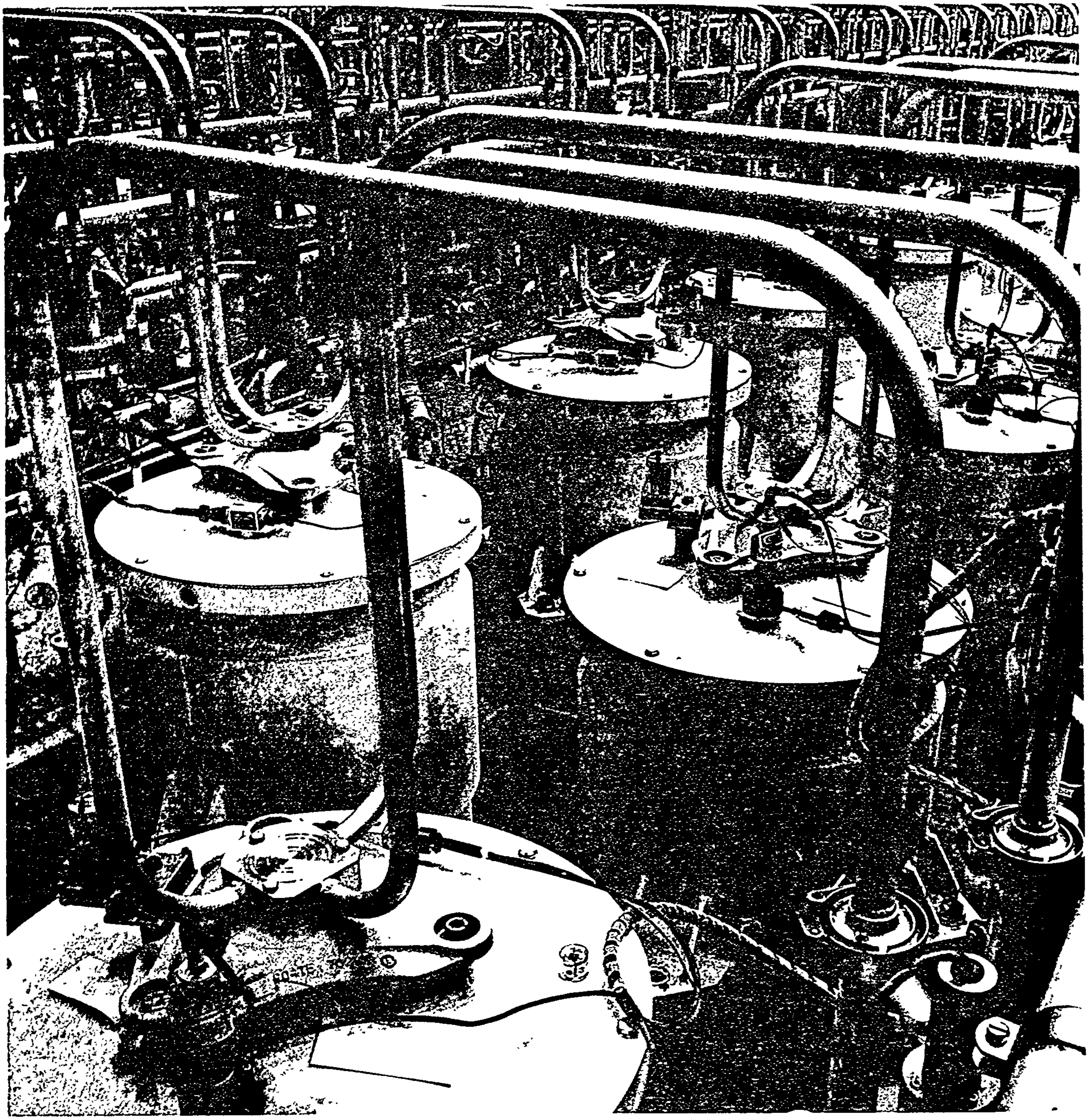
United States

# Gas Centrifuge Program

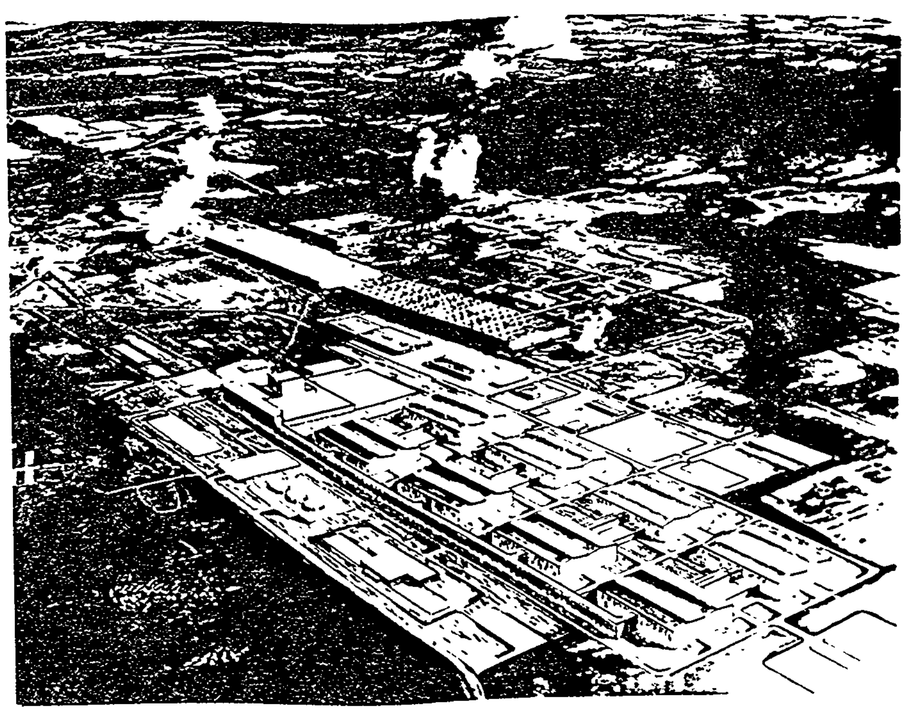
for Uranium Enrichment



COVER: Centrifuges in the Component Test Facility operated for the Department of Energy by Union Carbide Corporation-Nuclear Division at Oak Ridge, Tennessee.

**GAS CENTRIFUGE ENRICHMENT PLANT**

| | |
|---|---|
| Date Announced | April 20, 1977 |
| Start Site Work | 1978 |
| First Production | 1986 |
| Full Production | 1988 |
| Capacity | 8.8 Million SWU Per Year |
| Estimated Cost | $4.2 Billion (1978 Dollars) |



*A view of the Portsmouth Gaseous Diffusion Plant showing an artist's conception of the Gas Centrifuge Enrichment Plant.*

# Introduction

President Carter announced in his energy message of April 1977 that the next U.S. uranium enrichment facility would be a gas centrifuge plant instead of an add-on gaseous diffusion plant as originally planned. The new centrifuge plant will be built near Portsmouth, Ohio, at the site of the existing gaseous diffusion plant operated for the Department of Energy (DOE) by Goodyear Atomic Corporation under the direction of DOE's Division of Uranium Resources and Enrichment through the Oak Ridge Operations Office. The nominal capacity of this new gas centrifuge plant will be 8.8 million separative work units (SWU)* per year, the same as had been planned for the gaseous diffusion plant. This additional capacity will allow long-term operation of the enrichment complex in a manner which reduces the use of natural uranium reserves and will permit the United States to supply enrichment services to additional customers. The capital investment is estimated to be $4.2 billion without allowance for inflation.

In the United States the gas centrifuge process for enriching uranium has been under continuous development for over 20 years. Groups of centrifuges have been operated together in cascades for over 15 years, and high-capacity centrifuges have been operated for more than 5 million machine-hours. The U.S. centrifuge program has progressed to the point that the new plant at Portsmouth, Ohio, will require only tens of thousands of centrifuges, whereas a European centrifuge plant of similar size would require hundreds of thousands of centrifuges. This effort has resulted in a proven technology that is currently economically superior to gaseous diffusion and requires only 4% as much electrical energy.

