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Centrifuge in nuclear reactor

The Zippe-type centrifuge is a gas centrifuge designed to enrich the rare fissile isotope uranium-235 (235U) from the mixture of isotopes found in naturally occurring uranium compounds. The isotopic separation is based on the slight difference in mass of the isotopes. The Zippe design was originally developed in the Soviet Union by a team led by 60 Austrian and German scientists and engineers captured after World War II, working in detention. In the West (and now generally) the type is known by the name of the man who recreated the technology after his return to the West in 1956, based on his recollection of his work in (and contributions to) the Soviet program, Gernot Zippe. To the extent that it might be referred to in Soviet/Russian usage by any one person's name, it was known (at least at a somewhat earlier stage of development) as a Kamenev centrifuge (after Evgeni Kamenev).[1][2] Background Natural uranium consists of three isotopes; the majority (99.274%) is U-238, while approximately 0.72% is fissile U-235 and the remaining 0.0055% is U-234. If natural uranium is enriched to contain 3% U-235, it can be used as fuel for light water nuclear reactors. If it is enriched to contain 90% uranium-235, it can be used for nuclear weapons. Diagram of the principles of a Zippe-type gas centrifuge with U-238 represented in dark blue and U-235 represented in light blue. Centrifuge uranium enrichment Enriching uranium is difficult because the isotopes are practically identical in chemistry and very similar in weight: U-235 is only 1.26% lighter than U-238 (note this applies for solid Uranium). Separation efficiency in a centrifuge depends on weight difference. However, centrifuges need to work with a gas rather than a solid, and the gas used here is Uranium Hexafluoride. Here the mass difference between U(235)F6 and U(238)F6 is less than 0.86%. Separation of uranium isotopes requires a centrifuge that can spin at 1,500 revolutions per second (90,000 RPM). If we assume a rotor diameter of 20 cm (actual rotor diameter is likely to be less), this corresponds to a linear speed of greater than Mach 2 (Mach 1 ≈ 340 m/s at sea level). For comparison, automatic washing machines operate at only about 12 to 25 revolutions per second (720–1500 RPM) during the spin cycle, while turbines in automotive turbochargers can run up to around 2500–3333 revolutions per second (150,000–200,000 RPM).[3][4] A Zippe-type centrifuge has a hollow, cylindrical rotor filled with gaseous uranium hexafluoride. A rotating magnetic field at the bottom of the rotor, as used in an electric motor, is able to spin it quickly enough that the U-238 is thrown towards the edge. The lighter U-235 collects near the center. The bottom of the gaseous mix is heated, producing convection currents that move the U-238 down. The U-235 moves up, where scoops collect it.[1] Each centrifuge has one inlet and two output lines (corresponding to the heavy and the light fractions). At the high speed of rotation, the gas is compressed close to the wall of the rotor. The rotor can be several meters in length (diameter is likely to be less than 10 cm) and a temperature gradient of 300 °C between the top and bottom of the rotor produces a very strong convection current. In addition, the very strong Coriolis forces produced add to the separation efficiency. To reduce friction, the rotor spins in a vacuum. A magnetic bearing holds the top of the rotor steady, and the only physical contact is the conical jewel bearing on which the rotor sits.[1] The three gas lines must be concentric with the fixed axis as the outer rim is spinning very quickly, and the seal is very important. After the scientists were released from Soviet captivity in 1956,[1] Gernot Zippe was surprised to find that engineers in the West were years behind in their centrifuge technology. He was able to reproduce his design at the University of Virginia in the United States, publishing the results, even though the Soviets had confiscated his notes. Zippe left the United States when he was effectively barred from continuing his research: The Americans classified the work as secret, requiring him either to become a U.S. citizen (he refused), return to Europe, or abandon his research.[1] He returned to Europe where, during the 1960s, he and his colleagues made the centrifuge more efficient by changing the material of the rotor from aluminium to maraging steel, an alloy with a longer fatigue life, which allowed higher speed. This improved centrifuge design is used by the commercial company Urenco to produce enriched uranium fuel for nuclear power stations.