# Heavy Water Production

Heavy water is the key to one type of reactor in which plutonium can be bred from natural uranium. As such, the production of heavy water has always been monitored, and the material is export controlled. In addition, a source of deuterium is essential for the production of tritium and 6LiD, two ingredients of thermonuclear weapons. A nation seeking large quantities of heavy water probably wishes to use the material to moderate a reactor, and may be planning to produce plutonium. However, CANDU (CANadian Deuterium Uranium) reactors designed and built in Canada are used for commercial electric power production.

Deuterium, 2H, an atom whose nucleus includes one neutron, was discovered before the neutron itself. In 1931, most scientists thought the differing weights of isotopes were due to extra protons bound to "nuclear electrons." That year, at Columbia University, Harold Urey found the spectral lines of 2H in commercial hydrogen gas and, by Thanksgiving, identified it in a few cubic centimeters of concentrated liquid hydrogen. In February 1932, in Cambridge, England, James Chadwick discovered the neutron -- taking his cue from Irène and Frédéric Joliot-Curie, who had observed the effects of neutrons but misinterpreted them.

Deuterium is physically so different from ordinary hydrogen (roughly twice as massive, for one thing) that chemists eagerly turned their attention to it. They wondered what differences deuterium instead of ordinary hydrogen might make in the behavior of chemical compounds; what the effects on plants and animals of water with two deuterium atoms per molecule might be; and even what therapeutic potential this literally heavy water might possess.

Heavy water, D2O, is water in which both hydrogen atoms have been replaced with deuterium, the isotope of hydrogen containing one proton and one neutron. It is present naturally in water, but in only small amounts, less than 1 part in 5,000. Heavy water is one of the two principal moderators which allow a nuclear reactor to operate with natural uranium as its fuel. The other moderator is reactor-grade graphite (graphite containing less than 5 ppm boron and with a density exceeding 1.50 gm/cm 3 ). The first nuclear reactor built in 1942 used graphite as the moderator; German efforts during World War II concentrated on using heavy water to moderate a reactor using natural uranium.

The importance of heavy water to a nuclear proliferators is that it provides one more route to produce plutonium for use in weapons, entirely bypassing uranium enrichment and all of the related technological infrastructure. In addition, heavy-water-moderated reactors can be used to make tritium.

Deuterium occurs naturally at a concentration of about 0.015 percent in the element hydrogen. This naturally occurring isotope was concentrated to produce pure deuterium in the form of "heavy water." Heavy water was used as a coolant and moderator in nuclear materials production reactors. Heavy water can be made using hydrogen sulfide-water chemical exchange, water distillation, or electrolysis.

* Hydrogen Sulfide-Water Exchange - In a mixture of hydrogen sulfide (H2S) and water at chemical equilibrium, the concentration of deuterium in water is greater than the concentration in H2S. The difference in these concentrations depends on the temperature of the mixture. In practice, water and hydrogen sulfide gas are made to flow in opposite directions at two different temperatures. Deuterium is transferred from the gas to the water in the cold section. The depleted gas is recirculated to the hot section, where deuterium is transferred back into the gas from the water. Several stages of this process allow deuterium enrichments of up to 20-30%.
* Fractional Distillation - Water molecules containing deuterium atoms vaporize at a higher temperature than those without deuterium, so the boiling point of heavy water is slightly higher than that of normal water. Water vapor above a mixture of normal and heavy water will be slightly depleted in deuterium as a result, while the liquid will be slightly enriched. Enrichment results from successively boiling off and removing vapor containing normal hydrogen.
* Electrolysis - Water containing normal hydrogen is more easily disassociated into hydrogen and oxygen gases by an electric current than water containing deuterium. This allows the isotopes to be separated. The Savannah River Site heavy water plant used the hydrogen sulfide-water exchange process to partially enrich heavy water. Deuterium was further concentrated by fractional distillation, and then by electrolysis. The moderator rework unit at SRS used fractional distillation to re-enrich reactor moderator that had become depleted in deuterium.

