Nuclear Energy

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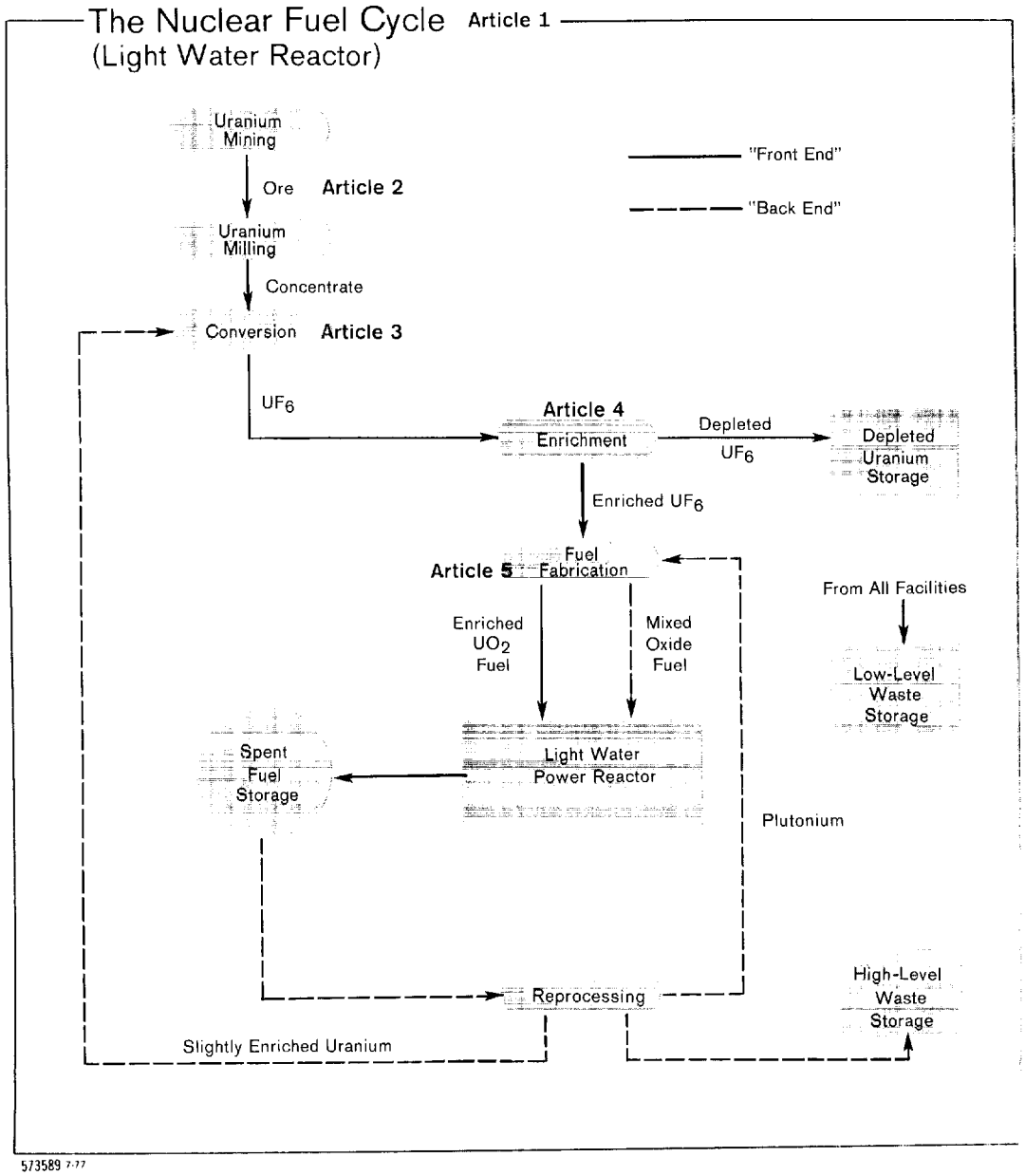
1. THE NUCLEAR FUEL CYCLE

Although fossil fuels (oil, natural gas, and coal) generally require processing prior to their use as fuel in electric generating stations, nuclear fuel must undergo a greater number of more complex operations before its use in a nuclear powerplant. The various operations collectively are referred to as the "nuclear fuel cycle." It is divided into a "front end" segment made up of those processes involved in the actual manufacture of nuclear fuel (uranium mining, milling, conversion,



enrichment, and fuel fabrication) and a "back end" segment dealing with the disposition of spent nuclear fuel after it is "burned" in a reactor. These operations include fuel reprocessing, recycling of uranium and plutonium, and disposal of radioactive wastes.

The steps in the nuclear fuel cycle discussed pertain to light water reactors (either pressurized water or boiling water reactors). Other reactor types, such as the pressurized heavy water reactor (CANDU), have slightly different fuel cycles. Fuel for the CANDU reactor, for example, need not be enriched.

The Front End Segment

The initial step in the nuclear fuel cycle is uranium mining, either open pit or underground. Following extraction, the uranium ore, normally containing 0.2 percent or less U_3O_8, is shipped to an ore concentration plant or mill, usually located relatively close to the mine. The mill extracts uranium by mechanical and chemical processing of the ore and produces a semifinished product commonly called "yellowcake." To supply the annual fuel requirements of a typical 1,000-megawatt (MW) light water reactor, about 91,000 tons of ore must be mined, which, when concentrated, yields 182 tons of U_3O_8 equivalent. Although this process takes only a few months, the utility usually must contract for raw material almost two years in advance of the time the finished fuel is needed because of the lead times involved in the remaining front end operations.

Annual Material Flow for a 1,000-MW Light Water Power Reactor

Fuel Cycle Operation	Output	Tons
Front end segment		
Uranium mining	Uranium ore	91,000
Uranium concentration	Yellowcake–U_3O_8 equivalent	182
Hexafluroide conversion	UF_6	270
Uranium enrichment	Enriched UF_6	52
	Depleted UF_6	218
Fuel fabrication	Enriched UO_2	35
Spent fuel storage	Irradiated fuel (uranium + plutonium + fission products)	35
Back end segment		
Fuel reprocessing	Slightly enriched uranium	34
	Plutonium	0.2
Radioactive waste disposal and storage	Low-level wastes	230
	High-level wastes	7

Nuclear Fuel Cycle Lead Times[1]

	Months	
	First Core	**Reloads**
Front end segment		
Uranium procurement and conversion	6	3
Enrichment	6	3
Fuel fabrication	6	3
Reactor storage (prior to commercial operation)	9[2]	4½
Back end segment		
Spent fuel discharge to reprocessing[3]	....	6
Reprocessing to re-use[3]		
Uranium	....	6
Plutonium	....	3

1. Applicable to light water reactors only.
2. Including 6 months for preoperational fuel testing.
3. The lead times for these stages of the fuel cycle are estimated; at present, these processes are not being used on a commercial scale.

The next stage is the conversion of yellowcake to uranium hexafluoride (UF_6), the feedstock for the enrichment plant. Uranium concentrate fed to a conversion facility normally contains the equivalent of 75-85 percent U_3O_8. In the most common conversion process, the uranium is first reduced to brown oxide (UO_2), then hydrofluorinated to uranium tetrafluoride (UF_4) or green salt. Following fluorination and distillation, a highly purified UF_6 product results. The annual output required for one 1,000-MW reactor is about 270 tons.

To be used as fuel in a light water reactor, uranium must be enriched in the fissionable isotope, uranium-235. This isotope makes up only 0.71 percent of naturally occurring uranium, most of which is heavier uranium-238. Several methods are available for separating these isotopes and artifically increasing the uranium-235 concentration. The process most commonly used is gaseous diffusion; an ultracentrifugation process is under development. Both methods depend on the difference in mass of the two isotopes to achieve separation.

In the enrichment plant, the natural UF_6 feed gas is divided into two components: a product stream containing 2-4 percent uranium-235 and a waste

or "tails" stream, which normally has a 0.2-0.3 percent uranium-235 concentration. With typical percentages of the fissionable isotope in the feed, product, and tails components, the annual output of an enrichment plant necessary to support the operation of a 1,000-MW power reactor is 52 tons of enriched UF_6. In the process of enrichment, 218 tons of UF_6 depleted in uranium-235 are also produced. Enrichment for annual reactor reloads must take place nearly one year before the fuel is required.

The final operation in the front end of the nuclear fuel cycle is the actual manufacture of fuel elements. This step usually occurs about nine months prior to the scheduled reloading date. Enriched UF_6 is converted to UO_2 fuel pellets, which, following sintering to achieve the desired density, are inserted into rods usually made of a zirconium alloy. This fuel "cladding" improves the corrosion resistance, radiation stability, and temperature range of the fuel. The rods are assembled into fuel elements, which are placed in the reactor core.

Fuel Use

While in the reactor, enriched uranium fuel undergoes nuclear fission, the splitting of the uranium-235 nucleus into two approximately equal parts accompanied by the release of energy. This energy is the heat source used to produce steam, which in turn is used to generate electricity in a nuclear powerplant. As more uranium-235 fissions, the level of enrichment of the fuel declines, but, at discharge, the fuel still contains a greater concentration of this isotope than natural uranium and is thus worth recovering.

In addition, the fission process releases one or more neutrons that not only sustain the nuclear chain reaction but are also captured by natural uranium-238, thereby forming plutonium. As the principal isotope of plutonium is itself a fissionable material, some plutonium can substitute for enriched uranium in nuclear fuel. Not only can plutonium be used as fuel for breeder reactors, but the use of "mixed oxide fuel" (enriched UO_2 and recycled plutonium) in conventional light water reactors can reduce the amount of natural uranium raw material and enrichment required to produce an equivalent amount of nuclear fuel. The spent fuel discharged annually from a 1,000-MW reactor will contain about 250 kilograms of plutonium.

Each year, a 1,000-MW light water reactor requires a reload of about 35 tons of nuclear fuel. At the same time that a fresh fuel load is inserted, a similar quantity of irradiated or spent fuel is discharged from the reactor. Following withdrawal,

the spent fuel is placed in "cooling" ponds at the reactor to allow for some decay of radioactivity. At present, the commercial nuclear fuel cycle ends here.

Back End Segment

Both industry and government officials have always assumed that the nuclear fuel cycle would be "closed," i.e., that spent fuel would be chemically processed to recover uranium and plutonium, thus conserving resources and improving the economics of nuclear power. This closing of the fuel cycle involves back end operations: fuel reprocessing, recycling or uranium and plutonium manufacture of mixed oxide fuel, and disposal of high-level radioactive wastes. With the exception of this last activity, the technology for each operation is available but has not yet been demonstrated commercially. In most countries with large nuclear power programs, the environmental, safety, regulatory, financial, and potential proliferation problems associated with these operations have not been solved, and the prospects for closing the fuel cycle remain uncertain.

The recovery of uranium and plutonium in spent fuel is accomplished by reprocessing, the first step in the back end of the nuclear fuel cycle. After cooling for a period of about six months, spent fuel is shipped to a reprocessing plant. The fuel elements are chopped into short sections and dissolved in acid. In a solvent extraction process, the uranium, plutonium, and fission products are separated by chemical means through countercurrent flow of aqueous and organic solutions. The separated uranium and plutonium are purified, and radioactive waste products are converted to a form compatible with their ultimate disposal. Almost all the uranium originally present in the nuclear fuel can be recovered, and, in a closed fuel cycle, it would be sent to a UF_6 plant for conversion and subsequent reenrichment. The plutonium would be shipped for fabrication into mixed oxide fuel.

The ultimate stage in the nuclear fuel cycle is the disposal of radioactive wastes. Low-level waste products result at all points in the fuel cycle and are safely handled and disposed of at commercial burial sites. High-level wastes from a reprocessing facility, primarily liquids containing most of the separated fission products and traces of uranium and plutonium, are extremely radioactive. Although procedures have been developed for converting these liquids to solids for final burial in stable geologic formations, most of the high-level wastes resulting from reprocessing—principally those connected with separating plutonium for nuclear weapons—remain in liquid form. After reprocessing one year's fuel supply for a 1,000-MW reactor, about seven tons of high-level waste products would be produced.

2. URANIUM EXPLORATION, MINING, AND MILLING

Uranium mining and milling methods are not unusual but exploration techniques do take advantage of the radioactive properties of uranium. The principal characteristics that distinguish uranium are its low concentration in the ore and its relatively high energy content.

Average uranium concentration levels range from more than 6 percent U_3O_8 (original pitchblende deposit in Zaire) to only 0.003 parts per million (ppm) in sea water. Typical deposits now being worked average about 0.15 percent -- roughly 1.5 kilograms of U_3O_8 per ton of ore. For exploitation of most minerals this would be an unprofitable level of concentration. Uranium, however, as used in conventional nuclear reactors, has roughly 100,000 times the energy content of a similar quantity of coal and 65,000 times that of oil, making the mining of low-grade uranium deposits economical.

