

# CONSOLIDATED TRIGGER LIST

## MEMORANDUM A

### 1. INTRODUCTION

The Government has had under consideration procedures in relation to exports of nuclear materials in the light of its commitment not to provide source or special fissionable material to any non-nuclear-weapon State for peaceful purposes unless the source or special fissionable material is subject to safeguards under an agreement with the International Atomic Energy Agency.

### 2. DEFINITION OF SOURCE AND SPECIAL FISSIONABLE MATERIAL

The definition of source and special fissionable material adopted by the Government shall be that contained in Article XX of the Agency's Statute:

(a) "SOURCE MATERIAL"

The term "source material" means uranium containing the mixture of isotopes occurring in nature; uranium depleted in the isotope 235; thorium; any of the foregoing in the form of metal, alloy chemical compound, or concentrate; any other material containing one or more of the foregoing in such concentration as the Board of Governors shall from time to time determine; and such other material as the Board of Governors shall from time to time determine.

(b) "SPECIAL FISSIONABLE MATERIAL"

i) The term "special fissionable material" means plutonium-239 ( $^{239}\text{Pu}$ ); uranium-233 ( $^{233}\text{U}$ ); uranium enriched in the isotopes 235 or 233; any material containing one or more of the foregoing; and such other fissionable material as the Board of Governors shall from time to time determine; but the term "special fissionable material" does not include source material;

ii) The term "uranium enriched in the isotopes 235 or 233" means uranium containing the isotopes 235 or 233 or both in an amount such that the abundance ratio of the sum of these isotopes to the isotope 238 is greater than the ratio of the isotope 235 to the isotope 238 occurring in nature.

### 3. THE APPLICATION OF SAFEGUARDS

The Government is solely concerned with ensuring, where relevant, the application of safeguards in non-nuclear-weapon States not party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT)\* with a view to preventing diversion of the safeguarded nuclear material from peaceful purposes to nuclear weapons or other nuclear explosive devices. If the Government wishes to supply source or special fissionable material for peaceful purposes to such a State, it will:

(a) Specify to the recipient State, as a condition of supply that the source or special fissionable

material or special fissionable material produced in or by the use thereof shall not be diverted to nuclear weapons or other nuclear explosive devices; and

(b) Satisfy itself that safeguards to that end, under an agreement with the Agency and in accordance with its safeguards system, will be applied to the source or special fissionable material in question.

#### **4. DIRECT EXPORTS**

In the case of direct exports of source or special fissionable material to non-nuclear-weapon States not party to the NPT, the Government will satisfy itself, before authorizing the export of the material in question, that such material will be subject to a safeguards agreement with the Agency as soon as the recipient State takes over responsibility for the material, but no later than the time the material reaches its destination.

#### **5. RETRANSFERS**

The Government, when exporting source or special fissionable material to a nuclear-weapon State not party to the NPT, will require satisfactory assurances that the material will not be reexported to a non-nuclear-weapon State not party to the NPT unless arrangements corresponding to those referred to above are made for the acceptance of safeguards by the State receiving such re-export.

#### **6. MISCELLANEOUS**

Exports of the items specified in subparagraph (a) below, and exports of source or special fissionable to a given recipient country, within a period of one calendar year (1 Jan – 31 Dec) , below the limits specified in subparagraph (b) below, shall be disregarded for the purpose of the procedures described above:

(a) Plutonium with an isotopic concentration of plutonium-238 ( $^{238}\text{Pu}$ ) exceeding 80%; Special fissionable material when used in gram quantities or less as a sensing component in instruments; and Source material which the Government is satisfied is to be used only in non-nuclear activities, such as the production alloys or ceramics;

(b) Special fissionable material 50 effective grams;  
Natural uranium 500 kilograms;  
Depleted uranium 1000 kilograms; and  
Thorium 1000 kilograms.

## MEMORANDUM B

### 1. INTRODUCTION

The Government has had under consideration procedures in relation to exports of certain categories of equipment and material, in the light of its commitment 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 produced, processed or used in the equipment or material in question is subject to safeguards under an agreement with the International Atomic Energy Agency.

### 2. THE DESIGNATION OF EQUIPMENT OR MATERIAL ESPECIALLY DESIGNED OR PREPARED FOR THE PROCESSING, USE OR PRODUCTION OF SPECIAL FISSIONABLE MATERIAL

The designation of items of equipment or material especially designed or prepared for the processing, use or production of special fissionable material (hereinafter referred to as the "Trigger List") adopted by Government is as follows (quantities below the levels indicated in the Annex being regarded as insignificant for practical purposes):

2.1. Nuclear reactors and especially designed or prepared equipment and components therefor (see Annex, section 1.);

2.2. Non-nuclear materials for reactors (see Annex, section 2.);

2.3. Plants for the reprocessing of irradiated fuel elements, and equipment especially designed or prepared therefor (see Annex, section 3.);

2.4. Plants for the fabrication of nuclear reactor fuel elements, and equipment especially designed or prepared therefor (see Annex, section 4.);

2.5. Plants for the separation of isotopes of natural uranium, depleted uranium or special fissionable material and equipment, other than analytical instruments, especially designed or prepared therefor (See Annex, section 5);

#### EXPLANATORY NOTE

The Government recognizes the close relationship for certain isotope separation processes between plants and equipment for uranium enrichment and that for isotope separation of stable isotopes for research, medical and other non-nuclear industrial purposes. In that regard, the Government should carefully review its legal measures, including export licensing regulations and security practices, for stable isotope separation activities to ensure the implementation of appropriate protection measures as warranted. The Government recognizes that, in particular cases, appropriate protection measures for stable isotope separation activities will be essentially the same as those for uranium enrichment. (See Introductory Note in Section 5 of the Annex to the Trigger List.)

2.6. Plants for the production or concentration of heavy water, deuterium and deuterium compounds and equipment especially designed or prepared therefor (see Annex, section 6.).

2.7. Plants for the conversion of uranium and plutonium for use in the fabrication of fuel elements and the separation of uranium isotopes as defined in Annex sections 4 and 5 respectively, and equipment especially designed or prepared therefor (see Annex, section 7.)

### **3. THE APPLICATION OF SAFEGUARDS**

The Government is solely concerned with ensuring, where relevant, the application of safeguards in non-nuclear-weapon States not party to the Treaty on the Non Proliferation of Nuclear Weapons (NPT) with a view to preventing diversion of the safeguarded nuclear material from peaceful purposes to nuclear weapons or other nuclear explosive devices. If the Government wishes to supply Trigger List items for peaceful purposes such a State, it will:

- (a) Specify to the recipient State, as a condition of supply, that the source or special fissionable material produced, processed or used in the facility for which the items is supplied shall not be diverted to weapons or other nuclear explosive devices; and
- (b) Satisfy itself that safeguards to that end, under an agreement with the Agency and in accordance its safeguards system, will be applied to the source or special fissionable material in question.

### **4. DIRECT EXPORTS**

In the case of direct exports to non-nuclear weapon States not party to the NPT, the Government will satisfy itself, before authorizing the export of the equipment or material in question, that such equipment or material will fall under a safeguards agreement with the Agency.

### **5. RETRANSFERS**

The Government, when exporting Trigger List items, will require satisfactory assurances that the items will not be re-exported to a non-nuclear weapon State not party to the NPT unless arrangements corresponding to those referred to above are made for the acceptance of safeguards by the State receiving such re-export.

### **6. MISCELLANEOUS**

The Government reserves to itself discretion as to interpretation and implementation of its commitment to in paragraph 1 above and the right to require, if it wishes, safeguards as above in relation to items it exports in addition to those items specified in paragraph 2 above.

**ANNEX**  
**CLARIFICATION OF ITEMS ON THE TRIGGER LIST**  
**(as designated in Section 2 of Memorandum B)**

**1. Nuclear reactors and especially designed or prepared equipment and components therefor**

INTRODUCTORY NOTE

Various types of nuclear reactors may be characterised by the moderator used (e.g., graphite, heavy water, light water, none), the spectrum of neutrons therein (e.g., thermal, fast), the type of coolant used (e.g., water, liquid metal, molten salt, gas), or by their function or type (e.g., power reactors, research reactors, test reactors). It is intended that all of these types of nuclear reactors are within scope of this entry and all of its sub-entries where applicable. This entry does not control fusion reactors.

**1.1. Complete nuclear reactors**

Nuclear reactors capable of operation so as to maintain a controlled self-sustaining fission chain reaction.

EXPLANATORY NOTE

A nuclear reactor basically includes the items within or attached directly to the reactor vessel, the equipment which controls the level of power in the core, and the components which normally contain or come in direct contact with or control the primary coolant of the reactor core.

EXPORTS

The export of the whole set of major items within this boundary will take place only in accordance with procedures of the Memorandum. Those individual items within this functionally defined boundary which will be exported only in accordance with the procedures of the Memorandum are listed in paragraphs 1.2. to 1.11. Pursuant to paragraph 6 of the Memorandum, the Government reserves the right to apply the procedures of the Memorandum to other items within the functionally defined boundary.

**1.2. Nuclear reactor vessels**

Metal vessels, or as major shop-fabricated parts therefor, especially designed or prepared to contain the core of a nuclear reactor as defined in paragraph 1.1. above, as well as relevant reactor internals as defined in paragraph 1.8. below.

EXPLANATORY NOTE

Item 1.2. covers nuclear reactor vessels regardless of pressure rating and includes reactor pressure vessels and calandrias. The reactor vessel head is covered by item 1.2. as a major shop-fabricated part of a reactor vessel.

### **1.3. Nuclear reactor fuel charging and discharging machines**

Manipulative equipment especially designed or prepared for inserting or removing fuel in a nuclear reactor as defined in paragraph 1.1. above.

#### **EXPLANATORY NOTE**

The items noted above are capable of on-load operation or of employing technically sophisticated positioning or alignment features to allow complex off-load fuelling operations such as those in which direct viewing of or access to the fuel is not normally available.

### **1.4. Nuclear reactor control rods and equipment**

Especially designed or prepared rods, support or suspension structures therefor, rod drive mechanisms or rod guide tubes to control the fission process in a nuclear reactor as defined in paragraph 1.1. above.

### **1.5. Nuclear reactor pressure tubes**

Tubes which are especially designed or prepared to contain both fuel elements and the primary coolant in a reactor as defined in paragraph 1.1. above.

#### **EXPLANATORY NOTE**

Pressure tubes are parts of fuel channels designed to operate at elevated pressure, sometimes in excess of 5 MPa.

### **1.6. Nuclear fuel cladding**

Zirconium metal tubes or zirconium alloy tubes (or assemblies of tubes), especially designed or prepared for use as fuel cladding in a reactor as defined in paragraph 1.1 above, and in quantities exceeding 10 kg.

N.B.: For zirconium pressure tubes see 1.5. For zirconium calandria tubes see 1.8.

#### **EXPLANATORY NOTE**

Zirconium metal tubes or zirconium alloy tubes for use in a nuclear reactor consist of zirconium in which the relation of hafnium to zirconium is typically less than 1:500 parts by weight.