Although one speaks of “making” heavy water, deuterium is not made in the process; rather, molecules of heavy water are separated from the vast quantity of water consisting of H2O or HDO (singly deuterated water), and the “dross” is discarded. Alternatively, the water may be electrolyzed to make oxygen and hydrogen containing normal gas and deuterium. The hydrogen can then be liquefied and distilled to separate the two species. Finally, the resulting deuterium is reacted with oxygen to form heavy water. No nuclear transformations occur.

The production of heavy water in significant amounts requires a technical infrastructure, but one which has similarities to ammonia production, alcohol distillation, and other common industrial processes. One may separate heavy water directly from natural water or first “enrich” the deuterium content in hydrogen gas. It is possible to take advantage of the different boiling points of heavy water (101.4 °C) and normal water (100 °C) or the difference in boiling points between deuterium (–249.7 °C) and hydrogen (–252.5 °C). However, because of the low abundance of deuterium, an enormous amount of water would have to be boiled to obtain useful amounts of deuterium. Because of the high heat of vaporization of water, this process would use enormous quantities of fuel or electricity. Practical facilities which exploit chemical differences use processes requiring much smaller amounts of energy. Separation methods include distillation of liquid hydrogen and various chemical exchange processes which exploit the differing affinities of deuterium and hydrogen for various compounds. These include the ammonia/hydrogen system, which uses potassium amide as the catalyst, and the hydrogen sulfide/water system (Girdler Sulfide process).

Separation factors per stage are significantly larger for deuterium enrichment than for uranium enrichment because of the larger relative mass difference. However, this is compensated for because the total enrichment needed is much greater. While 235U is 0.72 percent of natural uranium, and must be enriched to 90 percent of the product, deuterium is only .015 percent of the hydrogen in water and must be enriched to greater than 99 percent. If the input stream has at least 5 percent heavy water, vacuum distillation is a preferred way to separate heavy from normal water.

This process is virtually identical to that used to distill brandy from wine. The principal visible difference is the use of a phosphor-bronze packing that has been chemically treated to improve wettability for the distillation column rather than a copper packing. Most organic liquids are non-polar and wet virtually any metal, while water, being a highly polar molecule with a high surface tension, wets very few metals. The process works best at low temperatures where water flows are small, so wetting the packing in the column is of particular importance. Phosphor-bronze is an alloy of copper with .02–.05 percent lead, .05–.15 percent iron, .5–.11 percent tin, and .01–.35 percent phosphorus.

Heavy water is produced in Argentina, Canada, India, Iran and Norway. Presumably, all five declared nuclear weapons states can produce the material. The first commercial heavy water plant was the Norsk Hydro facility in Norway (built 1934, capacity 12 metric tons per year); this is the plant which was attacked by the Allies to deny heavy water to Germany. The largest plant was the Bruce Plant in Canada (1979; 700 metric tons/year), but this facility was closed in 1998. India’s apparent capacity is very high, but its program has been troubled. Accidents and shutdowns have led to effective limitations on production.

The Bruce Heavy Water Plant in Ontario, Canada, was the world’s largest producer of D2O. It used the Girdler Sulfide (GS) process which incorporates a double cascade in each step. In the upper (“cold,” 30–40 °C) section, deuterium from hydrogen sulfide preferentially migrates into water. In the lower (“hot,” 120–140 °C) section, deuterium preferentially migrates from water into hydrogen sulfide. An appropriate cascade arrangement actually accomplishes enrichment. In the first stage the gas is enriched from 0.015% deuterium to 0.07%. The second column enriches this to 0.35% , and the third column achieves an enrichment between 10% and 30% deuterium. This product is sent to a distillation unit for finishing to 99.75% "reactor-grade" heavy water. Only about one-fifth of the deuterium in the plant feed water becomes heavy water product. The production of a single pound of heavy water requires 340,000 pounds of feed water.