Private industry is an important part of the program. Centrifuges produced in private manufacturing plants have been successfully operated in government test facilities, and private industry will manufacture all the centrifuges for the full-size plant.

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*A separative work unit (SWU) is a measure of the effort expended in a uranium enrichment plant to separate uranium of a given U-235 content into two components, one having a higher percentage of U-235 and one having a lower percentage of U-235.

# Uranium Enrichment

Uranium as found in nature consists principally of two forms or isotopes,* U-235 and U-238. The U-235 isotope is fissionable, and this property of being able to split and give up heat makes it useful as a fuel in nuclear reactors. The U-235 isotope is present in the amount of only 0.711% by weight in natural uranium. Most of the nuclear power plants in the world today use uranium enriched to approximately 3% U-235 as fuel. There are a number of interrelated steps involved in locating, preparing, using, and disposing of fuel for these reactors. Enrichment, the fourth step in the process, increases the concentration of U-235 from 0.711% to about the 3% required in nuclear reactors.

## U.S. Gaseous Diffusion Complex

Almost all the world's current capacity to produce enriched uranium uses the gaseous diffusion process. The United States built the first gaseous diffusion plant at Oak Ridge, Tennessee, during World War II. Later the Oak Ridge plant was expanded, and two additional plants were built at Paducah, Kentucky, and Portsmouth, Ohio. Under direction of the DOE, the facilities at Oak Ridge and Paducah are operated by Union Carbide Corporation–Nuclear Division, the facility at Portsmouth by Goodyear Atomic Corporation. A $1.5 billion improvement and uprating program is now in progress which will increase the total capacity of these plants by 60% to approximately 27 million SWU per year.

