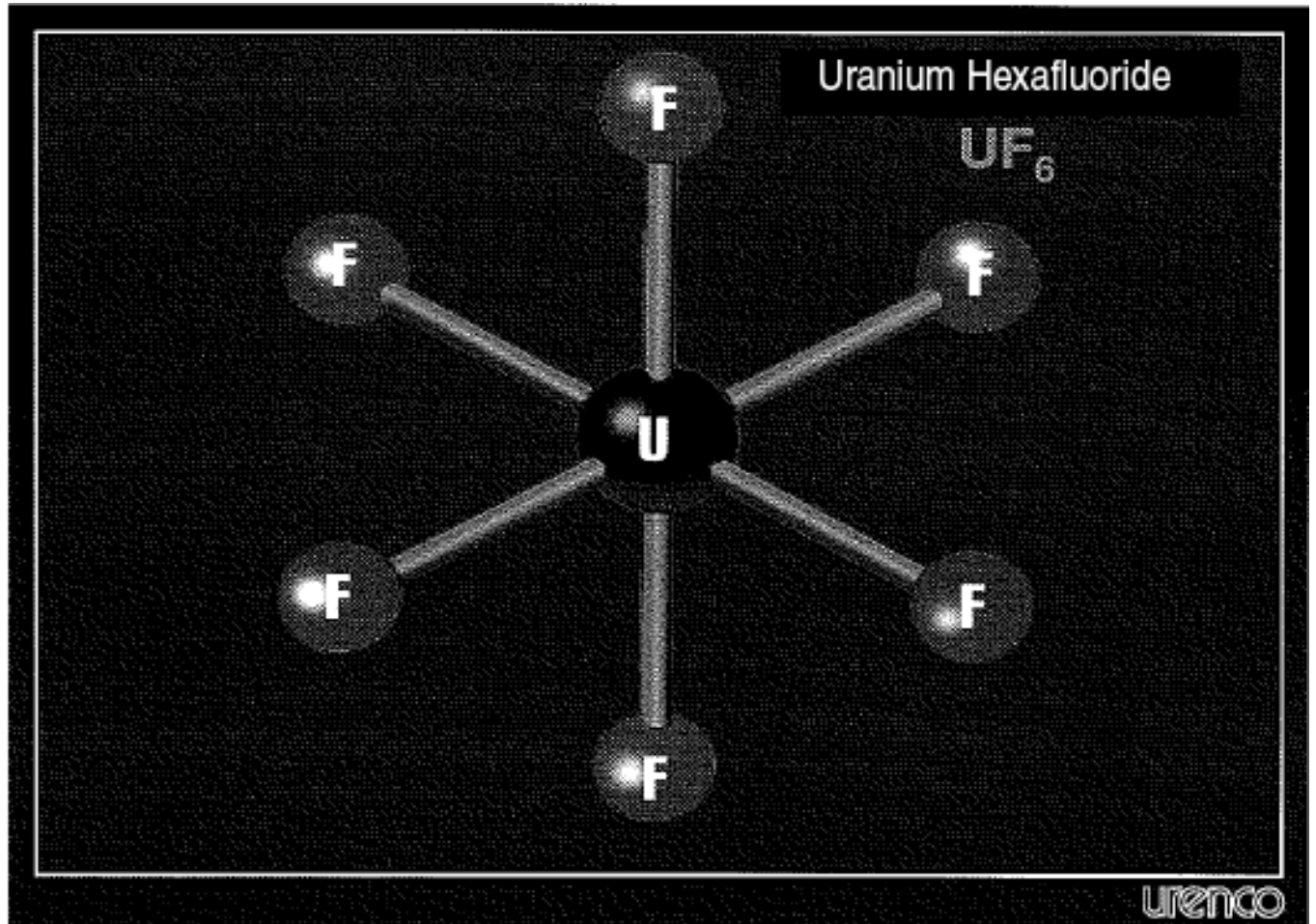


LES/NATIONAL ENRICHMENT FACILITY



UF₆ COMPENDIUM

SOURCE: URENCO DEUTSCHLAND
TRANSLATED FROM GERMAN



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1. SOURCES AND USES OF URANIUM

Natural uranium and uranium compounds are found in the outermost 16 km of the Earth's crust in average concentrations of 2 to 3 ppm¹. These concentrations are comparable to those for boron. It is found in greater quantities than, for example, silver (Ag), gold (Au), iodine (I), bismuth (Bi), and cadmium (Cd). The Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD) estimates worldwide mined uranium stockpiles of 4.4x10⁶ tons, valued at up to \$130/kg. Uranium is found in ocean water in concentrations of approximately 3 ppb². Uranium stocks in the world's oceans are estimated at 4x10⁹ tons.

Before the discovery of nuclear fission, uranium in the form of uranium ores³ was important almost exclusively as a source for radium extraction. Uranium ore was also used to a lesser extent as a colorant for glass and ceramics.

With the discovery of nuclear fission by Hahn and Strassman in 1938, interest in the relatively unknown element uranium suddenly increased. The potential release of energy through the splitting of the ²³⁵U isotope opened undreamed of perspectives on energy production.

Uranium then attained even greater importance as a raw material for the building of atom bombs. The peaceful use of nuclear energy worldwide began in the 1950s. Uranium became an important raw material for nuclear reactor fuel.

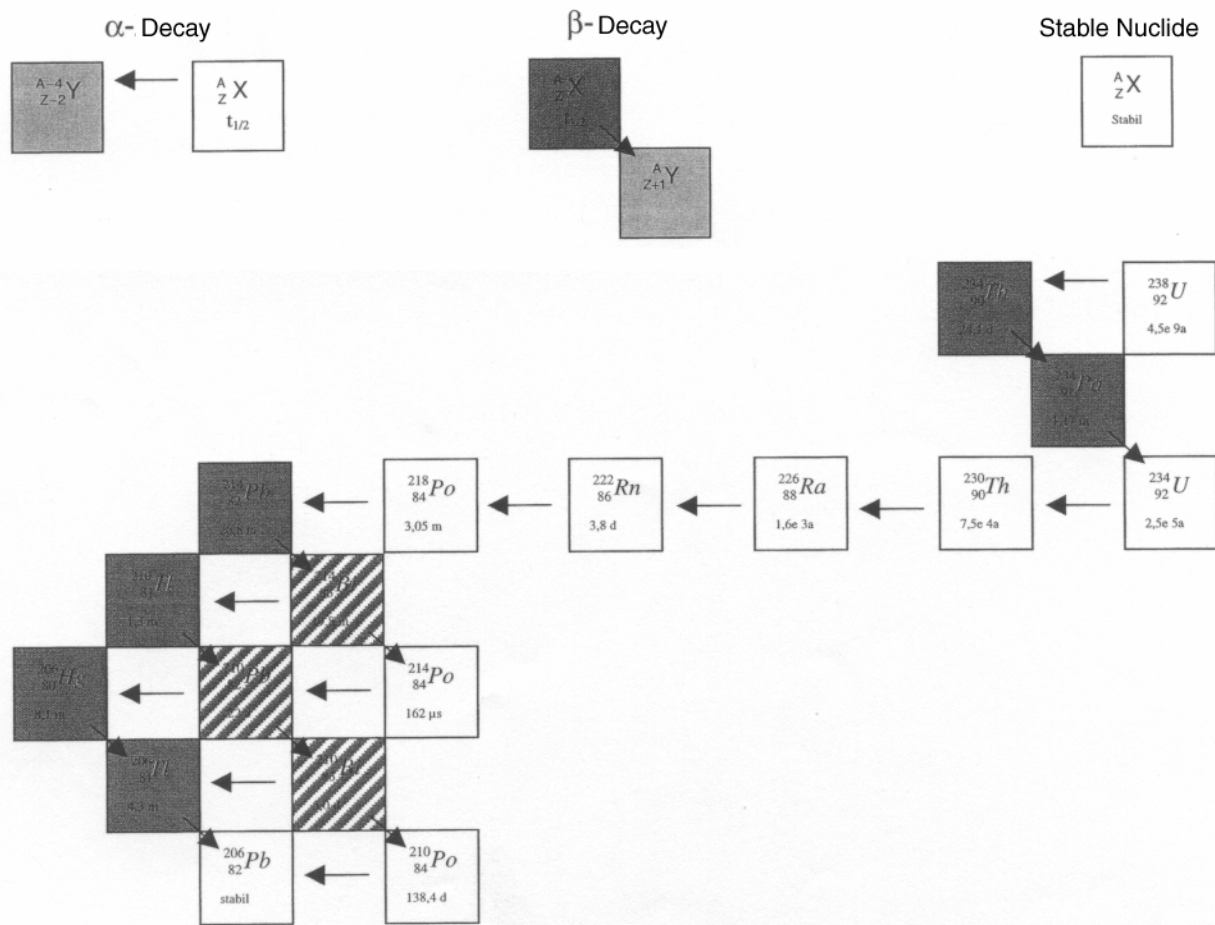
¹ ppm refers to parts per million (10⁻⁶); i.e., 1 mg/kg

² ppb refers to parts per billion (10⁻⁹); i.e., 1 mg/t

³ Important Uranium mineral ores are Pitchblende, Carnotite, Autunite, and Thorianite