### **1.7. Primary coolant pumps or circulators**

Pumps or circulators especially designed or prepared for circulating the primary coolant for nuclear reactors as defined in paragraph 1.1. above.

#### **EXPLANATORY NOTE**

Especially designed or prepared pumps or circulators include pumps for water-cooled reactors, circulators for gas-cooled reactors, and electromagnetic and mechanical pumps

for liquid-metal-cooled reactors. This equipment may include pumps with elaborate sealed or multi-sealed systems to prevent leakage of primary coolant, canned-driven pumps, and pumps with inertial mass systems. This definition encompasses pumps certified to Section III, Division I, Subsection NB (Class 1 components) of the American Society of Mechanical Engineers (ASME) Code, or equivalent standards.

### **1.8. Nuclear reactor internals**

Nuclear reactor internals especially designed or prepared for use in a nuclear reactor as defined in paragraph 1.1. above. This includes, for example, support columns for the core, fuel channels, calandria tubes, thermal shields, baffles, core grid plates, and diffuser plates.

#### **EXPLANATORY NOTE**

Nuclear reactor internals are major structures within a reactor vessel which have one or more functions such as supporting the core, maintaining fuel alignment, directing primary coolant flow, providing radiation shields for the reactor vessel, and guiding in-core instrumentation.

### **1.9. Heat exchangers**

- (a) Steam generators especially designed or prepared for the primary or intermediate coolant circuit of a nuclear reactor as defined in paragraph 1.1. above.
- (b) Other heat exchangers especially designed or prepared for the primary coolant circuit of a nuclear reactor as defined in paragraph 1.1. above.

#### **EXPLANATORY NOTE**

Steam generators are especially designed or prepared to transfer the heat generated in the reactor to the feed water for steam generation. In the case of a fast reactor for which an intermediate coolant loop is also present, the steam generator is in the intermediate circuit.

In a gas-cooled reactor, a heat exchanger may be utilised to transfer heat to a secondary gas loop that drives a gas turbine.

The scope of control for this entry does not include heat exchangers for the supporting systems of the reactor (e.g., the emergency cooling system or the decay heat cooling system).

### **1.10. Neutron detectors**

Especially designed or prepared neutron detectors for determining neutron flux levels within the core of a reactor as defined in paragraph 1.1. above.

#### **EXPLANATORY NOTE**

The scope of this entry encompasses in-core and ex-core detectors which measure flux levels in a wide range, typically from  $10^4$  neutrons per  $\text{cm}^2$  per second or more. Ex-core refers to those instruments outside the core of a reactor as defined in paragraph 1.1. above, but located within the biological shielding.

### **1.11. External thermal shields**

External thermal shields especially designed or prepared for use in a nuclear reactor as defined in paragraph 1.1 for reduction of heat loss and also for containment vessel protection.

#### EXPLANATORY NOTE

External thermal shields are major structures placed over the reactor vessel which reduce heat loss from the reactor and reduce temperature within the containment vessel.

## 2. Non-nuclear materials for reactors

### 2.1. Deuterium and heavy water

Deuterium, heavy water (deuterium oxide) and any other deuterium compound in which the ratio of deuterium to hydrogen atoms exceeds 1:5000 for use in a nuclear reactor as defined in paragraph 1.1. above, in quantities exceeding 200 kg of deuterium atoms for any one recipient country within a period of one calendar year (1 Jan – 31 Dec) .

### 2.2. Nuclear grade graphite

Graphite having a purity level better than 5 ppm (parts per million) boron equivalent and with a density greater than 1.50 g/cm<sup>3</sup> for use in a nuclear reactor as defined in paragraph 1.1. above, in quantities exceeding 1 kg .

#### EXPLANATORY NOTE

For the purpose of export control, the Government will determine whether or not the exports of graphite meeting the above specifications are for nuclear reactor use. [Graphite having a purity level better than 5 ppm \(parts per million\) boron equivalent and with a density greater than 1.50 g/cm<sup>3</sup> not for use in a nuclear reactor as defined in paragraph 1.1. above is not covered by this paragraph.](#)

Boron Equivalent (BE) may be determined experimentally or is calculated as the sum of BE<sub>z</sub> for impurities (excluding BE<sub>carbon</sub> since carbon is not considered an impurity) including boron, where:

BE<sub>z</sub> ppm = CF x concentration of element z (in ppm); CF is the conversion factor: ( $\sigma_z \times A_B$ ) divided by ( $\sigma_B \times A_z$ );  $\sigma_B$  and  $\sigma_z$  are the thermal neutron capture cross sections (in barns) for naturally occurring boron and element z respectively; and  $A_B$  and  $A_z$  are the atomic masses of naturally occurring boron and element z respectively.

## 3. Plants for the reprocessing of irradiated fuel elements, and equipment especially designed or prepared therefor

#### INTRODUCTORY NOTE

Reprocessing irradiated nuclear fuel separates plutonium and uranium from intensely radioactive fission products and other transuranic elements. Different technical processes can accomplish this separation. However, over the years Purex has become the most commonly used and accepted process. Purex involves the dissolution of irradiated nuclear fuel in nitric acid, followed by separation of the uranium, plutonium, and fission products by solvent extraction using a mixture of tributyl phosphate in an organic diluent.

Purex facilities have process functions similar to each other, including irradiated fuel element [decladding and/or](#) chopping, fuel dissolution, solvent extraction, and process liquor storage. There may also be equipment for thermal denitration of uranium nitrate, conversion of plutonium nitrate to oxide or metal, and treatment of fission product waste liquor to a form suitable for long term storage or disposal. However, the specific type and configuration of the equipment performing these functions may differ between Purex facilities for several reasons, including the type and quantity of irradiated nuclear fuel to be reprocessed and the intended disposition of the recovered materials, and the safety and maintenance philosophy incorporated into the design of the facility.

A plant for the reprocessing of irradiated fuel elements, includes the equipment and components which normally come in direct contact with and directly control the irradiated fuel and the major nuclear material fission-product processing streams.

These processes, including the complete systems for plutonium conversion and plutonium metal production, may be identified by the measures taken to avoid criticality (e.g., by geometry), radiation exposure (e.g., by shielding), and toxicity hazards (e.g., by containment).

## EXPORTS

The export of the whole set of major items within this boundary will take place only in accordance with the procedures of the Memorandum. Pursuant to paragraph 6 of the Memorandum, the Government reserves the right to apply the procedures of the Memorandum to other items within the functionally defined boundary.

Items of equipment that are considered to fall within the meaning of the phrase "and equipment especially designed or prepared" for the reprocessing of irradiated fuel elements include:

### 3.1. Irradiated fuel element [decladding equipment](#)

#### [and](#) chopping machines

Remotely operated equipment especially designed or prepared for use in a reprocessing plant as identified above and intended to ~~cut, chop or shear~~ [expose or prepare the](#) irradiated nuclear [material in](#) fuel assemblies, bundles or rods [for processing](#).

#### EXPLANATORY NOTE

This equipment [cuts, chops, shears or otherwise](#) breaches the cladding of the fuel to expose the irradiated nuclear material [for processing or prepares the fuel for processing to dissolution](#). Especially designed ~~metal~~-cutting shears are ~~the~~ most commonly employed, although advanced equipment, such as lasers, [peeling machines, or other techniques](#), may be used. [Decladding involves removing the cladding of the irradiated nuclear fuel prior to its dissolution.](#)

#### **Dissolvers**

Critically safe tanks (e.g., small diameter, annular or slab tanks) especially designed or prepared for use in a reprocessing plant as identified above, intended for dissolution of irradiated nuclear fuel and which are capable of withstanding hot, highly corrosive liquid, and which can be remotely loaded and maintained.

#### EXPLANATORY NOTE

Dissolvers normally receive the chopped-up spent fuel. In these critically safe vessels, the irradiated nuclear material is dissolved in nitric acid and the remaining hulls removed from the process stream.

### 3.3. Solvent extractors and solvent extraction equipment

Especially designed or prepared solvent extractors (such as packed or pulse columns, mixer settlers or centrifugal contactors) for use in a plant for the reprocessing of irradiated fuel. Solvent extractors must be resistant to the corrosive effect of nitric acid. Solvent extractors are normally fabricated to extremely high standards (including special welding and inspection and quality assurance and quality control techniques) out of low carbon stainless steels, titanium, zirconium, or other high quality materials.

#### EXPLANATORY NOTE

Solvent extractors both receive the solution of irradiated fuel from the dissolvers and the organic solution which separates the uranium, plutonium, and fission products. Solvent extraction equipment is normally designed to meet strict operating parameters, such as long operating lifetimes with no maintenance requirements or adaptability to easy replacement, simplicity of operation and control, and flexibility for variations in process conditions.

### 3.4. Chemical holding or storage vessels

Especially designed or prepared holding or storage vessels for use in a plant for the reprocessing of irradiated fuel. The holding or storage vessels must be resistant to the corrosive effect of nitric acid. The holding or storage vessels are normally fabricated of materials such as low carbon stainless steels, titanium or zirconium, or other high quality materials. Holding or storage vessels may be designed for remote operation and maintenance and may have the following features for control of nuclear criticality:

1. Walls or internal structures with a boron equivalent of at least 2 %;
2. A maximum diameter of 175 mm for cylindrical vessels; or
3. A maximum width of 75 mm for either a slab or annular vessel.

#### EXPLANATORY NOTE

Three main process liquor streams result from the solvent extraction step. Holding or storage vessels are used in the further processing of all three streams, as follows:

- (a) The pure uranium nitrate solution is concentrated by evaporation and passed to a denitration process where it is converted to uranium oxide. This oxide is re-used in the nuclear fuel cycle.
- (b) The intensely radioactive fission products solution is normally concentrated by evaporation and stored as a liquor concentrate. This concentrate may be subsequently evaporated and converted to a form suitable for storage or disposal.
- (c) The pure plutonium nitrate solution is concentrated and stored pending its transfer to further process steps. In particular, holding or storage vessels for plutonium solutions are designed to avoid criticality problems resulting from changes in

concentration and form of this stream.

### **3.5. Neutron measurement systems for process control**

Neutron measurement systems especially designed or prepared for integration and use with automated process control systems in a plant for the reprocessing of irradiated fuel elements.

#### EXPLANATORY NOTE

These systems involve the capability of active and passive neutron measurement and discrimination in order to determine the fissile material quantity and composition. The complete system is composed of a neutron generator, a neutron detector, amplifiers, and signal processing electronics.

The scope of this entry does not include neutron detection and measurement instruments that are designed for nuclear material accountancy and safeguarding or any other application not related to integration and use with automated process control systems in a plant for the reprocessing of irradiated fuel elements.

## **4. Plants for the fabrication of nuclear reactor fuel elements, and equipment especially designed or prepared therefor**

#### INTRODUCTORY NOTE

Nuclear fuel elements are manufactured from one or more of the source or special fissionable materials mentioned in Part A of this annex. For oxide fuels, the most common type of fuel, equipment for pressing pellets, sintering, grinding and grading will be present. Mixed oxide fuels are handled in glove boxes (or equivalent containment) until they are sealed in the cladding. In all cases, the fuel is hermetically sealed inside a suitable cladding which is designed to be the primary envelope encasing the fuel so as to provide suitable performance and safety during reactor operation. Also, in all cases, precise control of processes, procedures and equipment to extremely high standards is necessary in order to ensure predictable and safe fuel performance.