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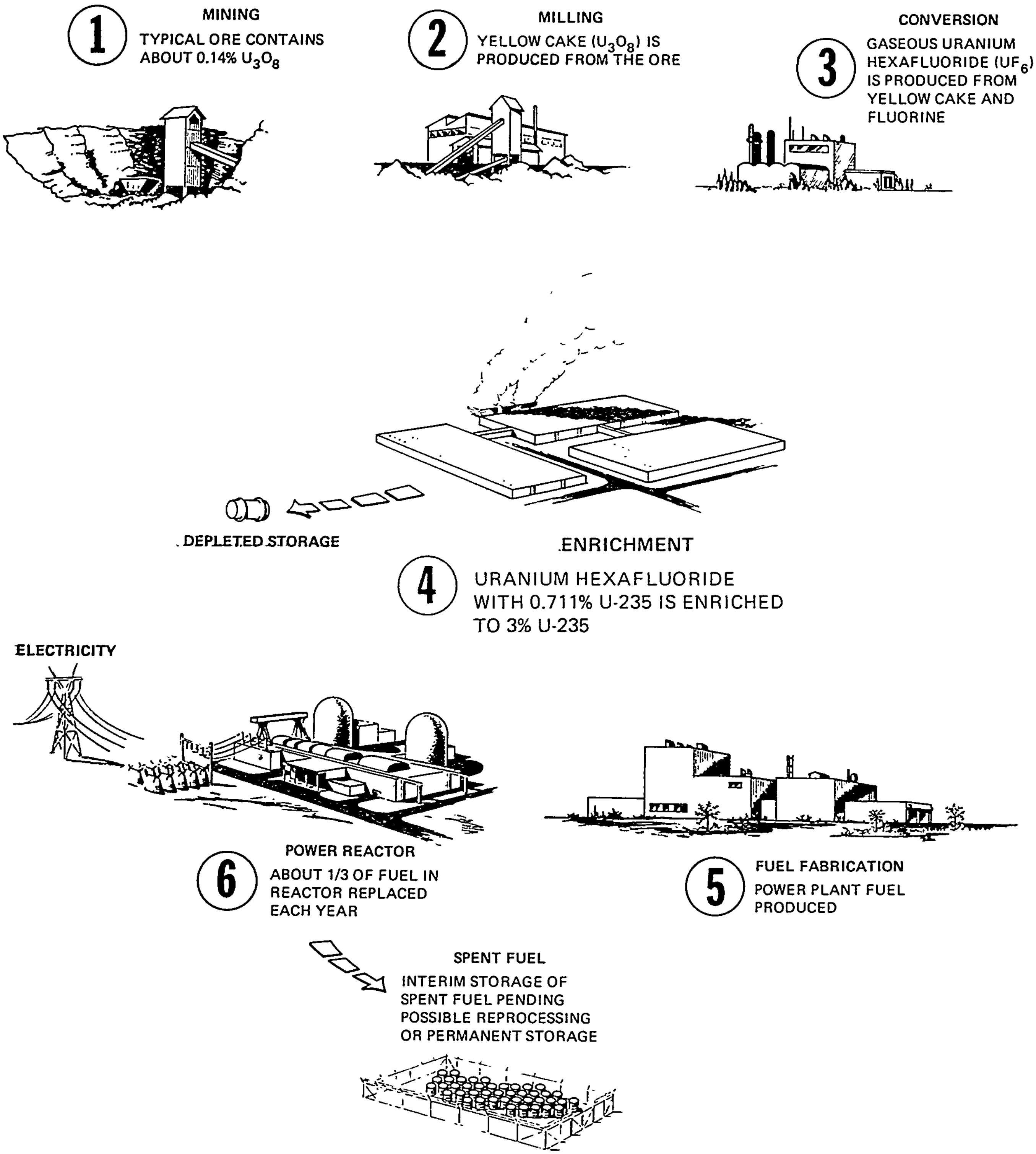
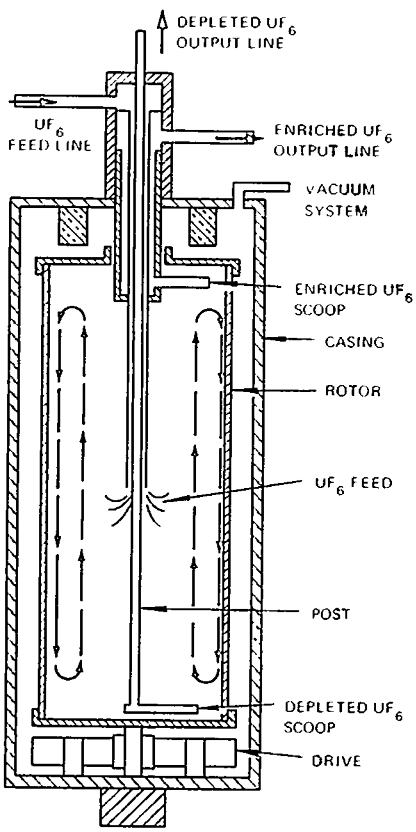
*Isotopes are atoms of the same chemical element, very similar in chemical behavior but distinguishable by radioactive transformations, differences in atomic weight, etc.