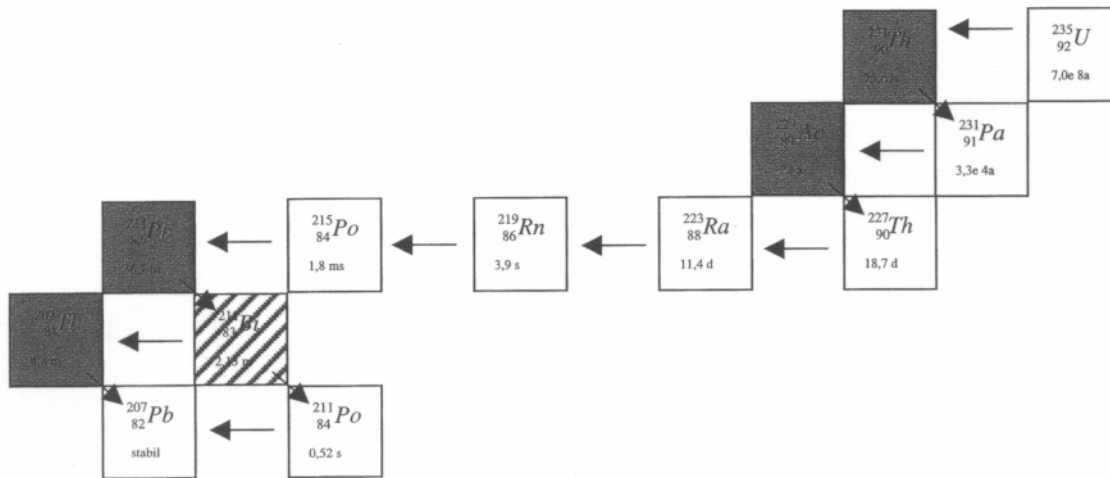
2. RADIOLOGICAL CHARACTERISTICS OF URANIUM

The uranium isotopes ^{238}U and ^{235}U are the starting nuclides represented in Figures 1a and 1b, below, which show the natural radioactive decay stages for the uranium-radium and uranium-actinium series, respectively. The succession of atomic weights in the two decay series is $A=4n+2$ (n integer) for the uranium-radium series and $A=4n+3$ for the uranium-actinium series. The decay of nuclides from stable (lasting hundreds of years) equilibrium occurs through the emission of α particles (Helium nucleus, comprising 2 protons and 2 neutrons) or β particles (electrons) in their decay products, which are constructed from their respective "parents." The uranium isotope ^{234}U is a component of the uranium-radium series, and is in equilibrium with the starting nuclide ^{238}U . Both decay series end in stable Lead isotopes, respectively ^{206}Pb and ^{207}Pb , after losing 32 atomic mass units (amu), corresponding to an 8 α decay in starting nuclide ^{238}U , and 28 amu, corresponding to a 7 α decay in starting nuclide ^{235}U .



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Figure 1a: Uranium-Radium Series, Starting Nuclide ^{238}U



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Figure 1b: Uranium-Actinium Series, Starting Nuclide ²³⁵U

Uranium is present in its natural state because of the long storage times of uranium ore in the soil, generally in equilibrium with daughter nuclides of the decay series. During the production of uranium ore concentrates, which are the output product of the UF₆ production described in Chapter 4, all decay products (daughter nuclides) of uranium are separated to a large extent by chemical processes. The overall α activity of natural uranium that has been converted to UF₆ results from ²³⁸U and ²³⁴U isotopes in equal parts (equilibrium) and to a small part from that of ²³⁵U, as shown in the following table:

Uranium Isotope Mass Number	α Activity [Bq/kg U]	Uranium Isotope Mass Number
234	1.22 x 10 ⁷	49
235	5.18 x 10 ⁵	2
238	1.22 x 10 ⁷	49
<i>Total</i>	2.49 x 10 ⁷	100

The daughter nuclides ²³⁴Th and ²³⁴Pa of ²³⁸U, and respectively the daughter nuclide ²³¹Th of ²³⁵U, have short radioactive half-lives (decay chains), and therefore decay relatively quickly (approx. ½ year) after chemical separation with their respective parent nuclide in equilibrium. Since these daughter nuclides decay through β emission, and the resulting activity cannot be greater than that from the decay of the parent nuclides, the total activity of the natural (chemically separated) uranium consists in equal parts of the α activity of the uranium isotopes and the β activity of their direct decay products.

The α and β radiation is absorbed as particle radiation entirely by the UF₆ container wall. Only a small part of the gamma radiation accompanying some α and/or β decay in the decay series is detectable as a type of radiation by measuring devices outside UF₆ containers. Neutron radiation is also detectable outside UF₆ containers. This radiation occurs through the reaction of α particles with fluorine atoms over the nuclear reaction ¹⁹F (α, n) ²²Na. Because of higher α activity, this is more pronounced with enriched uranium than

with natural uranium. In a container filled with enriched uranium, the equivalent dose rate of neutrons amounts to roughly half of the gamma radiation.

For enriched uranium with a ^{235}U content of 4%, the α activity contribution for the individual isotopes per kg of uranium is as follows:

Uranium Isotope Mass Number	α Activity [Bq/kg U]	Activity Contribution [%]
234	8.19×10^7	84.4
235	3.20×10^6	3.3
238	1.19×10^7	12.3
<i>Total</i>	9.70×10^7	100.0

The total α activity rises at a factor of approximately 3.9 compared to chemically separated natural uranium. While the activity of the ^{238}U remains approximately the same, the α activity of the uranium isotopes ^{235}U and ^{234}U rises at factors of approximately 6.2 and 6.7, respectively. The greatest percentage portion of α activity for enriched uranium comes from the isotope ^{234}U , which after the enrichment process is no longer in radioactive equilibrium with ^{238}U .

The portion of γ radiation that can penetrate a container wall is no higher with enriched uranium than it is with natural uranium. This is because the γ radiation is produced primarily by the daughter nuclides of ^{238}U and ^{235}U , and their shared portion of the total α activity is not higher than it is with natural uranium.

3. URANIUM FUEL CYCLE

Uranium, the fuel for energy production in nuclear reactors, is the heaviest of the naturally occurring elements. Like many other elements, naturally occurring uranium consists of various isotopes (different mass number with the same atomic number), all of which change into their daughter products through α decay with very long half-lives; the isotope concentration is practically constant everywhere on Earth:

Uranium Isotope Mass Number	Portion [% Weight]	Half-life [Years]
234	0.0054	2.45×10^5
235	0.711	7.04×10^8
238	99.283	4.47×10^9

Energy production in reactors take advantage of the fact that the ^{235}U isotope can be split especially effectively by the slow (thermal) deposit of neutrons; that is, it decays with the release of energy into two comparably large “fission products,” whereby 2-3 neutrons are created, which in turn can produce another fission reaction. However, in light water reactors, the natural concentration of ^{235}U isotopes is not sufficient to allow a self-sustaining chain reaction to occur; therefore, for these reactors, this isotope must be enriched compared to the far more common ^{238}U isotope. Currently, reactors require ^{235}U concentrations greater than 4%, with a trend towards higher enrichment grades (5% ^{235}U). Part of this trend is due to the desire for more effective fuel use through more complete burning, with associated savings in the reprocessing of irradiated fuel elements and disposal of radioactive wastes. In addition, with more highly enriched fuels, it is possible to achieve longer operating cycles between fuel element changes.

Two processes, gas diffusion and centrifuge, are used worldwide for industrial-scale enrichment. Because both processes require a gaseous process medium, uranium concentrate must be prepared in a chemical factory (conversion plant) that can provide sufficiently high vapor pressure and which is connected to the uranium mine. UF_6 , which is crystalline up to 64 °C and at room temperature at a vapor pressure of approximately 107 mbar, is particularly suited for this conversion. It is the only uranium compound that can be handled at room temperature in the ways necessary for both enrichment processes. In addition, it is beneficial that fluorine is a “pure element” (only one isotope), so the separation of uranium isotopes cannot be obstructed by fluorine atoms of different mass numbers. For the production of nuclear fuel, enriched UF_6 must be converted back (reconverted) to an oxidic form (UO_2).

Because spent fuel rods removed from a reactor still contain relatively high levels of ^{235}U (in general slightly higher than natural uranium), this material can be enriched again and reused in a reactor after an effective separation of fission products and transuranic elements in a reprocessing plant and reversion to UF_6 . This is the basis of the uranium fuel cycle represented in the schematic diagram in Figure 2, below. The alternative, direct permanent storage, is practiced in an increasing number of countries due to economic and political conditions.

The UF_6 recovered through reprocessing and conversion differs in its characteristics relatively little from natural uranium. Through the reprocessing of spent fuel, fission products such as plutonium and higher transuranic elements are reduced by a factor of approximately 10^6 . Reconversion separates at least 90% of the remaining material, so only slight amounts remain in the UF_6 . Beyond that, naturally occurring uranium isotopes (particularly ^{232}U and ^{236}U) are not recovered because their chemical identities cannot be separated during reprocessing. The resulting change in activity values here are a result of the radiological characteristics of UF_6 . For legal reasons, uranium that is reprocessed and converted to UF_6 is not processed at the uranium enrichment plant in Gronau.