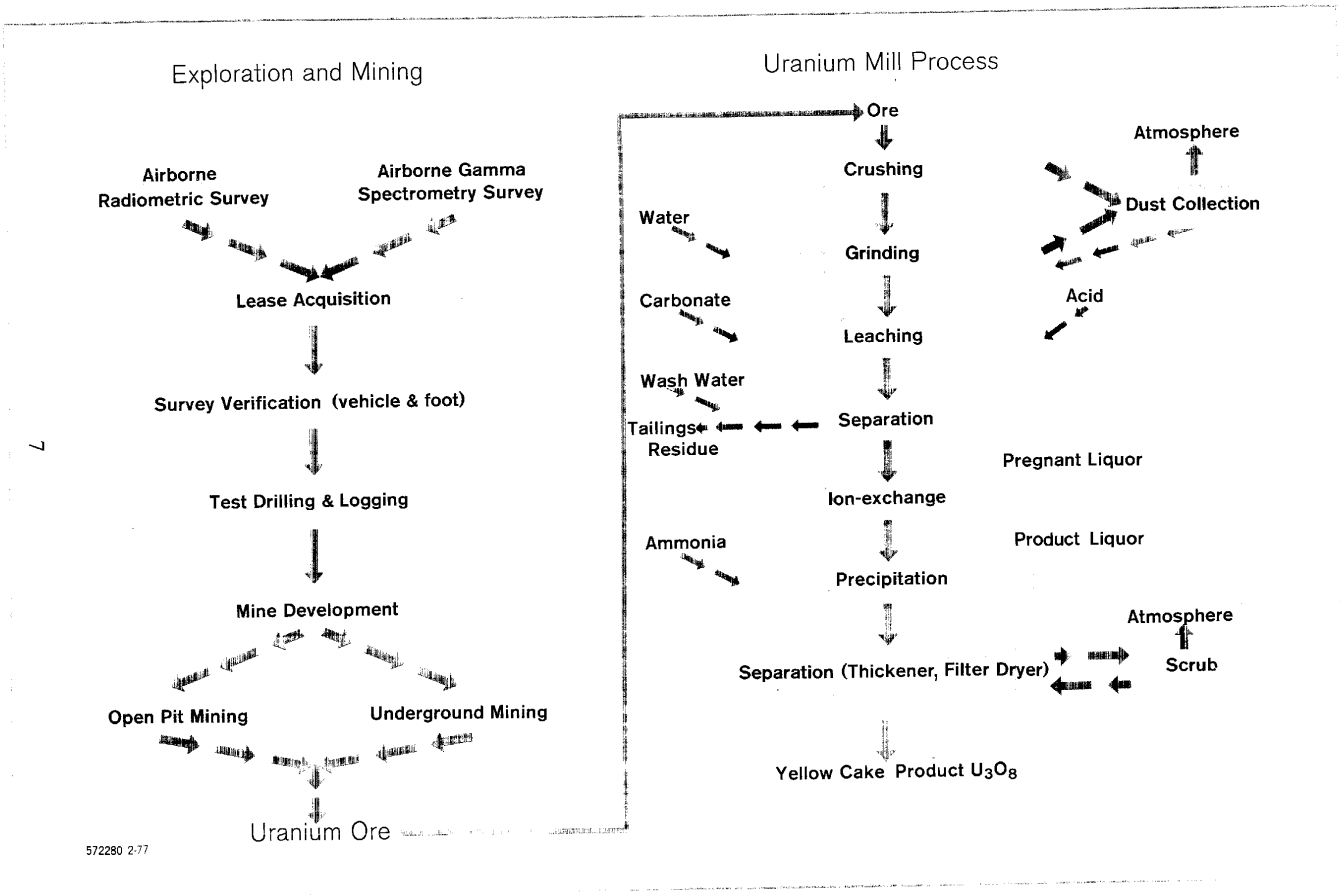
Exploration

Although natural uranium is only slightly radioactive, airborne radiometric surveys covering large areas can detect gamma emissions[1] from decaying uranium atoms. The accuracy of results depends on the amount of vegetation and other radioactivity-absorbing material overlying the deposit. Gamma spectrometry is a more expensive, but not necessarily a more effective, technique that distinguishes between differing radiation energies, helping to identify the nature of the deposit. Most initial exploratory work is done by these methods, but verification requires vehicle-borne instruments.

Once potential deposits are located, secondary ground checks are performed using instruments which detect changes of less than two ppm U_3O_8 in underlying strata. This is supplemented by gamma spectrometry and chemical analyses of soil, water, and vegetation. Test drillings may be made to specifically locate and evaluate the deposit, but core sample examination is being replaced by radiation logging equipment that evaluates deposits at greater depths. For example, logging has been used effectively in South Africa to depths of 5,000 meters.

This entire exploration, evaluation, and confirmation process may take 5 years or more and normally contributes 10-15 percent to the total cost of U_3O_8.

[1] Gamma rays are similar to X-rays but usually have more energy and are nuclear in origin.



Mining and Milling

Uranium is mined by either open pit or underground methods similar to those used in coal mining. Deposits located less than 120 meters from the surface are generally strip-mined. Only about 30 percent of uranium mines are open pit, but they supply some two-thirds of the ore produced. Because deep mining is more costly, ore concentration must be greater than surface deposits to justify underground operations.

Pregrading of the ore is often performed directly at the mine site using radiometric sorters. Ores with U_3O_8 content less than 0.03 percent are generally stockpiled either for later mixing with higher grade ores or for batch leaching. The ore is then trucked to the mill for concentration.

In the Free World, mills may handle up to 7,000 tons per day (tpd) of ore, but the average is about 2,000 tpd. Mills further sort and grind the ore, then mix it with water to form an aqueous slurry. The uranium is leached from the slurry by either acid or alkali, depending on the ore properties. The alkali leaching process is about 10 percent more costly than acid treatment and is used in only 20 percent of US mills. The uranium solution is then separated from the waste pulp by settling or filtration.

Processes using ion-exchange and anionic solvents -- which "pull" the uranium from the solution -- have yielded cost savings. The uranium is stripped from the solvent or resin, precipitated and dried in a kiln, and calcined in a furnace into uranium concentrate containing about 80 percent U_3O_8 equivalent.

New Techniques

The uranium industry has greatly benefited from advances in mineral extraction technology, although signs of diminishing returns are beginning to appear. Some new techniques can slow the rise of uranium processing costs: for example, better low-profile mining equipment that increases the efficiency of extraction in deep mines. At the mill, better crushing machinery cuts costs. Strong acid leaching is utilized for treating complex ores; bacterial leaching applied to bulk ore stocks may make treatment of very low grade ores economical.

Responding to environmental concerns will offset some of these cost savings. At present, reclamation of open pit mine sites -- regrading dumps, covering with topsoil, and reseeding -- adds about two cents per pound to U_3O_8 production costs.

Stiffer rules can add as much as 10 percent to costs where ore grade averages 0.15 percent -- the worldwide norm. In addition, pollution control at the mill could increase production costs by another 2 percent. Nonetheless, the impact of environmental restrictions on nuclear generating costs is small compared with that of controls on mining and burning coal.

3. URANIUM CONVERSION TO HEXAFLUORIDE

Following the concentration of uranium ore, the metal must be converted to a form suitable for enrichment. The primary techniques now used to enrich uranium require that the uranium be processed in a gaseous state. Because uranium hexafluoride (UF_6) is the only volatile compound of uranium, a hexafluoride conversion step is needed in the front end of the nuclear fuel cycle.

Technique

Uranium concentrate (yellowcake) usually contains the equivalent of 80 percent or more U_3O_8. In addition to converting the uranium to a gaseous feedstock (UF_6) for the enrichment plant, the conversion process removes almost all remaining impurities from the product. Conversion and purification is accomplished by one of two techniques. In the older, "wet" process, uranium is extracted by solvents from a slurry formed from the uranium concentrate. The product, orange oxide (UO_3), is calcined and passed on for conversion to UF_6. The new hydrofluor or "dry" process first converts the concentrate to UF_6 and then purifies the product by fractional distillation. Both purification processes produce the same product and are used about equally in the United States. The wet process, however, produces more wastes, mostly in liquid form, and is somewhat more costly. The dry process produces mainly gaseous and solid wastes. Most new facilities will use the "dry" process.

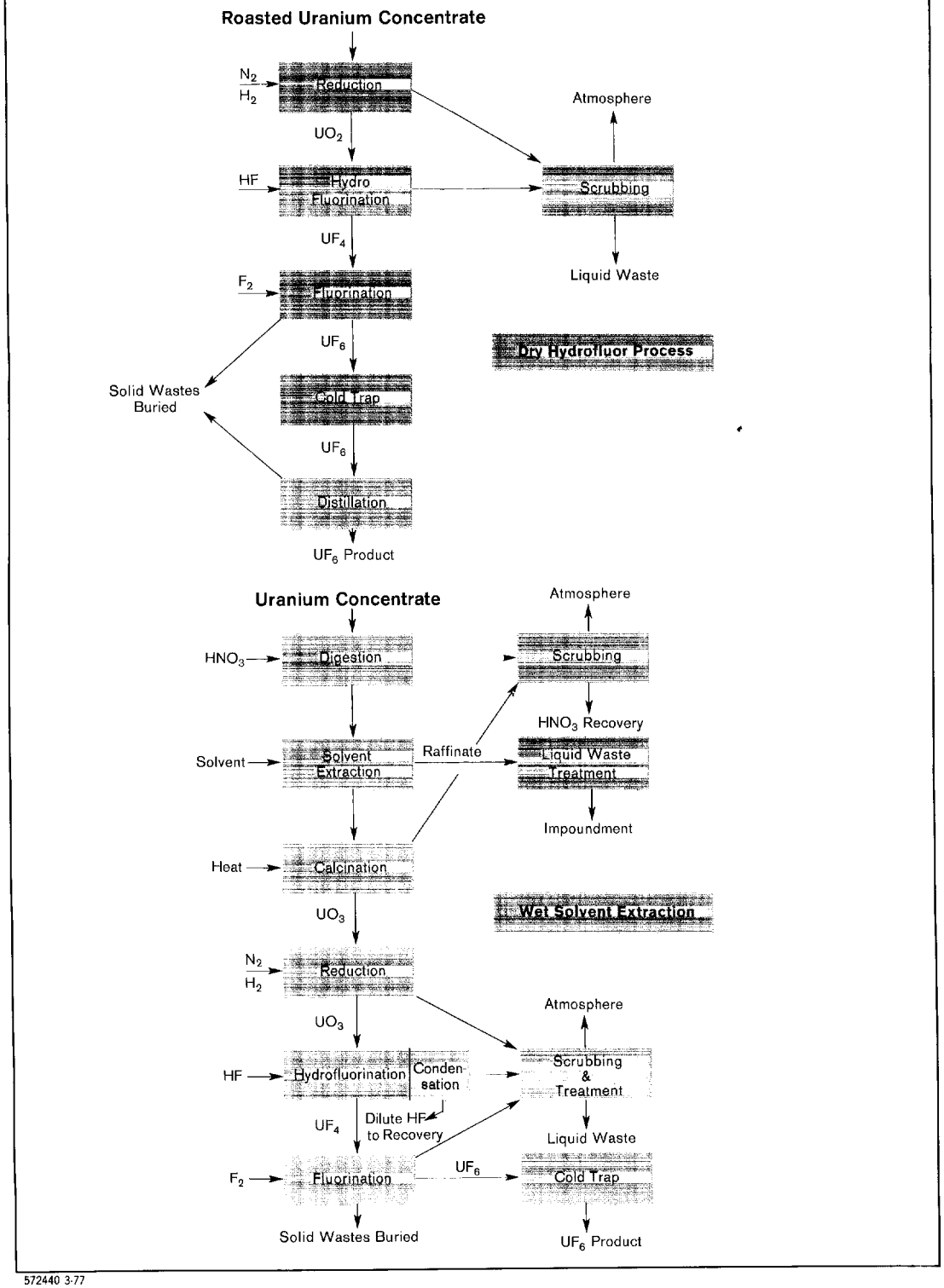
The fluoride conversion step, whether performed first or last, is almost identical in the two processes. The uranium concentrate or the orange oxide product of the wet purification process is reduced to uranium dioxide (UO_2) by reacting it with hydrogen and nitrogen gases. Hydrogen fluoride gas is then introduced to produce "green salt" (UF_4).

In a final and generally separate step, the green salt is reacted with fluorine gas to produce the volatile enrichment plant feedstock uranium hexafluoride. This last process is sometimes accomplished at the enrichment plant site.

Free World Facilities

At present, six commercial uranium hexafluoride conversion plants are operating in the Free World—two each in France and the United States and one each

Hydrofluorination Processes



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in Great Britain and Canada. The two French plants work together as a single operation to perform the entire hexafluorination process.

The commercial plants in ***France*** are located at Malvesi and Pierrelatte. They are run by Comurhex, a branch of Cogema, the public corporation created by the French atomic energy commission to manage French nuclear fuel production. As well as supplying French users, Comurhex processes uranium concentrate for foreign customers on a toll basis. The first steps of the conversion process resulting in production of green salt are performed at the Malvesi facility. Conversion to hexafluoride is done at the Pierrelatte plant. The capacity of the two-plant system is now 8,000 tons annually and is scheduled for expansion to 11,000 tons in 1978.

The ***United Kingdom's*** only plant, run by British Nuclear Fuels Ltd. (BNFL), is located at Springfields. Annual conversion capacity at present is 8,000 tons. Foreign customers are served on a toll basis.

In ***Canada,*** Eldorado Nuclear, a federally owned company also involved in uranium exploration and mining, runs a 5,000-ton-per-year plant at Port Hope, Ontario. Plans call for expansion to 10,000 tons by 1980. The "dry" hydrofluor process is used to produce green salt, which is then passed to two separate facilities in the plant—one producing uranium metal and uranium hexafluoride, the other making ceramic uranium dioxide fuel for use in Canada's CANDU reactors. (As Canadian reactors use natural uranium fuel, Eldorado's UF_6 conversion facilities largely serve foreign customers, many of which have purchased Canadian uranium concentrates.) Eldorado plans a second conversion plant and is now awaiting approval by Canada's Atomic Energy Control Board.

In the United States, Allied Chemical runs a 14,000-ton-per-year facility in Illinois and Kerr-McGee a 5,000-ton plant in Oklahoma. Kerr-McGee plans to complete expansion of its plant to 10,000 tons by early 1978.

The present capacity of these six plants is sufficient to handle all the output from Free World uranium mills—about 25,000 tons of U_3O_8 feedstock. Capacity expansions either planned or under way will boost annual hexafluoride output by 24 percent, to 47,000 tons, by 1980—sufficient to absorb uranium mill output of about 32,000 tons per year of U_3O_8.

4. URANIUM ENRICHMENT

Enrichment of uranium is the most technically difficult and costly step in the nuclear fuel cycle. Uranium as found in nature consists of several isotopes, the two principal ones being uranium-238, which predominates, and uranium-235, the isotope "burned" in conventional light-water reactors. Uranium enrichment accomplishes a partial separation of these isotopes, resulting in uranium which has a higher than natural concentration of fissionable uranium-235.

Enrichment processes are technically difficult because isotopes cannot be separated by chemical means. The methods used must instead rely on physical differences in mass or mass-related properties. In the case of uranium, such physical differences are extremely small and considerable effort is necessary to achieve separation.

Separative Work

An enrichment task can be described in terms of the physical quantities and uranium-235 concentrations of each component of material flow in an enrichment plant, that is, feed material, product, and waste (or tails). It is more common, and much simpler, however, to combine this information into a single number—the separative work unit (SWU)—by weighting the "importance" of each quantity and assay involved. This is accomplished by the use of numerical weights that reflect the "value" of uranium with varying concentrations of uranium-235; that is, more effort must be expended to achieve higher levels of enrichment than lower levels.

The amount of separative work required per unit of product is determined from the feed/product ratio (defined from the uranium-235 concentrations of each of the material flow components involved) and the value weights described above. The SWU, therefore, is not a unit of physical quantity but an indicator of the work required to perform an enrichment job. The production of one kilogram (kg) of 3 percent enriched uranium (product assay: 3 percent by weight uranium-235) from

natural uranium feed (feed assay: 0.71 percent uranium-235) in an enrichment plant operating at a 0.3 percent tails assay requires 3.42 SWU, for example. The same quantity of separative work could also be used in the same plant to produce 2 kg of 2 percent enriched uranium or 0.65 kg of 4 percent product. Thus, the SWU can be used to compare plant capacities or future demand for enrichment services regardless of the uranium-235 concentrations involved.