# Nuclear Fuel Cycle



# Gas Centrifuge Process

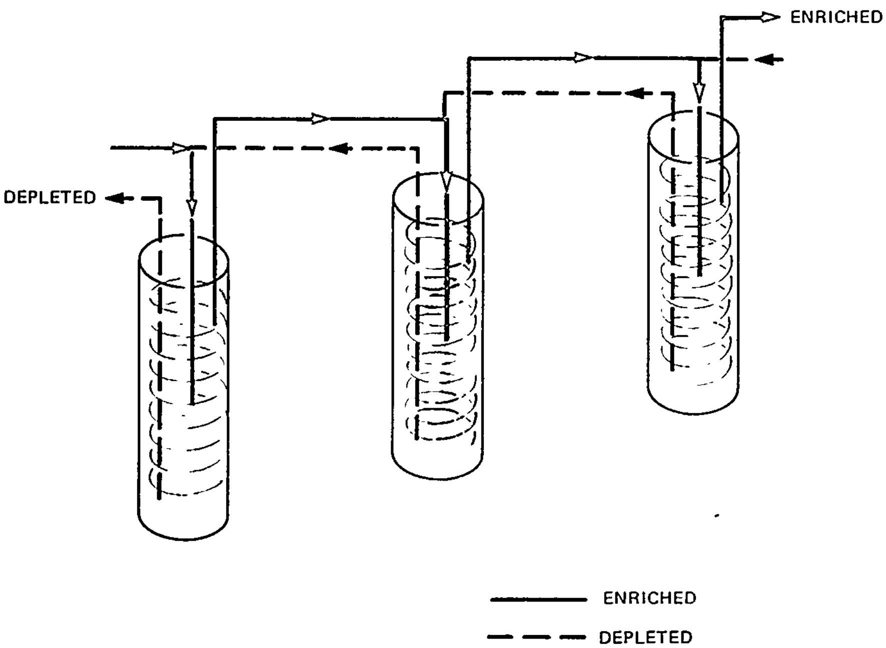



The degree of enrichment in a single centrifuge machine is dependent on the mass difference of the isotopes being separated, the length of the rotor, and most importantly the speed of rotation. In large, high-speed machines it is possible to obtain a degree of enrichment many times that of a diffusion stage. The principle of a gas centrifuge is illustrated at left. Gaseous uranium hexafluoride ($UF_6$) is fed into a rotor which spins at high speed inside an evacuated casing. The gas accelerates to approximately the speed of the rotor. Centrifugal force causes the heavier U-238 molecules to move closer to the wall of the rotor, producing partial separation of the U-235 and U-238 isotopes. This separative effect is increased by an axial countercurrent flow of gas within the centrifuge. Feed is introduced near the middle of the rotor, and enriched and depleted streams are removed near the ends.

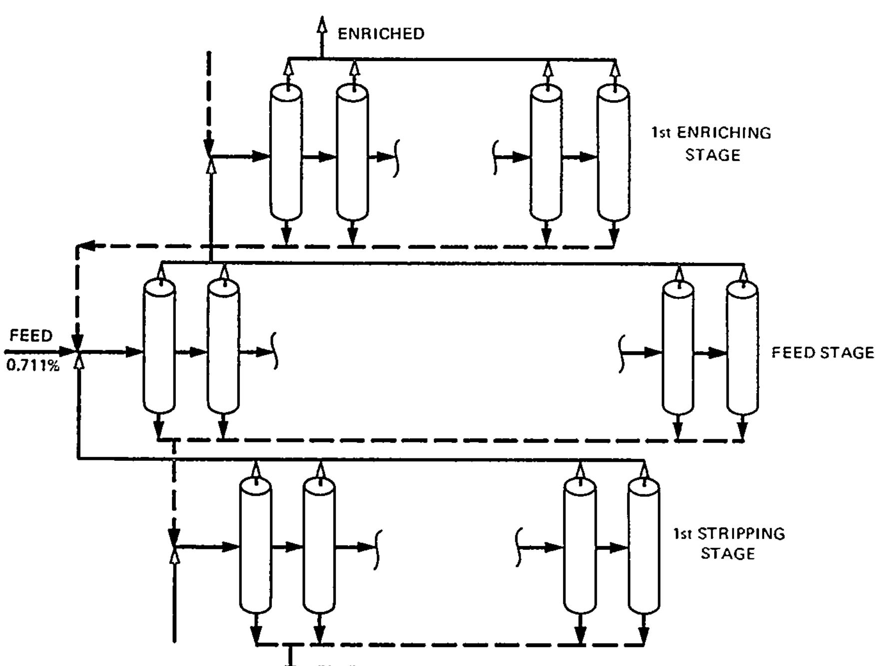
*Schematic representation of a gas centrifuge: The feed, enriched, and depleted lines are stationary. Centrifugal force causes the heavier U-238 molecules to move preferentially to the perimeter of the rotor, producing partial separation of molecules containing U-235 and U-238. This effect is increased by axial flow of the gas within the centrifuge (arrows).*

Since the desired enrichment is not obtained in a single centrifuge, several machines must be connected in a series known as a cascade. The gas flows are illustrated on the next page for a simple cascade. Only a small amount of gas will flow through a single centrifuge. Therefore a large number of machines must be connected in parallel to achieve the total flow necessary for a single stage of enrichment in a large-capacity plant. The arrangement of centrifuges into the stages of a cascade is shown schematically on the next page.

