichment facilities also perform a less detailed monthly book inventory.

Physical inventories are performed in the storage and process MBAs and involve the use of very different techniques. The storage MBA inventory involves the verification of the number of items and the verification of the identity of each item. Characteristics of some of the UF_6 cylinders (e.g., weight and isotopic concentration) may also be verified. Verification of the process MBA inventory is much more difficult.

The process system is a continuous operation and cannot be shutdown or cleaned out for the inventory. Therefore, the process system inventory is reduced as much as possible by minimizing the inventory in the desublimers and the attached, partially fed cylinders. This is performed by redirecting the process gas flow from on-line desublimers and feed cylinders to empty desublimers and preweighed feed cylinders. The desublimers are emptied to withdrawal cylinders that are then removed and inventoried. The cylinders are moved from the feed and withdrawal stations and weighed. Samples may be withdrawn from the cylinders to determine the uranium and isotopic concentrations. The remaining process system inventory consists of the gas-phase inventory and the solids inventory. For a 1-million-SWU/year gas centrifuge plant with a specific inventory of 0.0005 kg U/SWU/year (Table 3, Sect. II.C), the gas-phase inventory is expected to be approximately 500 kg U of material; the solids inventory would be approximately the same order of magnitude. The gas-phase inventory is estimated using volume, temperature, and pressure calculations, and the solids inventory is estimated using expected rates of deposition and reaction of UF_6 in the process

system. The inventory of scrap and waste materials (including laboratory sample materials) is usually reduced to the minimum feasible level before the physical inventory is performed, and the remainder is measured by the best available destructive or nondestructive analysis techniques.

Measurement and Measurement Control Systems

Enrichment facilities essentially handle one type of material (i.e., UF_6) of at least three different isotopic concentrations (i.e., natural feed, enriched product, and depleted tails). Depending on the plant operation, multiple product and tails streams with different isotopic concentrations may be withdrawn. The majority of the UF_6 is contained in the cylinders described in Sect IV.D. The remaining material is contained in the cascades with a small amount contained unmeasured discards.

All items received into or removed from an MBA are measured to determine the uranium and/or ^{235}U content. These measurements are performed on the item or on samples withdrawn from the item. Items that were accurately measured in the MBA from which they are received are generally accepted on that measured value. All cylinders (feed, product, and tails) received at an enrichment facility are weighed on receipt to verify the gross weight or to establish (if an empty cylinder) the cylinder's tare weight. Depending on the operator's confidence in the quality of the received UF_6, each feed cylinder may be sampled, accepted on shipper's values, or sampled on a random basis. Transfers from the storage MBA to the process MBA and vice versa are measured in only one of the MBAs. These measurements include total weight of contained UF_6, uranium concentration (generally by ignition gravimetry), isotopic abundances and ^{235}U content (generally by gas source mass spectrometry), and impurity concentrations (by assorted techniques). Scrap and waste materials may be measured for the contained uranium and ^{235}U contents by an assortment of destructive and nondestructive analysis techniques.

Approximate measurement uncertainties are provided in Table 9. Using platform scales, 10- and 14-ton UF_6 cylinders can be weighed very accurately. The relative limit of error (95% confidence level) for the net weight of UF_6 in these cylinders is less than 0.05%. Depending on the degree of heterogeneity, the sampling error for UF_6 cylinders is generally less than 0.10% after homogenization. UF_6 can be analyzed very accurately for uranium and isotopic concentrations by well-established destructive chemical methods. At a 95% confidence level, subsampling and analysis for both uranium content and ^{235}U isotopic concentration have a relative limit of error that is less than 0.05%. Heterogeneous waste

Table 9. Measurement uncertainties

Measurement	Uncertainty[a]
Weight	< 0.05%
Sampling	< 0.10%
Uranium content	< 0.05%
Isotopic concentration	< 0.05%
In-process inventory	~ 10%
Waste materials	< 10%

[a] At 95% confidence level.

materials from which representative samples are difficult to obtain generally can be measured with a measurement uncertainty of less than 10%. The in-process inventory is calculated from process system volumes, pressures, temperatures, and models of material deposition and holdup. The uncertainty of this inventory is approximately 10% of the quantity obtained; of this, the random error component would amount to only a few percent.

Confidence in the measurement results is ensured through the effective application of a measurement control program. The program includes (1) the qualification of measurement systems and of the measurement personnel that use the systems and (2) the periodic measurement of control samples and reference materials to verify that the measurement system meets required accuracy specifications. The control programs also include procedures for the calibration and requalification of the measurement systems following out-of-control occurrences. The calibration and control procedures utilize certified reference materials and ensure traceability of the measurement results to the national system.

Review Questions for Section IV.E

1. What are the MBAs in the standard MBA structure at a centrifuge enrichment plant?

2. How often are material balance closures performed at a centrifuge enrichment plant?

3. How do the inventories of the storage and process MBAs differ?

4. What measurements are made on the UF_6 contained in a full product cylinder when it is transferred from the process to the storage MBA?