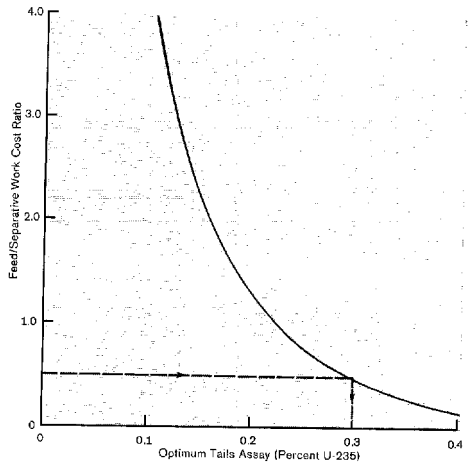
Feed and Separative Work Requirements for Production of 1 Kilogram of 3 Percent Enriched Uranium from Natural Feed

Tails Assay (Percent Uranium-235)	Feed (Kilograms)	SWU
0.15	5.08	4.98
0.2	5.48	4.31
0.25	5.97	3.81
0.3	6.57	3.42
0.35	7.34	3.11

Optimum Tails Assay

The tails assay at which the enrichment plant operates is usually determined by the relationship between the cost of the uranium hexafluoride feed material and the cost of uranium enrichment, expressed in dollars per SWU. The optimum concentration of uranium-235 in the tails stream is based on this cost relationship. As the tails assay is lowered, less feed material is required, but the amount of separative work must be increased to achieve the same degree of product concentration. When enrichment costs are high relative to feed costs, more feed can be supplied and the enrichment plant can operate at a higher tails assay. Conversely, if resource conservation is a goal, less feed need be provided if the tails assay is lower. The optimum tails concentration is independent of the uranium-235 concentration in the product being produced.

Determination of Optimum Enrichment Plant Tails Assay



Example (dashed line): Cost of Feed (as UF_6): $50 per kg
Cost of Separative Work: $100 per SWU
Feed/Separative Work Cost Ratio: 0.5
Optimum Tails Assay: about 0.3% uranium-235

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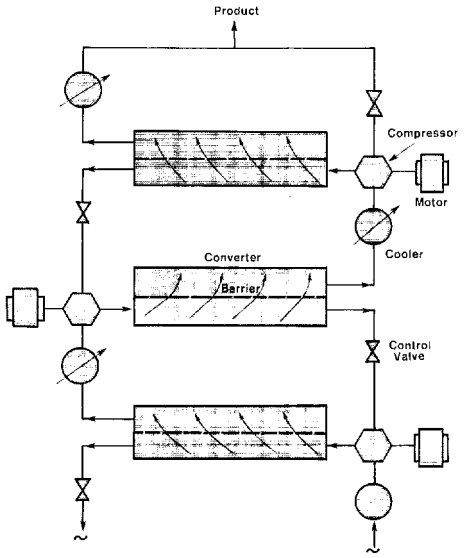
Technology

Although numerous processes to separate uranium isotopes have been proposed or demonstrated, only gaseous diffusion has so far been used on a commercial scale. Ultracentrifugation, several aerodynamic processes, and

Gaseous Diffusion Stage Arrangement



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laser isotope separation are under development.

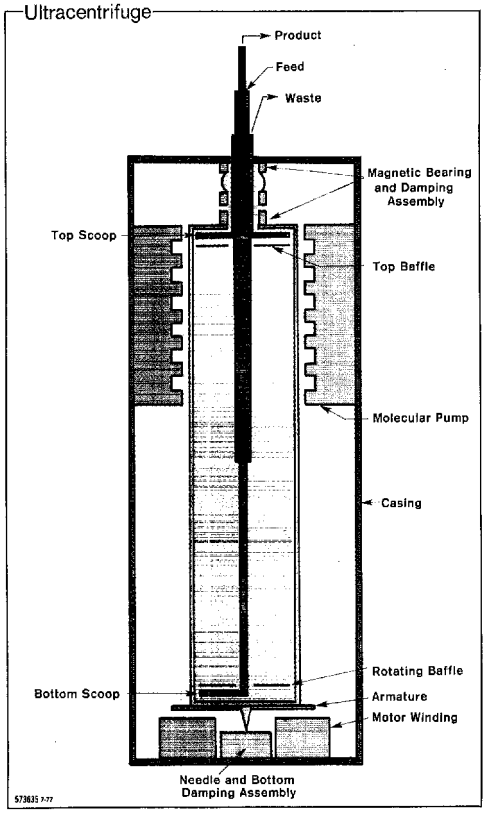
Uranium enrichment by the ***gaseous diffusion*** process relies on the differences in molecular weights of the two principal isotopic forms of gaseous uranium hexafluoride. The lighter uranium-235 hexafluoride molecules diffuse more rapidly through porous membranes or "barriers" than those of the heavier uranium-238 hexafluoride. The gas on one side of the barrier that is more heavily concentrated in uranium-235 is recompressed and sent on to subsequent stages to increase the uranium-235 concentration. The depleted gas is recycled to extract some of the remaining uranium-235.

Plants of this type operate in the United States, the USSR, the United Kingdom, France, and China. The three existing plants in the United States are now being improved and uprated to a capacity of 27 million SWU per year. In Western Europe, two small gaseous diffusion plants in the United Kingdom and France will be supplemented by a large (10.8 million SWU per year) plant in southern France under construction by the multinational consortium EURODIF.

Gaseous diffusion enrichment plants have huge power requirements. The three upgraded US facilities, for example, will consume the output of 7,000 MW of electric generating capacity annually. The EURODIF plant will have four 900-MW nuclear reactors dedicated to supplying the plant's electricity needs. As a result of improved designs and more efficient separation equipment, the practical limits of efficiency are being reached. Most isotope separation research and development is now concentrated on technologies other than gaseous diffusion.

The most technically advanced enrichment method other than gaseous diffusion is ***ultracentrifugation***. Considerable progress has been made in this

technology since its laboratory demonstration in 1934. The principal advantages of centrifuge enrichment are relatively low energy consumption (on the order of one-tenth that of gaseous diffusion) and the flexibility of plant design. Complete centrifuge enrichment facilities can be built on a small scale and expanded as necessary to meet demand, whereas gaseous difusion plants must have a minimum capacity for economic operation.



In the centrifuge process, UF_6 gas is fed into thousands of interconnected cylindrical containers, each spinning at very high speed. The centrifugal force generated by rotation forces the heavier gas fraction, that is, that containing uranium-238, to the periphery of the cylinder, while the lighter fraction remains nearer the axis. Enriched gas moves through a series of machines for further enrichment. In a variation of the basic process, countercurrent gas flow is introduced between the migrating fractions to improve separation as the feed moves down the cylinder.

Research has concentrated on increasing the rotational speed and capacity of machines under development. One of the interesting properties of the centrifuge process is that separative work varies as the fourth power of rotational speed, so a doubling of speed theoretically would increase separation 16 times. Velocity is limited by several factors, however, notably the mechanical strength of the materials involved. Most development work to date has been devoted to improving machine reliability.

Although several nations are developing centrifuges for uranium enrichment, the only commercially operating plants are run by URENCO, a British - Dutch - West German consortium. At present the group operates three pilot plants—German and Dutch plants at Almelo (Netherlands) and a British plant at Capenhurst. Full capacity of about 10 million SWU annually, equivalent to a large gaseous diffusion plant, is planned for the mid-1980s. The United States will build an 8.8-million-SWU centrifuge facility at Portsmouth (Ohio) in 1985.

Other uranium isotope separation processes, notably aerodynamic methods, are also being studied. But the two of these that have reached pilot plant stage are considered by US experts to have limited commercial potential at present because they are large consumers of electricity. These processes include the ***jet nozzle*** process under development in West Germany and a South African process called a "high-performance stationary-walled centrifuge." The actual separation technique is similar in both methods. Uranium hexafluoride in a "carrier" gas such as hydrogen is forced to flow at high speed in a curved path creating centrifugal forces. The heavier uranium-238 component is directed toward the outside of the curve while the lighter fraction becomes more concentrated near the inside of the curve. The gas is then split to form enriched and depleted streams by a "knife edge."

The most promising experimental enrichment technique is ***laser isotope separation*** (LIS), which has large potential for energy and resource saving. In this process laser light is used to selectively excite one isotope in uranium hexafluoride gas or metallic uranium vapor; the excited isotope can then be separated by physical or chemical means. Another technique uses laser light to deflect uranium-235 from a feed stream into a collector. LIS promises to enable uranium enrichment to be accomplished in one step. As large numbers of interconnected separations stages are not required in this process, the concept of separative work does not apply. However, several technical problems remain, and large-scale LIS plants are unlikely for a least a decade.

5. NUCLEAR FUEL FABRICATION

The final step in the processing of uranium prior to use in a nuclear reactor is the fabrication of fuel elements, including conversion of enriched uranium hexafluoride to uranium dioxide, mechanical processing, and final assembly. Most Free World power reactors use slightly enriched uranium dioxide as fuel. At present, about 30 plants in the Free World fabricate oxide fuels, of either natural or enriched uranium.

More than one-half of operating fuel fabrication capacity is in the United States: nine oxide plants and several others that make specialized fuels. All are privately owned, most by reactor manufacturers rather than by uranium producers. France, West Germany, and Italy each have four oxide fuel fabrication plants. The German plants are privately operated, but in France and Italy, joint government-private participation is the rule. Additional uranium oxide fabrication capacity is located in Japan, Canada, Belgium, Denmark, India, and the United Kingdom.

Present and planned Free World fuel fabrication facilities will be adequate to meet expected demand through the 1980s. Because most plants are owned by reactor manufacturers or government agencies, there will be a natural tendency to keep capacity abreast of power reactor expansion. In addition, fabrication facilities are not as expensive and construction times are shorter than for other processing plants, such as enrichment facilities. The technology involved is also considerably less complex.

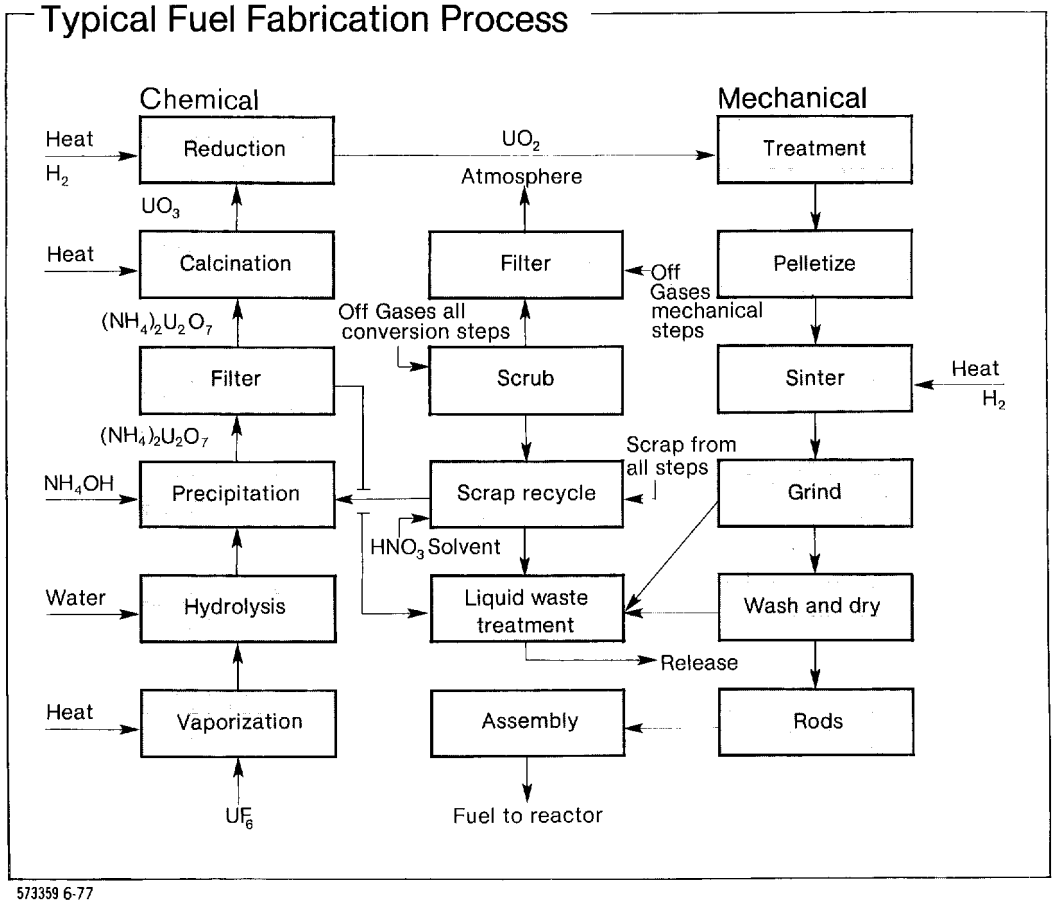
Free World: LWR Fuel Fabrication Capacity[1]

	Tons of Heavy Metal per Year		
	1975	Planned 1978	Projected 1985
Total	**5,410**	**7,110**	**15,560**
United States	2,750	3,350	8,200
West Germany	670	1,000	2,000
France	200	220	1,100
Japan	910	910	910
Belgium	200	500	900
Spain	0	300	800
Italy	300	300	600
Sweden	250	400	450
Denmark	0	0	300
Netherlands	30	30	200
United Kingdom	100	100	100

[1] Source: International Atomic Energy Agency, 1975.

The process of making an enriched uranium oxide fuel element for a conventional light water reactor (LWR) involves three principal steps. The enriched uranium hexafluoride (UF_6) is first converted from its gaseous state to uranium dioxide (UO_2) powder. Current technology involves a single-stage dry process in which UF_6 is transformed directly to ceramic oxide by reaction with hydrogen and steam in a kiln. The UF_6-steam mixture produces uranyl fluoride that is reduced in the kiln by hydrogen to UO_2 powder. The powder passes through a series of pressing and sieving operations before being compressed into pellets. These pellets are finally sintered to improve density and then ground to uniform size.

An older wet process, still widely used, converts UF_6 into orange oxide (UO_3) precipitate by reaction with water and ammonium hydroxide, prior to calcination. The orange oxide is reduced to UO_2 by hydrogen. It is then dried, pelletized,



sintered, and ground. This process is more expensive than the dry technique and will likely be phased out as new facilities are built.