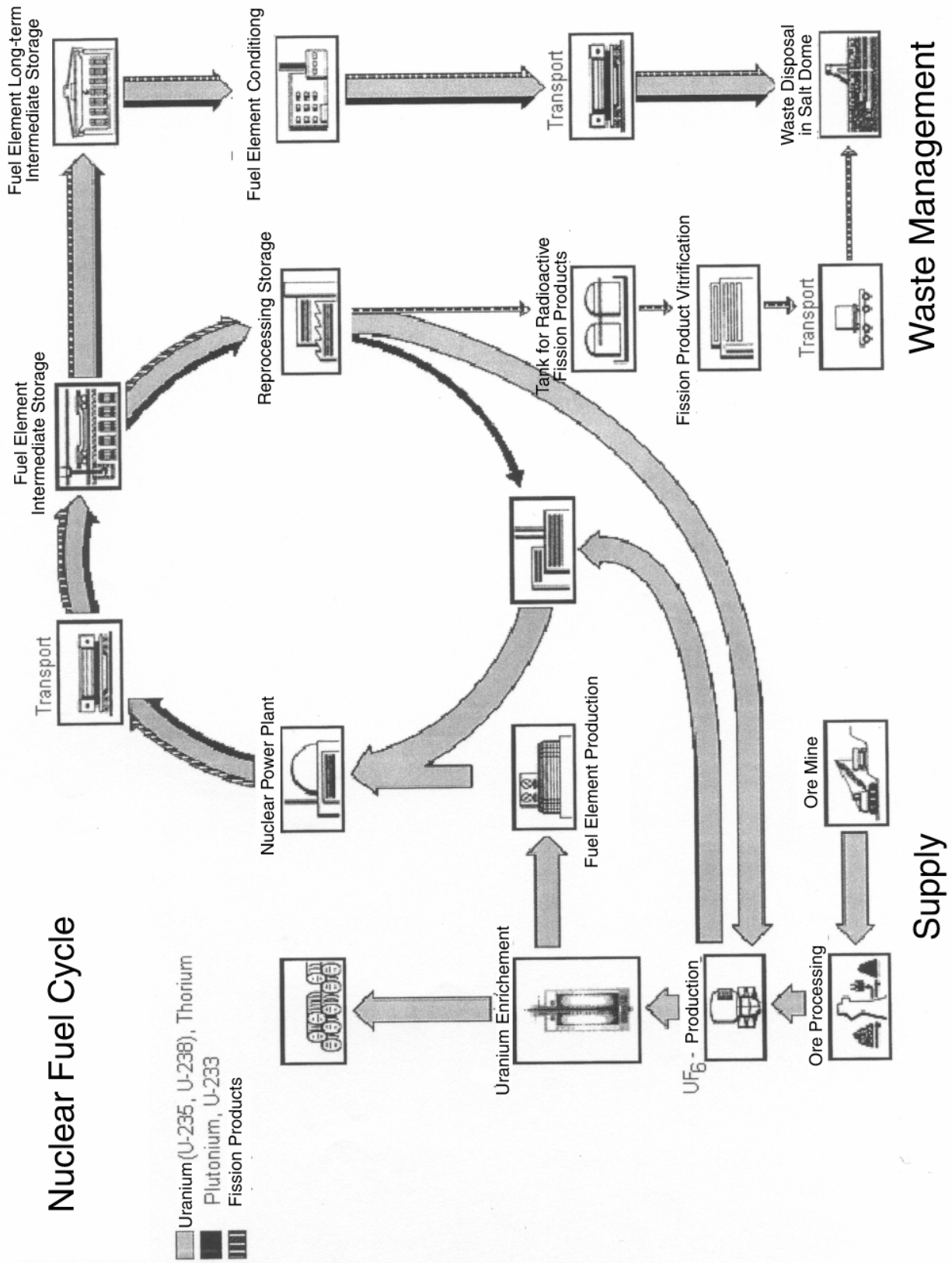


Figure 2: Nuclear Fuel Cycle

4. TECHNICAL PRODUCTION OF URANIUM HEXAFLUORIDE

Uranium is mined worldwide on a scale of between 30,000 and 35,000 tons per year, of which Canada, with a third of world production, has the principal part (Figure 3). The worldwide processing capacity for uranium ore is approximately 50,000 t/a (tons/annum). The yearly requirements for supplying nuclear power plants are roughly twice as high as current production. The difference is made up by the dismantling of downgraded weapons uranium stocks. The uranium ore concentrate resulting from this processing is ammonia diuranate (ADU, also known as “yellow cake”) and alkaline earth diuranate. These are the starting products for UF₆ production.

Using a wet scrubbing process, the production steps for which are illustrated in the schematic diagram in Figure 4, uranium ore concentrate is first dissolved in nitric acid (HNO₃) and then cleared of impurities through mechanical flotation. The filtered uranyl nitrate solution is then extracted with an organic solvent (tributyl phosphate with kerosene). At the same time, the uranium is separated from disruptive elements such as boron, rare earths, cadmium, and lithium. The purified uranyl nitrate solution is next evaporated (dehydrated) and through heating denitrated to UO₃. The UO₃ is then reduced in rotary kilns or fluidized bed reactors, first with hydrogen to UO₂ and then fluoridated at temperatures between 300-500 °C with HF gas to UF₄. The final reaction step in the fluidized bed reactor is the fluoridation at approximately 500 °C of UF₄ with elementary fluorine to UF₆. After the purification of light gasses, the UF₆ is condensed and transferred to transport containers at temperatures below -10 °C.

With dry processing (dry scrubbing), diuranate⁴ is fluoridated without extraction, and the resulting UF₆ is purified through fractional distillation.

⁴ Magnesium and Calcium diuranate are preferred: $\text{CaU}_2\text{O}_7 + 7\text{F}_2 \rightarrow 2\text{UF}_6 + \text{CaF}_2 + 7/2 \text{O}_2$

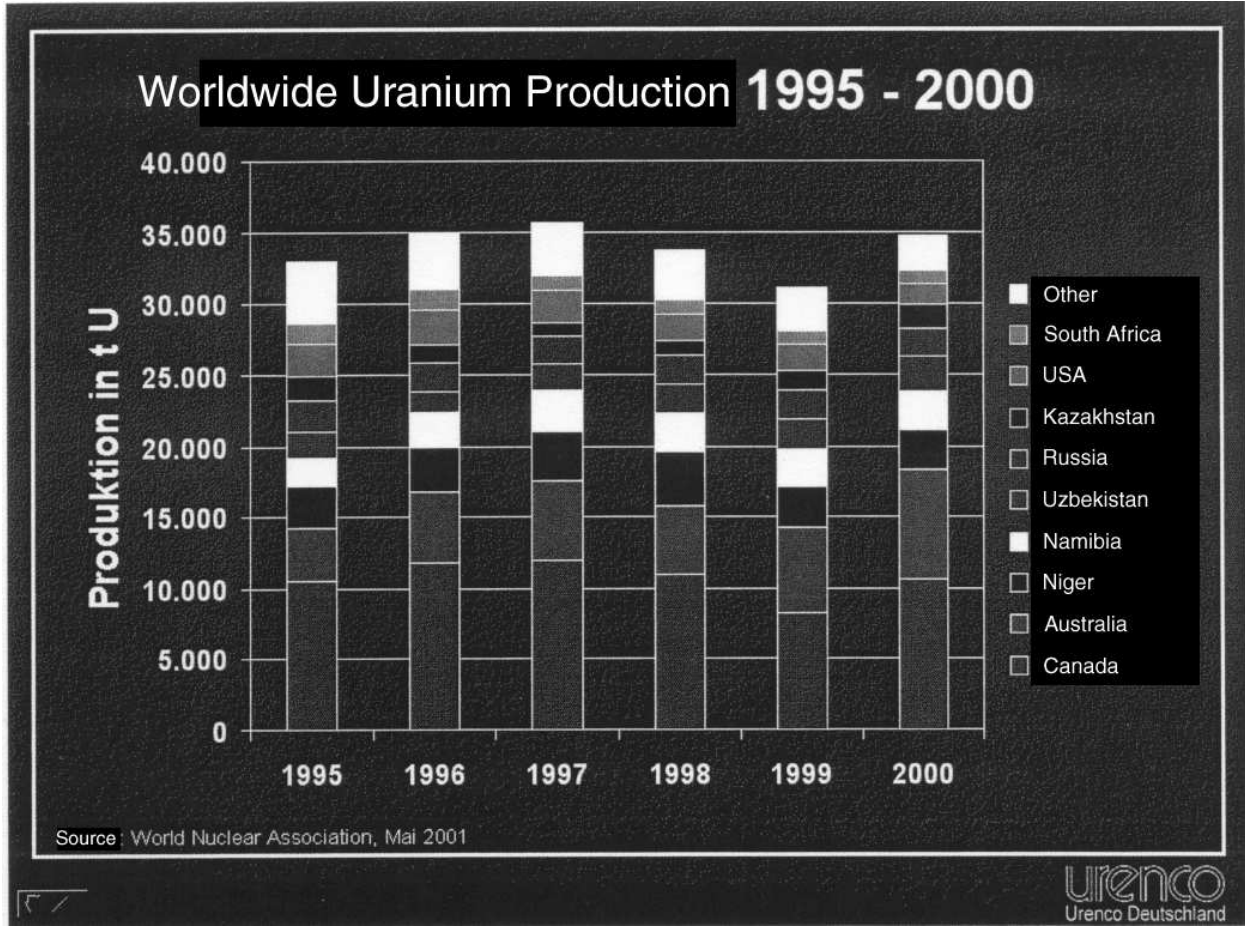


Figure 3: Worldwide Uranium Production

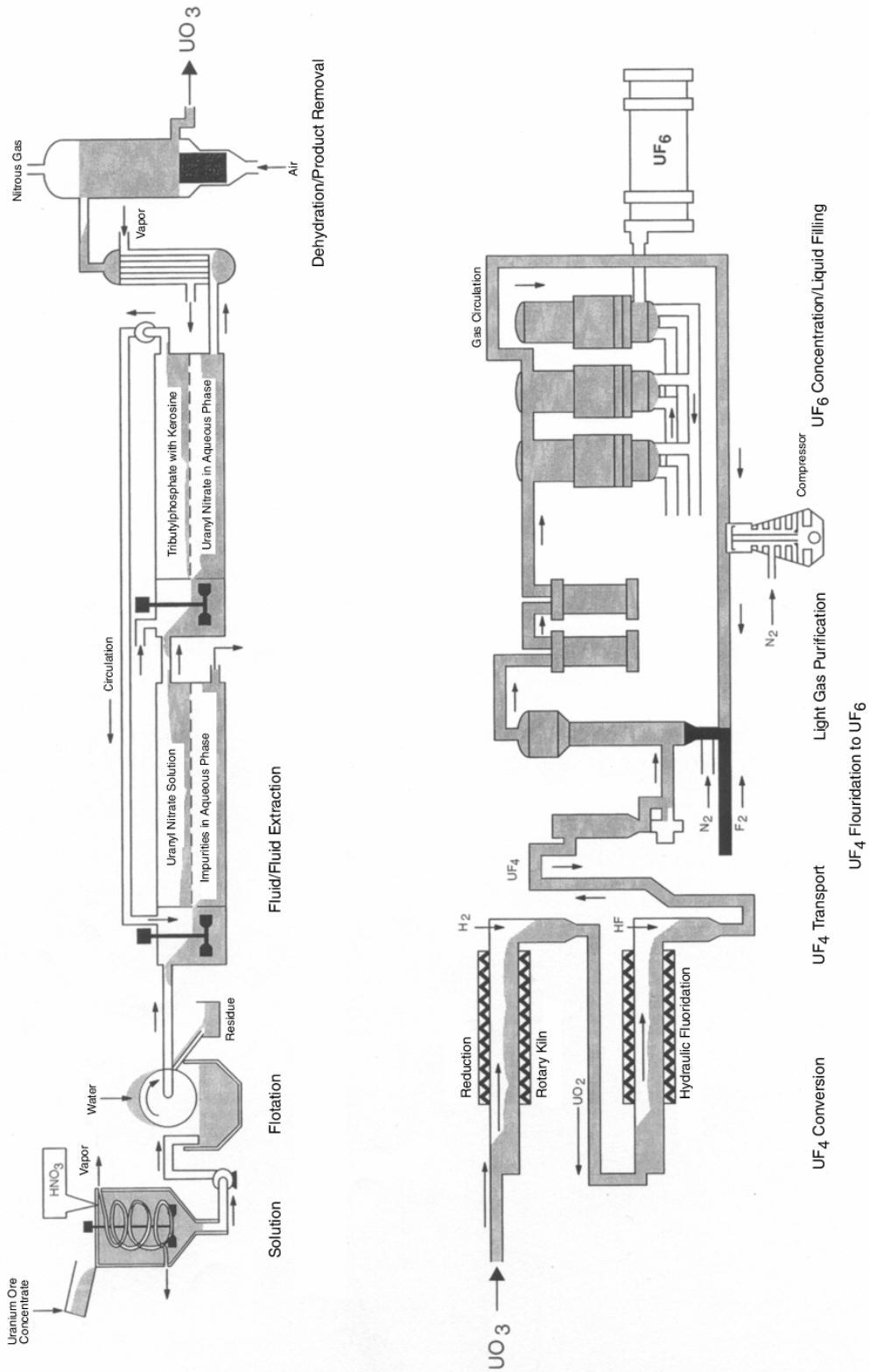


Figure 4: UF₆ Production (Wet Scrubbing Process)

