Uranium Enrichment Export Control Guide: Gaseous Diffusion

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September 1989

MARTIN MARIETTA

MARTIN MARIETTA ENERGY SYSTEMS, INC.

Prepared by the
International Technology Programs Division for the
U.S. Department of Energy, Office of Classification and Technology Policy,
and for the U.S. Department of State, Office of Nuclear Export Control, Washington, D.C.

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MARTIN MARIETTA ENERGY SYSTEMS, INC.
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Foreword

This document was prepared to serve as a guide for export control officials in their interpretation, understanding, and implementation of export laws that relate to the Zangger International Trigger List for gaseous diffusion uranium enrichment process components, equipment, and materials. Particular emphasis is focused on items that are especially designed or prepared since export controls are required for these by States that are party to the *International Nuclear Nonproliferation Treaty*.

Acknowledgments

Photographs and diagrams of Soviet, French, and U.S. gaseous diffusion technologies were provided by the State Committee on the Utilization of Atomic Energy (U.S.S.R.), Eurodif (France), and the U.S. Department of Energy, Office of Uranium Enrichment, respectively.

Introduction

NUCLEAR EXPORT CONTROLS: THE NONPROLIFERATION TREATY

The *International Nuclear Nonproliferation Treaty* states in Article III, paragraph 2 (b) that "each State party to the treaty undertakes not to provide equipment or material especially designed or prepared for the processing, use or production of special fissionable material, to any non-nuclear weapon State for peaceful purposes, unless the source or special fissionable material shall be subject to the safeguards required by this article."

CLARIFICATIONS TO THE TREATY: THE TRIGGER LIST

In its original form, the treaty did not specifically elaborate on, or define the meaning of, "especially designed or prepared" with reference to equipment or material. Furthermore, the terms "processing, use or production" for special fissionable material were not delineated. As a result, necessary definitions and clarifications of the intent of the treaty were prepared to facilitate its implementation. These clarifications consisted of a list of especially designed or prepared equipment or material referred to as the "Trigger List," which is described in International Atomic Energy Agency information circular INFCIRC/209 dated September 3, 1974, and subsequent addenda. Items that appear on the Trigger List require, or trigger the requirement of, safeguards on their export to nonnuclear weapons States.

CONTROLS ON URANIUM ENRICHMENT

Uranium enrichment was first mentioned in INFCIRC/209 as follows:

"2.5.1 Equipment, other than analytical instruments, especially designed or prepared for the separation of the isotopes of uranium."

In 1979 the above definition was clarified in INFCIRC/209/Mod. 1 as including the following:

"Such items include:
gaseous diffusion barriers
gaseous diffuser housings

gas centrifuge assemblies, corrosion resistant to
UF₆
jet nozzle separation units
vortex separation units
large UF₆ corrosion-resistant axial or
centrifugal compressors
special compressor seals for such compressors."

In 1984 an extensive review of gas centrifuge uranium enrichment processing led to a Trigger List clarification that appears in the Annex to INFCIRC/209. The single entry "gas centrifuge assemblies" was extended to include nine especially designed or prepared components of the gas centrifuge itself and four items relating to auxiliary systems, equipment, and components.

GASEOUS DIFFUSION EXPORT CONTROLS

In 1987–1989 an extensive review of gaseous diffusion uranium enrichment processing led to a Trigger List clarification that will appear in the Annex to INFCIRC/209. The four entries – gaseous diffusion barriers, gaseous diffuser housings, UF₆ compressors, and special compressor seals – were expanded to include assemblies, components, auxiliary systems, and auxiliary components especially designed or prepared for gaseous diffusion uranium enrichment.

This guide was prepared to assist export officials in the interpretation, understanding, and implementation of export laws relating to the Zangger International Trigger List for gaseous diffusion process equipment, components, and materials. The nuclear fuel cycle, uranium enrichment, and the gaseous diffusion process are briefly described; steps used to prepare Trigger List controls are cited; descriptions of controlled items are given; and special materials of construction are noted. This is followed by a comprehensive description of especially designed or prepared equipment, materials, and components of the gaseous diffusion process together with pictorial representations. The Trigger List, the nomenclature of which has been retained in the numbered sections of this document, is divided into two parts:

1. especially designed or prepared assemblies and components for use in gaseous diffusion enrichment, and
2. especially designed or prepared auxiliary systems, equipment, and components for use in gaseous diffusion enrichment.

Gaseous Diffusion Uranium Enrichment

Most of the nuclear power plants in the world today are designed to use uranium enriched to approximately 3% ^{235}U as fuel, while weapons can use uranium enriched to approximately 90%. As found in nature, uranium consists principally of two isotopes: ^{235}U and ^{238}U .^{*} The ^{235}U isotope is fissionable, and this property of being able to split and to give up heat makes it useful in both nuclear reactors and weapons. The ^{235}U isotope is present in the amount of only 0.711% by weight in natural uranium.

A number of interrelated steps are involved in locating, preparing, and using uranium for reactors and weapons. Enrichment, an important step in producing nuclear materials, can increase the assay of ^{235}U from 0.711% to almost pure concentrations. Separation of the natural mixture of uranium isotopes is a difficult task because such heavy isotopes behave almost identically in most chemical and physical processes. An intensive survey has been under way for many years to identify and to develop processes that have potential for isotope separation. The early research efforts were concentrated on electromagnetic processes, gaseous diffusion, thermal diffusion, and gas centrifugation. Although production-scale uranium enrichment plants using the first three of these processes were successfully built in the 1940s, the advantages of the gaseous diffusion process were quickly demonstrated. As a result of continued research and development of enrichment techniques in the last forty years, the technology now exists to enrich uranium for reactors and weapons efficiently by the process of gaseous diffusion.