The uranium dioxide pellets are stacked in a thin-walled metallic sheath of stainless steel or, more commonly, zircaloy as cladding material. Helium is then introduced into the tubes to assure thermal conductivity, and the tube ends are capped and welded shut. The tubes are arranged in a grid made to fit the reactor in which the fuel will be used. Hundreds of such fuel elements held into position by grid plates in the reactor vessel constitute the reactor core.

Despite the relatively simple processes used, fabrication of nuclear fuel is highly precise. Cladding material must be of high grade not only to resist corrosion, withstand extremely high temperatures, and contain radioactive fission products, but it must be free of materials which could hinder the chain reaction by absorbing neutrons. Precision machinery is also required to produce uniformly thin tube walls that allow efficient heat transfer without "hot spots." Tube arrangement in the grid must also be exact to mate properly with the reactor and to ensure adequate coolant flow through the core.

6. URANIUM RESOURCES IN THE FREE WORLD

The Free world has more than enough uranium to supply all foreseeable needs for nuclear energy production, probably at least through the end of this century. Shortages of nuclear fuel are much more likely to result from insufficient capacity in particular fuel cycle operations, such as ore concentration, uranium enrichment, or fuel reprocessing than from inadequacy of the uranium resource base.

Uranium is one of the more abundant minerals in the earth's crust and is also found in sea water. It occurs in about the same proportion as tungsten, molybdenum, cobalt, and lead and is more plentiful than such industrially important metals as cadmium, mercury, silver, and gold. Of known uranium reserves in the Free World, about three-fourths is in the United States, Canada, South Africa, and Australia. Large additional reserves may be found with more extensive exploration.

Extent of Reserves

Uranium reserves are classified according to recovery cost categories. Prices for uranium recently have moved up sharply enough to adequately cover exploitation of all reported reserves. In the broadest reserve category – recoverable at $30 or less per pound of U_3O_8 content – about 1.8 million tons of uranium metal is considered reasonably assured, with an additional 1.7 million tons believed to exist in surrounding strata or nearby areas.

Characteristics of Uranium

Uranium exists in numerous compounds. The high solubility of uranium compounds and ability of uranium to join with other elements result in its being found in combination with as many as 200 other minerals – frequently gold, copper, or vanadium. Thus, uranium is often a byproduct of the production of other minerals. In South Africa, for example, most uranium is produced as a residual in gold mining operations.

Because some uranium compounds are soluble, they migrate in ground water, concentrate, and then reprecipitate. The precipitate uranium is deposited either in veins within rock fractures – in which case it is commonly known as pitchblende – or in tabular masses in porous rock such as sandstone. Many uranium-bearing ores contain carbon substances into which the uranium has been

absorbed or finely scattered. The presence of certain clays, silica, sulfides, and alkalis in rocks such as granite and sandstone helps concentrate uranium into deposits.

In areas where ground water is present, existing uranium minerals are often leached by the water. As water action is generally responsible for low concentration of uranium in ore bodies, exploration and mining operations are often centered in arid areas high in silica or alkali content where water leaching is not extensive.

Geographic Distribution

The distribution of uranium deposits relates to the nature of the mineralizing solutions, the geologic structure through which the solutions move, and the type of rock in which the ore is deposited.

The most important reserve areas include western ***Canada***, where rich pitchblende veins are found along faults and adjacent fracture zones of the Great Bear and Athabasca lake regions. Additional uranium deposits in quartz beds are located in Ontario. The principal uranium areas in the ***United States*** are the Colorado Plateau, the Wyoming basin, and the Texas gulf coast. The most important area – the Colorado Plateau -- covers more than 360,000 square kilometers. Here uranium is found impregnated in sandstones and limestone, generally at depths of less than 245 meters. Pitchblende veins occur throughout the area but constitute only a small portion of total deposits.

Australia's richest deposits are found in the shale, slate, and adjacent granite regions near Darwin, Northern Territory. Uranium is also located in the iron-titanium veins of South Australia and in the granite area near Mt. Isa in western Queensland.

In ***South Africa*** uranium is produced by leaching the hydrocarbon slime residues from the gold mining of the Witwatersrand conglomerates near Johannesburg. ***Namibia*** is gearing up to exploit uranium-bearing sandstone deposits, which reportedly account for 5% of Free World reserves. Veins of pitchblende lie in overthrust faults in southern ***Zaire***. Uranium is also found in the sandstone areas of ***Gabon***. Development of pitchblende veins in ***Zambia*** and the phosphate beds of the ***Central African Empire*** could begin soon. Deposits also are found in the sandstone and clay formations of north-central ***Niger*** and, together with thorium, in high silica areas of southern ***Malagasy Republic***.

European deposits are modest by comparison. Rich ores are located in vein deposits of the Massif Central and Brittany in ***France***. Uranium is also found in

Free World: Uranium Resource Base[1] at $30 or Less per Pound of U_3O_8

Thousand Tons of Recoverable Uranium Metal[2]

	Reasonably Assured Resources	Estimated Additional Resources	Total
Total	**1,787**	**1,663**	**3,450**
United States[3]	523	838[4]	1,361[4]
Canada[5]	167	487	654
South Africa[6]	276	74	350
Sweden	300	0	300
Australia	237	42	279
France	55	40	95
Niger	50	30	80
Spain[7]	23	42	65
Argentina	21	39	60
India	29	23	52
Gabon	20	10	30
Algeria	28	0	28
Other	58	38	96

[1]Source: International Atomic Energy Agency, 1975, with revisions.
[2]One metric ton of uranium metal equals 1.3 short tons of U_3O_8.
[3]Excluding 70,000 tons of uranium as a possible byproduct of phosphate and copper production.
[4]Excluding "possible" and "speculative" resources of 1.2 million tons.
[5]The category refers to *price* of $40 or less per lb of uranium rather than *cost* of $30 or less per lb of uranium.
[6]Including Namibia.
[7]Excluding 145,000 tons uranium of additional resources in lignites for which availability is uncertain.

the Vosges region. Veins of pitchblende occur in granite formations of the Sierra Morena in south-central ***Spain*** as well in the Serra da Estrela in central ***Portugal***. Highly dispersed and less valuable shale deposits in Vastergotland and Narke provinces in ***Sweden*** also hold uranium.

Ore Quality

Most of the known uranium reserves consist of high-quality ores. About 60% of reserves in the Free World are considered relatively rich and extractable at costs less than $15 per pound U_3O_8. Only in Sweden, Spain, and India are the bulk of reserves of a lower grade.

Generally, a ton of average uranium ore yields only 1-2 kilograms of uranium oxide (0.1%-0.2% U_3O_8). A typical 1,000-MW nuclear reactor requires the uranium from nearly 150,000 tons of such quality ore annually. Even so, comparable coal-fired plants would consume 20 times as much coal, and overall fuel costs for coal or oil are much greater.

Only recently has interest in the lower grade ores increased, mainly because rapid jumps in uranium prices in the past three years have made their exploitation justifiable. Even so, the full extent of lower grade deposits has not yet been adequately established, because exploration has been concentrated in areas likely to yield ore rich in uranium. Experts agree that future exploration efforts will likely show a mix of rich and low-grade deposits similar to those already established.

7. STRUCTURE OF THE URANIUM INDUSTRY IN THE FREE WORLD

The uranium industry – composed of exploration, mining, and milling operations – is more fragmented and complex than most other resource industries. Firms range from very large conglomerates, such as the United Kingdom's Rio Tinto Zinc Corporation and South Africa's Anglo-American Corporation, with more than 100 subsidiaries each, to small, closely held operations. Industrial concentration is least in exploration and increases in downstream operations. Larger firms are often vertically integrated.

Joint ventures and participation arrangements are very common in the industry, leading to increasing industrial concentration. Smaller firms are being linked together into larger joint projects, and large companies, by buying into several joint projects, increase the degree of association among firms. Often this has been necessary to provide sufficient capital for exploitation and processing. This type of corporate behavior is most evident in Canada, Australia, and the United States. Operations in other major producing countries are already highly centralized.

Many larger companies do not confine their operations to the country of incorporation but are active in exploration abroad. The largest Free World uranium-producing countries are the United States, Canada, South Africa, France, Niger, and Gabon, which together account for 95% of total output. All of the industrialized producing countries have domestic corporations in the field, while developing countries rely heavily on foreign participation. In most producing nations the government plays a role in the industry.

Private mining interests account for the bulk of production in ***Canada***. At least 35 companies are active in exploration. There are 13 major producing firms, nine of which are foreign owned or controlled. All of the larger producers do their own exploratory work. Spurred by recent uranium price increases, the industry is expanding its exploration effort. Exploration spending this year will hit $50 million – about 40% of all expenditures for mineral exploration. Old mines and mills are being reactivated and new ventures are being started. Many firms have foreign participation, but government regulations may eventually limit foreign ownership.

Among the largest mining firms are Rio Algom (a subsidiary of the London-based Rio Tinto Zinc holding company), Denison mines, and federally owned Eldorado Nuclear. These three companies are expected to have a production

capacity of about 60,000 tons of ore daily by 1985. In the mid-1960s, these were the only uranium firms operating in Canada, and they still produce about 75% of output.

Several other firms have entered the field in recent years. Three of the new firms are wholly foreign owned or controlled. Amok, which has a rich reserve in northern Saskatchewan, is jointly owned by French interests -- Motka, Pechiney, and the Commissariat a l'Energie Atomique. At nearby Rabbit Lake, the Gulf-Uranerz (US-West German) joint venture operates. On the east coast, Brinex (United Kingdom) has joined with Urangesellschaft (West Germany) to exploit Labrador's Kitts/Michelin deposit.

Domestic companies new to the industry include Noranda Mines, a large Canadian multinational, multimineral company that operates in northern Saskatchewan as well as abroad. Noranda also controls Agnew Lake Mines (Ontario) through Kerr Addison Mines Ltd. Also on Lake Huron is Madawaska Mines – a joint project of Consolidated Canadian Faraday and Federal Resources (United States). The Key Lakes deposits – perhaps Canada's richest find yet – are being exploited by Saskatchewan Mining in conjunction with Uranerz (West Germany) and Inexco Oil (United States).

The discoveries made by the new entrants and the scale of facilities planned by them will probably end the older firms' domination of the industry in the next decade. By the end of the 1980s, Canadian production could easily expand by a factor of three, with the new firms increasing their share of the enlarged market to 50%.

Uranium production in ***South Africa*** – the Free World's third largest producer – is a byproduct of gold mining operations in the Transvaal and Orange Free State. Although the state participates through lease arrangements, the industry is privately owned. Concentration in the industry, as in all mining in South Africa, is high and will likely remain so. Most uranium producers are organized into a cooperative association known as the Transvaal and Orange Free State Chamber of Mines. Among the largest companies are the Anglo-American Corporation of South Africa, Anglo-Transvaal Consolidated, New Consolidated Goldfields, and Rand Mines.

At present 27 mines produce uranium, which is fed to 17 ore processing plants. The four largest mines produce nearly one-half of total output. Uranium ore is taken to a central filtering, drying, and calcining facility at Zuurbekom from which orange oxide (UO_3) is shipped. This plant is operated by the Nuclear Fuels

Free World: Uranium Production and Capacity[1]

Tons

	Annual Capacity			Production
	Existing	Projected 1980	Attainable 1985	1975[2]
Free World	**27,900**	**51,700**	**73,700**	**20,400**
Australia	760	3,260	5,000	0
Canada	6,500	7,950	12,500	4,700
France	1,800	3,000	3,500	1,700
Gabon	800	1,200	1,200	800
Niger	1,200	4,000	6,000	1,200
South Africa	2,700	10,000	12,700	2,600
United States	13,500	20,000	30,000	9,000
Other	640	2,290	2,800	400

[1] Source: International Atomic Energy Agency, 1975, with revisions.
[2] Estimated.

Corporation of South Africa (NUFCOR), which is jointly owned by all South African uranium producing gold mines and the seven principal mining finance groups. NUFCOR also markets the product – 75% of which is exported – subject to South African Atomic Energy Board controls. The remainder is stockpiled.

Neighboring ***Namibia*** is thought to have 100,000-200,000 tons of uranium in deposits located west of Karibib. Limited mining operations have begun at Rio Tinto's Rossing deposit – thought capable of yielding 5,000 tons of uranium annually. A concentration plant being built by South African firms will have a capacity of 40,000 tons of ore per day in 1978 and will be the world's largest. The companies operating in Namibia are privately owned, but the government retains all rights to minerals and controls licenses to mine and distribute the output. Large South African mining conglomerates -- principally General Mining and Finance, Johannesburg Consolidated Investment, and the Anglo-American Corporation of South Africa – are active in the area.

Australia currently produces less than 500 tons of uranium annually. Mary Kathleen Ltd. owns the country's only operating mine and treatment plant, in northwestern Queensland. The firm is controlled by Conzinc Riotinto of Australia. The mine is expected to be depleted by 1981.

The current Fraser government favors uranium development by the private sector, including foreign participation up to 25 percent of equity. Under the

preceding Whitlam government (1972-75) uranium development foundered; restrictive energy policies banned uranium mining and exports and sought an eventual 100-percent government ownership of the industry. Soon after Fraser took office in December 1975, the government permitted Mary Kathleen to resume mining and instructed the Australian Atomic Energy Commission to sell off its equity holdings in uranium projects.

The government recently approved the development of uranium projects. The final go ahead had been delayed pending the outcome of a special environmental inquiry. The inquiry commission's two reports, issued in October 1976 and May 1977, gave enough of a qualified okay to enable the government to decide in favor of development.

The Northern Territory, which contains 80 percent of the country's reserves, holds the greatest interest. The Ranger project, east of Darwin, is at a more advanced stage of readiness than others. The developer is Ranger Uranium Mines Pty. Ltd., a partnership between Peko Mines Ltd. and Electrolytic Zinc. Three other major deposits have been found near the Ranger site: Koongarra, held by Noranda Australia Ltd., a subsidiary of the Canadian firm Noranda Mines Ltd.; Jabiluka, held by Pancontinental Mining and Getty Oil Development Co.; and Nabarlek, a high-grade deposit held by Queensland Mines. Some of the other companies engaged in exploration in the Northern Territory are Project Mining Corp. Ltd, Pechiney (France), AGIP Nucleare (Italy), Magellan Petroleum (United States), and Urangesellschaft (German).

Exploration in other parts of the country is less intense. Queensland Mines, the Getty-Central Coast Exploration joint venture, and the French affiliate Pechiney Exploration are active in Queensland. Searches also are under way in South Australia – primarily by Western Uranium – and in West Australia by Western Mining.