5. CHARACTERISTICS OF UF₆, ITS REACTION PRODUCTS, AND U₃O₈

5.1 PHYSICAL CHARACTERISTICS OF UF₆

Up to temperatures of 64 °C, UF₆ forms a solid white crystal with an orthorhombic crystalline structure. As shown in the phase diagram in Figure 5, UF₆ is characterized by unusually high vapor pressure for a solid, which amounts, for example, to 24 mbar (atmospheric pressure) at approximately 0 °C, 100 mbar at 56 °C, and 1013 mbar at 56 °C. The melting point of UF₆ is 64 °C at a vapor pressure of 1.5 bar.

- The density of solid UF₆ is approximately 5 g/cm³. With liquefaction, density decreases sharply to 3.6 g/cm³ (see Figure 6).
- The enthalpy of sublimation (ΔH_s) for UF₆ amounts to:
 - 49.8 kJ/mol at 20 °C
 - 47.7 kJ/mol at 64 °C
- The enthalpy of evaporation (ΔH_v) for UF₆ amounts to:
 - 28.9 kJ/mol at 64 °C
- The enthalpy of fusion (ΔH_f) is calculated mathematically from the difference of sublimation and vaporization temperatures at the triple-point (64 °C):
 - $\Delta H_f = 18.8$ kJ/mol

Sample values for the specific thermal capacities (C_p) of UF₆ are listed in the following table:

Temperature [°C]	UF ₆ C _p [kJ/(mol K)]		
	Solid	Liquid	Gaseous
20	0.165	--	0.129
64	0.182	0.190	0.135

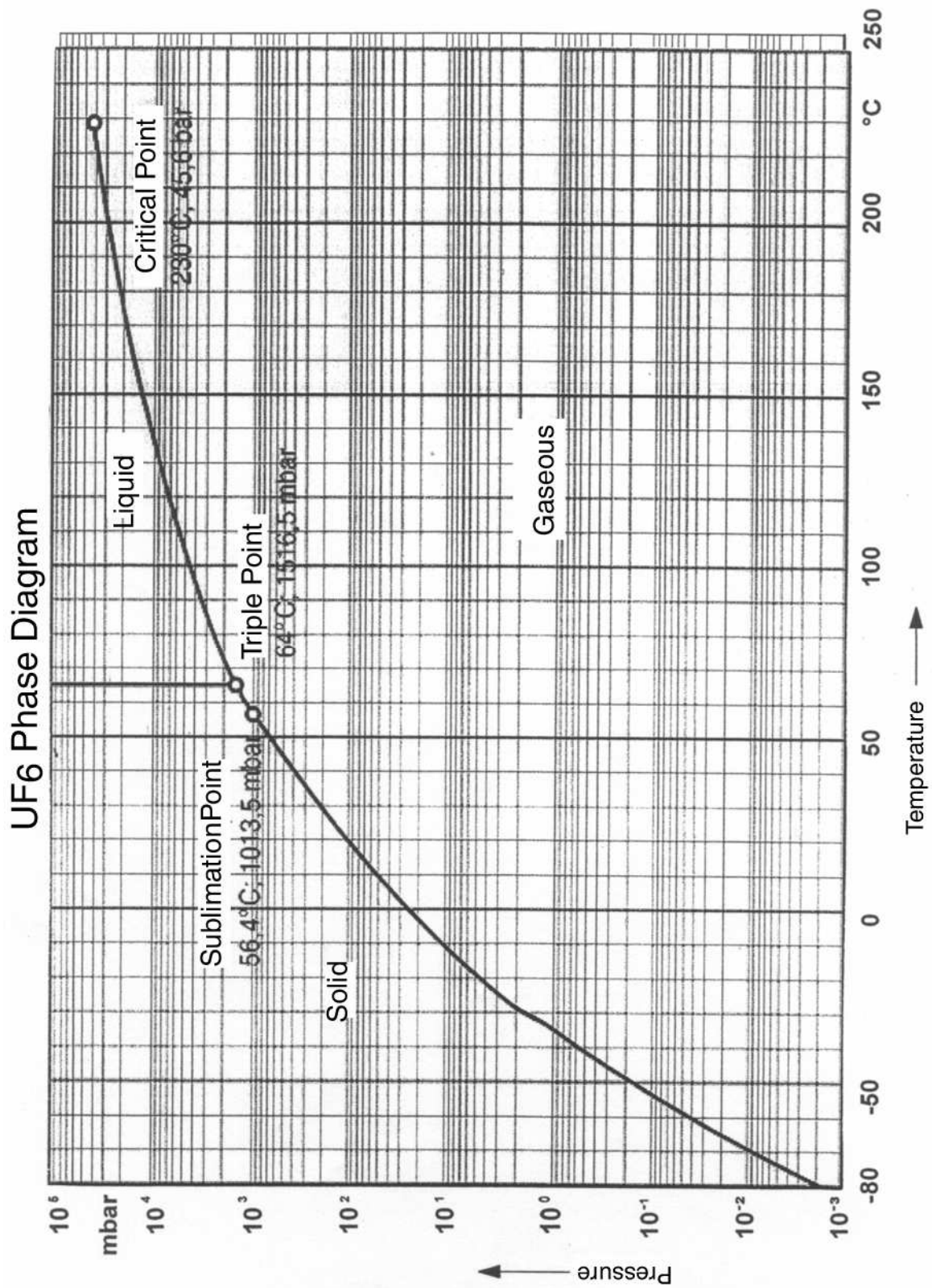


Figure 5: UF₆ Phase Diagram

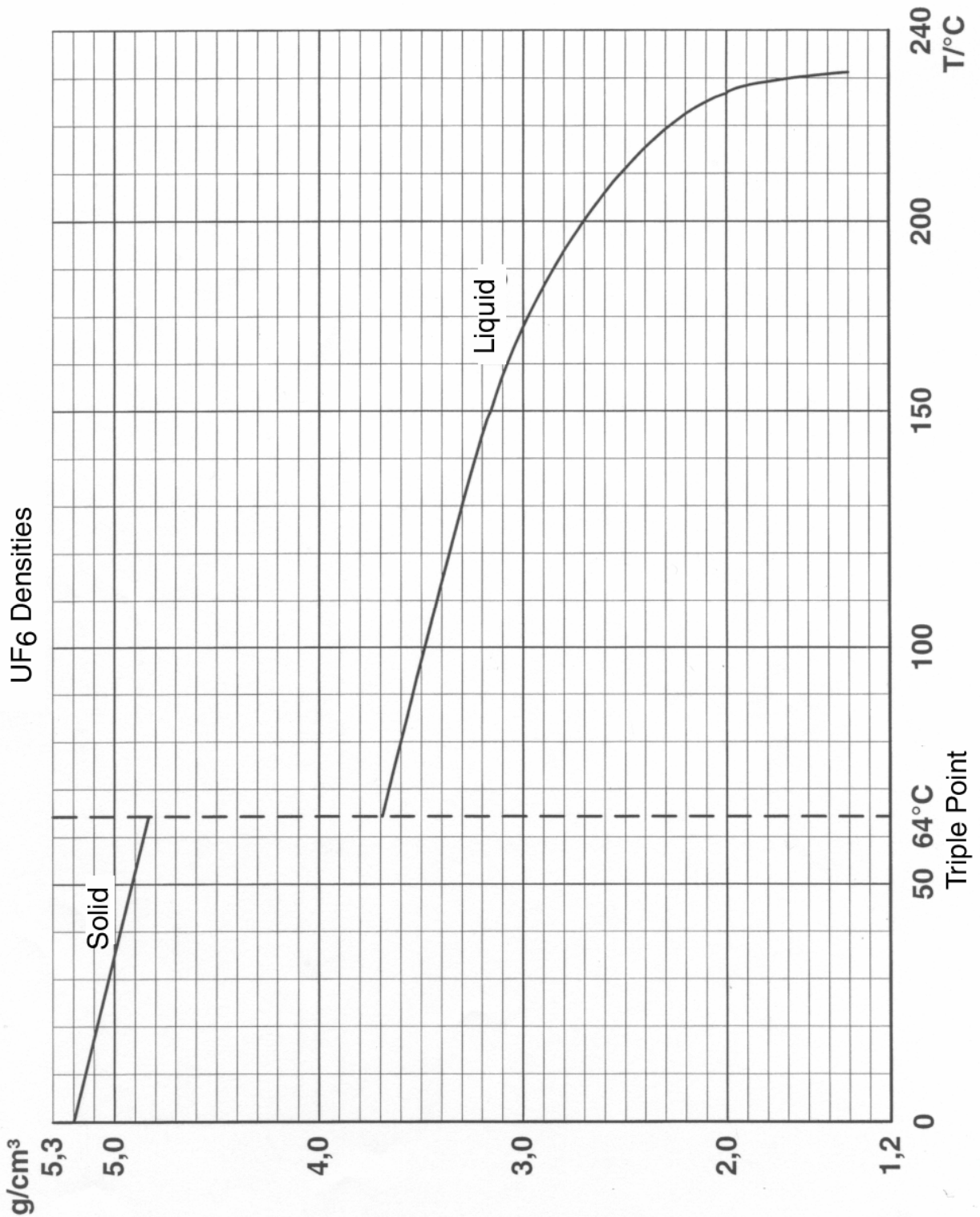
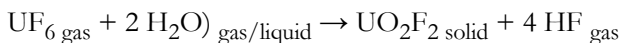


Figure 6: UF₆ Densities

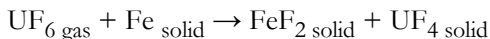
5.2 CHEMICAL PROPERTIES OF UF₆

UF₆ is not flammable and is resistant to dry air. However, it reacts rapidly with water according to the following reaction equation:



The resulting UO₂F₂ (uranylfluoride) is water soluble; HF with surplus water forms hydrofluoric acid.