[1] The exact details of advanced Zippe-type centrifuges are closely guarded secrets, but the efficiency of the centrifuges is improved by making them longer, and increasing their speed of rotation. To do so, even stronger materials, such as carbon fiber-reinforced composite materials, are used; and various techniques are used to avoid forces causing destructive vibrations, including the use of flexible "bellows" to allow controlled flexing of the rotor, as well as careful speed control to ensure that the centrifuge does not operate for very long at speeds where resonance is a problem. The Zippe-type centrifuge is difficult to build successfully and requires carefully machined parts. However, compared to other enrichment methods, it is much cheaper and more energy-efficient, and can be used in relative secrecy. This makes it ideal for covert nuclear-weapons programs and possibly increases the risk of nuclear proliferation. Centrifuge cascades also have much less material held in the machine at any time, unlike gaseous diffusion plants. Global usage Pakistan's atomic bomb program developed the P1 and P2 centrifuges; the first two centrifuges that Pakistan deployed in large numbers. The P1 centrifuge uses an aluminum rotor, and the P2 centrifuge uses a maraging steel rotor, which is stronger, spins faster, and enriches more uranium per machine than the P1. Russian and Soviet sources dispute the account of Soviet centrifuge development given by Gernot Zippe. They cite Max Steenbeck as the German scientist in charge of the German part of the Soviet centrifuge effort, which was started by German refugee Fritz Lange in the 1930s. The Soviets credit Steenbeck, Isaac Kikoin and Evgeni Kamenev with originating different valuable aspects of the design. They state Zippe was engaged in building prototypes for the project for two years from 1953. Since the centrifuge project was top secret the Soviets did not challenge any of Zippe's claims at the time.[2] See also Gas centrifuge Ultracentrifuge Magnetic levitation Thrust bearing German nuclear weapon project Germany and weapons of mass destruction Pakistan and weapons of mass destruction Netherlands and weapons of mass destruction Forced labor of Germans in the Soviet Union Russian Alsos Stuxnet References ^ a b c d e f Broad, William J. (2004-03-23). "Slender and Elegant, It Fuels the Bomb". The New York Times. Retrieved 2009-10-23. ^ a b Oleg Bukharin, Oleg. 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Gray, Vice Chairman of the Atlantic Council, citing Nuclear Fuel article Here Comes the Troika whilst testifying before the Subcommittee on Economic Stabilization (United States House Committee on Banking, Finance and Urbain Affaires) Retrieved from " Figure 1. A form of uranium ore known as Uraninite.[1] Uranium enrichment is a process that is necessary to create an effective nuclear fuel out of mined uranium by increasing the percentage of uranium-235 which undergoes fission with thermal neutrons. Although many reactors require enriched uranium fuel, the Canadian-designed CANDU, the British Magnox reactor and the proposed Molten salt reactor can use natural uranium as their fuel.[2] Nuclear fuel is mined from naturally occurring uranium ore deposits, and then isolated through chemical reactions and separation processes. These chemical processes used to separate the uranium from the ore are not to be confused with the physical and chemical processes used to enrich the uranium. In its isolated form, the uranium is known as yellowcake and has the chemical formula U3O8. However, naturally occurring uranium does not have a high enough concentration of 235U at only about 0.72% with the remainder being 238U.[3] Due to the fact that uranium-238 is fissionable and not fissile, the concentration of uranium-235 must be increased before it can be effectively used as a nuclear fuel. The purpose of uranium enrichment is to increase the percentage of the uranium-235 isotope with respect to others, with a necessary percentage of around 4% for light water reactors.[3] Enrichment Processes Figure 2. The blue atom in the centre of the molecule is uranium, surrounded by six fluorine atoms. This substance becomes a gas at fairly low temperatures. Enrichment requires uranium to be in a gaseous form, and the simplest way to achieve this is to convert it to a different chemical known as uranium hexafluoride. Uranium needs to be in a gaseous form for enrichment due to the varying chemical and physical properties the different isotopes (U-235 and U-238) have. These differences are most easily utilized and manipulated when uranium is in gaseous form. The process of changing uranium oxide concentrate to uranium hexafluoride takes place at a conversion plant, the first step for uranium after it leaves a mine. The main conversion process used in Canada, France and Russia is known as the 'wet process' and involves multiple chemical conversion stages. Firstly, the uranium oxide concentrate is dissolved in nitric acid (HNO3), which creates uranyl nitrate (UO2(NO3)2). This uranyl nitrate is then purified, evaporated and finally thermally decomposed to form uranium trioxide powder (UO3). After which there are two kiln processes wherein the UO3 is converted to UO2, then reacted with hydrogen fluoride (HF), to produce uranium tetrafluoride (UF4). Finally the UF4 is fed into a fluidized bed reactor and reacted with gaseous fluorine to produce UF6. After the conversion process, the UF6 needs to be further refined due to the presence of impurities.