#### EXPLANATORY NOTE

Items of equipment that are considered to fall within the meaning of the phrase "and equipment especially designed or prepared" for the fabrication of fuel elements include equipment which:

- a) normally comes in direct contact with, or directly processes, or controls, the production flow of nuclear material;
- b) seals the nuclear material within the cladding;
- c) checks the integrity of the cladding or the seal;
- d) checks the finish treatment of the sealed fuel; or
- e) is used for assembling reactor fuel elements.

Such equipment or systems of equipment may include, for example:

1. Fully automatic pellet inspection stations especially designed or prepared for checking final dimensions and surface defects of fuel pellets;

2. Automatic welding machines especially designed or prepared for welding end caps onto the fuel pins (or rods);
3. Automatic test and inspection stations especially designed or prepared for checking the integrity of completed fuel pins (or rods);
4. Systems especially designed or prepared to manufacture nuclear fuel cladding.

Item 3 typically includes equipment for: a) X-ray examination of pin (or rod) end cap welds; b) Helium leak detection from pressurised pins (or rods); and c) Gamma-ray scanning of the pins (or rods) to check for correct loading of the fuel pellets inside.

## **5. Plants for the separation of isotopes of natural uranium, depleted uranium or special fissionable material and equipment, other than analytical instruments, especially designed or prepared therefor**

### INTRODUCTORY NOTE

Plants and equipment for the separation of uranium isotopes have, in many instances, a close relationship to plants and equipment for the separation of stable isotopes. In particular cases, the controls under Section 5 also apply accordingly to plants and equipment that are intended for the separation of stable isotopes. These controls of plants and equipment for the separation of stable isotopes are complementary to controls on plants and equipment especially designed or prepared for the processing, use or production of special fissionable material covered by the Trigger List. These complementary Section 5 controls for stable isotope uses do not apply to the equipment using the electromagnetic isotope separation process.

Processes for which the controls in Section 5 equally apply whether the intended use is uranium isotope separation or stable isotope separation are: gas centrifuge, gaseous diffusion, the plasma separation process, and aerodynamic processes.

For some processes, the relationship to uranium isotope separation depends on the element (stable isotope) being separated. These processes are: laser-based processes (e.g., molecular laser isotope separation and atomic vapour laser isotope separation), chemical exchange, and ion exchange. Governments must therefore evaluate these processes on a case-by-case basis to apply Section 5 controls for stable isotope uses accordingly.

Items of equipment that are considered to fall within the meaning of the phrase "equipment, other than analytical instruments, especially designed or prepared" for the separation of isotopes of uranium include:

### **5.1. Gas centrifuges and assemblies and components especially designed or prepared for use in gas centrifuges**

#### INTRODUCTORY NOTE

The gas centrifuge normally consists of a thin-walled cylinder of between 75 mm and 650 mm diameter contained in a vacuum environment and spun at high peripheral speed of the order of 300 m/s or more with its central axis vertical. In order to achieve high speed the materials of construction for the rotating components have to be of a high strength to density ratio and the rotor assembly, and hence its individual components, have to be manufactured to very close tolerances in order to minimise the unbalance. In contrast

to other centrifuges, the gas centrifuge for uranium enrichment is characterised by having within the rotor chamber a rotating disc-shaped baffle (or baffles) and a stationary tube arrangement for feeding and extracting the uranium hexafluoride (UF<sub>6</sub>) gas and featuring at least three separate channels, of which two are connected to scoops extending from the rotor axis towards the periphery of the rotor chamber. Also contained within the vacuum environment are a number of critical items which do not rotate and, which although they are especially designed, are not difficult to fabricate nor are they fabricated out of unique materials. A centrifuge facility however requires a large number of these components, so that quantities can provide an important indication of end use.

### 5.1.1. Rotating components

(a) Complete rotor assemblies:

Thin-walled cylinders, or a number of interconnected thin-walled cylinders, manufactured from one or more of the high strength to density ratio materials described in the EXPLANATORY NOTE to this Section. If interconnected, the cylinders are joined together by flexible bellows or rings as described in section 5.1.1.(c) following. The rotor is fitted with an internal baffle (or baffles) and end caps, as described in section 5.1.1.(d) and (e) following, if in final form. However the complete assembly may be delivered only partly assembled.

(b) Rotor tubes:

Especially designed or prepared thin-walled cylinders with thickness of 12 mm or less, a diameter of between 75 mm and 650 mm, and manufactured from one or more of the high strength to density ratio materials described in the EXPLANATORY NOTE to this Section.

(c) Rings or Bellows:

Components especially designed or prepared to give localised support to the rotor tube or to join together a number of rotor tubes. The bellows is a short cylinder of wall thickness 3 mm or less, a diameter of between 75 mm and 650 mm, having a convolute, and manufactured from one of the high strength to density ratio materials described in the EXPLANATORY NOTE to this Section.

(d) Baffles:

Disc-shaped components of between 75 mm and 650 mm diameter especially designed or prepared to be mounted inside the centrifuge rotor tube, in order to isolate the take-off chamber from the main separation chamber and, in some cases, to assist the UF<sub>6</sub> gas circulation within the main separation chamber of the rotor tube, and manufactured from one of the high strength to density ratio materials described in the EXPLANATORY NOTE to this Section.

(e) Top caps/Bottom caps:

Disc-shaped components of between 75 mm and 650 mm diameter especially designed or prepared to fit to the ends of the rotor tube, and so contain the UF<sub>6</sub> within the rotor tube, and in some cases to support, retain or contain as an integrated part an element of the upper bearing (top cap) or to carry the rotating elements of the motor and lower bearing (bottom cap), and manufactured from one of the high strength to density ratio materials described in the EXPLANATORY NOTE to this Section.

#### EXPLANATORY NOTE

The materials used for centrifuge rotating components include the following:

- (a) Maraging steel capable of an ultimate tensile strength of 1.95 GPa or more;
- (b) Aluminium alloys capable of an ultimate tensile strength of 0.46 GPa or more;
- (c) Filamentary materials suitable for use in composite structures and having a specific modulus of  $3.18 \times 10^6$  m or greater and a specific ultimate tensile strength of  $7.62 \times 10^4$  m or greater ('Specific Modulus' is the Young's Modulus in N/m<sup>2</sup> divided by the specific weight in N/m<sup>3</sup>; 'Specific Ultimate Tensile Strength' is the ultimate tensile strength in N/m<sup>2</sup> divided by the specific weight in N/m<sup>3</sup>).

### 5.1.2. Static components

(a) Magnetic suspension bearings:

1. Especially designed or prepared bearing assemblies consisting of an annular magnet suspended within a housing containing a damping medium. The housing will be manufactured from a UF<sub>6</sub>-resistant material (see EXPLANATORY NOTE to Section 5.2.). The magnet couples with a pole piece or a second magnet fitted to the top cap described in Section 5.1.1.(e). The magnet may be ring-shaped with a relation between outer and inner diameter smaller or equal to 1.6:1. The magnet may be in a form having an initial permeability of 0.15 H/m or more, or a remanence of 98.5% or more, or an energy product of greater than 80 kJ/m<sup>3</sup>. In addition to the usual material properties, it is a prerequisite that the deviation of the magnetic axes from the geometrical axes is limited to very small tolerances (lower than 0.1 mm) or that homogeneity of the material of the magnet is specially called for.
2. Active magnetic bearings especially designed or prepared for use in gas centrifuges.

#### EXPLANATORY NOTE

These bearings usually have the following characteristics:

- Designed to keep centred a rotor spinning at 600 Hz or more, and
- Associated to a reliable electrical power supply and/or to an uninterruptible power supply (UPS) unit in order to function for more than one hour.

(b) Bearings/Dampers:

Especially designed or prepared bearings comprising a pivot/cup assembly mounted on a damper. The pivot is normally a hardened steel shaft with a hemisphere at one end with a means of attachment to the bottom cap described in section 5.1.1.(e) at the other. The shaft may however have a hydrodynamic bearing attached. The cup is pellet-shaped with a hemispherical indentation in one surface. These components are often supplied separately to the damper.

(c) Molecular pumps:

Especially designed or prepared cylinders having internally machined or extruded helical grooves and internally machined bores. Typical dimensions are as follows: 75 mm to 650 mm internal diameter, 10 mm or more wall thickness, with the length equal to or

greater than the diameter. The grooves are typically rectangular in cross-section and 2 mm or more in depth.

(d) Motor stators:

Especially designed or prepared ring-shaped stators for high speed multiphase AC hysteresis (or reluctance) motors for synchronous operation within a vacuum at a frequency of 600 Hz or greater and a power of 40 VA or greater. The stators may consist of multi-phase windings on a laminated low loss iron core comprised of thin layers typically 2. mm thick or less.

(e) Centrifuge housing/recipients:

Components especially designed or prepared to contain the rotor tube assembly of a gas centrifuge. The housing consists of a rigid cylinder of wall thickness up to 30 mm with precision machined ends to locate the bearings and with one or more flanges for mounting. The machined ends are parallel to each other and perpendicular to the cylinder's longitudinal axis to within 0.05° or less. The housing may also be a honeycomb type structure to accommodate several rotor assemblies.

(f) Scoops:

Especially designed or prepared tubes for the extraction of UF<sub>6</sub> gas from within the rotor tube by a Pitot tube action (that is, with an aperture facing into the circumferential gas flow within the rotor tube, for example by bending the end of a radially disposed tube) and capable of being fixed to the central gas extraction system.

## **5.2. Especially designed or prepared auxiliary systems, equipment and components for gas centrifuge enrichment plants**

### INTRODUCTORY NOTE

The auxiliary systems, equipment and components for a gas centrifuge enrichment plant are the systems of plant needed to feed UF<sub>6</sub> to the centrifuges, to link the individual centrifuges to each other to form cascades (or stages) to allow for progressively higher enrichments and to extract the 'product' and 'tails' UF<sub>6</sub> from the centrifuges, together with the equipment required to drive the centrifuges or to control the plant.

Normally UF<sub>6</sub> is evaporated from the solid using heated autoclaves and is distributed in gaseous form to the centrifuges by way of cascade header pipework. The 'product' and 'tails' UF<sub>6</sub> gas streams flowing from the centrifuges are also passed by way of cascade header pipework to cold traps (operating at about 203 K (-70°C)) where they are condensed prior to onward transfer into suitable containers for transportation or storage. Because an enrichment plant consists of many thousands of centrifuges arranged in cascades there are many kilometres 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.

### EXPLANATORY NOTE

Some of the items listed below either come into direct contact with the UF<sub>6</sub> process gas or directly control the centrifuges and the passage of the gas from centrifuge to centrifuge

and cascade to cascade. Materials resistant to corrosion by UF<sub>6</sub> include copper, copper alloys, stainless steel, aluminium, aluminium oxide, aluminium alloys, nickel or alloys containing 60% by weight or more nickel and fluorinated hydrocarbon polymers.