The Commissariat a l'Energie Atomique (CEA), through the Compagnie Generale des Matieres Nucleaires (Cogema) and affiliated firms, produces all uranium in ***France***. Cogema is a wholly owned government firm with private legal status. Through its own departments and its principal affiliates -- Pechiney, Motka, and Compagnie Francaise des Minerais d'Uranium (CFMU) – it controls the entire French nuclear fuel industry. Cogema owns and operates mines in the districts of La Crouzille, Vendee, and Forez and processing plants at Gueugnon, Bessines, Forez, and L'Ecarpiere. Private mining operations controlled by the group are located in the Massif-Central and Brittany. Pechiney also runs its own ore processing facilities.

The CEA, together with Pechiney, Motka, and CFMU, has joined the Rothschild-controlled conglomerate Imetal and Minatome, a joint Pechiney-Compagnie Francaise des Petroles enterprise, to control several operating companies abroad such as Amefco in Australia and Amok in Canada.

The French group also has extensive operations in West Africa. In ***Niger*** there are four large uranium mining consortia. The French group and the government of Niger – which holds all mineral rights through its Bureau de Recherche et Exploitation Miniere (BUREMI) – have major interests in all four consortia. US, Japanese, Italian, West German, and private French companies have partial interests in one or more of the groups. Somaire and Cominak, led by the French CEA and its private affiliates, are the largest consortia. Through Pechiney they also operate processing facilities. In addition to the French companies, Continental Oil (United States), OURD (Japan), PNC (Japan), AGIP (Italy), and Urangesellschaft (West Germany) are represented.

The government of ***Gabon*** has a 25% interest in another consortium – the Compagnie des Mines d'Uranium de Franceville (COMUF) – dominated by the French CEA and the private Imetal and Minatome groups. Imetal, the Alusuisse (Swiss) group, and the CEA together participate as majority partners with the state in URBA – the uranium mining consortium in the ***Central African Empire.***

By comparison, the structure of the uranium industry in the ***United States*** is diffuse. All production is privately owned but large tracts of uranium mining land are leased from the government. International oil companies and diversified mining firms dominate the industry. Joint ventures are common, especially in processing operations. Nearly half the firms are involved in domestic or foreign joint projects.

All the major US companies operate in Wyoming, Colorado, New Mexico, and Utah. Of the 25 largest firms, only five have sizable domestic operations outside this area – principally in Washington and Texas. The largest producers are Kerr-McGee, Utah International, United Nuclear, Exxon, Phillips, Union Carbide, and Gulf. These firms have a combined annual capacity of about 25 million pounds U_3O_8 – 85% of the US total. The principal US firms with major foreign operations are Getty (Australia), Gulf and Inexco (Saskatchewan), and Federal Resources (Ontario).

The present diversified structure of the industry probably will continue, with the major oil and mining companies remaining industry leaders. Recent increases in uranium prices should benefit smaller firms in maintaining competitiveness.

Virtually all companies are heavily engaged in exploration, and most are planning increases in production capacity through the next decade. US output is expected at least to double by 1985.

As part of this expansion, foreign companies may intensify efforts to enter the US industry to assure themselves a continued supply of nuclear fuel. Rio Algom, a British-owned Canadian firm, Pechiney (France), and Urangesellschaft (West Germany) are among those already active in the United States. Participation agreements and joint ventures are the most likely avenues foreign firms will take to enter the US industry.

8. THE URANIUM MARKET

The price of nuclear fuel paid by the ultimate consumers -- the electric utilities – is only partially determined by the price for uranium concentrate -- U_3O_8, commonly called yellowcake. About 40%-50% of "front end" nuclear fuel cycle costs[2] are due to hexafluoride conversion, enrichment, and fuel fabrication that transform yellowcake into finished fuel elements enriched in the fissionable uranium isotope, uranium-235, ready for use in power reactors.

Typically, these procedures are performed or contracted for by a fuel fabricator – often a subsidiary of a large conglomerate involved in other aspects of the nuclear industry – or a government-owned firm. The fabricator is not usually the agent of the utilities or mining interests but rather a separate operator filling contracts with buyers. Conversion and enrichment of uranium concentrates are performed on a toll basis by governmental agencies or private firms in their own plants. With few exceptions – France being a notable one – complete vertical integration in the nuclear fuel cycle does not exist. Likewise, no single production stage has in the past exerted an overriding influence in determining final fuel prices.

Price Trends

During the last four years a complete turnaround has taken place in the market for uranium. The buyers' market of 1973 became a sellers' market in the wake of the OPEC price hikes. During this period prices rose sixfold. The transformation resulted from restrictive uranium export policies, inflation, repeated changes in terms for enrichment contracts, and intensified competition for uncertain uranium supplies.

Prior to 1973, the price of uranium for immediate delivery was less than $6 per pound of U_3O_8. Slack demand and continued drawdown of excess stocks led to cutrate competition among producers with excess capacity. New supplies from Namibia and Australia were expected to add to already plentiful and cheap Canadian, South African, and French uranium. In this easy market, producer prices barely covered costs.

The first upward pressure on prices came in 1973. The former US Atomic Energy Commission (USAEC) announced that it would require long-term

[2] If estimated costs of a complete nuclear fuel cycle (spent fuel storage, transportation, fuel reprocessing, and waste disposal) were included, uranium concentrates would represent only about 30% of total fuel costs.

commitments for uranium enrichment services. Demand increased as large spot purchases were made to comply with the new USAEC regulations. The supply picture tightened further when the Whitlam government embargoed Australian uranium exports and restricted uranium development. In South Africa, rising gold prices made gold mining more profitable, and exports of uranium concentrates fell off. Uranium producers, sensing the tighter market, hardened their price demands. Concurrent with the OPEC oil embargo, prices climbed 18% to $7 per pound.

The Price Spiral

The oil embargo and subsequent oil price hikes focused attention on the need for alternative energy sources. Nuclear power programs were greatly expanded. France and Canada severely restricted uranium exports to assure their own supplies. The USAEC notified its domestic and foreign customers that tails assays would be increased to reduce workloads on enrichment plants. Feedstocks therefore would have to increase. It became apparent that fuel reprocessing would not be commercially available for several years, thus eliminating the possible use of recycled uranium and plutonium in nuclear fuel. Buyers scrambled for available supplies, building stocks and placing long-term contracts at indexed or unspecified prices. By yearend 1974, prices of yellowcake for immediate delivery had doubled to more than $15 per pound.

In mid-1975, a major US firm announced to its customers (utilities in the United States and Sweden) it could not deliver 65 million pounds of U_3O_8 covered in existing contracts. Because a large percentage of deliveries were to be made at the low prices quoted in these contracts rather than at higher spot prices, the company claimed the average delivery price it would receive was not adequate to make delivery profitable. Foreign firms have been similarly afflicted, but to a lesser degree because of lower production costs. To obtain release from the low-price contracts, fuel fabricators went to court, throwing the market into confusion. The affected customers rushed to the market to secure new supplies. By December 1975, spot prices had again more than doubled to $35 per pound.

Since that time, uranium price increases have slowed, creeping to $40-$42 per pound. Average delivery prices – as opposed to spot prices – have gradually moved upwards as well. By 1980, most of the old low-price contracts will have lapsed and average delivery prices will more closely follow spot prices. The growing number of contracts at unspecified or indexed prices will ensure this.

The uncertainties that provoked the 1973-76 uranium price spiral still persist. The threat of potentially adverse effects of new OPEC price increases, the resurgence of worldwide inflation, the increasing costs of mining low-grade uranium at greater depths, and the realization that large-scale reprocessing is uncertain continue to exert pressure on prices.

Several factors are now acting to stabilize the market. Sharp construction cost increases for nuclear powerplants have led to cutbacks in nuclear power programs. The new Australian government is gradually reversing restrictive policies. South African uranium production has continued to strengthen, as gold prices have stabilized. Output from neighboring Namibia is expected soon. Perhaps most important is the beneficial effect higher uranium prices have had on producers, placing them in a better position to increase production. Nevertheless, despite more plentiful supplies and an easing of demand, expansion efforts will have to intensify because of the long lead time (eight to 10 years) needed to bring new facilities on line.

Need for Expansion

The International Atomic Energy Agency estimates that demand will rise to 80,000-100,000 tons of uranium metal per year by 1985 compared with present production capacity of 25,000 tons per year. The recent severe cutbacks in nuclear power programs, though, will probably hold 1985 demand to about 55,000-60,000 tons per year. Nevertheless, we estimate that expansion to this level will require investment of $5-$6 billion (current prices) in uranium exploration, mining, and milling. Additional funds will be needed to replace many outdated existing facilities built in the 1950s.

Both uranium producers and consumers question whether such large investment funds will be available. Producers frequently point to rising costs as a major restraint on their ability to amass capital. Although yellowcake represents only a fraction of total nuclear fuel costs, it is perhaps the most volatile component. Yellowcake costs are mainly a function of ore quality. As ore quality drops, production costs rise more than proportionally because larger quantities of ore must be processed and excavation and exploration expenses involved in exploiting low-grade, widely dispersed ores are higher. Over the last 10 years, average ore grades in most producing nations have dropped about 40%. The resulting increased production costs and the effect of worldwide inflation have been only partially offset by technological improvements.

Typical Yellowcake (U_3O_8) Production Costs[1]

US $ per Pound of U_3O_8

	1970		1976	
	Deep Mine	Open Pit	Deep Mine	Open Pit
Total	**11.97**	**7.47**	**17.46**	**11.28**
Exploration[2]	1.00	0.93	1.60	1.50
Amortization (mine and mill–2,000 tons per day)	3.01	2.79	4.22	3.91
Mining	6.27	1.74	9.09	2.53
Milling	1.67	1.67	2.50	2.50
Reclamation[3]	0.02	0.34	0.05	0.84

1. Based on US experience (0.15% ore grade and 2,000 ton per day mill).
2. At 3 pounds of U_3O_8 per foot drilled; costs at 4 pounds per foot are 30% less and at 5 pounds per foot are 40% less.
3. Moderate reclamation–severe costs are 80% higher, mild costs are 60% lower.

Effect of Ore Grade on Production Costs, 1976

US $ per Pound of U_3O_8

Ore Grade Percent U_3O_8	Operating Cost		Production Cost	
	Deep Mine	Open Pit	Deep Mine	Open Pit
0.075	22.81	11.51	28.63	16.92
0.100	16.99	8.57	22.81	13.98
0.125	13.74	6.93	19.56	12.34
0.150	11.64	5.87	17.46	11.28
0.200	8.85	4.46	14.67	9.87
0.250	7.33	3.70	13.15	9.11

Our analysis indicates that uranium production is now becoming sufficiently profitable to provide the funds needed for expansion. The current spot price for uranium concentrate is about $42 per pound of U_3O_8, with delivered prices in 1976 averaging $16.10 per pound. Despite an estimated 50% increase since 1970, our calculations indicate that production costs average less than $14 per pound[3] for processing ore containing 0.15% U_3O_8.

Outlook

The outlook is favorable during the next decade for increasing uranium supplies while avoiding the massive price hikes of 1973-75. Existing producers will likely be able to expand output without undue financial strain, and large-scale production from new deposits in Namibia and Canada is expected by 1980. Australia is also likely to become a major producer in the next decade. The present practice of contracting for fuel supplies prior to nuclear powerplant construction should help control any excess demand. If bottlenecks do occur, they will likely be at the hexafluoride conversion or enrichment stages of the fuel cycle. Moreover, the impact of anticipated uranium price increases on generating costs is likely to be small. Though uranium may increase in price more rapidly than other fuels, nuclear fuel accounts for a much smaller percentage of total generating costs than either coal or oil.

[3] Assuming a 60%-40% distribution of open-pit and deep (underground) mining; this approximates the present distribution in the United States.

9. SUPPLY AND DEMAND FOR URANIUM ENRICHMENT SERVICES

World capacity to perform uranium enrichment services for nuclear power-plants is currently about 22 million separative work units[4] annually. By 1985, capacity is slated to rise to nearly 45 million SWU per year. The United States now operates almost all existing capacity, but by the mid-1980s, its share will drop to less than 70 percent of the total.

The bulk of the increase in production capacity over the next several years will take place in Western Europe, where two multinational consortia are building facilities. A French-led group, EURODIF, which involves Italian, Belgian, Spanish, and Iranian participation, is constructing a 10.8 million-SWU-per-year gaseous diffusion plant at Tricastin. This plant is scheduled to reach full capacity by 1982. The technology is based on improvements in equipment used by France in its small Pierrelatte enrichment plant—originally built for military use—located adjacent to the EURODIF facility. EURODIF, together with the French nuclear fuel company, COGEMA, and the Atomic Energy Organization of Iran, have formed COREDIF, which is studying the possibility of building another large gaseous diffusion plant in Western Europe.

Projected 1985 Uranium Enrichment Capacity[1]

	Million SWU per Year
Total	**44.7**
United States	28.0
EURODIF (France, Italy, Belgium, Spain, and Iran)	10.8
USSR[2]	3.0
United Kingdom	0.4
France	0.4
URENCO (United Kingdom, Netherlands, and West Germany)	2.1

[1] Excluding capacity still in planning stages.
[2] Capacity believed to be allocated for export sales to the West. The capacity allocated for internal use of the USSR and Eastern Europe is not included.

The second consortium, URENCO, is concentrating on the development of the ultracentrifuge process. The group involves equal participation of the United Kingdom, West Germany, and the Netherlands. Currently operating three pilot plants, URENCO plans an orderly expansion of its enrichment facilities at Capenhurst (UK) and Almelo (Netherlands) including intermediate-sized demonstration plants. The first increment of commercial enrichment capacity, about two million SWU per year, will be available in the early 1980s. This capacity is already fully committed by contracts, but further additions will be made as needed.

[4] Excluding enrichment capacity in the USSR allocated to fulfilling internal Soviet and East European power plant requirements.

Several other countries are planning uranium enrichment facilities, including South Africa, Japan, and Brazil. Given the long lead time and the demand outlook, it is unlikely that large increments of new capacity will be brought on stream before 1985. In addition to Free World suppliers, the Soviet Union apparently has allocated a portion of its enrichment capacity—on the order of three million SWU annually—to Western customers. The USSR already holds contracts totaling 38 million SWU, some of which run to 1990.