Perhaps the most significant difference between the gaseous diffusion and gas centrifuge processes is power usage. A centrifuge plant requires only about 4% of the power needed for a diffusion plant. For a plant of 8.8 million SWU per year capacity, about 2700 megawatts (MW) of electrical power would be required for a diffusion plant and only about 100 MW for a centrifuge plant. In addition to the energy saved by this lower power demand, corresponding environmental benefits result from lower demands on water resources for cooling.




*In each centrifuge the uranium hexafluoride ($UF_6$) gas is partially separated into the heavier U-238 isotope and the lighter U-235 isotope. The stream enriched in U-235 flows to the next stage of higher enrichment as designated by the blue lines. The stream depleted in U-235 flows to the stage with lower enrichment. A series of stages connected in this manner can produce $UF_6$ enriched in U-235 to the desired assay.*




*Each centrifuge can process only a small amount of $UF_6$. Therefore a number of units must be connected in parallel to achieve the desired throughput. The number of centrifuges per stage is reduced in each succeeding stage as the gas moves from the feed point.*

# History and Background of the Gas Centrifuge

The U.S. government program to develop the gas centrifuge has been directed by the Oak Ridge Operations Office under the Atomic Energy Commission, the Energy Research and Development Administration, and the Department of Energy. The contractors who have been involved in the program since its early stages are the University of Virginia, Union Carbide Corporation-Nuclear Division, AiResearch Manufacturing Company, and a theory committee headed by the late Nobel Laureate, Dr. Lars Onsager.

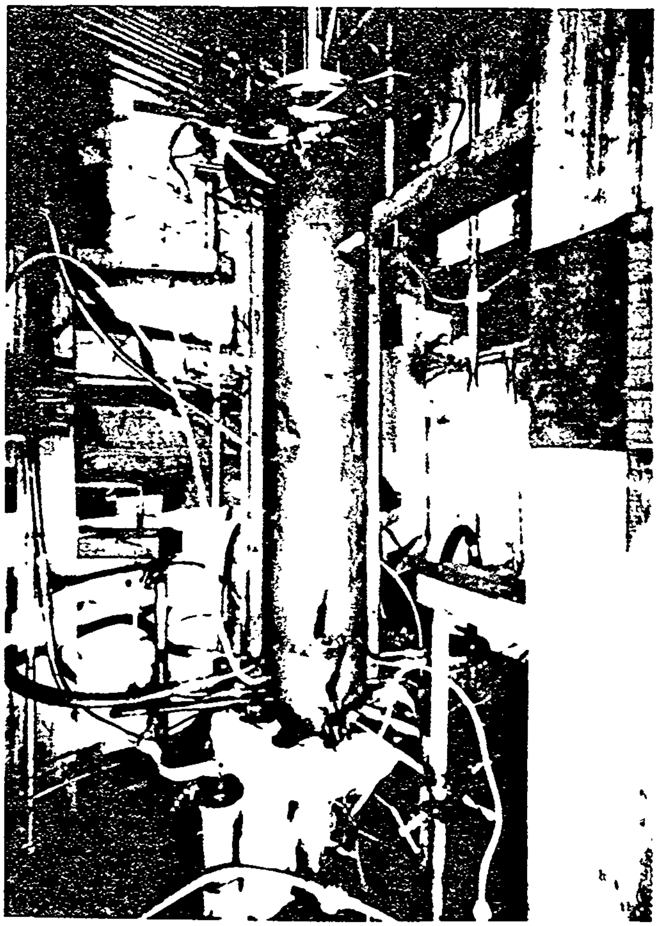
## Early Developments

The use of gas centrifuges to separate isotopes was suggested soon after researchers recognized the existence of isotopes. In 1913 the physicist J. J. Thomson found that ordinary neon contained both a mass 20 and a mass 22; his assistant, F. W. Aston, achieved slight separation of these by diffusion through clay pipes; and F. Soddy coined the word *isotope* (from the Greek words *iso* meaning "same" and *topos* meaning "place"). Six years later, in 1919, Aston and Dr. F. A. Lindemann suggested gas centrifugation as a means of isotope separation.

During the next several years a number of researchers failed in attempts to make a centrifuge work. In 1934, however, Dr. Jesse W. Beams of the University of Virginia demonstrated an operating centrifuge and soon thereafter successfully separated the isotopes of chlorine. Dr. Beams remained prominently associated with the U.S. development effort and was working actively on the centrifuge until his death in July 1977.