### 5.2.1. Feed systems/product and tails withdrawal systems

Especially designed or prepared process systems or equipment for enrichment plants, made of or protected by materials resistant to corrosion by UF<sub>6</sub>, including:

- (a) Feed autoclaves, ovens, or systems used for passing UF<sub>6</sub> to the enrichment process;
- (b) Desublimers, cold traps or pumps used to remove UF<sub>6</sub> from the enrichment process for subsequent transfer upon heating;
- (c) Solidification or liquefaction stations used to remove UF<sub>6</sub> from the enrichment process by compressing and converting UF<sub>6</sub> to a liquid or solid form;
- (d) 'Product' or 'tails' stations used for transferring UF<sub>6</sub> into containers.

### 5.2.2. Machine header piping systems

Especially designed or prepared piping systems and header systems for handling UF<sub>6</sub> within the centrifuge cascades. The piping network is normally of the 'triple' header system with each centrifuge connected to each of the headers. There is thus a substantial amount of repetition in its form. It is wholly made of or protected by UF<sub>6</sub>-resistant materials (see EXPLANATORY NOTE to this section) and is fabricated to very high vacuum and cleanliness standards.

### 5.2.3. Special shut-off and control valves

- a) Shut-off valves especially designed or prepared to act on the feed, product or tails UF<sub>6</sub>, gas streams of an individual gas centrifuge.
- b) Bellows-sealed valves, manual or automated, shut-off or control, made of or protected by materials resistant to corrosion by UF<sub>6</sub>, with an inside diameter of 10 to 160 mm, especially designed or prepared for use in main or auxiliary systems of gas centrifuge enrichment plants.

#### EXPLANATORY NOTE

Typical especially designed or prepared valves include bellow-sealed valves, fast acting closure-type valves, fast acting valves and others.

### 5.2.4. UF<sub>6</sub> mass spectrometers/ion sources

Especially designed or prepared mass spectrometers capable of taking on-line samples from UF<sub>6</sub> gas streams and having all of the following characteristics:

1. Capable of measuring ions of 320 atomic mass units or greater and having a resolution of better than 1 part in 320;
2. Ion sources constructed of or protected by nickel, nickel-copper alloys with a nickel

- content of 60% by weight or more, or nickel-chrome alloys;
3. Electron bombardment ionisation sources; and
  4. Having a collector system suitable for isotopic analysis.

### **5.2.5. Frequency changers**

Frequency changers (also known as converters or inverters) especially designed or prepared to supply motor stators as defined under 5.1.2.(d), or parts, components and sub-assemblies of such frequency changers having both of the following characteristics:

1. A multiphase frequency output of 600 Hz or greater; and
2. High stability (with frequency control better than 0.2%).

### **5.3. Especially designed or prepared assemblies and components for use in gaseous diffusion enrichment**

#### 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  $UF_6$ , 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.

#### **5.3.1. Gaseous diffusion barriers and barrier materials**

- (a) Especially designed or prepared thin, porous filters, with a pore size of 10 – 100 nm, 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  $UF_6$  (see EXPLANATORY NOTE to section 5.4.).
- (b) Especially prepared compounds or powders for the manufacture of such filters. Such compounds and powders include nickel or alloys containing 60% by weight or more nickel, aluminium oxide, or  $UF_6$ -resistant fully fluorinated hydrocarbon polymers having a purity of 99.9% by weight or more, a particle size less than 10  $\mu m$ , and a high degree of particle size uniformity, which are especially prepared for the manufacture of gaseous diffusion barriers.

#### **5.3.2. Diffuser housings**

Especially designed or prepared hermetically sealed vessels for containing the gaseous diffusion barrier, made of or protected by  $UF_6$ -resistant materials (see EXPLANATORY NOTE to section 5.4.).

#### **5.3.3. Compressors and gas blowers**

Especially designed or prepared compressors, or gas blowers with a suction volume capacity of 1 m<sup>3</sup> per minute or more of  $UF_6$ , with a discharge pressure of up to 500 kPa, and designed for long-term operation in the  $UF_6$  environment, as well as separate assemblies

of such compressors and gas blowers. These compressors and gas blowers have a pressure ratio of 10:1 or less and are made of, or protected by, materials resistant to UF<sub>6</sub> (see EXPLANATORY NOTE to section 5.4.).

#### **5.3.4. 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<sub>6</sub>. Such seals are normally designed for a buffer gas in-leakage rate of less than 1000 cm<sup>3</sup> per minute.

#### **5.3.5. Heat exchangers for cooling UF<sub>6</sub>**

Especially designed or prepared heat exchangers made of or protected by UF<sub>6</sub>-resistant materials (see EXPLANATORY NOTE to section 5.4.), and intended for a leakage pressure change rate of less than 10 Pa/h under a pressure difference of 100 kPa.

### **5.4. Especially designed or prepared auxiliary systems, equipment and components for use in gaseous diffusion enrichment**

#### INTRODUCTORY NOTE

The auxiliary systems, equipment and components for gaseous diffusion enrichment plants are the systems of plant needed to feed UF<sub>6</sub> 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<sub>6</sub> from the diffusion cascades. Because of the high inertial properties of diffusion cascades, any interruption in their operation, and especially their shut-down, 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<sub>6</sub> 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<sub>6</sub> gas streams flowing from exit points are passed by way of cascade header pipework to either cold traps or to compression stations where the UF<sub>6</sub> gas is liquefied 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 kilometres of cascade header pipework, incorporating thousands of welds with substantial amounts of repetition of layout. The equipment, components and piping systems are fabricated to very high vacuum and cleanliness standards.

#### EXPLANATORY NOTE

The items listed below either come into direct contact with the UF<sub>6</sub> process gas or directly control the flow within the cascade. Materials resistant to corrosion by UF<sub>6</sub> include copper, copper alloys, stainless steel, aluminium, aluminium oxide, aluminium alloys, nickel or alloys containing 60% by weight or more nickel and fluorinated hydrocarbon polymers.

**5.4.1. Feed systems/product and tails withdrawal systems**

Especially designed or prepared process systems or equipment for enrichment plants made of or protected by materials resistant to corrosion by UF<sub>6</sub>, including:

- (a) Feed autoclaves, ovens, or systems used for passing UF<sub>6</sub> to the enrichment process;
- (b) Desublimers, cold traps or pumps used to remove UF<sub>6</sub> from the enrichment process for subsequent transfer upon heating;
- (c) Solidification or liquefaction stations used to remove UF<sub>6</sub> from the enrichment process by compressing and converting UF<sub>6</sub> to a liquid or solid form;
- (d) 'Product' or 'tails' stations used for transferring UF<sub>6</sub> into containers.

**5.4.2. Header piping systems**

Especially designed or prepared piping systems and header systems for handling UF<sub>6</sub> within the gaseous diffusion cascades.

**EXPLANATORY NOTE**

This piping network is normally of the 'double' header system with each cell connected to each of the headers.

**5.4.3. Vacuum systems**

- (a) Especially designed or prepared vacuum manifolds, vacuum headers and vacuum pumps having a suction capacity of 5 m<sup>3</sup>/min or more.
- (b) Vacuum pumps especially designed for service in UF<sub>6</sub>-bearing atmospheres made of, or protected by, materials resistant to corrosion by UF<sub>6</sub> (see EXPLANATORY NOTE to this section). These pumps may be either rotary or positive, may have displacement and fluorocarbon seals, and may have special working fluids present.

**5.4.4. Special shut-off and control valves**

Especially designed or prepared bellows-sealed valves, manual or automated, shut-off or control, made of or protected by materials resistant to corrosion by UF<sub>6</sub> (see EXPLANATORY NOTE to this section), for installation in main and auxiliary systems of gaseous diffusion enrichment plants.

**5.4.5. UF<sub>6</sub> mass spectrometers/ion sources**

Especially designed or prepared mass spectrometers capable of taking on-line samples from UF<sub>6</sub> gas streams and having all of the following:

1. Capable of measuring ions of 320 atomic mass units or greater and having a resolution of better than 1 part in 320;

2. Ion sources constructed of or protected by nickel, nickel-copper alloys with a nickel content of 60% by weight or more , or nickel-chrome alloys;
3. Electron bombardment ionisation sources; and
4. Having a collector system suitable for isotopic analysis.

## **5.5. Especially designed or prepared systems, equipment and components for use in aerodynamic enrichment plants**

### INTRODUCTORY NOTE

In aerodynamic enrichment processes, a mixture of gaseous UF<sub>6</sub> and light gas (hydrogen or helium) is compressed and then passed through separating elements wherein isotopic separation is accomplished by the generation of high centrifugal forces over a curved-wall geometry. Two processes of this type have been successfully developed: the separation nozzle process and the vortex tube process. For both processes the main components of a separation stage include cylindrical vessels housing the special separation elements (nozzles or vortex tubes), gas compressors and heat exchangers to remove the heat of compression. An aerodynamic plant requires a number of these stages, so that quantities can provide an important indication of end use. Since aerodynamic processes use UF<sub>6</sub>, all equipment, pipeline and instrumentation surfaces (that come in contact with the gas) must be made of or protected by materials that remain stable in contact with UF<sub>6</sub>.

### EXPLANATORY NOTE

The items listed in this section either come into direct contact with the UF<sub>6</sub> 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 protected by UF<sub>6</sub>-resistant materials. For the purposes of the section relating to aerodynamic enrichment items, the materials resistant to corrosion by UF<sub>6</sub> include copper, copper alloys, stainless steel, aluminium, aluminium oxide, aluminium alloys, nickel or alloys containing 60% by weight or more nickel and fluorinated hydrocarbon polymers.

#### **5.5.1. Separation nozzles**

Especially designed or prepared separation nozzles and assemblies thereof. The separation nozzles consist of slit-shaped, curved channels having a radius of curvature less than 1 mm, resistant to corrosion by UF<sub>6</sub> and having a knife-edge within the nozzle that separates the gas flowing through the nozzle into two fractions.

#### **5.5.2. Vortex tubes**

Especially designed or prepared vortex tubes and assemblies thereof. The vortex tubes are cylindrical or tapered, made of or protected by materials resistant to corrosion by UF<sub>6</sub>, and with one or more tangential inlets. The tubes may be equipped with nozzle-type appendages at either or both ends.

### EXPLANATORY NOTE

The feed gas enters the vortex tube tangentially at one end, or through swirl vanes, or at numerous tangential positions along the periphery of the tube.

### **5.5.3. Compressors and gas blowers**

Especially designed or prepared compressors or gas blowers made of or protected by materials resistant to corrosion by the UF<sub>6</sub>/carrier gas (hydrogen or helium) mixture.

### **5.5.4. Rotary shaft seals**

Especially designed or prepared rotary shaft seals, with seal feed and seal exhaust connections, for sealing the shaft connecting the compressor rotor or the gas blower rotor with the driver motor so as to ensure a reliable seal against out-leakage of process gas or in-leakage of air or seal gas into the inner chamber of the compressor or gas blower which is filled with a UF<sub>6</sub>/carrier gas mixture.