GASEOUS DIFFUSION PROCESS

Today most of the world capacity for uranium enrichment is provided by gaseous diffusion, a process that has been in continuous use on a large scale in the United States since 1948. In concept, it is a simple process based on the fact that the velocity of a gas molecule at a given

^{*}Isotopes are atoms of the same chemical element – very similar in chemical behavior but distinguishable by differences in atomic weight, radioactive transformations, etc.

NUCLEAR FUEL CYCLE

1

MINING

TYPICAL ORE CONTAINS
ABOUT 0.14% U_3O_8

2

MILLING

YELLOW CAKE (U_3O_8) IS
PRODUCED FROM THE ORE

4

ENRICHMENT

URANIUM HEXAFLUORIDE
WITH 0.711% ^{235}U IS ENRICHED
TO 3% ^{235}U

6

POWER REACTOR

ABOUT ONE-THIRD OF FUEL
IN REACTOR REPLACED
EACH YEAR

SPENT FUEL

INTERIM STORAGE OF
SPENT FUEL PENDING
POSSIBLE REPROCESSING
OR PERMANENT STORAGE

ELECTRICITY

CONVERSION

- 3 GASEOUS URANIUM HEXAFLUORIDE (UF_6) IS PRODUCED FROM YELLOW CAKE AND FLUORINE

FUEL FABRICATION

POWER PLANT FUEL PRODUCED

REPROCESSING

SPENT NUCLEAR FUEL IS PROCESSED TO RECOVER URANIUM AND PLUTONIUM FOR RECYCLE

temperature depends on the mass of the molecule. In the gaseous diffusion process, uranium hexafluoride (UF_6) molecules bearing ^{235}U have a higher random molecular velocity; the gas that passes through the barrier pores is slightly enriched in the ^{235}U isotope, and the gas that does not pass through is depleted in the ^{235}U . The enrichment obtained in a single diffusion operation is quite small. To enrich ^{235}U to concentrations above 90%, this diffusion process must be repeated thousands of times by coupling the diffuser units in series.

The gaseous diffusion process for uranium enrichment is based upon the fact that lighter molecules flow slightly faster than heavier molecules through the walls of a porous tube called a barrier. The portion of gas passing through the barrier wall is slightly richer in ^{235}U . The molecular speeds of the two types of UF_6 molecules differ by only about 0.4%.

DIFFUSION PROCESS IMPLEMENTATION

The next figure depicts typical equipment used in the gaseous diffusion process. The basic building block of this cascade is called a stage, and eight are shown here in a grouping known as a cell. Each stage is composed of a diffuser vessel, a gas compressor, a motor, a control valve, and the associated piping.

The diffuser vessel contains tubular barrier material that actually performs the isotopic enrichment and a gas cooler or heat exchanger to control the stage temperature. The key to the success of the entire process is the barrier material itself. The gas cooler, operating on the low-pressure diffused gas, removes about 95% of the energy added to the gas by the compressor. The individual diffusers containing the barrier tubes are quite large.

Typical U.S. gaseous diffusion equipment

Normally, axial flow or centrifugal compressors are used to compress the UF_6 gas to the pressures needed to cause the gas flow through the barrier tubes and from one stage to another. The gas compressors are powered by electrical motors.

Control valves are necessary to adjust the gas flow and pressure conditions to obtain the best performance from both the barrier and the compressors. The pressure drop caused by this valve cannot be very large since this represents a source of stage power inefficiency. Large block valves are used between successive groups of eight to ten stages to allow isolating stages for maintenance.

In addition to the process stage equipment, the gaseous diffusion plants require auxiliary systems, such as the uranium hexafluoride feed and withdrawal systems, an extensive electrical power distribution system, and cooling towers to dissipate the waste process heat.

Steps Used To Prepare Trigger List Controls

The following actions were taken to prepare the Trigger List:

- developed a comprehensive, preliminary list of equipment, materials, and technology;
- established priorities for items on the developed list based on their uniqueness of function or design features;
- developed simplified descriptions that contain key specifications;
- determined domestic and foreign suppliers;
- evaluated potential impacts on suppliers that could result from establishment of controls on each individual item;
- evaluated potential effectiveness of proposed controls;
- identified and determined alternatives as required;
- refined the list of items by avoiding end-use specifications whenever possible;
- initiated bilateral discussions; and
- initiated multilateral discussions among technology holders and key supplier States.

The International Zangger Committee then adopted a Trigger List of the gaseous diffusion process equipment, components, and materials.

Special Materials of Construction

The gaseous diffusion uranium enrichment process relies on the use of uranium in a volatile gaseous form: uranium hexafluoride (UF_6). This is pumped from stage to stage through a special diffusion barrier. Because UF_6 is a very corrosive gas, similar to fluorine in this respect, all process surfaces that come into direct contact with this gas must be fabricated or lined with special materials. Such materials include stainless steel, aluminum, aluminum alloys, aluminum oxide, nickel or its alloys containing 60% or more nickel, and UF_6 -resistant fully fluorinated hydrocarbon polymers.

Descriptions of Controlled Items

The descriptions, special design features, photographs, and sketches of gaseous diffusion components, equipment, and materials that follow are intended to be representative of typical gaseous diffusion uranium enrichment plants. Because of the wide variety of specific process designs that are possible, there may be a considerable difference in the appearance of equipment and components for any one given design from that given in the photographs and sketches shown in this guide. Space limitations preclude the inclusion in this guide of all possible variants; however, illustrations representative of Soviet, French, and U.S. gaseous diffusion technologies are shown. For each item on the control list, a description of the item, its special design features, and a photograph or sketch is given. The descriptions are taken verbatim from the Zangger International Trigger List.