Because the demand for enrichment services is closely linked to nuclear generating capacity, recent developments in the nuclear industry have outdated most enrichment demand projections. Financial constraints, reduced projections of electricity demand, and environmental and safety concerns continue to hamper nuclear power development. In December 1975, the OECD Nuclear Energy Agency and the International Atomic Energy Agency were forecasting generating capacity in 1985 at about 500,000 MW and projecting annual enrichment demand at 57 million to 65 million SWU. A March 1977 estimate of the International Energy Agency projects world nuclear capacity at only slightly more than 300,000 MW in 1985, with enrichment demand at 42.5 million SWU. Present and planned enrichment capacity should be adequate to meet requirements through the mid-1980s, if all projects now under construction or planned are completed on schedule.

Projected Nuclear Electric Generating Capacity, Yearend

	Thousand MW
1976	88
1980	164
1985	312

Projected Supply and Demand for Uranium Enrichment Services

	Million SWU	
	Supply	Demand
1976	21.9	12.4
1977	22.2	14.1
1978	25.1	16.1
1979	29.2	19.8
1980	36.6	21.6
1981	41.4	24.7
1982	42.3	27.3
1983	42.3	31.1
1984	42.3	35.1
1985	44.7	42.5

By the early 1990s, however, demand for enrichment services could approach 70 million SWU per year—roughly three times present capacity. A switch to higher enrichment plant tails assays would reduce the amount of separative work required to produce the equivalent amount of enriched uranium, but would increase the need for uranium enrichment plant feed (concentrates), effectively transferring the pressure to that part of the industry. Because of the lead time of five to 10 years needed to complete new enrichment plants, the planning of additional capacity must begin fairly soon.

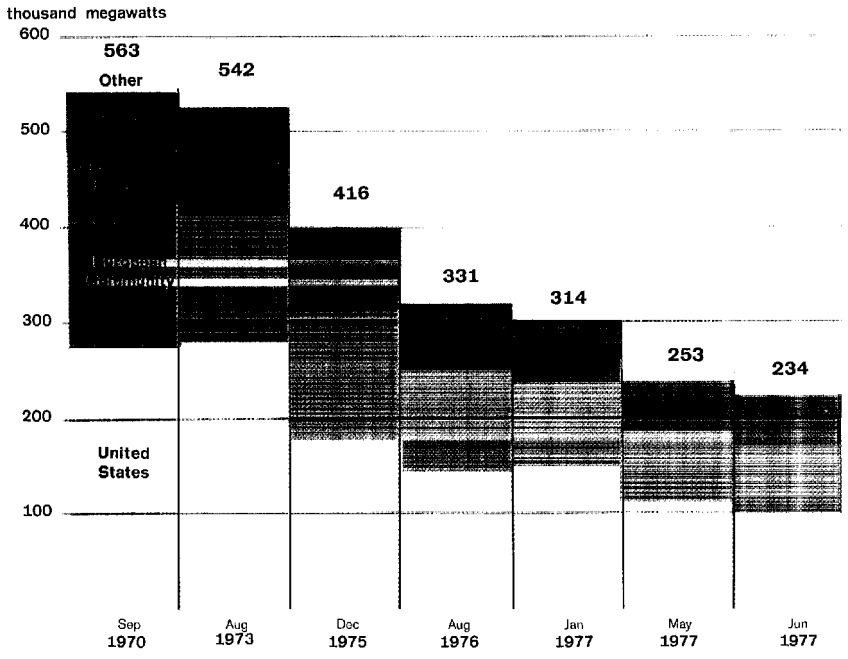
Even so, the uncertainty associated with nuclear power development will probably continue to cloud the enrichment market picture. Many firms are reluctant to commit themselves to plants that may not be needed or would be subject to obsolescence by technological developments.

10. NUCLEAR ENERGY PROSPECTS IN THE DEVELOPED COUNTRIES IN 1985

Projections of nuclear electric generating capacity in the developed countries continue to be revised downward. The International Energy Agency (IEA) now places OECD nuclear capacity in 1985 at only 253,000 megawatts (MW), down sharply from the OECD projection of 314,500 MW published in its *World Energy Outlook* (January 1977). CIA now projects 233,500 MW, the annual equivalent of 6.2 million b/d of oil.

The latest estimates for the developed countries as a whole are 58 percent below those made seven years ago and, more importantly, almost 100,000 MW below last year's projections. Many countries now realize that earlier estimates were unrealistic, and even "official" government targets have been cut. Japan, which had projected 49,000 MW of capacity in 1985, has lowered its goal to 27,000 to 33,000

OECD Countries
Projections of 1985 Nuclear Generating Capacity by Date of Estimates



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MW. In a recent meeting of European Community ministers, West Germany projected its nuclear capability at 25,000 to 30,000 MW—down from 38,000 MW projected in 1976. We estimate 1985 nuclear capacity in these countries at 23,000 MW and 20,000 MW, respectively.

As with previous downward revisions, explanatory factors include (a) lower forecasts of total electricity demand and hence less need for electric power stations of all types and (b) the inability of electric utilities to raise capital for new construction, a situation aggravated by the rapidly increasing cost of nuclear plants.

These reductions, however, are increasingly attributable to noneconomic factors, notably the growing public debate about the efficacy and desirability of using nuclear energy on a large scale. The IEA's Nuclear Sub-Group of the Standing Group on Long-Term Cooperation, responsible for evaluating member countries' nuclear goals, observed that the debate has now expanded from simply "questioning the desirability of constructing nuclear power stations to questioning the reprocessing and waste management aspects of the fuel cycle and has involved political parties and governments to an even greater degree than in previous years." This debate has delayed nuclear powerplant construction and the development of fuel cycle policies. Indeed, several European countries may be faced with government or parliamentary decisions to halt or prevent the start of nuclear energy development.

We are apparently approaching an effective lower limit on capacity estimates. In the past, most projection cutbacks occurred in capacity still in the planning stage. Now, with 93 percent of projected nuclear capacity already in operation or under construction, significant cutbacks are less likely. Nevertheless, further setbacks in nuclear energy production having a variety of new causes are possible. For example, a curtailment of planned fuel reprocessing could cause a shortage of spent fuel storage capacity, and ensuing reactor shutdowns would have a potentially greater impact upon nuclear power generation than delays in new plant construction.

11. MARKET OUTLOOK AND INTERNATIONAL COMPETITION

Only four nuclear power reactors for export were ordered from international suppliers in 1976, a period of rising prices, declining forecasts of future electricity demand, and increasing public debate over the safety and environmental impact of nuclear plants. Although no new orders have been placed so far this year, prospects are brighter for the next 12 months or so.

Since the first nuclear power reactors were sold outside supplying countries in the mid-1950s, a total of 119 export orders or letters of intent have been placed throughout the world, 67 of them with the US companies Westinghouse and General Electric. These sales represent 76,000 megawatts—nearly equivalent to total world nuclear generating capacity at yearend 1976. The US position in the market has declined in recent years, with 59 percent of all orders placed during 1973-76 going to foreign firms. Prior to 1973, foreign suppliers were able to win only one-third of all export orders.

Chronology of Nuclear Powerplant Export Orders

	Total	Before 1970	1970	1971	1972	1973	1974	1975	1976
Total	**119**	**43**	**4**	**12**	**9**	**13**	**19**	**15**	**4**
Westinghouse	37	13	0	8	3	2	6	5	0
General Electric	30	14	2	2	4	3	2	2	1
Atomenergoexport	26	8	2	1	2	4	3	5	1
Kraftwerk Union	9	2	0	1	0	1	2	3	0
Framatome	6	0	0	0	0	0	4	0	2
AECL	4	2	0	0	0	2	0	0	0
ASEA-Atom	2	0	0	0	0	1	1	0	0
Other	5	4	0	0	0	0	1	0	0

The Changing Market

The structure of the nuclear power plant export market has changed radically since 1972. Several countries have developed the ability to compete with US firms on a large scale, not only because of intensified domestic research and development

and transfers of US technology through licensing arrangements, but also because of their ability in many cases to offer very favorable financing or package deals. In several instances, both General Electric and Westinghouse lost contracts despite low bids.

The large markets in Western Europe and Japan have largely been captured by local suppliers, and, with the possible exceptions of Spain, Italy, and Scandinavia, the nuclear export market is now confined to the less developed countries. Of the 25 export orders that may be awarded in the next year or so, more than half are expected from LDCs.

Competing with US firms for business abroad are six companies: one each in Canada, France, Sweden, and the USSR and two in West Germany. Only two are licensees of US technology. Stagnation in domestic ordering is causing suppliers to look more and more to the export market in order to maintain employment and earnings.

Key International Suppliers

Framatome is the French licensee of Westinghouse and manufactures a pressurized water reactor (PWR). The majority shareholder is the French steel company, Creusot-Loire. Minority interests are held by the French Atomic Energy Commission (30 percent), Westinghouse (15 percent), and the Empain-Schneider group (4 percent). Framatome, the sole builder of conventional nuclear power plants in France since the industry was reorganized in 1975, is aiming at the development of a 1,300-megawatt PWR system of its own design when its license agreement with Westinghouse runs out in 1982. Its most recent order, for two reactors in South Africa, came in 1976 after intense competition with West Germany and a US-Dutch-Swiss consortium. It is actively trying to sell more reactors abroad and appears likely to gain orders for at least two units in South Korea and possibly one in Pakistan in the near future.

Kraftwerk Union (KWU) began as a joint venture of the West German firms Siemens and AEG-Telefunken. It was formed in 1969 for the purpose of marketing complete fossil-fueled and nuclear power stations and associated components. In January 1977, AEG dropped out of KWU with Siemens picking up its 50-percent share. Although originally a Westinghouse licensee, KWU now sells PWR systems of its own design. Since its formation—prior to 1969, Siemens sold a reactor to

Nuclear Powerplant Export Orders[1]

Supplier	Unit Name and Type[2]	Capacity (Megawatts Electrical Net)	Country	Ordered	Operation	Status
ASEA-Atom (Sweden)	Olkiluoto-1 (BWR)	660	Finland	1973	1979	U/C[3]
	Olkiluoto-2 (BWR)	660	Finland	1974	1980	U/C
Atomenergoexport (USSR)	Rheinsberg (PWR)	70	East Germany	1956	1966	Oper.[4]
	Greifswald-1 (PWR)	408	East Germany	1965	1974	Oper.
	Greifswald-2 (PWR)	408	East Germany	1965	1975	Oper.
	Paks-1 (PWR)	408	Hungary	1967	1980	U/C
	Paks-2 (PWR)	408	Hungary	1967	1981	U/C
	Kozloduy-1 (PWR)	408	Bulgaria	1967	1974	Oper.
	Kozloduy-2 (PWR)	408	Bulgaria	1967	1975	Oper.
	Loviisa-1 (PWR)	408	Finland	1969	1977	Oper.
	Bohunice-1 (PWR)	408	Czechoslovakia	1970	1978	U/C
	Bohunice-2 (PWR)	408	Czechoslovakia	1970	1979	U/C
	Loviisa-2 (PWR)	408	Finland	1971	1979	U/C
	Dukovany-1 (PWR)	408	Czechoslovakia	1972	1980	U/C
	Dukovany-2 (PWR)	408	Czechoslovakia	1972	1981	U/C
	Greifswald-3 (PWR)	408	East Germany	1973	1978	U/C
	Greifswald-4 (PWR)	408	East Germany	1973	1979	U/C
	Kozloduy-3 (PWR)	408	Bulgaria	1973	1980	U/C
	Kozloduy-4 (PWR)	408	Bulgaria	1973	1980	U/C
	Magdeburg-1 (PWR)	408	East Germany	1974	1980	U/C
	Magdeburg-2 (PWR)	408	East Germany	1974	1980	U/C
	Zarnowieckie-1 (PWR)	408	Poland	1974	NA[5]	Planned
	Paks-3 (PWR)	408	Hungary	1975	NA	Planned
	Paks-4 (PWR)	408	Hungary	1975	NA	Planned
	Olt (PWR)	408	Romania	1975	NA	Planned
	Cienfuegos-1 (PWR)	408	Cuba	1975	NA	Planned
	Cienfuegos-2 (PWR)	408	Cuba	1975	NA	Planned
	Zarnowieckie-2 (PWR)	408	Poland	1976	NA	Planned
Atomic Energy of Canada Limited	Rajasthan-1 (PHWR)	200	India	1963	1972	Oper.
	Rajasthan-2 (PHWR)	200	India	1967	1978	U/C
	Wolsung-1 (PHWR)	629	South Korea	1973	1982	U/C
	Rio Tercero (PHWR)	600	Argentina	1973	1981	U/C
Babcock-Brown Boveri Reaktor (West Germany)	Remerschen (PWR)	1,247	Luxembourg	1974	NA	Planned
Canadian General Electric	Kanupp (PHWR)	125	Pakistan	1965	1972	Oper.
Framatome (France)	Tihange-2 (PWR)	910	Belgium	1974	1980	U/C
	Doel-3 (PWR)	910	Belgium	1974	1980	U/C
	Iran-3 (PWR)	900	Iran	1974	1983	U/C
	Iran-4 (PWR)	900	Iran	1974	1984	U/C
	Koeburg-1 (PWR)	922	South Africa	1976	1982	U/C
	Koeburg-2 (PWR)	922	South Africa	1976	1983	U/C

Nuclear Powerplant Export Orders[1]
(Continued)

Supplier	Unit Name and Type[2]	Capacity (Megawatts Electrical Net)	Country	Ordered	Operation	Status
The General Electric Co. (UK)	Tokai-1 (Magnox)	159	Japan	1960	1966	Oper.
General Electric (US)	Kahl VAK (BWR)	15	West Germany	1958	1960	Oper.
	Tokai JDPR-2 (BWR)	10	Japan	NA	1963	Oper.
	Garigliano (BWR)	150	Italy	1959	1964	Oper.
	Gundremmingen (BWR)	237	West Germany	1962	1967	Oper.
	Dodewaard (BWR)	52	Netherlands	1963	1969	Oper.
	Tarapur-1 (BWR)	190	India	1963	1969	Oper.
	Tarapur-2 (BWR)	190	India	1963	1969	Oper.
	Garona (BWR)	440	Spain	1965	1971	Oper.
	Tsuruga-1 (BWR)	340	Japan	1965	1970	Oper.
	Fukushima-1 (BWR)	439	Japan	1966	1971	Oper.
	Muehleberg (BWR)	306	Switzerland	1966	1972	Oper.
	Fukushima-2 (BWR)	760	Japan	1967	1974	Oper.
	Caorso (BWR)	800	Italy	1969	1977	U/C
	Chin-shan-1 (BWR)	604	Taiwan	1969	1978	U/C
	Chin-shan-2 (BWR)	604	Taiwan	1970	1979	U/C
	Kaiseraugst (BWR)	925	Switzerland	1970	NA	Planned
	Fukushima-6 (BWR)	1,100	Japan	1971	1979	U/C
	Tokai-2 (BWR)	1,100	Japan	1971	1978	U/C
	Laguna Verde-1 (BWR)	654	Mexico	1972	1982	U/C
	Leibstadt (BWR)	942	Switzerland	1972	1982	U/C
	Kuo-sheng-1 (BWR)	951	Taiwan	1972	1980	U/C
	Kuo-sheng-2 (BWR)	951	Taiwan	1972	1981	U/C
	Laguna Verde-2 (BWR)	654	Mexico	1973	1983	U/C
	Cofrentes (BWR)	930	Spain	1973	1981	U/C
	Montalto di Castro-1 (BWR)	982	Italy	1973	1983	U/C
	Montalto di Castro-2 (BWR)	982	Italy	1974	1984	U/C
	Graben (BWR)	1,140	Switzerland	1974	NA	Planned
	Valdecaballeros-1 (BWR)	977	Spain	1975	NA	Planned
	Valdecaballeros-2 (BWR)	977	Spain	1975	NA	Planned
	Santillan (BWR)	970	Spain	1976	NA	Planned
Groupement Constructeurs Francais	Vandellos-1 (GCR)	480	Spain	1967	1972	Oper.
Kraftwerk Union (West Germany)	Atucha-1 (PHWR)	319	Argentina	1968	1974	Oper.
	Borssele (PWR)	450	Netherlands	1969	1973	Oper.
	Tullnerfeld (BWR)	692	Austria	1971	1978	U/C
	Goesgen-Daeniken (PWR)	920	Switzerland	1973	1979	U/C
	Bushehr-1 (PWR)	1,196	Iran	1974	1981	U/C
	Bushehr-2 (PWR)	1,196	Iran	1974	1982	U/C
	Angra-dos-Reis-2 (PWR)	1,245	Brazil	1975	1983	U/C
	Angra-dos-Reis-3 (PWR)	1,245	Brazil	1975	1984	U/C
	Trillo-1 (PWR)	990	Spain	1975	1982	U/C
The Nuclear Power Group (UK)	Latina (Magnox)	200	Italy	1958	1964	Oper.