With most metals and alloys (e.g. iron, cobalt, chrome, aluminum, magnesium, high-grade steels, brass), UF₆ in the form of metal fluorides reacts very slowly at ambient temperature, at increased temperatures somewhat faster. Since the formed fluorides evaporate slowly, depending on reaction conditions, dark grey, brown, or green deposits can form on the reactant surfaces, which can prevent further reactions. A characteristic example is the reaction with iron, shown below:



The product of the reaction is solid: iron fluoride (FeF₂) is white and uranium tetrafluoride (UF₄) green.

It is also possible to form additional uranium fluoride, with the following compounds playing a role: uranium pentafluoride (UF₅), white, diuranium nonafluoride (U₂F₉), black, and tetrauranium heptadecafluoride (U₄F₁₇), dark brown to black.

At more than 100 °C, particular metals like nickel and platinum, and related alloys such as Monel, Inconel, Nimonic, and Hastelloy remain practically resistant, so materials made from these metals can be used in these reaction applications. Likewise, stable boilerplate (fine-grain structural steel suitable for low temperatures, P275NL1) can be made from these materials for UF₆ transport containers (30", 48") that meet international standards.

Dry glass and quartz are unaffected by UF₆ at room temperature. In addition, certain synthetic high polymer formulations; for example, Teflon (PTFE) and KeIF (polychlorotrifluoroethylene, PCTFE), and some copolymers demonstrate good chemical resistance to UF₆.

By contrast, organic substances, such as alcohols, ethers, ester, ketones as well as most saturated and nonsaturated hydrocarbons and mineral oils (like those used in pumps), react with UF₆ through fluoridation reactions depending on conditions present at room temperature. Particularly with liquid UF₆ and solid UF₆, these reactions can become very violent shortly before reaching melting point (64 °C).

Conversely, perfluorinate synthetic oils (for example, Tyreno) show good resistance to UF₆, and are thus preferred for use in pumps.

The adsorption of UF₆ on activated carbons is very effective, which is why it is used, for example, for cleaning uranium residues from pump exhausts.

5.3 UF₆ – SPECIFICATIONS

The international specifications of the American Society for Testing and Materials (ASTM), “Standard Specification for Uranium Hexafluoride for Enrichment” and “Standard Specification for Uranium Hexafluoride Enriched to Less Than 5% ²³⁵U” are relevant to uranium enrichment worldwide. The Urenco Standard Specifications for natural and enriched uranium in the form of UF₆ are based upon these standards.

International and Urenco specification are also created for feed UF₆ from the reprocessing of spent fuel rods and the resulting enriched material. Because this UF₆ is not yet handled in the Gronau enrichment plant, a detailed statement of these specifications is not yet being made.

5.3.1 URENCO SPECIFICATION FOR NATURAL UF₆

Because natural uranium can be contaminated with small amounts of uranium or other nuclides resulting from reprocessing during processing in a facility or while being filled in containers, so called “commercial natural uranium” has been defined. Limit values have been established for these materials, as well as for the uranium isotopes ²³²U and ²³⁶U, which arise only from reprocessed uranium, and similarly for the other nuclides resulting from reprocessing. These specifications also apply to external enriched UF₆ tails of 0.711% ²³⁵U (feed concentration).

Isotope	Limit Value	
²³⁵ U	0.711 +/- 0.004	g/100 g total uranium
²³⁴ U	≤ 58.0	μ g/g total uranium
²³⁶ U	≤ 20.0	μ g/g total uranium
²³² U	≤ 0.00001	μ g/g total uranium
⁹⁹ Tc	≤ 0.001	μ g/g total uranium

²³⁶U serves as an indicator for the nuclides ²³²U, ²³⁴U, and ⁹⁹Tc; if instrumentation can prove compliance with the limit values for ²³⁶U, measurement of these nuclides is not necessary.

The following limit values also apply:

Limit Value	Comment
UF ₆ content > 99.5% wt.	Starting from this concentration, criticality safety also exists with undesirable compounds of the residual content
Percentage of hydrocarbons, chlorinated hydrocarbons, and part-halogenous hydrocarbons < 0.01 % mol.	Through this can be prevented the occurrence of a UF ₆ liquefaction reaction that develops unallowable container pressure build up.

5.3.2 URENCO SPECIFICATION FOR ENRICHED URANIUM IN THE FORM OF UF₆

This specification correlates to the Urenco "enriched commercial grade" product material that is produced from "commercial natural uranium." It assures, by adhering to the defined limit values for enriched UF₆, that the requirements are met for fuel assembly production and reactor fuel.

Isotope	Limit Value	
²³⁵ U	< 5	g/1000 g total uranium
²³⁴ U	≤ 10.000	μ g/g ²³⁵ U
²³⁶ U	≤ 2.500	μ g/g ²³⁵ U
²³² U	≤ 0.002	μ g/g ²³⁵ U
⁹⁹ Tc	≤ 0.2	μ g/g ²³⁵ U

Here as well, ²³⁶U serves as an indicator for the nuclides ²³²U and ⁹⁹Tc; by adhering to these limit values, the analytic determination of the nuclides ²³²U and ⁹⁹Tc is not necessary.

The following limit values also apply:

Limit Value	Comment
UF ₆ content > 99.5% wt.	Starting from this concentration, criticality safety also exists with undesirable compounds of the residual content
Percentage of hydrocarbons, chlorinated hydrocarbons, and part-halogenous hydrocarbons < 0.01 % mol.	Through this can be prevented the occurrence of a UF ₆ liquefaction reaction that develops unallowable container pressure build up.
Boron content ≤ μg B/g total uranium	Boron, as a neutron absorber, is not desirable in nuclear fuel.
Silicon content ≤ 250 μg Si/g total uranium	Silicon at high concentrations disturbs the sinter processing of uranium pellets during fuel element production.

5.3.3 SPECIAL IMPURITIES IN UF₆

Impurities in UF₆ have a variety of sources and various consequences for the enrichment process and the longevity of centrifuges. Sources include first the uranium ore itself, the processing of ores, and the UF₆ production process in question. In addition contamination of UF₆ materials is possible during handling (i.e., filling), or through inadequate cleaning of containers.

Of particular significance for the longevity of centrifuges is macromolecular fluorocarbon compounds (CF compounds), which have been found in varying concentrations up to some ppm in UF₆ feed material from BNFL (British Nuclear Fuels) and the Russian enrichment plants (Angarsk, Tomsk, and Novouralsk).

The CF compounds in BNFL material originate with the fluorine used in the fluoridation of UF₄ to UF₆ (see Figure 4). The fluorine is produced in an electrolysis process from water-free hydrogen fluoride (HF), to

which potassium fluoride is added to increase conductivity. Carbon is used here as an anode material. Depending on processing conditions, because the fluorine forms on the anode, traces of the anode material can also be fluoridated. The thus formed macromolecular CF compounds then end up with the fluorine in the UF₆.

The CF compounds in the feed UF₆ from the Russian plants vary in their chemical structure from that of the BNFL material. Different causes come into consideration here.

When UF₆ contaminated with CF compounds is fed into a centrifuge cascade, these macromolecular CF compounds form deposits on the rotors. If a certain amount of deposits form in a rotor, it will cause the rotor to crash. Regular check analysis and production testing of feed materials is currently performed before feeding into to the array. Because of the different types of centrifuge installations currently in use exhibit different sensitivities to CF compounds, decisions about which materials will be fed into which cascades are made on the basis of analysis.

5.4 REACTION PRODUCTS OF UF₆

5.4.1 URANYL FLOURIDE UO₂F₂

This is formed from the hydrolysis of UF₆ with water (see Section 5.2). Uranyl fluoride is a pale yellow solid, is strongly hygroscopic (that is, absorbs moisture), and also partially binds to hydrogen fluoride created during hydrolysis reaction. Solubility in water is gut.

5.4.2 URANIUM TETRAFLUORIDE UF₄

This is an intermediate product of industrial-scale production of UF₆ (see Section 4), and can be created from reactions of UF₆ with metals and/or organic materials. Uranium tetrafluoride is a dark green solid that is almost insoluble in water.

5.4.3 URANIUM PENTAFLUORIDE UF₅

This is a potential reaction product of UF₆ from reactions predominately with organic materials, but is also possible from reactions with metals. Uranium pentafluoride is a white solid that reacts rapidly with humidity according to the following reaction equation:



With the UF₄ produced by this reaction, the UF₅ gradually turns green on exposure to air.

5.4.4 DIURANIUM NONAFLUORIDE U_2F_9 AND TETRAURANIUM HEPTADEC AFLORIDE U_4F_{17}

This is formed primarily by reactions of UF_6 with metals; their formation is also possible by reactions with organic materials. It is a dark brown to black solid. It reacts like UF_5 in humid air to UF_4 and UO_2F_2 , however much more slowly, whereby it also slowly turns green through the formed UF_4 .

5.5 CHARACTERISTICS OF U_3O_8 , TRIURANIUM OCTAOXIDE (URANIUM OXIDE)

U_3O_8 is a greenish-black solid with a density of 8.3 g/cm^3 . U_3O_8 is practically insoluble in water. It is the end product of oxidation of uranium compounds in air or oxygen. For example, it is created by the thermal decomposition of uranium and/or uranyl compounds in air or oxygen. U_3O_8 is stable in air up to about $900 \text{ }^\circ\text{C}$, and right before reaching melting point, between $900 \text{ }^\circ\text{C}$ and $1500 \text{ }^\circ\text{C}$, decomposes under formation of UO_3 .

Industrial uranium oxide produced for stockpiling is a compressed powder with a bulk density of 3 g/cm^3 . It is composed of $> 97\%$ U_3O_8 , and can contain up to 3% uranyl fluoride and traces of hydrogen fluoride (HF).