1. Assemblies and Components

DESCRIPTION

Especially designed or prepared assemblies and components for use in gaseous diffusion enrichment

SPECIAL DESIGN FEATURES

In the gaseous diffusion method of uranium isotope separation, the main technological assembly is comprised of a special porous gaseous diffusion barrier, a heat exchanger for cooling the gas (which is heated by the process of compression), seal valves and control valves, and pipelines. Inasmuch as gaseous diffusion technology uses UF_6 , all equipment, pipeline, and instrumentation surfaces (that come in contact with the gas) must be made of materials that remain stable in contact with UF_6 . A gaseous diffusion facility requires a large number of these assemblies, so quantities can provide an important indication of end use.

An overview of a portion of a Soviet gaseous diffusion plant.

An overview of a portion of a U.S. plant having intermediate size diffusers. The process piping is at the same level as the diffusers, and the overhead piping is part of the cooling system.

Illustrating a portion of a U.S. plant, eight stages – each of which has a diffuser, a barrier, a motor, a compressor, a heat exchanger, a control valve, and process piping – constitute a cell, the smallest unit of incremental productive capacity that can be added to, or removed from, the operating cascade. Note the cell bypass piping and the cell and bypass block valves.

Other configurations are also possible. These might have different numbers of diffusers in a cell, the diffusers might be vertically oriented with the piping modified accordingly, or there might be separate compressors handling the diffused and undiffused flow.

The elements of an assembly may be mounted horizontally, as is done in the United States, or they may be mounted vertically, as is done in the French diffusion plant at Tricastin (see drawing at right.)

Illustrating a portion of a Soviet plant, twenty-two stages – each of which has a diffuser, a barrier, two motors, two compressors, two heat exchangers, a control valve, and process piping – constitute a cell, the smallest unit of incremental productive capacity that can be added to, or removed from, the operating cascade. Note the cell bypass piping and the cell and bypass block valves.

1.1 Gaseous Diffusion Barriers

DESCRIPTION

Especially designed or prepared thin, porous filters [with a pore size of 100 to 1000 Å, a thickness of 5 mm (0.20 in.) or less, and for tubular forms, a diameter of 25 mm (0.98 in.) or less] made of metallic, polymer, or ceramic materials resistant to corrosion by UF_6 , and especially prepared compounds or powders for the manufacture of such filters. Such compounds and powders include nickel or alloys containing 60% or more nickel, aluminum oxide, or UF_6 -resistant fully fluorinated hydrocarbon polymers (having a purity of 99.9% or more, a particle size less than 10 μ , and a high degree of particle size uniformity) that are especially prepared for the manufacture of gaseous diffusion barriers

SPECIAL DESIGN FEATURES

The key to the gaseous diffusion process is the barrier material itself. Good barrier must have a very small pore size and yet a porosity to UF_6 as high as possible, a thickness as small as possible, and yet sufficient mechanical strength. Additionally, the barrier must be stable and chemically inert under years of exposure to corrosive UF_6 under a strong pressure gradient.

Ceramic barrier used in the French gaseous diffusion plant at Tricastin. Source: Rapport Annuel 1987, Cogema, Washington, D.C., Dec. 31, 1987.

Magnification of barrier material.

*Ceramic barrier used in the Soviet
gaseous diffusion plant.*

Barrier tubes, disks, and sheets.

1.2 Diffuser Housings

DESCRIPTION

Especially designed or prepared hermetically sealed cylindrical vessels greater than 30 cm (11.8 in.) in diameter and greater than 90 cm (35.1 in.) in length (or rectangular vessels of comparable dimensions) that have an inlet connection and two outlet connections [all of which are greater than 5 cm (1.9 in.) in diameter] for containing the gaseous diffusion barrier, made of, or lined with, UF₆-resistant materials and designed for horizontal or vertical installation.

SPECIAL DESIGN FEATURES

Vessels of this type are especially designed and prepared to high vacuum standards. They are made of nickel-plated steel, aluminum, or Monel.

Sketch showing a diffuser housing of the shape (cylindrical) and dimensions that might be expected in a very small diffusion stage. The gas inlet is at the left, the undiffused gas outlet is at the right, and the diffused gas outlet is at the top. Also shown are connections for inlet and outlet flow of coolant. The location of the connection could vary from those shown.

A small U.S. diffuser housing. Note the inlet at the center left and the two coolant connections below it. The section between the two left ridges on the diffuser is the location of the cooler.

The right end of the diffuser housing in the preceding illustration is shown. The outlet at the center of the housing is for the diffused low-pressure flow, while that above and beyond it is for the high-pressure undiffused flow. The diffused flow is passing into the inlet of a centrifugal compressor in order to be advanced to the next higher stage. The undiffused flow passes through a control valve (whose stem can be seen) and is blended with the diffused flow from stage two below it.

Interior elements of a large diffuser housing. Here only the diffused gas is cooled at the outlet end of the diffuser housing, while the undiffused gas passes directly to the inlet of the compressor of the next lower stage.

Shown is a diffuser housing for a Soviet gaseous diffusion plant. The gas inlet is at the top; gas flows through the heat exchanger mounted on the diffuser housing. The gas outlet at the right of the housing is for the diffused low-pressure flow, while that below it is for the undiffused high-pressure flow. The diffused flow passes into the inlet of a centrifugal compressor in order to be advanced to the next higher stage. The undiffused flow passes through a control valve and is blended with the diffused flow from the previous stage.

1.3 Compressors and Gas Blowers

DESCRIPTION

Especially designed or prepared axial, centrifugal, or positive displacement compressors or gas blowers with a suction volume capacity of 1 m³/min or more of UF₆ and with a discharge pressure of up to several hundred kN/m² (100 psi), designed for long-term operation in the UF₆ environment with or without an electrical motor of appropriate power, as well as separate assemblies of such compressors and gas blowers. These compressors and gas blowers have a pressure ratio between 2:1 and 6:1 and are made of, or lined with, materials resistant to UF₆

SPECIAL DESIGN FEATURES

A major feature of these compressors is their materials of construction. Casings may be made of nickel or a high-nickel alloy, or may be plated with one of these materials. Rotor blades and impellers may be made of these materials or of high-strength aluminum alloys. A second requirement is the use of a seal that absolutely precludes leakage between the process system and the atmosphere. For low-flow applications, screw compressors, rotary blowers, or other positive displacement compressors manufactured of the appropriate materials would also be feasible.