*Dr. Jesse Beams, pioneer developer of the gas centrifuge at the University of Virginia*

*Flow-through gas centrifuge, University of Virginia, 1942*



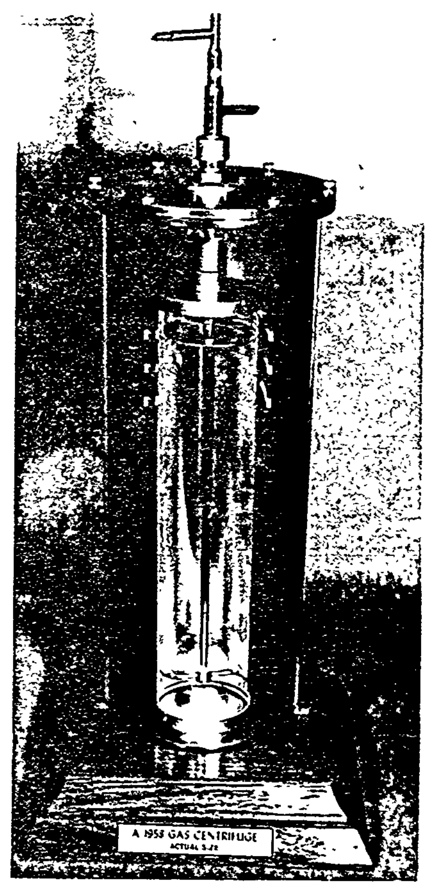
## World War II Work

The first attempt to use the gas centrifuge for achieving significant separation of uranium isotopes was made during World War II. The purpose was to enrich uranium in the fissionable isotope U-235 for military use. Individual centrifuges were developed, built, and operated successfully. Considering the technology and materials available at that time, these separating machines represented a remarkable accomplishment. The materials then available, however, were not strong enough to withstand the high speeds necessary for a practical enriching process. The wartime centrifuge effort was discontinued, and available resources were directed toward the development of other processes such as gaseous diffusion, thermal diffusion, and electromagnetic separation.

## Activities in the 1950's

After World War II, developmental work on centrifuges for other applications continued at the University of Virginia by Dr. Beams. Developmental work was also being performed

*Gas centrifuge, 1958*



### U.S. Gas Centrifuge Program Summary

| Highlight | Year |
|---|---|
| University of Virginia centrifuge development program reactivated | 1955 |
| Union Carbide Corporation-Nuclear Division (UCC-ND) research and development program started | 1960 |
| First cascade demonstrated | 1961 |
| AiResearch Manufacturing Company added to research and development program | 1961 |
| Construction of development laboratories for testing prototype centrifuges | 1967 |
| Reliability testing started (Equipment Test Facility) | 1971 |
| Industrial participation program started | 1972 |
| Gas Centrifuge Enrichment Plant (GCEP) conceptual design initiated | 1973 |
| Component Preparation Laboratories (CPL) operational (producibility tests) | 1974 |
| Component Test Facility (CTF) initial operation | 1975 |
| GCEP conceptual design completed | 1975 |
| First Goodyear Aerospace Corporation centrifuges received for qualification testing | 1975 |
| Configuration of production centrifuge selected | 1977 |
| President Carter announced plans to use centrifuge for next enrichment plant | 1977 |
| Goodyear Aerospace Corporation supplied first industry centrifuge for CTF | 1977 |
| First Exxon Nuclear Corporation centrifuges received for qualification testing | 1977 |
| Initial operation of Advanced Equipment Test Facility (AETF) | 1978 |
| Start site work for GCEP | 1978 |
| Award contracts for GCEP centrifuges | 1979 |
| Start Centrifuge Plant Demonstration Facility (CPDF) operations | 1981 |
| Begin delivery of production centrifuges | 1983 |
| First GCEP production building erected and utilities installed | 1983 |
| First production train* operational | 1984 |
| First GCEP production building operational | 1986 |
| GCEP full production | 1988 |

*There will be 8 production trains per process building, each train consisting of 6 production cascades.

during this period by Dr. M. Steenbeck, Dr. G. Zippe, and others in Russia and by Dr. W. E. Groth in the Federal Republic of Germany (West Germany). In 1958 Groth demonstrated his machines in West Germany by separating argon isotopes, and some research and development was also performed in England. In 1955 the Atomic Energy Commission (AEC) provided funds to reactivate work on gas centrifuges at the University of Virginia.

## Program of the 1960's

The promising results achieved by the University of Virginia group led the AEC to authorize, in 1960, a three-year program at a funding level of $6 million for the purpose of developing and demonstrating the gas centrifuge and assessing its economic potential. Technical objectives of the program were divided into the following three segments:

*Cascade pilot plant*—to improve existing laboratory centrifuges; to study aerodynamic and hydrodynamic problems; to test units for reliability, stability, and reproducibility; to design flexible cascades; to minimize cost and to predict the economic future of the process.