6. TOXICITY CONSIDERATIONS OF URANIUM IN GENERAL AND UF₆

When considering toxicity, the most important criterion in deciding whether a material has toxic effects is the quantity of the material causing the effect.

Even materials necessary for life, for example, water, oxygen, common salt, vitamins, can become lethal poisons if they are supplied to the body in excessive amounts or improper ways. In this sense, there are thousands of materials in modern industrial life that play many not unimaginable roles – chemicals, gasses, metals, petroleum products – that are powerful poisons when they are supplied to living organisms. By learning about and handling these materials in accordance with regulations, these materials can be used safely and the dangers to life can be avoided.

The same also applies to the materials in the nuclear fuel cycle, which because of their radioactive properties must be handled particularly sensitively. Safeguards in processing, transport, and use are much more widely developed than with many other chemicals.

Uranium, as a heavy metal and in its compounds, is not as poisonous as lead and mercury. Many more people have day-to-day contact with relatively high concentrations of lead (previously used in gasoline as an anti-knock agent) and mercury (batteries, amalgam in dental fillings, thermometers, etc.) than with uranium. All life forms are constantly exposed to small concentrations of uranium, as uranium is widespread in the soil (2-3 ppm) and in seawater (3 ppb), as well as in plant and animal foods and in water (0.0001 to 40 ppb).

When thinking about the overall toxicity of uranium, two fundamental effects must be considered: those from radiologically toxic and chemically toxic components. For both components, the chemical compounds in which the uranium exists have a fundamental influence on the mechanisms of the toxic effects.

6.1 RADIOTOXICITY OF URANIUM AND ITS COMPOUNDS

The radiotoxicity of uranium in general is based primarily on the α activity of the uranium isotope (see Section 2). This α radiation has a significantly higher damage efficiency (factor 20) than γ radiation, but at the same time a very limited range of transmission (a few cm in air, some μm in bodily tissue). The limited range of α radiation means that it is not particularly critical to think about external exposure, because the radiation cannot penetrate the body. However, if uranium enters the body, the α radiation can damage the haematonic bone marrow cells that produce red blood cells in humans. From the point of view of water soluble uranium compounds (for example, UF₆, UO₂F₂), the bones are the critical organ.

However, slowly soluble uranium compounds, like U_3O_8 or UO_2 , are radiotoxic when inhaled because they remain in the lungs for a long time.

With enrichment grades up to 10% ^{235}U by weight, radiotoxicity is for the most part less significant than chemical toxicity, due to the low specific activity values.

6.2 CHEMICAL TOXICITY OF URANIUM AND ITS COMPOUNDS

With water soluble uranium compounds containing fluorine, it is important to be aware that besides the toxicity of uranium as a heavy metal, fluorine as fluoride also contributes a not insignificant component of chemical toxicity.

This is especially important to bear in mind with the handling of UF_6 , because when released it hydrolyzes to uranyl fluoride (UO_2F_2) and hydrogen fluoride (HF) by reacting with the humidity in the air or the water in human bodies (see Section 5.2).

6.2.1 THE URANIUM COMPONENTS

The chemical toxicity of uranium and its compounds is comparable with the other heavy metals. It is based on the fact that uranium can form stable complexes with the proteins in body cells. The kidneys are the critical organ here, because it is here that an accumulation of uranium compounds takes place. This applies particularly to the six-valent uranium compounds, like UF_6 and water soluble UO_2F_2 produced from it through transformation with water, which are classified as more toxic than the four-valent and/or water insoluble compounds like UF_4 and U_3O_8 .

With all uranium compounds, a concentration in the kidneys of 3×10^{-6} g U/g kidney is regarded as absolutely harmless. This corresponds to about 1 mg of uranium in a kidney with an average weight of 300 g. One must take into account that only a small percent of uranium taken through the mouth is reabsorbed, and only 10% to 15% of ingested uranium accumulates in the kidneys – the largest portion is expelled within 24 hours – so the absorption of soluble uranium compounds like UO_2F_2 through ingestion on the order of a combined 10 mg is not dangerous at all. The German Statutes Governing Radiation Protection (Strahlenschutzverordnung (StrlSchV) version 1989) thus state that the inhalation and ingestion of soluble uranium compounds over the course of one day should not exceed 2.5 mg and 150 mg, respectively. With a biological half-life of approximately 15 days for the breakdown of these compounds in the kidneys, such ingestion repeated at greater intervals would also be harmless.

For uranium compounds, the specified highest permissible levels of pollutants in the workplace (Maximum Workplace Concentration; German MAK-Wert) amount to 0.25 mg U/m^3 . With an 8-hour workday, and a general breathing rate of 830 l/h as a basis, this corresponds to a stipulated maximum workplace concentration for inhalation of approximately 1.6 mg/workday. This value is somewhat under the

above stipulated value for inhalation (StrlSchV, version 1989). By way of comparison, the maximum workplace concentration for lead compounds, set at 0.1 mg Pb/m^3 , is less than for uranium compounds.

6.2.2 THE FLUORINE COMPONENTS

Fluorine is an essential component for organisms, and is absorbed with food by humans on the general order of up to 1 mg/day . A single ingestion of 200 mg of fluorine is regarded as harmless. Over the long term, daily absorption of an additional 1 to 2 mg is totally harmless. To bring about fluorosis (thickening and stiffening of the joints and bones), a daily absorption of 20 - 80 mg F/day is required; more important, with a daily absorption of 50 - 100 mg , other effects, such as kidney and thyroid damage, can also occur.

With a half-life of less than nine hours, extra fluorine is for the most part excreted from the body.

Since the early 1930s, it has been known that small concentrations of fluoridation in drinking water offer excellent protection against tooth decay. The World Health Organization (WHO) therefore regards a fluoride content of 1.0 to 1.2 mg/l in drinking water as not only unproblematic, but recommends it as a prophylaxis against tooth decay.

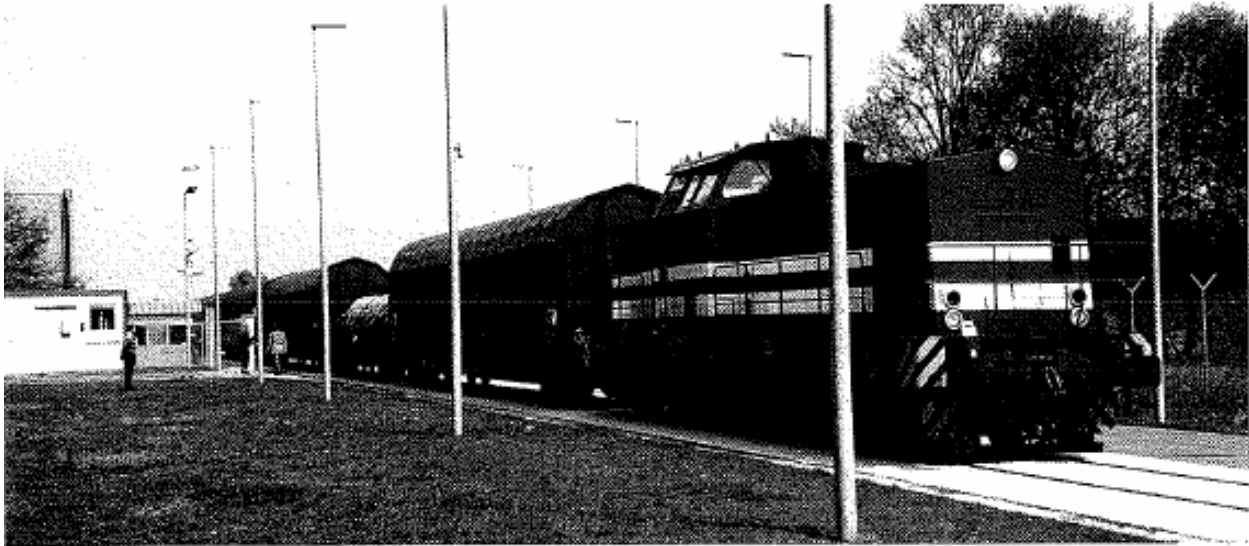
Even with very small concentrations of 0.03 to 1.3 mg/m^3 in the air – well before any possible health risk – hydrofluoric acid (aqueous solution of hydrogen fluoride (HF)), produces a clearly visible grayish-white cloud with a perceptible acrid-sour smell. As a result, one can get to safety and/or initiate protective measures early. A prolonged stay in an area with a maximum workplace concentration (MAK-Wert) of 2.5 mg/m^3 is therefore unlikely.

At higher concentrations, the gaseous and also aqueous solution can cause serious injury to the eyes and skin, and the inhalation of gases irritates the respiratory tract. It can damage the lungs to the point of edema.

50 ppm (about 42 mg HF/m^3) for 30 - 60 minutes is proven to be lethal. Concentrations above 50 ppm for even short periods of time are hazardous.

7. TRANSPORT OF UF₆





UF_6 is transported on land routes and/or waterways with motor vehicles, trains and/or ships in containers that meet international standards (ANSI N14.1, ISO 7195). Uranium hexafluoride is transported as solid matter. During transport, a pressure of approximately 0.1 bar is maintained in the transport container, which corresponds to approximately 10% of atmospheric pressure. Because of this negative pressure within the container, any leak will result in the inflow of air until pressure equalization is reached.

The containers in which natural uranium (Feed) and spent uranium (Tails) are transported differ from the containers for enriched uranium (Product) in terms of size and capacity as well as safety requirements. Containers for Feed and Tails contain a maximum of 12.5 t UF_6 . Product containers are filled with a

maximum of 2.27 t of uranium hexafluoride. Because of the fissile properties of the product, these containers are subject to additional criticality controls.

For the transport of smaller amounts (Samples), UF_6 is filled into ampoules made from nickel, Monel, stainless steel, steel, or plastic. These are likewise transported over land routes, seaways, and even airways.

7.1 LEGAL FUNDAMENTALS

All conveyances of uranium hexafluoride are categorized as hazardous good transports according to extensive national and international regulations. In the Federal Republic of Germany, they are subject to the Guidelines for the Transport of Hazardous Goods (Rahmengesetz über die Beförderung gefährlicher Güter (GGBefG)), which establishes separate regulations for each of the modes of transport. The Hazardous Goods Regulations Road/Rail (Gefahrgutverordnung Straße/Schiene (GGVSE)) refer, in attachments A and B respectively, to the “European conventions of September 30, 1957 on the international transport of hazardous goods on roadways” (ADR) and the “Regulations for the international railway transport of hazardous goods” (RID). All particulars for the classification and transport of hazardous materials are detailed in these regulations.