Diagrammatic cross section of a centrifugal gas compressor in the United States. Such a compressor can be mounted with its central drive axis vertical or horizontal. It may also have a diameter as small as 10 cm (3.9 in.) and operate to accept as little as 1 m³/min. For UF₆ service, centrifugal gas compressors must be made of material that resists UF₆ attack.

Rotary blowers, such as those shown in the photograph and diagram, operate at low volume and horsepower levels. They may have suction volumes between 3 m³/min and 30 m³/min at 30 hp. Their flow connections can be either horizontal or vertical, and for UF₆ service they would be built of UF₆-resistant materials.

A row of centrifugal compressors and associated motors intended for UF₆ service. These are of an intermediate size among the various ones that have been used in the United States. In this particular array, the compressors were modified to pump a mixture of UF₆ and nitrogen as part of a cascade used to purge the latter from the former. The motor shaft connects to a speed-changing device rather than being coupled directly to the compressor.

Assembled and exploded diagrams of a U.S. intermediate size axial flow UF_6 compressor. The drive motor (not shown) is attached at the right, or high-pressure gas discharge end, to the rotor shaft assembly. The latter fits inside the A-stator, spider, and B-stator. The spider serves to guide the gas entering through the side inlet nozzle on an optimal flow path into the B-Section of the compressor. After having passed through this section of the compressor, the full gas flow is discharged through the discharge nozzle.

The internal elements of the rotor and stator sections of a U.S. axial flow compressor. The multiple rows of blades in each section can be seen as well as the large number of blades in each individual row of both the stator and the rotor.

1.4 Rotary Shaft Seals

DESCRIPTION

Especially designed or prepared vacuum seals with seal feed and seal exhaust connections for sealing the shaft connecting the compressor or the gas blower rotor with the driver motor to ensure a reliable seal against inleaking of air into the inner chamber of the compressor or gas blower that is filled with UF_6 . Such seals are normally designed for a buffer gas inleakage rate of less than $1000 \text{ m}^3/\text{min}$

SPECIAL DESIGN FEATURES

Shaft seals have stringent requirements because UF_6 is a toxic, highly reactive material. Neither substantial inleakage of atmospheric gases nor outleakage of UF_6 can be tolerated from the thousands of shaft seals operating in a diffusion cascade. Long-term running reliability, adaptability to sealing a wide range of gas pressures, ability to allow transmission of high levels of power, tolerance of cascade pressure disturbances and equipment start/stop cycles, and ease of maintenance are some of the further requirements imposed on economically practical seals. They are wholly made of, or lined with, materials corrosion resistant to UF_6 .

Representation of the design basis of a rotary shaft seal in the United States. This seal serves to isolate the Process Gas System from the atmosphere where the drive motor is attached to the compressor by means of a rotating shaft. This is accomplished in a viscosity seal of the kind shown by causing gas to flow between the rotating shaft and the stationary shaft seal. On the inner, or process gas, side of the seal, nitrogen flows around the rotating shaft into both the Process Gas System and into a Seal Exhaust System. On the atmosphere, or motor, end of the seal, dry air rather than nitrogen is used, and this flows into both the Seal Exhaust System and out into the atmosphere.

Another type of rotary shaft seal is a labyrinth seal in which there is some transfer of gas between the atmosphere and the Process Gas System, but because of the use of a tortuous flow path, the flow is very small. In the diagram, the upper portion is the stationary element, the lower portion is rotating, and the finger-like contacts between the stationary housing and rotating shaft are the elements of the labyrinth.

A mechanical shaft seal for application to rotating systems consists of a rotating ring or shoulder attached to the shaft and breaking contact with a flat face attached to the stationary pump housings. Seals of this sort can be either inside, as on the left, in which the internal pressure tends to tighten the seal, or outside, as on the right, in which the external pressure tightens the seal.

Representation of the design bases of a Soviet rotary shaft seal. This seal serves to isolate the Process Gas System from the atmosphere where the drive motor is attached to the compressor by means of a rotating shaft. Isolation is achieved by a hydraulic oil seal, two pairs of contacting rings, outleakages from which are compensated for by oil from the feeder. Oil used would be UF_6 resistant.

1.5 Heat Exchangers for Cooling UF₆

DESCRIPTION

Especially designed or prepared heat exchangers made of, or lined with, UF₆-resistant materials (except stainless steel) or with copper or any combination of those metals, and intended for a leakage pressure change rate of less than 10 N/m² per hour (0.0015 psi) under a pressure difference of 100 kN/m² (15 psi)

SPECIAL DESIGN FEATURES

The primary heat exchanger in a gaseous diffusion plant is likely to be external when part of a very small diffusion stage and internal to the diffuser when part of larger ones. The latter would not be accessible for visual inspection but could be surmised from the external coolant connections. Heat exchangers suitable for use in gaseous diffusion plants are likely to be made of aluminum, copper, nickel, alloys of nickel content greater than 60%, or combinations of these materials.

A small heat exchanger in service in a U.S. pilot plant used for testing equipment. The heat exchanger is in the center of the photograph and has UF_6 flowing upward through it. The coolant flow is counter to that of the UF_6 entering the heat exchanger at the upper left and leaving it at the lower right. A portion of a second heat exchanger can be seen at the upper right. Such heat exchangers may have process line diameters of 5 cm (1.9 in.) or greater and have very stringent leak rate requirements.