### **5.5.5. Heat exchangers for gas cooling**

Especially designed or prepared heat exchangers made of or protected by materials resistant to corrosion by UF<sub>6</sub>.

### **5.5.6. Separation element housings**

Especially designed or prepared separation element housings, made of or protected by materials resistant to corrosion by UF<sub>6</sub>, for containing vortex tubes or separation nozzles.

### **5.5.7. Feed systems/product and tails withdrawal systems**

Especially designed or prepared process systems or equipment for enrichment plants, made of or protected by materials resistant to corrosion by UF<sub>6</sub>, including:

- (a) Feed autoclaves, ovens, or systems used for passing UF<sub>6</sub> to the enrichment process;
- (b) Desublimers (or cold traps) used to remove UF<sub>6</sub> from the enrichment process for subsequent transfer upon heating;
- (c) Solidification or liquefaction stations used to remove UF<sub>6</sub> from the enrichment process by compressing and converting UF<sub>6</sub> to a liquid or solid form;
- (d) 'Product' or 'tails' stations used for transferring UF<sub>6</sub> into containers.

### **5.5.8. Header piping systems**

Especially designed or prepared header piping systems, made of or protected by materials resistant to corrosion by UF<sub>6</sub>, for handling UF<sub>6</sub> within the aerodynamic cascades. This piping network is normally of the 'double' header design with each stage or group of stages connected to each of the headers.

### **5.5.9. Vacuum systems and pumps**

- (a) Especially designed or prepared vacuum systems consisting of vacuum manifolds,

vacuum headers and vacuum pumps, and designed for service in UF<sub>6</sub>-bearing atmospheres,

- (b) Vacuum pumps especially designed or prepared for service in UF<sub>6</sub>-bearing atmospheres and made of or protected by materials resistant to corrosion by UF<sub>6</sub>. These pumps may use fluorocarbon seals and special working fluids.

#### **5.5.10. Special shut-off and control valves**

Especially designed or prepared bellows-sealed valves, manual or automated, shut-off or control, made of or protected by materials resistant to corrosion by UF<sub>6</sub> with a diameter of 40 mm or greater, for installation in main and auxiliary systems of aerodynamic enrichment plants.

#### **5.5.11. UF<sub>6</sub> mass spectrometers/ion sources**

Especially designed or prepared mass spectrometers capable of taking on-line samples from UF<sub>6</sub> gas streams and having all of the following:

1. Capable of measuring ions of 320 atomic mass units or greater and having a resolution of better than 1 part in 320;
2. Ion sources constructed of or protected by nickel, nickel-copper alloys with a nickel content of 60% by weight or more, or nickel-chrome alloys;
3. Electron bombardment ionisation sources; and
4. Having a collector system suitable for isotopic analysis.

#### **5.5.12. UF<sub>6</sub>/carrier gas separation systems**

Especially designed or prepared process systems for separating UF<sub>6</sub> from carrier gas (hydrogen or helium).

##### EXPLANATORY NOTE

These systems are designed to reduce the UF<sub>6</sub> content in the carrier gas to 1 ppm or less and may incorporate equipment such as:

- (a) Cryogenic heat exchangers and cryoseparators capable of temperatures of 153 K (-120°C) or less;
- (b) Cryogenic refrigeration units capable of temperatures of 153 K (-120°C) or less;
- (c) Separation nozzle or vortex tube units for the separation of UF<sub>6</sub> from carrier gas; or
- (d) UF<sub>6</sub> cold traps capable of freezing out UF<sub>6</sub>.

### **5.6. Especially designed or prepared systems, equipment and components for use in chemical exchange or ion exchange enrichment plants**

##### INTRODUCTORY NOTE

The slight difference in mass between the isotopes of uranium causes small changes in chemical reaction equilibria that can be used as a basis for separation of the isotopes. Two processes have been successfully developed: liquid-liquid chemical exchange and solid-liquid ion exchange.

In the liquid-liquid chemical exchange process, immiscible liquid phases (aqueous and organic) are countercurrently contacted to give the cascading effect of thousands of separation stages. The aqueous phase consists of uranium chloride in hydrochloric acid solution; the organic phase consists of an extractant containing uranium chloride in an organic solvent. The contactors employed in the separation cascade can be liquid-liquid exchange columns (such as pulsed columns with sieve plates) or liquid centrifugal contactors. Chemical conversions (oxidation and reduction) are required at both ends of the separation cascade in order to provide for the reflux requirements at each end. A major design concern is to avoid contamination of the process streams with certain metal ions. Plastic, plastic-lined (including use of fluorocarbon polymers) and/or glass-lined columns and piping are therefore used.

In the solid-liquid ion exchange process, enrichment is accomplished by uranium adsorption/desorption on a special, very fast-acting, ion exchange resin or adsorbent. A solution of uranium in hydrochloric acid and other chemical agents is passed through cylindrical enrichment columns containing packed beds of the adsorbent. For a continuous process, a reflux system is necessary to release the uranium from the adsorbent back into the liquid flow so that 'product' and 'tails' can be collected. This is accomplished with the use of suitable reduction/oxidation chemical agents that are fully regenerated in separate external circuits and that may be partially regenerated within the isotopic separation columns themselves. The presence of hot concentrated hydrochloric acid solutions in the process requires that the equipment be made of or protected by special corrosion-resistant materials.

### **5.6.1. Liquid-liquid exchange columns (Chemical exchange)**

Countercurrent liquid-liquid exchange columns having mechanical power input, especially designed or prepared for uranium enrichment using the chemical exchange process. For corrosion resistance to concentrated hydrochloric acid solutions, these columns and their internals are normally made of or protected by suitable plastic materials (such as fluorinated hydrocarbon polymers) or glass. The stage residence time of the columns is normally designed to be 30 s or less.

### **5.6.2. Liquid-liquid centrifugal contactors (Chemical exchange)**

Liquid-liquid centrifugal contactors especially designed or prepared for uranium enrichment using the chemical exchange process. Such contactors use rotation to achieve dispersion of the organic and aqueous streams and then centrifugal force to separate the phases. For corrosion resistance to concentrated hydrochloric acid solutions, the contactors are normally made of or protected by suitable plastic materials (such as fluorinated hydrocarbon polymers) or glass. The stage residence time of the centrifugal contactors is designed to be short (30 s or less).

### **5.6.3. Uranium reduction systems and equipment (Chemical exchange)**

(a) Especially designed or prepared electrochemical reduction cells to reduce uranium from one valence state to another for uranium enrichment using the chemical exchange process. The cell materials in contact with process solutions must be corrosion resistant to concentrated hydrochloric acid solutions.

#### **EXPLANATORY NOTE**

The cell cathodic compartment must be designed to prevent re-oxidation of uranium to

its higher valence state. To keep the uranium in the cathodic compartment, the cell may have an impervious diaphragm membrane constructed of special cation exchange material. The cathode consists of a suitable solid conductor such as graphite.

(b) Especially designed or prepared systems at the product end of the cascade for taking the  $U^{+4}$  out of the organic stream, adjusting the acid concentration and feeding to the electrochemical reduction cells.

#### EXPLANATORY NOTE

These systems consist of solvent extraction equipment for stripping the  $U^{+4}$  from the organic stream into an aqueous solution, evaporation and/or other equipment to accomplish solution pH adjustment and control, and pumps or other transfer devices for feeding to the electrochemical reduction cells. A major design concern is to avoid contamination of the aqueous stream with certain metal ions. Consequently, for those parts in contact with the process stream, the system is constructed of equipment made of or protected by suitable materials (such as glass, fluorocarbon polymers, polyphenyl sulphate, polyether sulphone, and resin-impregnated graphite).

#### 5.6.4. Feed preparation systems (Chemical exchange)

Especially designed or prepared systems for producing high-purity uranium chloride feed solutions for chemical exchange uranium isotope separation plants.

#### EXPLANATORY NOTE

These systems consist of dissolution, solvent extraction and/or ion exchange equipment for purification and electrolytic cells for reducing the uranium  $U^{+6}$  or  $U^{+4}$  to  $U^{+3}$ . These systems produce uranium chloride solutions having only a few parts per million of metallic impurities such as chromium, iron, vanadium, molybdenum and other bivalent or higher multi-valent cations. Materials of construction for portions of the system processing high-purity  $U^{+3}$  include glass, fluorinated hydrocarbon polymers, polyphenyl sulphate or polyether sulphone plastic-lined and resin-impregnated graphite.

#### 5.6.5. Uranium oxidation systems (Chemical exchange)

Especially designed or prepared systems for oxidation of  $U^{+3}$  to  $U^{+4}$  for return to the uranium isotope separation cascade in the chemical exchange enrichment process.

#### EXPLANATORY NOTE

These systems may incorporate equipment such as:

- (a) Equipment for contacting chlorine and oxygen with the aqueous effluent from the isotope separation equipment and extracting the resultant  $U^{+4}$  into the stripped organic stream returning from the product end of the cascade;
- (b) Equipment that separates water from hydrochloric acid so that the water and the concentrated hydrochloric acid may be reintroduced to the process at the proper locations.

#### 5.6.6. Fast-reacting ion exchange resins/adsorbents (Ion exchange)

Fast-reacting ion exchange resins or adsorbents especially designed or prepared for uranium

enrichment using the ion exchange process, including porous macroreticular resins, and/or pellicular structures in which the active chemical exchange groups are limited to a coating on the surface of an inactive porous support structure, and other composite structures in any suitable form including particles or fibres. These ion exchange resins/adsorbents have diameters of 0.2 mm or less and must be chemically resistant to concentrated hydrochloric acid solutions as well as physically strong enough so as not to degrade in the exchange columns. The resins/adsorbents are especially designed to achieve very fast uranium isotope exchange kinetics (exchange rate half-time of less than 10 s) and are capable of operating at a temperature in the range of 373 K (100 °C) to 473 K (200°C).

### **5.6.7. Ion exchange columns (Ion exchange)**

Cylindrical columns greater than 1000 mm in diameter for containing and supporting packed beds of ion exchange resin/adsorbent, especially designed or prepared for uranium enrichment using the ion exchange process. These columns are made of or protected by materials (such as titanium or fluorocarbon plastics) resistant to corrosion by concentrated hydrochloric acid solutions and are capable of operating at a temperature in the range of 373 K (100°C) to 473 K (200°C) and pressures above 0.7 MPa.

### **5.6.8. Ion exchange reflux systems (Ion exchange)**

- (a) Especially designed or prepared chemical or electrochemical reduction systems for regeneration of the chemical reducing agent used in ion exchange uranium enrichment cascades.
- (b) Especially designed or prepared chemical or electrochemical oxidation systems for regeneration of the chemical oxidising agent (agents) used in ion exchange uranium enrichment cascades.

#### **EXPLANATORY NOTE**

The ion exchange enrichment process may use, for example, trivalent titanium ( $Ti^{+3}$ ) as a reducing cation in which case the reduction system would regenerate  $Ti^{+3}$  by reducing  $Ti^{+4}$ .