Because of the radiological characteristics of uranium, transport of UF_6 is for the most part classified as Hazardous Material Class 7 (Gefahrgutklasse 7) – “Radioactive Materials.” Because of the fact that UF_6 in combination with water (for example, humidity in the air) releases caustic hydrofluoric acid, it is additionally legally classified as Hazardous Material Class 8 – “Caustic.” This has consequences for the marking and tagging of pieces to be sent, particularly for the transport of small quantities, with which the secondary caustic hazard becomes a primary hazard. This considerably changes the requirements for transport.

For the transport of larger amounts of non-enriched materials (Feed or Tails) on roadways, separate transport approval is required for each administrative region, according to Section 16 of the Statutes Governing Radiation Protection (StrlSchV).

Because of its fissile properties, enriched uranium hexafluoride falls into the category of nuclear fuel, and therefore requires transport approval from the Federal Agency for Radiation Protection according to Section 4 of the Atomic Energy Act. A detailed report, in which all required specifications for the transport are declared, must be provided by the licensee to all relevant authorities at least 48 hours before the start of transport. It is only permissible to use the sections of roadway specified in the 48 hour report.

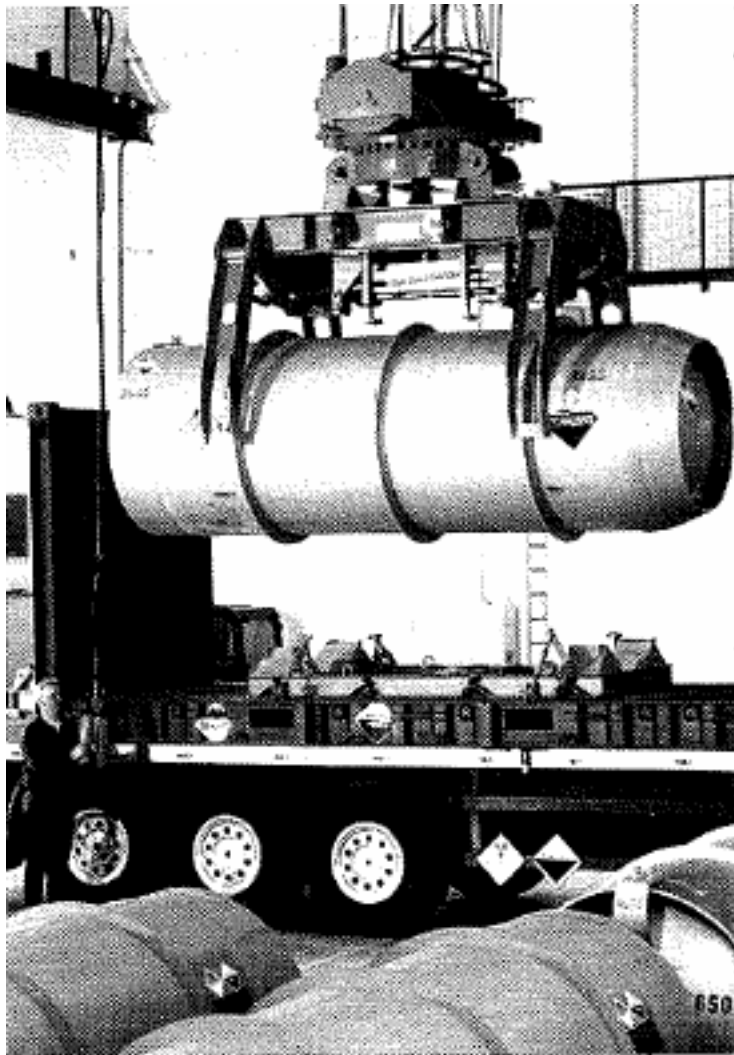
All transports are carried out by experienced transport companies holding government licenses for this type of activity. These licenses are for limited times only and have high safety requirements.

7.2 UF₆ TRANSPORT CONTAINERS

The containers used for transporting UF₆ also serve as storage and processing containers. They have been used for decades, and have been proven through routine use as well as accident conditions.

All UF₆ containers that are designed to hold at least 100 g UF₆ must comply with international specifications (ANSI N 14.1 or ISO 7195) and are subject to licensing.

7.2.1 CONTAINERS FOR FEED AND TAILS (TYPE 48Y)



Technical Data for 48Y Containers

Diameter	1,250 mm
Length	3,810 mm
Wall Thickness	16 mm
Weight Empty	2,359 kg
Maximum UF ₆ Content	12,501 kg
Total Weight	14,860 kg
Volume	4.04 m ³
Maximum Operating Pressure	14 bar positive pressure
Hydrostatic Proof Pressure	28 bar positive pressure
Valve	1" Superior type
Material	Fine grain structural steel for low temperatures, P275 NL1

As a rule, Feed and Tails are transported and stored in 48Y containers. Since 01/01/2002, these containers are subject to prototype proof check requirements and transport licensing, which in Germany are issued by the Federal Office for Material Research and Testing (BAM).

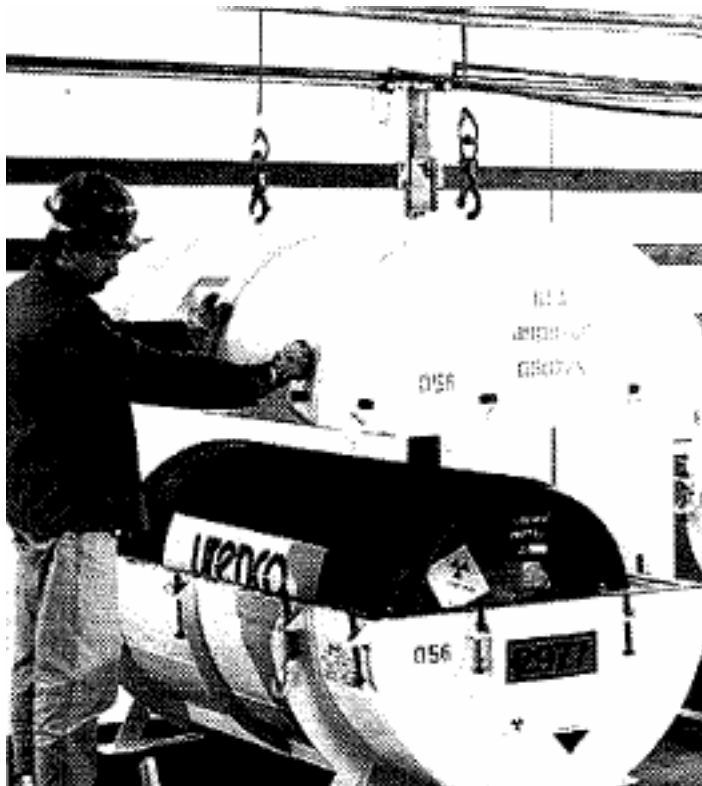
The testing requirements leading to licensing for containers is defined in the recommendation of the International Atomic Energy Agency (IAEA), “Regulations for the Safe Transport of Radioactive Material – TS-R-1.”

Besides the general requirements for the transport of radioactive materials, 48Y containers must be able to survive undamaged a fall from a height of 0.6 m onto an inflexible steel reinforced concrete slab. For this reason, the containers are provided with special valve protection (VPA).

Before commissioning and after every 5 years, every container undergoes a hydraulic interior pressure test to 28 bar by technical experts. As of 01/01/2004, the containers must additionally be equipped with fire protection that enables them to withstand a fully enclosed fire of 800 °C for 30 minutes. For this reason, international levels for thermal insulation have been established to help carriers meet these requirements.

In Germany, because of roadway weight restrictions of 40 t per truck, a truck can only transport one of these Feed/Tails containers at a time. By rail, each freight car can serve for up to three full Feed/Tails containers.

7.2.2 CONTAINERS FOR PRODUCT (TYPE 30B AND OVERPACKS)



Technical Data for 30B Containers	
Diameter	762 mm
Length	2,070 mm
Wall Thickness	13 mm
Weight Empty	635 kg
Maximum UF ₆ Content	2,277 kg
Total Weight	2,912 kg
Volume	0.736 m ³
Maximum Operating Pressure	14 bar positive pressure
Hydrostatic Proof Pressure	28 bar positive pressure
Valve	1” Superior type
Material	Fine grain structural steel for low temperatures, P275 NL1

As a rule, product material is stored and internally transported in 30B containers. As with 48Y containers, when transporting product material on open roads, mechanical and thermal stress on the material being shipped comes into consideration. On account of easily elevated ²³⁵U components, additional safety aspects with regard to criticality must be considered.

For these reasons, overpack (secondary packaging) rules have been developed, which broadly satisfy all these requirements. From a legal standpoint regarding hazardous materials, the material being shipped must be regarded in its totality, so a 30B container + overpack must be considered as one. Prototype proof testing or licensing always pertain to the total package being shipped.

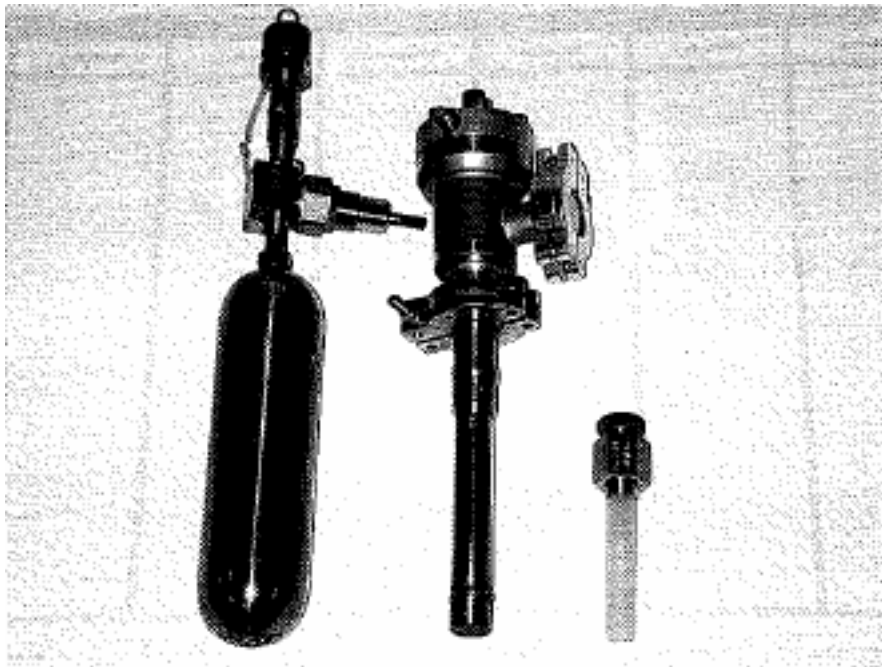
In addition to the testing of 48Y containers that must be fulfilled because of the properties of UF_6 , the tests related to the shipping of fissile materials that 30B + overpack bundles must also fulfill are as follows:

- Water spray test
- Free fall onto a steel reinforced concrete platform from a height of 9 m
- Stacking test
- Breakthrough test with 6 kg steel bolts from a distance of 1 m
- Fall of 1 m onto a spike
- Fire test, 30 min, 800 °C
- Water penetration test

Pursuant to IAEA transport regulations, overpacks in combination with UF_6 constitute a so called Type B(U)F and/or Type AF packaging. These likewise require permits through responsible authorities.