A large heat exchanger in service in the largest U.S. gaseous diffusion stages. The heat exchanger, or gas cooler, is in the shape of a large flat disk; the process gas flows axially through the disk, and the coolant flows through circumferential coils. In other heat exchanger designs, the process gas flows radially inward over the coolant coils.

A heat exchanger for cooling UF_6 and cooling section of a Soviet gaseous diffusion plant. The heat exchanger includes steel housing enclosing an assembly of aluminum sections. The latter is made in the ribbed form. Gas flows between ribs. The coolant flows through the section coils.

2. Auxiliary Systems, Equipment, and Components

DESCRIPTION

Especially designed or prepared auxiliary systems, equipment, and components for use in gaseous diffusion enrichment plants

SPECIAL DESIGN FEATURES

The auxiliary systems, equipment, and components for gaseous diffusion enrichment plants are the systems of plants needed to feed UF_6 to the gaseous diffusion assembly, to link the individual assemblies to each other, to form cascades (or stages) to allow for progressively higher enrichments, and to extract the "product" and "tails" UF_6 from the technological process. Because of the high inertial properties of diffusion cascades, any interruption in their operation, and especially their shutdown, leads to serious consequences. Therefore a strict and constant maintenance of vacuum in all technological systems, automatic protection from accidents, and precise automated regulation of the gas flow is of importance in a gaseous diffusion plant. All this leads to a need to equip the plant with a large number of special measuring, regulating, and controlling systems.

Normally UF_6 is evaporated from cylinders placed within autoclaves and is distributed in gaseous form to the entry point by way of cascade header pipework. The "product" and "tails" UF_6 gaseous streams flowing from exit points are passed by way of cascade header pipework either to cold traps or to compression stations where the UF_6 gas is liquified prior to onward transfer into suitable containers for transportation or storage. Because a gaseous diffusion enrichment plant consists of a large number of gaseous diffusion assemblies arranged in cascades, there are many kilometers of cascade header pipework incorporating thousands of welds with a substantial amount of repetition of layout. The equipment, components, and piping systems are fabricated to very high vacuum and cleanliness standards.

The following items either come into direct contact with the UF_6 process gas or directly control the flow within the cascade. All surfaces that come into contact with the process gas are wholly made of, or lined with, UF_6 -resistant materials.

2.1 (a) Feed Systems

DESCRIPTION

Especially designed or prepared process systems including feed autoclaves (or systems) used for passing UF_6 to the gaseous diffusion cascades and capable of operating at pressures of 300 kN/m^2 (45 psi) or less

SPECIAL DESIGN FEATURES

The Process Feed System consists of vaporizing autoclaves, feed headers for the distribution of feed, flow control equipment, instrumentation, various cranes and scales, and the storage cylinders in which feed is received. The dimensions of the Process Feed System will generally be large [i.e., cylinders and autoclaves being as much as 3.05 m (10 ft) long and perhaps 1.83 m (6 ft) in diameter]. All internal surfaces exposed to UF_6 would be resistant to corrosion by it.

Two U.S. autoclaves ready to receive cylinders of liquid UF_6 . The cylinders are placed in the recessed openings opposite the dished heads. Note the complexity of piping and controls necessary to operate a facility of this kind.

A more general view of the autoclaves in the feed vaporization area of a feed and withdrawal facility. A number of autoclaves can be seen with the autoclave cover in place over the cylinder position.

This U.S. cylinder is of a nominal 2-1/2-ton capacity and is used for storing and transporting UF₆. As is indicated in the table of specifications, it may be used at ²³⁵U concentrations of up to 5%. Such a cylinder can also be used in UF₆ withdrawal and storage operations.

NOMINAL 2-1/2-TON CYLINDER

Nominal diameter	0.76 m
Nominal length	2.05 m
Wall thickness	1.3 cm
Nominal tare weight	635 kg (1400 lb)
Maximum net weight	2277 kg (5020 lb)
Nominal gross weight	2912 kg (6420 lb)
Minimum volume	736 L (26 ft ³)
Basic material of construction	Steel
Service pressure	1380 kPa
Hydrostatic test pressure	2760 kPa
Isotopic content limit	5% ²³⁵ U

Valve used: 1-in. valve.

Other configurations including vertical designs also exist, and capacities can be as much as 100,000 kg.

NOMINAL 10-TON CYLINDER

Nominal diameter	1.22 m
Nominal length	3.07 m
Wall thickness	16 mm
Nominal tare weight	2041 kg (4500 lb)
Maximum net weight	9539 kg (21,030 lb)
Nominal gross weight	11,580 kg (25,530 lb)
Minimum volume	3.085 m ³ (108.9 ft ³)
Basic material of construction	Steel
Service pressure	1380 kPa
Hydrostatic test pressure	2760 kPa
Isotopic content limit	4.5% ²³⁵ U max. with moderation control

Valve used: 1-in. valve.

NOMINAL 14-TON CYLINDER

Nominal diameter	1.22 m
Nominal length	3.81 m
Wall thickness	16 mm
Nominal tare weight	2359 kg (5200 lb)
Maximum net weight	12,501 kg (27,560 lb)
Nominal gross weight	14,860 kg (32,760 lb)
Minimum volume	4.04 m ³ (142.7 ft ³)
Basic material of construction	Steel
Service pressure	1380 kPa
Hydrostatic test pressure	2760 kPa
Isotopic content limit	4.5% ²³⁵ U max. with moderation control

Valve used: 1-in. valve.