The process may use, for example, trivalent iron ( $Fe^{+3}$ ) as an oxidant in which case the oxidation system would regenerate  $Fe^{+3}$  by oxidising  $Fe^{+2}$ .

## **5.7. Especially designed or prepared systems, equipment and components for use in laser-based enrichment plants**

#### **INTRODUCTORY NOTE**

Present systems for enrichment processes using lasers fall into two categories: those in which the process medium is atomic uranium vapour and those in which the process medium is the vapour of a uranium compound, sometimes mixed with another gas or gases. Common nomenclature for such processes include:

- first category - atomic vapour laser isotope separation;
- second category - molecular laser isotope separation including chemical reaction by isotope selective laser activation.

The systems, equipment and components for laser enrichment plants include :

- (a) Devices to feed uranium-metal vapour (for selective photo-ionisation) or devices to feed the vapour of a uranium compound (for selective photo-dissociation or selective excitation/activation);
- (b) Devices to collect enriched and depleted uranium metal as 'product' and 'tails' in the first category, and devices to collect enriched and depleted uranium compounds as 'product' and 'tails' in the second category;
- (c) Process laser systems to selectively excite the uranium-235 ( $^{235}\text{U}$ ) species;
- (d) Feed preparation and product conversion equipment. The complexity of the spectroscopy of uranium atoms and compounds may require incorporation of any of a number of available laser and laser optics technologies.

#### EXPLANATORY NOTE

Many of the items listed in this section come into direct contact with uranium metal vapour or liquid or with process gas consisting of  $\text{UF}_6$  or a mixture of  $\text{UF}_6$  and other gases. All surfaces that come into direct contact with the uranium or  $\text{UF}_6$  are wholly made of or protected by corrosion-resistant materials. For the purposes of the section relating to laser-based enrichment items, the materials resistant to corrosion by the vapour or liquid of uranium metal or uranium alloys include yttria-coated graphite and tantalum; and the materials resistant to corrosion by  $\text{UF}_6$  include copper, copper alloys, stainless steel, aluminium, aluminium oxide, aluminium alloys, nickel or alloys containing 60% by weight or more nickel and fluorinated hydrocarbon polymers.

#### **5.7.1. Uranium vaporisation systems (atomic vapour based methods)**

Especially designed or prepared uranium metal vaporisation systems for use in laser enrichment.

#### EXPLANATORY NOTE

These systems may contain electron beam guns and are designed to achieve a delivered power (1 kW or greater) on the target sufficient to generate uranium metal vapour at a rate required for the laser enrichment function.

#### **5.7.2. Liquid or vapour uranium metal handling systems and components (atomic vapour based methods)**

Especially designed or prepared systems for handling molten uranium, molten uranium alloys or uranium metal vapour for use in laser enrichment, or especially designed or prepared components therefor.

**EXPLANATORY NOTE**

The liquid uranium metal handling systems may consist of crucibles and cooling equipment for the crucibles. The crucibles and other parts of this system that come into contact with molten uranium, molten uranium alloys or uranium metal vapour are made of or protected by materials of suitable corrosion and heat resistance. Suitable materials may include tantalum, yttria-coated graphite, graphite coated with other rare earth oxides or mixtures thereof.

**5.7.3. Uranium metal 'product' and 'tails' collector assemblies (atomic vapour based methods)**

Especially designed or prepared 'product' and 'tails' collector assemblies for collecting uranium metal in liquid or solid form.

**EXPLANATORY NOTE**

Components for these assemblies are made of or protected by materials resistant to the heat and corrosion of uranium metal vapour or liquid (such as yttria-coated graphite or tantalum) and may include pipes, valves, fittings, gutters, feed-throughs, heat exchangers and collector plates for magnetic, electrostatic or other separation methods.

**5.7.4. Separator module housings (atomic vapour based methods)**

Especially designed or prepared cylindrical or rectangular vessels for containing the uranium metal vapour source, the electron beam gun, and the 'product' and 'tails' collectors.

**EXPLANATORY NOTE**

These housings have multiplicity of ports for electrical and water feed-throughs, laser beam windows, vacuum pump connections and instrumentation diagnostics and monitoring. They have provisions for opening and closing to allow refurbishment of internal components.

**5.7.5. Supersonic expansion nozzles (molecular based methods)**

Especially designed or prepared supersonic expansion nozzles for cooling mixtures of UF<sub>6</sub> and carrier gas to 150 K (- 123 °C) or less and which are corrosion resistant to UF<sub>6</sub>.

**5.7.6. 'Product' or 'tails' collectors (molecular based methods)**

Especially designed or prepared components or devices for collecting uranium product material or uranium tails material following illumination with laser light.

**EXPLANATORY NOTE**

In one example of molecular laser isotope separation, the product collectors serve to collect enriched uranium pentafluoride (UF<sub>5</sub>) solid material. The product collectors may consist of filter, impact, or cyclone-type collectors, or combinations thereof, and must be corrosion resistant to the UF<sub>5</sub>/ UF<sub>6</sub> environment.

**5.7.7. UF<sub>6</sub>/carrier gas compressors (molecular based methods)**

Especially designed or prepared compressors for UF<sub>6</sub>/carrier gas mixtures, designed for long term operation in a UF<sub>6</sub> environment. The components of these compressors that come into contact with process gas are made of or protected by materials resistant to corrosion by UF<sub>6</sub>.

#### **5.7.8. Rotary shaft seals (molecular based methods)**

Especially designed or prepared rotary shaft seals, with seal feed and seal exhaust connections, for sealing the shaft connecting the compressor rotor with the driver motor so as to ensure a reliable seal against out-leakage of process gas or in-leakage of air or seal gas into the inner chamber of the compressor which is filled with a UF<sub>6</sub>/carrier gas mixture.

#### **5.7.9. Fluorination systems (molecular based methods)**

Especially designed or prepared systems for fluorinating UF<sub>5</sub> (solid) to UF<sub>6</sub> (gas).

##### EXPLANATORY NOTE

These systems are designed to fluorinate the collected UF<sub>5</sub> powder to UF<sub>6</sub> for subsequent collection in product containers or for transfer as feed for additional enrichment. In one approach, the fluorination reaction may be accomplished within the isotope separation system to react and recover directly off the 'product' collectors. In another approach, the UF<sub>5</sub> powder may be removed/transferred from the 'product' collectors into a suitable reaction vessel (e.g., fluidised-bed reactor, screw reactor or flame tower) for fluorination. In both approaches, equipment for storage and transfer of fluorine (or other suitable fluorinating agents) and for collection and transfer of UF<sub>6</sub> are used.

#### **5.7.10. UF<sub>6</sub> mass spectrometers/ion sources (molecular based methods)**

Especially designed or prepared mass spectrometers capable of taking on-line samples from UF<sub>6</sub> gas streams and having all of the following:

1. Capable of measuring ions of 320 atomic mass units or greater and having a resolution of better than 1 part in 320;
2. Ion sources constructed of or protected by nickel, nickel-copper alloys with a nickel content of 60% by weight or more, or nickel-chrome alloys;
3. Electron bombardment ionisation sources; and
4. Having a collector system suitable for isotopic analysis.

#### **5.7.11. Feed systems/product and tails withdrawal systems (molecular based methods)**

Especially designed or prepared process systems or equipment for enrichment plants made of or protected by materials resistant to corrosion by UF<sub>6</sub>, including:

- (a) Feed autoclaves, ovens, or systems used for passing UF<sub>6</sub> to the enrichment process;
- (b) Desublimers (or cold traps) used to remove UF<sub>6</sub> from the enrichment process for subsequent transfer upon heating;
- (c) Solidification or liquefaction stations used to remove UF<sub>6</sub> from the enrichment

process by compressing and converting UF<sub>6</sub> to a liquid or solid form;  
 (d) 'Product' or 'tails' stations used for transferring UF<sub>6</sub> into containers.

### 5.7.12. UF<sub>6</sub>/carrier gas separation systems (molecular based methods)

Especially designed or prepared process systems for separating UF<sub>6</sub> from carrier gas.

#### EXPLANATORY NOTE

These systems may incorporate equipment such as:

- (a) Cryogenic heat exchangers or cryoseparators capable of temperatures of 153 K (-120°C) or less;
- (b) Cryogenic refrigeration units capable of temperatures of 153 K (-120°C) or less;
- (c) UF<sub>6</sub> cold traps capable of freezing out UF<sub>6</sub>.

The carrier gas may be nitrogen, argon, or other gas.

### 5.7.13. Laser systems

Lasers or laser systems especially designed or prepared for the separation of uranium isotopes.

#### EXPLANATORY NOTE

The laser system typically contains both optical and electronic components for the management of the laser beam (or beams) and the transmission to the isotope separation chamber. The laser system for atomic vapour based methods usually consists of tunable dye lasers pumped by another type of laser (e.g., copper vapour lasers or certain solid-state lasers). The laser system for molecular based methods may consist of carbondioxide lasers or excimer lasers and a multi-pass optical cell. Lasers or laser systems for both methods require spectrum frequency stabilisation for operation over extended periods of time.

The lasers and laser components in laser-based enrichment processes include the following:

Lasers, laser amplifiers and oscillators as follows:

- a. Copper vapour lasers having both of the following characteristics:
  - 1. Operating at wavelengths between 500 and 600 nm; and
  - 2. An average output power equal to or greater than 30 W;
- b. Argon ion lasers having both of the following characteristics:
  - 1. Operating at wavelengths between 400 and 515 nm; and
  - 2. An average output power greater than 40 W;
- c. Neodymium-doped (other than glass) lasers with an output wavelength between 1000 and 1100 nm having either of the following:

1. Pulse-excited and Q-switched with a pulse duration equal to or greater than 1 ns, and having either of the following:
  - a. A single-transverse mode output with an average output power greater than 40 W; or
  - b. A multiple-transverse mode output with an average output power greater than 50 W;

or
2. Incorporating frequency doubling to give an output wavelength between 500 and 550 nm with an average output power of greater than 40 W;\_
- d. Tunable pulsed single-mode dye laser oscillators having all of the following characteristics:
  1. Operating at wavelengths between 300 and 800 nm;\_
  2. An average output power greater than 1 W;\_
  3. A repetition rate greater than 1 kHz; and
  4. Pulse width less than 100 ns;\_
- e. Tunable pulsed dye laser amplifiers and oscillators having all of the following characteristics:
  1. Operating at wavelengths between 300 and 800 nm;\_
  2. An average output power greater than 30 W;\_
  3. A repetition rate greater than 1 kHz; and
  4. Pulse width less than 100 ns;\_

Note: Item 3.A.2.e. does not control single mode oscillators.
- f. Alexandrite lasers having all of the following characteristics:
  1. Operating at wavelengths between 720 and 800 nm;\_
  2. A bandwidth of 0.005 nm or less;\_
  3. A repetition rate greater than 125 Hz; and
  4. An average output power greater than 30 W;\_
- g. Pulsed carbon dioxide (CO<sub>2</sub>) lasers having all of the following characteristics:
  1. Operating at wavelengths between 9000 and 11000 nm;\_
  2. A repetition rate greater than 250 Hz;
  3. An average output power greater than 500 W; and
  4. Pulse width of less than 200 ns;\_

Note: Item g. does not control the higher power (typically 1 to 5 kW) industrial CO<sub>2</sub> lasers used in applications such as cutting and welding, as these latter lasers are either continuous wave or are pulsed with a pulse width greater than 200 ns.