Nuclear Powerplant Export Orders[1]
(Continued)

Supplier	Unit Name and Type[2]	Capacity (Megawatts Electrical Net)	Country	Ordered	Oper-ation	Status
Westinghouse (US)	Mol BR-3 (PWR)	10	Belgium	1956	1962	Oper.
	Trino Vercellese (PWR)	247	Italy	1958	1965	Oper.
	Chooz SENA (PWR)	270	France	1961	1967	Oper.
	Jose Cabrera (PWR)	153	Spain	1964	1968	Oper.
	Beznau-1 (PWR)	350	Switzerland	1965	1969	Oper.
	Kori-1 (PWR)	564	South Korea	1965	1977	Oper.
	Mihama-1 (PWR)	320	Japan	1966	1970	Oper.
	Beznau-2 (PWR)	350	Switzerland	1967	1972	Oper.
	Ringhals-2 (PWR)	822	Sweden	1968	1975	Oper.
	Doel-1 (PWR)	390	Belgium	1969	1975	Oper.
	Doel-2 (PWR)	390	Belgium	1969	1976	Oper.
	Tihange-1 (PWR)	870	Belgium	1969	1975	Oper.
	Takahama-1 (PWR)	781	Japan	1969	1974	Oper.
	Angra-dos-Reis-1 (PWR)	626	Brazil	1971	1979	U/C
	Ohi-1 (PWR)	1,122	Japan	1971	1978	U/C
	Ohi-2 (PWR)	1,122	Japan	1971	1978	U/C
	Almaraz-1 (PWR)	902	Spain	1971	1977	U/C
	Almaraz-2 (PWR)	902	Spain	1971	1979	U/C
	Lemoniz-1 (PWR)	902	Spain	1971	1978	U/C
	Lemoniz-2 (PWR)	902	Spain	1971	1980	U/C
	Ringhals-3 (PWR)	900	Sweden	1971	1979	U/C
	Ringhals-4 (PWR)	900	Sweden	1972	1979	U/C
	Asco-1 (PWR)	902	Spain	1972	1979	U/C
	Asco-2 (PWR)	902	Spain	1972	1980	U/C
	Krsko (PWR)	615	Yugoslavia	1973	1980	U/C
	ENEL-5 (PWR)	952	Italy	1973	NA	Planned
	Doel-4 (PWR)	1,006	Belgium	1974	NA	Planned
	Tihange-3 (PWR)	1,006	Belgium	1974	1983	U/C
	ENEL-7 (PWR)	952	Italy	1974	NA	Planned
	Kori-2 (PWR)	605	South Korea	1974	1983	U/C
	TPC-5 (PWR)	907	Taiwan	1974	1983	U/C
	TPC-6 (PWR)	907	Taiwan	1974	1984	U/C
	Bagac-1 (PWR)	626	Philippines	1975	1982	U/C
	Vandellos-2 (PWR)	1,000	Spain	1975	1982	U/C
	Sayago-1 (PWR)	1,000	Spain	1975	NA	Planned
	Escatron-1 (PWR)	1,200	Spain	1975	NA	Planned
	Escatron-2 (PWR)	1,200	Spain	1975	NA	Planned

[1] Firm orders or letters of intent.
[2] PWR (pressurized water reactor); BWR (boiling water reactor); PHWR (pressurized heavy water or CANDU reactor); and GCR (gas-cooled reactor).
[3] U/C: under construction.
[4] Oper.-operational.
[5] NA-not available or not applicable.

Argentina—KWU has built or is building reactors in West Germany, Austria, Brazil, Iran, the Netherlands, Spain, and Switzerland. Although it has been two years since KWU has received a nuclear powerplant order, either domestic or export, the company will provide six more units to Brazil as part of the comprehensive agreement between Bonn and Brasilia. Largely as a result of the Brazilian orders and the two plants KWU is now building in Iran, the company reported the first profit in its eight-year history in 1976. KWU is bidding for additional orders in Spain and has had extensive contacts with Nigeria and Portugal. For the foreign market, KWU has developed standardized nuclear plant designs for 600-, 900-, and 1,300-megawatt reactors and is developing a 100- to 300-megawatt, dual-purpose (water desalinization and electricity production) system particularly suited to less developed countries. In this regard, KWU is in an advantageous position, as no other reactor manufacturer (US or foreign) has such a comprehensive capability at present.

Babcock-Brown Boveri Reaktor (BBR) was founded in 1971 to adapt the PWR system of Babcock and Wilcox (US) to West German and European market requirements. Babcock and Wilcox and its German subsidiary control 74 percent of BBR, with the remainder belonging to Brown, Boveri, and Company of Switzerland. With the exception of an order for a large PWR in Luxembourg, construction of which has not yet begun, BBR's activities are concentrated in West Germany.

ASEA-Atom is jointly owned by the Swedish electrical firm Allmanna Svenska Elektriska Aktiebolaget (ASEA) and the Swedish government. It markets boiling water reactor (BWR) systems of its own design, and is, with KWU, one of only two manufacturers of light water reactors in the Free World not under license by a US company. In addition to five reactors in operation and two under construction in Sweden, ASEA-Atom has landed export orders for two reactors in Finland and has actively bid on plants elsewhere in Europe.

Atomic Energy of Canada Limited (AECL), wholly owned by the Canadian government, formed its Nuclear Power Plant Division in 1958. Its principal activity is the engineering and constructing of reactors of the CANDU (Canadian deuterium-uranium) design which utilize natural uranium fuel. The technical designation for the CANDU system is pressurized heavy water reactor (PHWR) because the reactor uses heavy water (deuterium oxide, D_2O) instead of ordinary or light water as moderator and coolant. AECL is actively marketing overseas a 600-megawatt version of its CANDU reactor, several of which are now being built in Canada. Despite its advantages (natural rather than enriched fuel, on-line reloading,

and high reliability), AECL is building only two reactors overseas, one each in Argentina and South Korea. The firm lost the opportunity for a second unit in South Korea because of lack of Canadian financing but may receive another order from Argentina.

Atomenergoexport (AEE) is the export arm of the Soviet nuclear power industry. Together with its predecessor, Technopromexport, it has sold 26 reactors abroad, all but two to Communist countries. The standard product is the so-called VVER-440 pressurized water reactor. Technical plans and major reactor components are supplied by the USSR, with the receiving country providing additional equipment such as turbine-generators. Although the Soviets want to market a 1,000-megawatt PWR, potential customers are waiting to see how this reactor performs in the Soviet Union; the first is due on line at Novovoronezh in 1978. AEE has never actually competed with Western reactor suppliers for orders either in Eastern Europe or elsewhere, except with Sweden's ASEA-Atom for its Finnish contracts.

Potential Near-Term Nuclear Powerplant Export Orders

Country	Unit Name and Type	Capacity (Megawatts)	Likely Suppliers
Argentina	Atucha-2 (PHWR)	Undetermined	AECL
Brazil	Undetermined (PWR)	1,200	Kraftwerk Union
	Undetermined (PWR)	1,200	Kraftwerk Union
Egypt	Sidi Krier (PWR)	600	Westinghouse
Finland	Loviisa-3 (PWR)	1,000	Atomenergoexport
Greece	Undetermined (PWR/BWR)	600	Undetermined
Iran	Isfahan-1 (PWR)	1,200	Kraftwerk Union
	Isfahan-2 (PWR)	1,200	or US supplier
Israel	Nitzamin-1 (PWR/BWR)	960	US supplier
	Nitzamin-2 (PWR/BWR)	960	US supplier
Libya	Undetermined (PWR)	400-600	French or Soviet supplier
Nigeria	Undetermined (PWR)	600	Kraftwerk Union
Pakistan	Chasma (PWR)	600	Framatome
Philippines	Bagac-2 (PWR)	600	Westinghouse
Portugal	Ferrol (PWR)	600-1,000	Kraftwerk Union
South Korea	Wolsung-2 (PWR/PHWR)	600	Framatome or AECL
	Kori-3 (PWR)	900	Framatome or Combustion
	Kori-4 (PWR)	900	Engineering (US)
Spain	Regodola (PWR/BWR)	900	Undetermined
	Trillo-2 (PWR)	1,000	Kraftwerk Union
	Vandellos-3 (PWR)	1,000	Westinghouse
	Sayago-2 (PWR)	1,000	Westinghouse
Thailand	Sri Racha (PWR/BWR)	600	Westinghouse or GE
Turkey	Akkuyu (PWR/BWR)	600	Undetermined

US firms may retain about half of the export market for nuclear powerplants over the next several years, despite increased competition from foreign reactor suppliers. Once agreements for cooperation are approved, US companies are virtually assured of orders from Egypt and Israel. Westinghouse appears likely to sign more contracts with Spain and possibly the Philippines. South Korea reportedly is interested in picking up two units recently canceled by a US utility, and US firms are in the running for first plants in Greece, Thailand, and Turkey. Nonetheless, the US position as the major export supplier has been permanently eroded. In addition to stronger competition, continued delays in the granting of export licenses for nuclear reactors, components, and fuel have further weakened the position of US firms.

12. NUCLEAR PLANT PERFORMANCE: SOME IMPROVEMENT IN 1977

Not only are projections of future nuclear electric generating capacity being revised downward, but the performance of nuclear plants already in operation continues to fall well below expectations. During the first five months of 1977, the average plant capacity factor for all Free World power reactors 200 MW and larger was 63.5 an improvement from 59.6% in 1976 but considerably below the 70%-80% considered technically feasible on a sustained basis.

Plant capacity factor is the ratio of the average power load of an electric powerplant to its rated capacity. A 1,000 MW plant could produce 8.76 billion kilowatt-hours (kWh) per year if operated continuously, but refueling, repairs, and the like rarely make this possible. If such a plant actually produced 5 billion kWh during one year, its capacity factor would be 57.1%.

Capacity factors for the three major reactor types in operation and under construction (pressurized water reactor, boiling water reactor, and CANDU or pressurized heavy water reactor) have not been appreciably different in recent years. Most of the variations can be explained by unusual circumstances at particular plants, which have tended to distort individual reactor type averages. After a relatively poor performance in 1975, the PHWR demonstrated a higher capacity factor in 1976, primarily because of its on-line refueling capability but its record so far in 1977 has not been as good. The time required for annual inspection, maintenance, and refueling of a light water reactor (PWR or BWR) is normally about six weeks and necessitates the shutdown of the plant. This action reduces the theoretically attainable annual capacity factor for these plants to 88.5%.

Free World: Nuclear Powerplant Capacity Factors[1]

	PWR		BWR		PHWR		All Types[2]	
	Percent	Number of Units	Percent	Number of Units	Percent	Number of Units	Percent	Number of Units
1973	58.1	16	61.4	19	78.6	4	58.2	59
1974	56.2	24	50.3	20	73.9	5	56.1	69
1975	65.3	36	46.1	32	63.8	7	56.9	96
1976	60.5	46	56.1	35	82.4	7	59.6	109
1977[3]	65.1	52	59.6	39	73.0	8	63.5	122

[1] Including only reactors 200 MW and larger that were in commercial service for the entire year indicated.
[2] Including reactor types other than those shown.
[3] First five months only.

Nuclear powerplants continue to be plagued by a variety of problems, most of which are also associated with conventional thermal power stations. Recent problems include vibration and resulting damage in turbines; generator malfunctions; leakage or corrosion in pumps, valves, and associated piping; and foreign objects in cooling water supplies. Unusual factors, such as the fire at a large US plant and the discovery of structural defects in a West German reactor, further exacerbate the poor performance record of nuclear plants. Nontechnical problems also are becoming more prevalent. Several reactors undergoing extensive modifications owing to revisions in regulatory requirements are licensed for operation at only partial power, and legal actions by environmental groups are restricting output from a number of plants.