2.1 (b) Product and Tails Withdrawal Systems

DESCRIPTION

Desublimers (or cold traps) used to remove UF₆ from diffusion cascades. Liquefaction stations where UF₆ gas from the cascade is compressed and cooled to form liquid UF₆. Product and tails stations for transferring UF₆ into containers suitable for shipping, storage, or other uses. These especially designed or prepared process systems are capable of operating at pressures of 300 kN/m² (45 psi) or less

SPECIAL DESIGN FEATURES

For low ²³⁵U assays, the Product Withdrawal System may consist of a compression liquefaction cycle in which UF₆ is compressed to above the triple-point pressure and cooled in a gas cooler. For higher assays and presumably lower product rates, refrigerated cold traps could be used. The Tails Withdrawal System may also operate on a compression liquefaction cycle or may have a cold trap cooled with chilled water or brine in which UF₆ is desublimed for isolation before vaporization into a collection cylinder. All internal surfaces in contact with UF₆ in these systems must be made of materials resistant to UF₆ (i.e., nickel, high-nickel alloys, aluminum, or copper). This equipment will generally be large – of the order of 1 m (3.3 ft) in diameter when insulated and 2 or 3 m (6.6 or 9.8 ft) long. Also, a product system designed to handle highly enriched uranium will have had geometric constraints imposed on it. Specifically, cylindrical vessels will be no more than 12.5 cm (4.9 in.) in diameter. Boron alloys may also be present; these serve as neutron absorbers and preclude the possibility of a critical nuclear reaction.

Cold traps shown in the elevated area are used in the United States to remove cascade tails from the Process System. Tails so removed are then transferred to large storage cylinders. Such cold traps are operated with chilled water for the condensation step and then with heated water for the subsequent volatilization. The use of water in such low-assay UF_6 systems is permissible.

View of an uninsulated cold trap functioning as part of a Product Withdrawal System. Although such a cold trap would ordinarily be used for removing either tails or operating inventory from a cascade, it could also be used for product removal.

Motor drive speed increaser and compressor for a typical U.S. compression-liquefaction station.

The sampling cylinder including the attached valve shown is one used in the United States to collect UF₆ at high-²³⁵U-assay levels. The special features for the cylinder indicate a capacity of slightly over 2.2 kg (4.8 lb) of UF₆.

GENERAL DATA

Nominal diameter	9 cm
Nominal length	29 cm
Wall thickness	3.0 mm
Nominal tare weight	1.91 kg (4.2 lb)
Maximum net weight	2.22 kg (4.9 lb)
Nominal gross weight	4.13 kg (9.1 lb)
Minimum volume	736 cm ³ (0.026 ft ³)
Basic material of construction	Nickel
Service pressure	1380 kPa
Hydrostatic test pressure	2760 kPa
Isotopic content limit	100% ²³⁵ U max.

The product cylinder shown is used in the United States to collect UF₆ at high-²³⁵U assay levels. The connections permit UF₆ to be passed through the cylinder while the product is being frozen out. Such a cylinder has a capacity of about 25 kg (55.1 lb).

GENERAL DATA

Nominal diameter	12.7 cm
Nominal length	91 cm
Wall thickness	6.4 mm
Nominal tare weight	24.95 kg (55 lb)
Maximum net weight	24.95 kg (55 lb)
Nominal gross weight	49.9 kg (110 lb) (without cap)
Minimum volume	8.4 L (0.284 ft ³)
Basic material of construction	Monel
Service pressure	1380 kPa
Hydrostatic test pressure	2760 kPa
Isotopic content limit	100% ²³⁵ U max.

2.2

Header Piping Systems

DESCRIPTION

Especially designed or prepared piping systems and header systems for handling UF_6 within the gaseous diffusion cascades. This piping network is normally of the "double" header system with each cell connected to each of the headers

SPECIAL DESIGN FEATURES

This system consists of an array of pipes carrying the process gas between the various stages, sections, and buildings of the plant. These pipes may be upward of 5.08 cm (2 in.) in diameter; they are wholly made of, or lined with, UF_6 -resistant materials and are fabricated to very high vacuum and cleanliness standards. Materials resistant to UF_6 include stainless steel, aluminum, aluminum alloys, nickel or alloys containing 60% or more of nickel, and UF_6 -resistant fully fluorinated hydrocarbon polymers.

Details of a Header Piping System based on a U.S. design can be seen in this diagram. In normal cell operation, valves A, B, E, and F are open, and valves C and D are closed. During cell bypass, the valve positions are reversed.

An example of a large metal bellows in the United States; these are an essential part of the Process Piping System and come in a wide variety of sizes from 2 cm (0.78 in.) in diameter or larger. Bellows made of materials such as nickel or high-nickel alloys would be resistant to UF_6 attack and would be appropriate for diffusion plant service.

*Details of a Header Piping System
based on a Soviet design.*

Process piping and equipment are usually connected, at least in larger sizes, by welded (commonly referred to as Van Stone) joints made up of pairs of opposed flanges with nickel-plated facings. The flanges extend some distance beyond the outer pipe wall and are closed at their peripheries with carbon steel seal welds. Alternately, piping may use bolted flanges equipped with UF_6 -resistant gasketing material.

A typical two-ply bellows assembly. Expansion joints are a necessary part of the Process Piping System in order to allow for some pipe misalignment and to compensate for the effects of temperature changes on pipe lengths. The buffer connection permits the introduction of a buffering gas between the bellows and the sleeve.

2.3 Vacuum Systems

DESCRIPTION

Especially designed or prepared (a) large vacuum manifolds, vacuum headers, and vacuum pumps having a suction capacity of 5 m³/min or more and (b) vacuum pumps for service in UF₆-bearing atmospheres made of, or lined with, aluminum, nickel, or alloys bearing more than 60% nickel. These pumps may be either rotary or positive, may have displacement and fluorocarbon seals, and may have special working fluids present

SPECIAL DESIGN FEATURES

Vacuum pumps are specially designed for service in UF₆-bearing atmospheres and are made of, or lined with, aluminum, nickel, or alloys bearing more than 60% nickel.