A single truck can transport up to six 30B containers and trains up to ten containers per car.

7.2.3 CONTAINERS FOR SMALL QUANTITIES



For the transport of small quantities (samples), UF_6 is carried in ampoules of various shapes and sizes made from nickel, Monel, stainless steel, or Kel-F (PCTFE). These are transported on both land and seaways as well as airways. Because these ampoules are designed for less than 100 g UF_6 , the stringent testing and licensing requirements for UF_6 packaging do not apply. Nonetheless, transport of small amounts of UF_6 in these ampoules is still considered to be hazardous materials transport.

7.2.4 CONTROL OF UF_6 CONTAINERS BEFORE FILLING WITH UF_6 MODERATION CONTROL

Before filling new or cleaned and washed out containers with UF_6 , inspections must be performed to ensure that the containers contain no foreign materials that could lead to violent reactions or critical structures during filling or subsequent processing (heating, condensing).

These inspections are:

- Internal inspection of containers for the potential presence of oils, grease, liquids, cleansing residues, and other deposits
- Evacuation of containers with low pressure to exclude water and other volatile substances while monitoring with connected high pressure gauges
- Pressure measurement before direct filling
- Passivation (filling a small amount of UF_6 under observation of pressure development)

The filling process including the auxiliary systems (vacuum systems, etc.) is in this way designed so that no substances with potential chemical or nuclear hazards can get into the containers.

7.3 CONSIDERATIONS OF DANGERS OF UF_6 TRANSPORT

7.3.1 RADIATION EXPOSURE

UF_6 is a radioactive material that emits ionizing radiation. Near the area of transport, radiation from the shipping container produces an additional radiation dose. Empirical values show that the limit values for dose rates stipulated by transport laws are only partially exhausted.

Assuming that a person spends 20% of a year (1700 hours) on the roadside along a transport route near a uranium enrichment plant with a separation processing capacity of 1800 t per year, he or she would receive an additional radiation dose of 0.002 mSv (millisievert) per year. That is less than a thousandth of the dose that a person in Germany receives in any case through exposure to natural radiation.⁵

⁵ These results are based on the expert opinion of the Environmental Institute of Darmstadt as part of the environmental impact assessment of the expansion of uranium enrichment plants in Gronau.

7.3.2 CONTAMINATION

Legal limits for possible pollution from radioactive particles (contamination) on the outer surfaces of containers have likewise been established. Before a container leaves the factory, it must be verified through precise inspection measures that it complies with the very strict contamination limit values.

7.3.3 UF₆ EMISSIONS

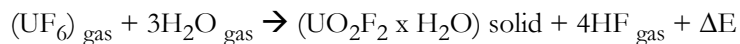
Uranium hexafluoride is a solid during transport. A pressure of approximately 0.1 bar is maintained in the transport container during transport; this corresponds to roughly 10% of air pressure, so in the event of a leak, air streams immediately into the container. When pressure equilibrium is reached, a small quantity of HF can escape as a visible cloud.

UF₆ is neither flammable nor explosive. The possibility that a container will suddenly shatter is regarded as extremely small.⁶

Because of the negative pressure in containers at ambient temperature, potential small leaks result in almost no UF₆ escaping as air streams into the container until equilibrium is reached. Moisture in the air reacts according formula with the remaining UF₆ to form solid uranyl fluoride and gaseous HF. When pressure equilibrium is reached, small quantities of gaseous HF escapes out in the form of a white cloud.

With small leaks, a self-sealing occurs; the uranyl fluoride settles as a solid plug in the leak hole and consequently prevents further escape of HF. Larger leaks can be sealed by relatively simple means; for this purpose, Urenco has prepared a repair kit containing the required auxiliary equipment.

The reaction proceeds according to the following equation:



Solid uranyl fluoride (UO₂F₂ x H₂O) and gaseous hydrogen fluoride (4HF gas) are formed from gaseous UF₆ and steam.

7.4 SCOPE AND SECURITY OF TRANSPORTS

For a uranium enrichment facility with a capacity of 1,800 t separative work units (SWU) per year that are transported exclusively on the roadways, approximately 760 tractor-trailer loads should be expected.

By comparison: 12.5 t uranium hexafluoride (Feed) are transported per truckload. In a hard coal power plant, to produce the same amount of electric current as in a nuclear power plant with 12.5 t uranium hexafluoride, approximately 125,000 t of hard coal would be necessary. To transport this quantity of hard coal would require around 5,000 tractor-trailers or 2,500 freight cars.

⁶ Excluding consequences of deliberate acts of war, terrorism, or sabotage.

The security of uranium hexafluoride transports is ensured through, among others, the following measures:

- Use of internationally licensed, tested pressure vessels
- Certification of the reliability and appropriate specialized knowledge of all people involved in the transport
- Proper inspection of the vehicles and pieces to be shipped before every transport
- Outfitting vehicles with security technology including rescue equipment and accident instructions
- Using drivers trained in transporting hazardous materials

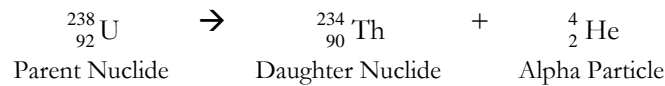
8. GLOSSARY

activity

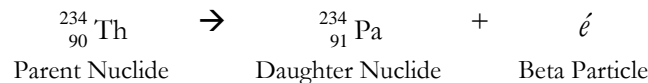
is the quantity per second of nuclear decay of a radioactive nuclide or radioactive nuclide mixture; the unit of measure is the Becquerel (Bg).

 α (alpha) radiation/decay

is the least penetrating radiation, and is even halted by a piece of paper. It is produced as an emission of the radioactive decay of a helium nucleus (${}^4_2\text{He}$); for example:

 **β (beta) radiation/decay**

is the emission of an electron (and an antineutrino) after the transformation of a neutron into a proton; for example:

**enthalpy**

the concepts of enthalpy of fusion, enthalpy of sublimation, and enthalpy of evaporation refer to the quantities of energy (heat) required for the respective transitions, whereby the following relationship exists:

$$\text{Enthalpy of Sublimation} = \text{Enthalpy of Fusion} + \text{Enthalpy of Evaporation}$$

feed

is the starting uranium material for the enrichment process in the form of UF_6 , with a natural configuration of isotopes.

 γ (gamma) radiation

is produced as accompanying radiation with many α and β decay reactions. It is the strongest penetrating radiation and therefore also detectable by instruments outside of uranium-containing vessels. γ radiation is the same as the X-ray radiation used in medicine. The difference is only in the generation, as γ radiation is formed with the reaction or decay of an atomic nucleus, while X-ray radiation is produced through the variation of an atom's electron shell.

half-life, $t_{1/2}$

is the time span during which half of a radioactive material decays. With it, the activity also decreases to half the value it was at the beginning of the time span.

ingestion

refers to the absorption or ingestion of a substance through foodstuffs.

inhalation

refers to the absorption or ingestion of a substance through the air one breathes.

incorporation

general absorption or ingestion of a substance by human organisms.

isotope

are atoms (nuclides) that represent the same chemical element but have different masses.

MAK value

maximum workplace concentration (Maximale Arbeitsplatzkonzentration) is the highest allowable concentration of a working substance in the form of gas, vapor, or suspended solids in the air of a workplace over the course of eight hours in a day and 40 hours per week.

nuclide

is the designation for atoms of an homogeneous species. For the purpose of unambiguous identification, the following notation is used: ${}^A_Z X$, whereby X stands for the chemical symbol of the element, A is the mass number (sum of protons and neutrons), and Z the atomic number (number of protons and electrons) of the nuclide, for example ${}^{238}_{92}\text{U}$ or ${}^{234}_{90}\text{Th}$. The individual nuclides of a chemical element (that is, nuclides with the same atomic number) are called isotopes. The natural nuclides (isotope) of uranium are therefore ${}^{238}_{92}\text{U}$, ${}^{235}_{92}\text{U}$, and ${}^{234}_{92}\text{U}$. In practical use, when the element has already been clearly indicated, the reference to the atomic number is often dropped: ${}^{238}\text{U}$, ${}^{235}\text{U}$, and ${}^{234}\text{U}$.

product

is the material produced through the enrichment process, by which the portion of ${}^{235}\text{U}$ isotopes is increased over the natural isotope composition.

radioactivity

refers to the spontaneous decay of atomic nuclei, accompanied by α , β , and γ radiation.

melting

is the transition of a solid substance into a liquid state. The reverse of this process is called solidification.

sublimation

is the direct transition from the solid to the gaseous state without going through the liquid state. This is possible with all substances as long as pressure and temperature are below the triple point for the substance. The triple point refers to the point at which a substance can exist in all three phases (gas, liquid, solid). For example, the triple point temperature for water = 0.01 °C, UF_6 , see Figure 5.

tails

accrued during the enrichment process, it is material that contains a reduced concentration of the isotope ^{235}U compared to the natural isotope composition.

vaporization

is the transition of a liquid substance to a gaseous state. The reverse of this process is called condensation.

specific heat

is the amount of heat that must be applied to a unit of mass (g or kg) of a substance to raise its temperature by one degree.