- h. Pulsed excimer lasers (XeF, XeCl, KrF) having all of the following characteristics:
  1. Operating at wavelengths between 240 and 360 nm;\_
  2. A repetition rate greater than 250 Hz; and
  3. An average output power greater than 500 W;\_
- i. Para-hydrogen Raman shifters designed to operate at 16 µm output wavelength and at a repetition rate greater than 250 Hz.
- j. Pulsed carbon monoxide (CO) lasers having all of the following characteristics:
  1. Operating at wavelengths between 5000 and 6000 nm;
  2. A repetition rate greater than 250 Hz;
  3. An average output power greater than 200 W; and
  4. Pulse width of less than 200 ns.

Note: Item j. does not control the higher power (typically 1 to 5 kW) industrial CO lasers used in applications such as cutting and welding, as these latter lasers are either continuous wave or are pulsed with a pulse width greater than 200 ns.

## **5.8. Especially designed or prepared systems, equipment and components for use in plasma separation enrichment plants**

### INTRODUCTORY NOTE

In the plasma separation process, a plasma of uranium ions passes through an electric field tuned to the <sup>235</sup>U ion resonance frequency so that they preferentially absorb energy and increase the diameter of their corkscrew-like orbits. Ions with a large-diameter path are trapped to produce a product enriched in <sup>235</sup>U. The plasma, which is made by ionising uranium vapour, is contained in a vacuum chamber with a high-strength magnetic field produced by a superconducting magnet. The main technological systems

of the process include the uranium plasma generation system, the separator module with superconducting magnet, and metal removal systems for the collection of 'product' and 'tails'.

### **5.8.1. Microwave power sources and antennae**

Especially designed or prepared microwave power sources and antennae for producing or accelerating ions and having the following characteristics: greater than 30 GHz frequency and greater than 50 kW mean power output for ion production.

**5.8.2. Ion excitation coils**

Especially designed or prepared radio frequency ion excitation coils for frequencies of more than 100 kHz and capable of handling more than 40 kW mean power.

**5.8.3. Uranium plasma generation systems**

Especially designed or prepared systems for the generation of uranium plasma for use in plasma separation plants.

**5.8.4. Uranium metal 'product' and 'tails' collector assemblies**

Especially designed or prepared 'product' and 'tails' collector assemblies for uranium metal in solid form. These collector assemblies are made of or protected by materials resistant to the heat and corrosion of uranium metal vapour, such as yttria-coated graphite or tantalum.

**5.8.5. Separator module housings**

Cylindrical vessels especially designed or prepared for use in plasma separation enrichment plants for containing the uranium plasma source, radio-frequency drive coil and the 'product' and 'tails' collectors.

**EXPLANATORY NOTE**

These housings have a multiplicity of ports for electrical feed-throughs, diffusion pump connections and instrumentation diagnostics and monitoring. They have provisions for opening and closing to allow for refurbishment of internal components and are constructed of a suitable non-magnetic material such as stainless steel.

**5.9. Especially designed or prepared systems, equipment and components for use in electromagnetic enrichment plants****INTRODUCTORY NOTE**

In the electromagnetic process, uranium metal ions produced by ionisation of a salt feed material (typically uranium tetrachloride ( $UCl_4$ )) are accelerated and passed through a magnetic field that has the effect of causing the ions of different isotopes to follow different paths. The major components of an electromagnetic isotope separator include: a magnetic field for ion-beam diversion/separation of the isotopes, an ion source with its acceleration system, and a collection system for the separated ions. Auxiliary systems for the process include the magnet power supply system, the ion source high-voltage power supply system, the vacuum system, and extensive chemical handling systems for recovery of product and cleaning/recycling of components.

**5.9.1. Electromagnetic isotope separators**

Electromagnetic isotope separators especially designed or prepared for the separation of uranium isotopes, and equipment and components therefor, including:

**(a) Ion sources**

Especially designed or prepared single or multiple uranium ion sources consisting of a

vapour source, ioniser, and beam accelerator, constructed of suitable materials such as graphite, stainless steel, or copper, and capable of providing a total ion beam current of 50 mA or greater.

(b) Ion collectors

Collector plates consisting of two or more slits and pockets especially designed or prepared for collection of enriched and depleted uranium ion beams and constructed of suitable materials such as graphite or stainless steel.

(c) Vacuum housings

Especially designed or prepared vacuum housings for uranium electromagnetic separators, constructed of suitable non-magnetic materials such as stainless steel and designed for operation at pressures of 0.1 Pa or lower.

EXPLANATORY NOTE

The housings are specially designed to contain the ion sources, collector plates and water-cooled liners and have provision for diffusion pump connections and opening and closing for removal and reinstallation of these components.

(d) Magnet pole pieces

Especially designed or prepared magnet pole pieces having a diameter greater than 2 m and used to maintain a constant magnetic field within an electromagnetic isotope separator and to transfer the magnetic field between adjoining separators.

### 5.9.2. High voltage power supplies

Especially designed or prepared high-voltage power supplies for ion sources, having both of the following characteristics:

1. Capable of continuous operation, output voltage of 20,000 V or greater, output current of 1 A or greater; and
2. Voltage regulation of better than 0.01% over a time period of 8 h.

### 5.9.3. Magnet power supplies

Especially designed or prepared high-power, direct current magnet power supplies having both of the following characteristics:

1. Capable of continuously producing a current output of 500 A or greater at a voltage of 100 V or greater; and
2. Current or voltage regulation better than 0.01 % over a period of 8 h.

## 6. Plants for the production or concentration of heavy water, deuterium and deuterium compounds and equipment especially designed or prepared therefor

INTRODUCTORY NOTE

Heavy water can be produced by a variety of processes. However, the two processes that have proven to be commercially viable are the water - hydrogen sulphide exchange

process (GS process) and the ammonia-hydrogen exchange process.

The GS process is based upon the exchange of hydrogen and deuterium between water and hydrogen sulphide within a series of towers which are operated with the top section cold and the bottom section hot. Water flows down the towers while the hydrogen sulphide gas circulates from the bottom to the top of the towers. A series of perforated trays are used to promote mixing between the gas and the water. Deuterium migrates to the water at low temperatures and to the hydrogen sulphide at high temperatures. Gas or water enriched in deuterium is removed from the first stage towers at the junction of the hot and cold sections and the process is repeated in subsequent stage towers. The product of the last stage, water enriched up to 30% by weight in deuterium, is sent to a distillation unit to produce reactor grade heavy water: i.e., 99.75% by weight deuterium oxide (D<sub>2</sub>O).

The ammonia - hydrogen exchange process can extract deuterium from synthesis gas through contact with liquid ammonia (NH<sub>3</sub>) in the presence of a catalyst. The synthesis gas is fed into exchange towers and then to an ammonia converter. Inside the towers the gas flows from the bottom to the top while the liquid NH<sub>3</sub> flows from the top to the bottom. The deuterium is stripped from the hydrogen in the synthesis gas and concentrated in the NH<sub>3</sub>. The NH<sub>3</sub> then flows into an ammonia cracker at the bottom of the tower while the gas flows into an ammonia converter at the top. Further enrichment takes place in subsequent stages and reactor grade heavy water is produced through final distillation. The synthesis gas feed can be provided by an ammonia plant that, in turn, can be constructed in association with a heavy water ammonia-hydrogen exchange plant. The ammonia - hydrogen exchange process can also use ordinary water as a feed source of deuterium.

Many of the key equipment items for heavy water production plants using the GS or the ammonia - hydrogen exchange processes are common to several segments of the chemical and petroleum industries. This is particularly so for small plants using the GS process. However, few of the items are available 'off-the-shelf'. The GS and the ammonia - hydrogen processes require the handling of large quantities of flammable, corrosive and toxic fluids at elevated pressures. Accordingly, in establishing the design and operating standards for plants and equipment using these processes, careful attention to the materials selection and specifications is required to ensure long service life with high safety and reliability factors. The choice of scale is primarily a function of economics and need. Thus, most of the equipment items would be prepared according to the requirements of the customer.

Finally, it should be noted that, in both the GS and the ammonia - hydrogen exchange processes, items of equipment which individually are not especially designed or prepared for heavy water production can be assembled into systems which are especially designed or prepared for producing heavy water. The catalyst production system used in the ammonia - hydrogen exchange process and water distillation systems used for the final concentration of heavy water to reactor-grade in either process are examples of such systems.

The items of equipment which are especially designed or prepared for the production of heavy water utilising either the water - hydrogen sulphide exchange process or the ammonia - hydrogen exchange process include the following:

### **6.1. Water - hydrogen sulphide exchange towers**

Exchange towers with diameters of 1.5 m or greater and capable of operating at pressures greater than or equal to 2 MPa, especially designed or prepared for heavy water production utilising the water-hydrogen sulphide exchange process.

**6.2. Blowers and compressors**

Single stage, low head (i.e., 0.2 MPa) centrifugal blowers or compressors for hydrogen-sulphide gas circulation (i.e. gas containing more than 70% by weight hydrogen sulphide H<sub>2</sub>S) especially designed or prepared for heavy water production utilising the water-hydrogen sulphide exchange process. These blowers or compressors have a throughput capacity greater than or equal to 56 m<sup>3</sup>/s while operating at pressures greater than or equal to 1.8 MPa suction and have seals designed for wet H<sub>2</sub>S service.

**6.3. Ammonia - hydrogen exchange towers**

Ammonia-hydrogen exchange towers greater than or equal to 35 m in height with diameters of 1.5 m to 2.5 m capable of operating at pressures greater than 15 Mpa especially designed or prepared for heavy water production utilising the ammonia -hydrogen exchange process. These towers also have at least one flanged, axial opening of the same diameter as the cylindrical part through which the tower internals can be inserted or withdrawn.

**6.4. Tower internals and stage pumps**

Tower internals and stage pumps especially designed or prepared for towers for heavy water production utilising the ammonia-hydrogen exchange process. Tower internals include especially designed stage contactors which promote intimate gas/liquid contact.

Stage pumps include especially designed submersible pumps for circulation of liquid NH<sub>3</sub> within a contacting stage internal to the stage towers.

**6.5. NH<sub>3</sub> crackers**

NH<sub>3</sub> crackers with operating pressures greater than or equal to 3 MPa especially designed or prepared for heavy water production utilising the ammonia - hydrogen exchange process.

**6.6. Infrared absorption analysers**

Infrared absorption analysers capable of on-line hydrogen/deuterium ratio analysis where deuterium concentrations are equal to or greater than 90% by weight.

**6.7. Catalytic burners**

Catalytic burners for the conversion of enriched deuterium gas into heavy water especially designed or prepared for heavy water production utilising the ammonia - hydrogen exchange process.