A pump having size and capacity characteristics used in a U.S. gaseous diffusion plant Process Vacuum System. Such a pump having working oil of fluorocarbon resistant to UF_6 would be especially appropriate for UF_6 service.

SPECIFICATIONS

Pump displacement	30 m ³ /min.
Motor horsepower	50
Motor speed, rpm	1200
Oil capacity	
Standard "D"	189 L
Vapor purge	83 L
Piping sizes	
Suction	20.3 cm
Discharge	2.0 cm
Net weight with motor	3084 kg
Length	2.36 m
Width	1.63 m
Height	2.23 m

A vacuum pump and associated drive motor intended for service in a U.S. plant. It is necessary that such a system also have equipment such as traps and filters needed to protect against the effect of UF_6 contamination.

2.4 Special Shutoff and Control Valves

DESCRIPTION

Especially designed or prepared manual or automated shutoff and control bellows valves made of UF_6 -resistant materials with a diameter of 4 cm to 1.5 m (1.6 in. to 4.9 ft) for installation in main and auxiliary systems of gaseous diffusion enrichment plants

SPECIAL DESIGN FEATURES

Process Vacuum System valves are built of, or coated with, material such as nickel or high-nickel alloys that are resistant to UF_6 . Valves for UF_6 service may have bores of 0.5 cm or more and have bellows seals rather than packing glands. The flow diameter of such valves may be as high as 121.92 cm (48 in.), but this would be only for a very large plant. Such valves are fabricated in accordance with stringent requirements regarding hermeticity and finish.

Shown is a Soviet control valve for the undiffused UF_6 flow.

Shown is a Soviet motor-operated valve intended for UF_6 service in a line 40 cm (16 in.) in diameter. It is flanged, has internal bellows, and can be operated electrically or by hand.

Shown is a motor-operated isolation valve used in the United States. Intended for UF_6 service in a line 20 cm (8 in.) in diameter, it is flanged, has internal bellows, and can be operated electrically or by hand. The valve as shown was undergoing tests, and some additional probe lines are shown.

Schematic representation of a large motor-operated process block valve used in the United States. The various parts are used as either elements necessary for valve operation, requirements for ensuring seating integrity, or requirements for buffering the bellows system or purging the valve of process gas when it is to be worked on. Such valves could come with bores of as little as 3 cm (1.2 in.), but the central element would be the presence of bellows for isolation of the Process Vacuum System from the atmosphere.

Schematic representation of a large motor-operated (or by hand) process block valve used in a Soviet gaseous diffusion plant. The various parts are used either as elements necessary for valve operation, as a requirement for ensuring seating integrity, or as a requirement for buffering the bellows system when it is closed or purging the valve of process gas when it is open.

A small process block valve such as that used in the United States (see schematic at right) may be pneumatically operated. The solenoid control valve on the air inlet admits air; this operates on a piston and opens the valve against the spring pressure. When the solenoid is deactivated, the air flow is cut off, and the spring pressure forces the valve closed.

2.5

UF₆ Mass Spectrometers/ Ion Sources

DESCRIPTION

Especially designed or prepared magnetic or quadrupole mass spectrometers capable of taking on-line samples of feed, product, or tails from UF₆ gas streams and having all of the following characteristics: (1) unit resolution for mass greater than 320; (2) ion sources constructed of, or lined with, nichrome or Monel or nickel plated; (3) electron bombardment ionization sources; and (4) a collector system suitable for isotopic analysis

SPECIAL DESIGN FEATURES

The key elements of this instrument are the unit resolution of mass greater than 320, the presence of an ion bombardment source in a UF₆-resistant chamber made of, or lined with, nickel, nichrome, or Monel, and a collector system capable of taking on-line samples for two or more isotopic species.

In the United States, mass spectrometers to measure concentrations of UF_6 samples come in a wide range of dimensions and configurations. In this photograph, the sample and ion source are in the equipment on the left, while measurements are recorded in the equipment on the right.

U.S. ion sources are made of, or are internally lined with, materials that are corrosive-resistant to UF_6 . An ion source ionizes molecules from a gas sample and shoots them in a collimated beam down a curved channel. Only the molecules with the desired mass track the channel to a collecting device that samples the different isotopes.

Appendix

GASEOUS DIFFUSION TRIGGER LIST* OCTOBER 1989†

Introductory Note

In the gaseous diffusion method of uranium isotope separation, the main technological assembly is a special porous gaseous diffusion barrier, heat exchanger for cooling the gas (which is heated by the process of compression), seal valves and control valves, and pipelines. Inasmuch as gaseous diffusion technology uses uranium hexafluoride (UF_6), all equipment, pipeline and instrumentation surfaces (that come in contact with the gas) must be made of materials that remain stable in contact with UF_6 . A gaseous diffusion facility requires a number of these assemblies, so that quantities can provide an important indication of end use.

The auxiliary systems, equipment and components for gaseous diffusion enrichment plants are the systems of plant needed to feed UF_6 to the gaseous diffusion assembly to link the individual assemblies to each other to form cascades (or stages) to allow for progressively higher enrichments and to extract the "product" and "tails" UF_6 from the diffusion cascades. Because of the high inertial properties of diffusion cascades, any interruption in their operation, and especially their shutdown, leads to serious consequences. Therefore, a strict and constant maintenance of vacuum in all technological systems, automatic protection from accidents, and precise automated regulation of the gas flow is of importance in a gaseous diffusion plant. All this leads to a need to equip the plant with a large number of special measuring, regulating and controlling systems.