*Centrifuge flow theory*—to study flow patterns in the centrifuge.

*Advanced centrifuges*—to develop a centrifuge with high separative capacity and high mechanical reliability at a reasonable cost.

Contractors for this purpose were the University of Virginia, for basic research and theoretical analysis; Union Carbide Corporation–Nuclear Division, to develop advanced centrifuges, manufacturing techniques, and techniques of cascading centrifuges, and to improve reliability and operability; Garrett Corporation, AiResearch Manufacturing Company, to develop advanced gas centrifuges and manufacturing techniques; a theory committee headed by Nobel Laureate Dr. Lars Onsager to develop a fundamental understanding of the gas dynamics and separation mechanism within a centrifuge. Electro-Nucleonics, Inc., was added later for development of special instrumentation.

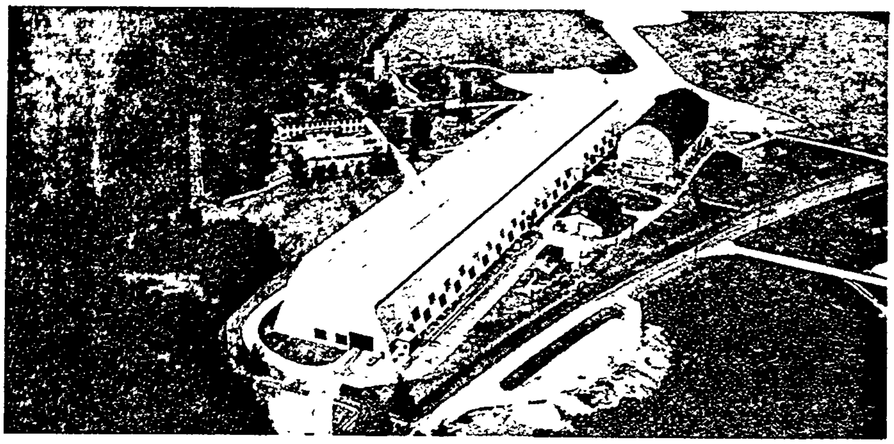
During the 1960's the feasibility of the process was demonstrated and machine performance was greatly improved. Small machines were successfully cascaded in 1961, and when the last units were shut down in 1972, some machines had run continuously for about eight years. By 1968, the program had reached the point where adequate data were available to design a facility for testing the reliability of the high-capacity centrifuges of the present program.

## Industrial Activities in the 1970's

Since 1972, several industrial firms or consortia have participated in a technology transfer program for uranium enrichment. These industrial firms have invested in commercial centrifuge facilities, conducted economic studies, designed enrichment facilities, invested in privately funded research and development, and established independent vendor networks for materials, components, and services. They have obtained over 2,500 security clearances for access to enrichment technology for personnel of over 150 companies, including the vendor networks.

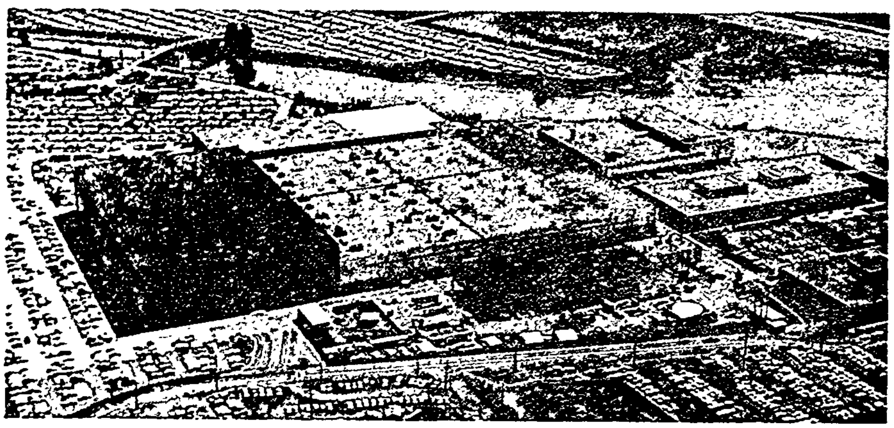
The six major industrial firms currently active have invested over $60 million in this technology transfer and in their studies and facilities. Two of the companies, Goodyear Aerospace and Exxon Nuclear, have commercial centrifuge manufacturing capability and have delivered machines to DOE contractor test facilities. Two additional firms, Boeing Engineering & Construction and Garrett Corporation, have initiated programs for commercial centrifuge manufacturing capability. Two of these four companies, plus two additional firms or consortia, Bechtel (UEA) and Electro-Nucleonics (CENTAR), earlier completed design studies for proposed private enrichment plants.

In FY 1978, Goodyear, Exxon, Boeing, Electro-Nucleonics, and Garrett will have DOE contracts to perform centrifuge-related research and development. Work carried out under these contracts will be incorporated into the total government program. In the future, several industrial firms are expected to manufacture centrifuges for the GCEP.