[4] Gaseous Diffusion main article For many years the main process was gaseous diffusion. In order to physically separate the uranium the yellowcake uranium was first chemically transformed into uranium hexafluoride (UF6). This chemical is in its solid form under normal conditions, but transforms into a gas if the temperature is raised slightly or the pressure is lowered.[3] Since the 235UF6 molecules are slightly lighter than the 238UF6 molecules, they move more quickly as a gas through diffusion. Thus if uranium hexafluoride is passed through a very long pipe, the gas that emerges at the far end of the pipe will have a slightly higher percentage of 235U. However, the pipe must be extremely long as the lighter 235UF6 diffuses only 0.43% faster than 238UF6.[3] Because of this, the method of gaseous diffusion is not widely used anymore. Gas Centrifuges main article Figure 2. Cascade of centrifuges used to produce enriched uranium.[5] Today, enrichment is achieved using a special centrifuge called a gas centrifuge. The separation process here relies on the mass difference of the molecules (see gaseous diffusion above). Here, uranium hexafluoride is fed into an evacuated cylinder containing a rotor. When these rotors are spun at a high speed, the heavier 238UF6 collects near the walls of the cylinder while the slightly lighter 235UF6 collects near the central axis. The enriched product is then drawn off. This method is preferred over gaseous diffusion as it requires only about 3% of the power to separate the uranium.[3] A centrifugal separation method is much more energy-efficient than diffusion, as it requires only about 50-60 kWh per SWU (separative work unit, which is the amount of separation done by an enrichment process).[2] Additionally, these plants can be smaller as they don't require an extremely long pipe. For efficient separation to occur, these centrifuges must rotate quickly - generally at 50 000-70 000 rpm.[6] Although centrifuges hold less uranium than a diffusion stage, they are able to separate isotopes much more efficiently. Centrifuge stages generally are composed of a large number of centrifuges in parallel, forming a cascade. Laser Isotope Separation main article The use of lasers in a separation process is still being developed. This separation technique requires lower energy input and other economic advantages. In this process, a laser with a very specific frequency interacts with a gas or vapour. Since the frequency has an associated energy, the interaction of the beam with the gas allows for the excitation or ionization of certain isotopes in the vapour. With this excitement, it may be possible to separate molecules containing a specific isotope to collect only the excited isotope.[6] Environmental Issues Most enrichment processes involve only natural, long-lived radioactive materials. Uranium is only weakly radioactive, but its chemical toxicity is much more significant . Thus protective measures required for an enrichment plant are similar to those in other chemical industries. When exposed to moisture, uranium hexafluoride forms a very corrosive acid, hydrofluoric acid. Any leakage of this chemical is undesirable and to prevent this almost all areas of an enrichment plant keep the uranium hexafluoride gas below atmospheric pressure.[2] This stops any outward leakage. Additionally, double containment is provided in areas where higher pressures are required and venting gases are collected and treated. Enrichment accounts for around half of the cost of nuclear fuel in a light water reactor (a BWR or PWR) and 5% of the cost of the electricity generated. Previously enrichment has been the main source of greenhouse gases from the nuclear fuel cycle as electricity used for enrichment was generated using coal. Although there are associated greenhouse gas emissions, it is only about 0.1% of the emissions of an equivalent coal-fired power plant.[2] References ↑ Wikimedia Commons. (May 5, 2016). Uraninite [Online]. Available: Uraninite-usa32abg.jpg ↑ 2.0 2.1 2.2 2.3 World Nuclear Association. (June 17, 2015). Uranium Enrichment [Online]. Available: ↑ 3.0 3.1 3.2 3.3 3.4 Jeff C. Bryan. (June 17, 2015). Introduction to Nuclear Science, 1st ed. Boca Raton, FL, U.S.A: CRC Press, 2009. ↑ World Nuclear Association. (May 12, 2016). 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