**6.8. Complete heavy water upgrade systems or columns therefore**

Complete heavy water upgrade systems, or columns therefore, especially designed or prepared for the upgrade of heavy water to reactor-grade deuterium concentration.

**EXPLANATORY NOTE**

These systems, which usually employ water distillation to separate heavy water from light water, are especially designed or prepared to produce reactor-grade heavy water (i.e.

typically 99.75% by weight D<sub>2</sub>O) from heavy water feedstock of lesser concentration.

## **6.9. NH<sub>3</sub> synthesis converters or synthesis units**

NH<sub>3</sub> synthesis converters or synthesis units especially designed or prepared for heavy water production utilising the ammonia-hydrogen exchange process.

### EXPLANATORY NOTE

These converters or units take synthesis gas (nitrogen and hydrogen) from an NH<sub>3</sub>/hydrogen high-pressure exchange column (or columns), and the synthesised NH<sub>3</sub> is returned to the exchange column (or columns).

## **7. Plants for the conversion of uranium and plutonium for use in the fabrication of fuel elements and the separation of uranium isotopes as defined in sections 4 and 5 respectively, and equipment especially designed or prepared therefor**

### EXPORTS

The export of the whole set of major items within this boundary will take place only in accordance with the procedures of the Memorandum. All of the plants, systems, and especially designed or prepared equipment within this boundary can be used for the processing, production, or use of special fissionable material.

### **7.1. Plants for the conversion of uranium and equipment especially designed or prepared therefor**

#### INTRODUCTORY NOTE

Uranium conversion plants and systems may perform one or more transformations from one uranium chemical species to another, including: conversion of uranium trioxide (UO<sub>3</sub>) to uranium dioxide (UO<sub>2</sub>), conversion of uranium oxides to uranium tetrafluoride (UF<sub>4</sub>), UF<sub>6</sub> or UCl<sub>4</sub>, conversion of UF<sub>4</sub> to UF<sub>6</sub>, conversion of UF<sub>6</sub> to UF<sub>4</sub>, conversion of UF<sub>4</sub> to uranium metal, and conversion of uranium fluorides to UO<sub>2</sub>. Many of the key equipment items for uranium conversion plants are common to several segments of the chemical process industry. For example, the types of equipment employed in these processes may include: furnaces, rotary kilns, fluidised bed reactors, flame tower reactors, liquid centrifuges, distillation columns and liquid-liquid extraction columns. However, few of the items are available 'off the shelf'; most would be prepared according to the requirements and specifications of the customer. In some instances, special design and construction considerations are required to address the corrosive properties of some of the chemicals handled (hydrogen fluoride (HF), fluorine (F<sub>2</sub>), chlorine trifluoride (ClF<sub>3</sub>), and uranium fluorides) as well as nuclear criticality concerns. Finally, it should be noted that, in all of the uranium conversion processes, items of equipment which individually are not especially designed or prepared for uranium conversion can be assembled into systems which are especially designed or prepared for use in uranium conversion.

#### **7.1.1. Especially designed or prepared systems for the conversion of UO<sub>3</sub> to UF<sub>6</sub>**

**EXPLANATORY NOTE**

Conversion of  $\text{UO}_3$  to  $\text{UF}_6$  can be performed directly by fluorination. The process requires a source of  $\text{F}_2$  or  $\text{ClF}_3$ .

**7.1.2. Especially designed or prepared systems for the conversion of  $\text{UO}_3$  to  $\text{UO}_2$** **EXPLANATORY NOTE**

Conversion of  $\text{UO}_3$  to  $\text{UO}_2$  can be performed through reduction of  $\text{UO}_3$  with cracked gaseous  $\text{NH}_3$  or hydrogen.

**7.1.3. Especially designed or prepared systems for the conversion of  $\text{UO}_2$  to  $\text{UF}_4$** **EXPLANATORY NOTE**

Conversion of  $\text{UO}_2$  to  $\text{UF}_4$  can be performed by reacting  $\text{UO}_2$  with gaseous  $\text{HF}$  at 573-773 K (300-500 °C).

**7.1.4. Especially designed or prepared systems for the conversion of  $\text{UF}_4$  to  $\text{UF}_6$** **EXPLANATORY NOTE**

Conversion of  $\text{UF}_4$  to  $\text{UF}_6$  is performed by exothermic reaction with fluorine in a tower reactor.  $\text{UF}_6$  is condensed from the hot effluent gases by passing the effluent stream through a cold trap cooled to 263 K (-10 °C). The process requires a source of gaseous  $\text{F}_2$ .

**7.1.5. Especially designed or prepared systems for the conversion of  $\text{UF}_4$  to uranium metal****EXPLANATORY NOTE**

Conversion of  $\text{UF}_4$  to uranium metal is performed by reduction with magnesium (large batches) or calcium (small batches). The reaction is carried out at temperatures above the melting point of uranium (1403 K (1130 °C)).

**7.1.6. Especially designed or prepared systems for the conversion of  $\text{UF}_6$  to  $\text{UO}_2$** **EXPLANATORY NOTE**

Conversion of  $\text{UF}_6$  to  $\text{UO}_2$  can be performed by one of three processes. In the first,  $\text{UF}_6$  is reduced and hydrolysed to  $\text{UO}_2$  using hydrogen and steam. In the second,  $\text{UF}_6$  is hydrolysed by solution in water,  $\text{NH}_3$  is added to precipitate ammonium diuranate, and the diuranate is reduced to  $\text{UO}_2$  with hydrogen at 1093 K (820 °C). In the third process, gaseous  $\text{UF}_6$ ,  $\text{CO}_2$ , and  $\text{NH}_3$  are combined in water, precipitating ammonium uranyl carbonate. The ammonium uranyl carbonate is combined with steam and hydrogen at 773-873 K (500-600 °C) to yield  $\text{UO}_2$ .

$\text{UF}_6$  to  $\text{UO}_2$  conversion is often performed as the first stage of a fuel fabrication plant.

**7.1.7. Especially designed or prepared systems for the conversion of  $\text{UF}_6$  to  $\text{UF}_4$** **EXPLANATORY NOTE**

Conversion of  $UF_6$  to  $UF_4$  is performed by reduction with hydrogen.

### **7.1.8. Especially designed or prepared systems for the conversion of $UO_2$ to $UCl_4$**

#### EXPLANATORY NOTE

Conversion of  $UO_2$  to  $UCl_4$  can be performed by one of two processes. In the first,  $UO_2$  is reacted with carbon tetrachloride ( $CCl_4$ ) at approximately 673 K (400 °C). In the second,  $UO_2$  is reacted at approximately 973 K (700 °C) in the presence of carbon black (CAS 1333-86-4), carbon monoxide, and chlorine to yield  $UCl_4$ .

## **7.2. Plants for the conversion of plutonium and equipment especially designed or prepared therefor**

#### INTRODUCTORY NOTE

Plutonium conversion plants and systems perform one or more transformations from one plutonium chemical species to another, including: conversion of plutonium nitrate ( $PuN$ ) to plutonium dioxide ( $PuO_2$ ), conversion of  $PuO_2$  to plutonium tetrafluoride ( $PuF_4$ ), and conversion of  $PuF_4$  to plutonium metal. Plutonium conversion plants are usually associated with reprocessing facilities, but may also be associated with plutonium fuel fabrication facilities. Many of the key equipment items for plutonium conversion plants are common to several segments of the chemical process industry. For example, the types of equipment employed in these processes may include: furnaces, rotary kilns, fluidised bed reactors, flame tower reactors, liquid centrifuges, distillation columns and liquid-liquid extraction columns. Hot cells, glove boxes and remote manipulators may also be required. However, few of the items are available 'off the shelf'; most would be prepared according to the requirements and specifications of the customer. Particular care in designing for the special radiological, toxicity and criticality hazards associated with plutonium is essential. In some instances, special design and construction considerations are required to address the corrosive properties of some of the chemicals handled (e.g., HF). Finally, it should be noted that, for all plutonium conversion processes, items of equipment which individually are not especially designed or prepared for plutonium conversion can be assembled into systems which are especially designed or prepared for use in plutonium conversion.

### **7.2.1. Especially designed or prepared systems for the conversion of plutonium nitrate to oxide**

#### EXPLANATORY NOTE

The main functions involved in this process are: process feed storage and adjustment, precipitation and solid/liquor separation, calcination, product handling, ventilation, waste management, and process control. The process systems are particularly adapted so as to avoid criticality and radiation effects and to minimise toxicity hazards. In most reprocessing facilities, this process involves the conversion of  $PuN$  to  $PuO_2$ . Other processes can involve the precipitation of plutonium oxalate or plutonium peroxide.

### **7.2.2. Especially designed or prepared systems for plutonium metal production**

#### EXPLANATORY NOTE

This process usually involves the fluorination of  $PuO_2$ , normally with highly corrosive HF,

to produce plutonium fluoride which is subsequently reduced using high purity calcium metal to produce metallic plutonium and a calcium fluoride slag. The main functions involved in this process are fluorination (e.g., involving equipment fabricated or lined with a precious metal), metal reduction (e.g., employing ceramic crucibles), slag recovery, product handling, ventilation, waste management and process control. The process systems are particularly adapted so as to avoid criticality and radiation effects and to minimise toxicity hazards. Other processes include the fluorination of plutonium oxalate or plutonium peroxide followed by reduction to metal.

Commonly used abbreviations (and their prefixes denoting size) in the Annex are as follows:

A	-	ampere(s)	-	Electric current
CAS	-	Chemical Abstracts Service	-	
°C	-	degree(s) Celsius	-	Temperature
cm	-	centimetre(s)	-	Length
cm <sup>2</sup>	-	square centimetre(s)	-	Area
cm <sup>3</sup>	-	cubic centimetre(s)	-	Volume
°	-	degree(s)	-	Angle
g	-	gram(s)	-	Mass
GHz	-	gigahertz	-	Frequency
GPa	-	gigapascal(s)	-	Pressure
H	-	henry(s)	-	Electrical inductance
h	-	hour(s)	-	Time
Hz	-	hertz	-	Frequency
kg	-	kilogram(s)	-	Mass
kHz	-	kilohertz	-	Frequency
kJ	-	kilojoule(s)	-	Energy, work, heat
kPa	-	kilopascal(s)	-	Pressure
kW	-	kilowatt(s)	-	Power
K	-	kelvin	-	Thermodynamic temperature
m	-	metre(s)	-	Length
m <sup>2</sup>	-	square metre(s)	-	Area
m <sup>3</sup>	-	cubic metre(s)	-	Volume
mA	-	milliampere(s)	-	Electric current
min	-	minute(s)	-	Time
MPa	-	megapascal(s)	-	Pressure
mm	-	millimetre(s)	-	Length
µm	-	micrometre(s)	-	Length
N	-	newton(s)	-	Force
nm	-	nanometre(s)	-	Length
Pa	-	pascal(s)	-	Pressure
s	-	second(s)	-	Time
V	-	volt(s)	-	Electrical potential
VA	-	volt-ampere(s)	-	Electric power