The introduction of larger and presumably more efficient nuclear units in recent years has so far failed to improve overall performance averages. Although

Free World: Plant Capacity Factors for Large Power Reactors[1]

	Capacity (MW Gross)	Percent			
		1974	1975	1976	1977[2]
United States					
Zion-1 (PWR)	1,085[3]	39.2	55.1	51.7	85.8
Zion-2 (PWR)	1,085[3]	[4]	53.8	52.7	41.4
Browns Ferry-1 (BWR)[5]	1,098	[4]	14.7	14.0	76.8
Browns Ferry-2 (BWR)[5]	1,098	[4]	15.2	16.7	78.9
Browns Ferry-3 (BWR)	1,098	[4]	[4]	[4]	15.2
Peach Bottom-2 (BWR)	1,098	[4]	55.1	60.1	52.3
Peach Bottom-3 (BWR)	1,098	[4]	57.3	65.2	22.4
Cook-1 (PWR)	1,060	[4]	[4]	76.0	42.7
Indian Point-3 (PWR)	1,005	[4]	[4]	[4]	77.4
West Germany					
Biblis-A (PWR)[6]	1,200	[4]	[4]	51.6	65.5

[1] Reactors larger than 1,000 MW.
[2] First five months only.
[3] Reactor power limited to 85% of rated capacity by the US Nuclear Regulatory Commission because units are "first-of-a-kind."
[4] Reactor not in service for the entire year.
[5] Reactor out of service for 17 months following a fire in the third unit under construction.
[6] Reactor out of service for four months following the discovery of structural problems in plant components.

operating experience with large power reactors is extremely limited (only 10 reactors larger than 1,000 MW were in service for the period January-May 1977), preliminary indications are that little improvement can be expected in the near future. Moreover, the increase in plant performance as a result of "aging-in," i.e., improving capacity factor after several years' operation, has yet to be demonstrated at most facilities. Between 1973 and 1975, only 19% of Free World power reactors in service three years or longer showed a consistent improvement in capacity factor.

A considerable loss in energy output results from operation well below maximum attainable levels. If installed nuclear generating capacity in the Free World (about 73,000 MW at yearend 1976) had operated at a 75% plant capacity factor in 1976 rather than about 60%, the net addition to energy supply would have been equivalent to 480,000 barrels per day (b/d) of oil. At projected capacity levels in 1980 (about 150,000 MW) the impact of poor performance would be much greater—nearly 1 million b/d of oil equivalent.

The arguments in favor of increased use of nuclear energy to reduce import dependence of the major oil-consuming countries are becoming less convincing. Construction delays, siting problems, inflation, and uncertainty over fuel reprocessing and uranium/plutonium recycling reduced nuclear power's competitive edge over coal in most countries, and poor performance is contributing to shifts in relative economics. Base-loaded coal-fired generating plants have consistently achieved a higher level of performance than nuclear powerplants.

13. A NUCLEAR ENERGY GLOSSARY

Blanket	A layer of fertile material, such as uranium-238 or thorium-232, placed around the fissionable material in a nuclear reactor.
Boiling water reactor (BWR)	A reactor in which water, used as both coolant and moderator, is allowed to boil in the core. The resulting steam can be used directly to drive a turbine.
Black oxide	Uranous uranyl oxide (U_3O_8).
Breeder	A reactor that produces fissionable material as well as consuming it, especially one that creates more than it consumes. The new fissionable material is created by capture in fertile materials of neutrons from fission.
Brown oxide	Uranium dioxide (UO_2).
Burnup	A measure of fuel consumption in a nuclear reactor. It is usually expressed as the amount of energy produced per unit weight of fuel in the reactor—for example, megawatt-days (thermal) per ton (MWD/t).
CANDU reactor	Canadian deuterium uranium reactor; a natural uranium-fueled, heavy-water moderated and cooled, pressure tube reactor of Canadian design.
Chain reaction	A reaction that stimulates its own repetition. In a fission chain reaction, a fissionable nucleus absorbs a neutron and then fissions, releasing additional neutrons. These in turn can be absorbed by other fissionable nuclei, releasing still more neutrons. A fission chain reaction is self-sustaining when the neutrons produced by each fissioning atom cause at least one other atom to fission.

Cladding	A protective coating for reactor fuel materials to prevent corrosion or erosion by the reactor coolant, to increase the strength of the material, and to contain fission products to prevent contamination of the coolant.
Containment	The provision of a gastight shell or other enclosure around a reactor to confine fission products that otherwise might be released to the atmosphere in the event of an accident.
Control rod	A rod, plate, or tube containing a material that readily absorbs neutrons which is used to control the power of a nuclear reactor.
Coolant	A substance circulated through a nuclear reactor to remove or transfer heat. Common coolants are water, heavy water, air, carbon dioxide, and liquid sodium.
Core	The central portion of the nuclear reactor containing fuel elements, and usually the moderator, but not the reflector.
Criticality	The state of a nuclear reactor sustaining a chain reaction. The date of criticality is an important milestone in the commissioning of a nuclear power reactor.
Depleted uranium	Uranium having a smaller percentage of uranium-235 than the 0.71 percent found in natural uranium. It is obtained from spent fuel or as byproduct tails of uranium enrichment.
Deuterium	An isotope of hydrogen (symbol D). Approximately twice as heavy as normal hydrogen, deuterium occurs naturally as one atom to 6,500 atoms of normal hydrogen.
Enriched uranium	Uranium in which the percentage of the fissionable isotope, uranium-235, has been artificially increased above the naturally occurring percentage (0.71 percent). Most light water reactors use uranium enriched to 2 to 4 percent as fuel.

Enrichment	A process by which the relative abundances of the isotopes of a given element are altered, thus producing a form of the element which has been enriched in one particular isotope. In the enrichment process, the natural feed is separated into a product stream (enriched) and a tails or waste stream (depleted).
Fertile material	A material, not itself fissionable, which can be converted into a fissile material by irradiation in a reactor. Two basic fertile materials are uranium-238 and thorium-232, which are converted into fissile plutonium-239 and uranium-233, respectively, when these materials capture neutrons.
Fissile material	Any material fissionable by neutrons, principally uranium-233, uranium-235, and plutonium-239.
Fission	The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons.
Fission fragments	The two nuclei formed by the fission of a nucleus. Fission fragments are nuclei of elements of medium atomic weight and are radioactive.
Fission products	Fission fragments plus the material formed by their radioactive decay.
Fuel	Fissionable material used or usable to produce energy in a nuclear reactor.
Fuel cycle	The series of steps involved in supplying fuel for nuclear power reactors. The "front end" of the nuclear fuel cycle includes uranium mining, concentration, conversion, enrichment, and the original fabrication of fuel elements. The "back end" of the fuel cycle includes the chemical reprocessing to recover the fissionable material remaining in spent fuel, re-enrichment of the fuel material, refabrication into new fuel elements, and radioactive waste disposal.

Fuel element	A rod, tube, plate, or other mechanical form into which nuclear fuel is fabricated for use in a reactor.
Fuel reprocessing	The processing of spent (irradiated) reactor fuel to recover unused fissionable material.
Gas centrifuge process	A method of isotope separation in which the heavier gaseous atoms or molecules are separated from lighter ones by centrifugal force.
Gaseous diffusion process	A method of isotope separation based on the fact that gaseous atoms or molecules with different masses will diffuse through a porous barrier (or membrane) at different rates.
Green salt	Uranium tetrafluoride (UF_4).
Heavy water	(Symbol D_2O). Water containing significantly more than the natural proportion (one in 6,500) of deuterium to normal hydrogen.
Isotope	One of two or more atoms with the same atomic number; that is, the same chemical element, but with different atomic weights. Uranium-235 and uranium-238 are examples of isotopes. Isotopes usually have nearly identical chemical properties, but somewhat different physical properties.
Light water	Ordinary water (H_2O), as distinguished from heavy water (D_2O).
Light water reactor (LWR)	A reactor cooled and moderated by light water; for example, a boiling water reactor or a pressurized water reactor.
Load factor	The ratio of average load carried by an electric powerplant or system during a specific period to its peak load during that period.

Magnox reactor	A gas-cooled, graphite-moderated reactor developed in the United Kingdom and France. The first commercial reactors of this type are known in the United Kingdom as magnox reactors from the name of a magnesium alloy used as fuel cladding material.
Moderator	A material, such as light water, heavy water, or graphite, used in a reactor to slow down high-velocity neutrons, thus increasing the likelihood of further fission.
Natural uranium	Uranium as found in nature, containing 99.28 percent uranium-238, 0.71 percent uranium-235, and 0.01 percent uranium-234.
Neutron	An uncharged elementary particle found in the nucleus of every atom heavier than hydrogen. Neutrons sustain the fission chain reaction in a nuclear reactor.
Nuclear energy	The energy liberated by a nuclear reaction (fission or fusion) or by radioactive decay.
Nuclear reactor	A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential component is a core with fissionable fuel. It usually has a moderator, a reflector, shielding, coolant, and control mechanisms.
Nuclear steam supply system (NSSS)	That portion of a nuclear powerplant containing the nuclear reactor and its associated equipment, but excluding such items as water supply and ventilation and emergency power supply systems, as well as the conventional electrical equipment such as turbines and generators found in all powerplants. The NSSS plus related equipment (excluding conventional equipment) is sometimes called the "nuclear island."
Orange oxide	Uranium trioxide (UO_3).
Plant factor	The ratio of the average power load of an electric powerplant to its rated capacity, sometimes called "capacity factor."

Plutonium	(Symbol, Pu). A heavy, radioactive, man-made, metallic element whose most important isotope, plutonium-239, is a primary fissile material and is produced by neutron irradiation of uranium-238. Plutonium is used for reactor fuel and in nuclear weapons.
Plutonium recycle	A procedure whereby plutonium, recovered from spent fuel by reprocessing, can be combined with uranium to manufacture "mixed oxide" fuel elements for use in nuclear reactors. The recycling of plutonium reduces the amount of raw uranium and enrichment required to produce an equivalent amount of nuclear fuel.
Pressure tube reactor	A reactor in which the fuel elements are located inside tubes containing coolant circulating at high pressure. The tube assembly is surrounded by a tank containing the moderator at low pressure.
Pressure vessel	A strong-walled container housing the core of most types of power reactors. It usually contains the moderator, reflector, thermal shield, and control rods.
Pressurized water reactor (PWR)	A power reactor in which heat is transferred from the core to a heat exchanger (steam generator) by water kept under high pressure to achieve high temperature without boiling.
Radioactivity	The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by radiation.
Reflector	A layer of material immediately surrounding a reactor core which scatters back or reflects neutrons that otherwise would escape. The returned neutrons can then cause more fissions to occur. Common reflector materials are graphite, beryllium, and natural uranium.
Separative work unit (SWU)	A measure of the effort required to separate uranium-235 and uranium-238 isotopes in an enrichment plant. An enrichment task may be described in terms of the physical

Separative work unit (SWU) (Continued)	quantities and uranium-235 assays in each of three streams (feed, product, and tails). It is more useful, however, to combine this information into a single number, the amount of separative work, by weighting the importance of each quantity and assay involved. This is accomplished by the use of weights which reflect the importance or "value" of uranium with varying uranium-235 concentrations. The amount of separative work required per unit of product is determined from the feed/product ratio and the value weights. A SWU is not a unit of quantity in physical terms, but is a useful measure for comparisons of enrichment contracts, plant capacities, or enrichment demand, as it is independent of the uranium-235 concentrations involved.
Shielding	A body of material used to reduce the passage of radiation.
Tails assay	The uranium-235 concentration of the waste or tails from a uranium enrichment plant, usually in the range of 0.2 percent to 0.3 percent. The lower the tails assay, the more separative work must be performed to achieve the same degree of enrichment, but, at the same time, the smaller the amount of uranium feed required.
Thorium	(Symbol, Th). A naturally radioactive element whose most abundant isotope, thorium-232, can be transmuted into fissile uranium-233 by neutron irradiation.
Toll enrichment	A procedure whereby a customer supplies natural uranium raw material to an enrichment facility and is charged a "toll" (usually expressed in dollars per SWU) for having his raw material enriched in the fissionable isotope, uranium-235, for eventual use as nuclear fuel.
Uranium	(Symbol, U). A naturally occurring radioactive element whose principal isotopes are uranium-235 (0.71 percent of natural uranium) and uranium-238 (99.28 percent). Uranium-235 is fissionable and uranium-238 is fertile. Natural uranium also includes a minute amount of uranium-234. Uranium is the basic material of nuclear energy.

Uranium concentrate	The product of a uranium ore concentration plant. Uranium concentrates typically assay 65-85 percent uranium expressed as U_3O_8. They are usually in the form of orange oxide (UO_3), black oxide (U_3O_8), or sodium or ammonium diuranate (yellowcake).
Uranium dioxide	(Symbol, UO_2). The most commonly used form of uranium in nuclear fuel; also an intermediate product in the production of uranium tetrafluoride from uranium trioxide. Commonly called brown oxide.
Uranium hexafluoride	(Symbol, UF_6). A volatile compound of uranium and fluorine, produced by fluorination of uranium tetrafluoride. UF_6 is the process gas in most uranium enrichment processes.
Uranium reserves	The quantity of uranium which analysis or geologic and engineering data demonstrate with reasonable certainty to be recoverable from the earth. Uranium reserves have tended to be expressed in a more rigorous form than those of other raw materials. Traditionally, uranium reserves have been specified within various "cost categories," which theoretically represent the cost to mine and concentrate uranium from various deposits. These cost categories, almost universally expressed in dollars per pound of U_3O_8, represent only those costs incurred after geologic investigation, land acquisition, and exploration are complete. No allowance for profit is included. The categories are not "total" costs, nor do they represent prices at which U_3O_8 will be marketed. In international usage, the term *reasonably assured resources* refers to uranium which occurs in known ore deposits of such grade, quantity, and configuration that it could be recovered within the given cost category with current mining and processing technology. *Estimated additional resources* consist of uranium believed to occur in unexplored extensions of known deposits or in undiscovered deposits in known areas of uranium occurrence which could be produced in the given cost range.

Uranium tetrafluoride	(Symbol, UF_4). A solid compound of uranium and fluorine commonly referred to as green salt. UF_4 is an intermediate product in the production of uranium hexafluoride or of natural uranium metal. It is produced by hydrofluorination of uranium dioxide.
Uranium trioxide	(Symbol, UO_3). An intermediate product in the refining of uranium and in the treatment of uranium recovered from fuel reprocessing operations. Also called orange oxide.
Uranous uranyl oxide	(Symbol, U_3O_8). A mixed oxide ($2UO_3 \cdot UO_2$) of uranium known as black oxide. The uranium content of various ores and concentrates is usually expressed, for convenience, in terms of U_3O_8 equivalent.
Waste	Equipment, but usually more specifically, material from nuclear operations which are radioactive and for which there is no further use. Waste is usually classified as high-level waste requiring long-term storage and low-level waste, which, under certain circumstances, can be safely dispersed.
Yellowcake	A term applied to certain products of uranium concentration plants; specifically, those in the form of ammonium diuranate–$(NH_4)_2U_2O_7$–or sodium diuranate–$Na_2U_2O_7$.
Zircaloy	Any of several alloys of zirconium most commonly used as fuel cladding to improve the corrosion resistance, radiation stability, and the temperature range of the fuel.

29 August 1977

MEMORANDUM FOR: Chief, Distribution Section, P&PD/OL

FROM: Chief, Registry and Dissemination Branch, PPG

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