Normally UF_6 is evaporated from cylinders placed within autoclaves and is distributed in gaseous form to the entry point by way of cascade header pipework. The "product" and "tails" UF_6 gaseous streams flowing from exit points are passed by way of cascade header pipework to either cold traps or to compression stations where the UF_6 gas is liquified prior to onward transfer into suitable containers for transportation or storage. Because a gaseous diffusion enrichment plant consists of a large number of gaseous diffusion assemblies arranged in cascades, there are many kilometers of cascade header pipework, incorporating thousands of welds and substantial amounts of repetition of layout. The equipment, components and piping systems are fabricated to very high vacuum and cleanliness standards. The items listed below either come into direct contact with the UF_6 process gas or directly control the flow within the cascade. All surfaces which come into contact with the process gas are wholly made of, or lined with, UF_6 -resistant materials.

For the purposes of this annex the materials resistant to corrosion by UF_6 include stainless steel, aluminum, aluminum alloys, aluminum oxide, nickel or alloys containing 60 percent or more nickel, and UF_6 -resistant fully fluorinated hydrocarbon polymers.

1. ESPECIALLY DESIGNED OR PREPARED ASSEMBLIES AND COMPONENTS FOR USE IN GASEOUS DIFFUSION ENRICHMENT

1.1 Gaseous Diffusion Barriers

Especially designed or prepared thin, porous filters, with a pore size of 100-1000 Å (angstroms), a thickness of 5 mm or less, and for tubular forms, a diameter of 25 mm or less, made of metallic, polymer or ceramic materials resistant to corrosion by UF_6 , and especially prepared compounds or powders for the manufacture of

* Pending Annex (unedited and printed verbatim) to "Communications Received from Members Regarding the Export of Nuclear Materials and of Certain Categories of Equipment and Other Material," INFCIRC/209, International Atomic Energy Agency, Vienna.

† Incorporates editorial revisions suggested to add clarity to the list.

such filters. Such compounds and powders include nickel or alloys containing 60 percent or more nickel, aluminum oxide, or UF_6 -resistant fully fluorinated hydrocarbon polymers having a purity of 99.9 percent or more, a particle size less than 10 microns, and a high degree of particle size uniformity, which are especially prepared for the manufacture of gaseous diffusion barriers.

1.2 Diffuser Housings

Especially designed or prepared hermetically sealed cylindrical vessels greater than 30 cm in diameter and greater than 90 cm in length, or rectangular vessels of comparable dimensions, which have an inlet connection and two outlet connections all of which are greater than 5 cm in diameter, for containing the gaseous diffusion barrier, made of or lined with UF_6 -resistant materials and designed for horizontal or vertical installation.

1.3 Compressors and gas blowers

Especially designed or prepared axial, centrifugal, or positive displacement compressors, or gas blowers with a suction volume capacity of 1 cu m/min or more of UF_6 , and with a discharge pressure of up to several hundred kN/m^2 (100 psi), designed for long-term operation in the UF_6 environment with or without an electrical motor of appropriate power, as well as separate assemblies of such compressors and gas blowers. These compressors and gas blowers have a pressure ratio between 2/1 and 6/1 and are made of, or lined with, materials resistant to UF_6 .

1.4 Rotary shaft seals

Especially designed or prepared vacuum seals, with seal feed and seal exhaust connections, for sealing the shaft connecting the compressor or the gas blower rotor with the driver motor so as to ensure a reliable seal against in-leaking of air into the inner chamber of the compressor or gas blower which is filled with UF_6 . Such seals are normally designed for a buffer gas in-leakage rate of less than 1000 cubic cm/min.

1.5 Heat Exchangers for Cooling UF_6

Especially designed or prepared heat exchangers made of or lined with UF_6 -resistant materials (except stainless steel) or with copper or any combination of those metals, and intended for a leakage pressure change rate of less than 10 N/m^2 (0.0015 psi) per hour under a pressure difference of 100 kN/m^2 (15 psi).

2. ESPECIALLY DESIGNED OR PREPARED AUXILIARY SYSTEMS, EQUIPMENT AND COMPONENTS FOR USE IN GASEOUS DIFFUSION ENRICHMENT

2.1 Feed Systems/Product and Tails Withdrawal Systems

Especially designed or prepared process systems, capable of operating at pressures of 300 kN/m^2 (45 psi) or less, including:

Feed autoclaves (or systems), used for passing UF_6 to the gaseous diffusion cascades;

Desublimers (or cold traps) used to remove UF_6 from diffusion cascades;

Liquefaction stations where UF_6 gas from the cascade is compressed and cooled to form liquid UF_6 ;

"Product" or "tails" stations used for transferring UF_6 into containers.

2.2 Header Piping Systems

Especially designed or prepared piping systems and header systems for handling UF_6 within the gaseous diffusion cascades. This piping network is normally of the "double" header system with each cell connected to each of the headers.

2.3 Vacuum Systems

(A) Especially designed or prepared large vacuum manifolds, vacuum headers and vacuum pumps having a suction capacity of 5 cubic m/minute (5 cubic metres per minute) or more.

(B) Vacuum pumps especially designed for service in UF_6 -bearing atmospheres made of, or lined with, aluminum, nickel, or alloys bearing more than 60 percent nickel. These pumps may be either rotary or positive, may have displacement and fluorocarbon seals, and may have special working fluids present.

2.4 Special Shut-off and Control Valves

Especially designed or prepared manual or automated shut-off and control bellows valves made of UF_6 -resistant materials with a diameter of 4 cm to 1.5 m for installation in main and auxiliary systems of gaseous diffusion enrichment plants.

2.5 UF_6 Mass Spectrometers/Ion Sources

Especially designed or prepared magnetic or quadrupole mass spectrometers capable of taking "on-line" samples of feed, product or tails, from UF_6 gas streams and having all of the following characteristics:

- (A) Unit resolution for mass greater than 320;
- (B) Ion sources constructed of or lined with nichrome or Monel or nickel plated;
- (C) Electron bombardment ionization sources;
- (D) Having a collector system suitable for isotopic analysis.