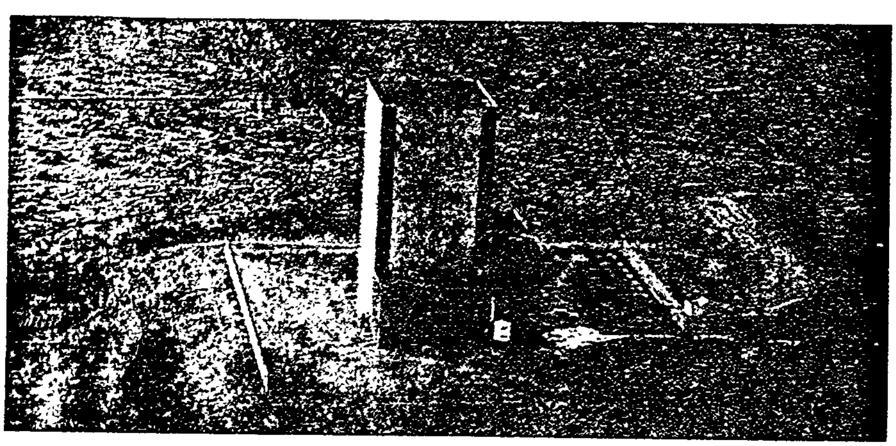
GOODYEAR AEROSPACE CORPORATION

*Gas centrifuge machine manufacturing equipment, test facilities, and an advanced technology development laboratory have been installed in this airship hangar located at Wingfoot Lake near Akron, Ohio.*



BOEING ENGINEERING AND CONSTRUCTION

*Gas centrifuge machine manufacturing equipment and test facilities are being installed in a small portion of this Boeing plant in Seattle, Washington.*



EXXON NUCLEAR COMPANY

*Gas centrifuges are assembled, balanced, and tested in this Exxon Nuclear Company Centrifuge Test Facility in Richland, Washington.*

# Current Centrifuge Program

By the end of the 1960's, results from the U.S. centrifuge program had established the potential attractiveness of the gas centrifuge process. The scope of the program has been systematically expanded to ensure capability in all areas essential to the eventual construction and operation of a production-scale facility. The major areas of the current program include:

*Basic Studies*—Acquire better understanding of centrifuge theory.

*Machine Development*—Increase separative capacity, safety, and efficiency of centrifuges.

*Reliability*—Determine the nature and frequency of machine failures.

*Producibility*—Develop methods of producing high-capacity, high-reliability machines at low cost.

*Operability*—Demonstrate the operation of the centrifuge process on a significant scale.

*Constructibility*—Develop and demonstrate designs and fabrication and construction methods for a large-scale plant.

*Engineering*—Prepare plant criteria and detailed design.

Since early in the program, Union Carbide and AiResearch have worked concurrently on centrifuges of independent design. By 1976 both organizations had developed high-capacity, efficient, and reliable machines. A key action taken early in 1977 was the selection of a single design to be developed by both organizations for ultimate use in the full-size enrichment plant.

All phases of the current and future program have been coordinated in a comprehensive 10-year plan to ensure availability of machines and plant technology.

## Gas Centrifuge Development Facilities

Several development facilities have been or are being constructed to improve centrifuges, associated equipment, and operating procedures. AiResearch at Torrance, California, operates machine development, machine production, and test facilities; the University of Virginia has limited development facilities; and the remaining facilities are operated by Union Carbide at Oak Ridge, Tennessee. Lawrence Livermore Laboratory and Los Alamos Scientific Laboratory provide support by developing hydrodynamic flow models. Mechanical Technology, Inc., performs rotor dynamics and balancing studies.

The Equipment Test Facility (ETF) began operation in 1971 for examining the reliability of four types of high-capacity centrifuges. Reliability testing is continuing on some of these earlier machines.

Completed in 1974, the Component Preparation Laboratories (CPL) at Oak Ridge and Torrance were built to aid the development and demonstration of techniques for manufacturing centrifuges and to reduce the time and cost of the manufacturing process. These manufacturing techniques are being provided to private industry.

The Component Test Facility (CTF) began initial operation in 1975 and is used to test the reliability and operability of substantial numbers of centrifuges. This facility serves as a pilot plant cascade and now operates centrifuges produced by Union Carbide, AiResearch, and private industry. Although a test facility, the CTF has a production capacity of about 50,000 SWU per year.

## Gas Centrifuge Research and Development Contractors

AiResearch Manufacturing Company, Division of Garrett Corporation, Torrance, California

Boeing Engineering & Construction, Seattle, Washington

Electro-Nucleonics, Inc., Pompton Plains, New Jersey

Exxon Nuclear Company, Bellevue, Washington

Garrett Corporation, Los Angeles, California

Goodyear Aerospace Corporation, Akron, Ohio

Goodyear Atomic Corporation, Piketon, Ohio

Lawrence Livermore Laboratory, Livermore, California

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Mechanical Technology, Inc., Latham, New York

Union Carbide Corporation–Nuclear Division, Oak Ridge, Tennessee

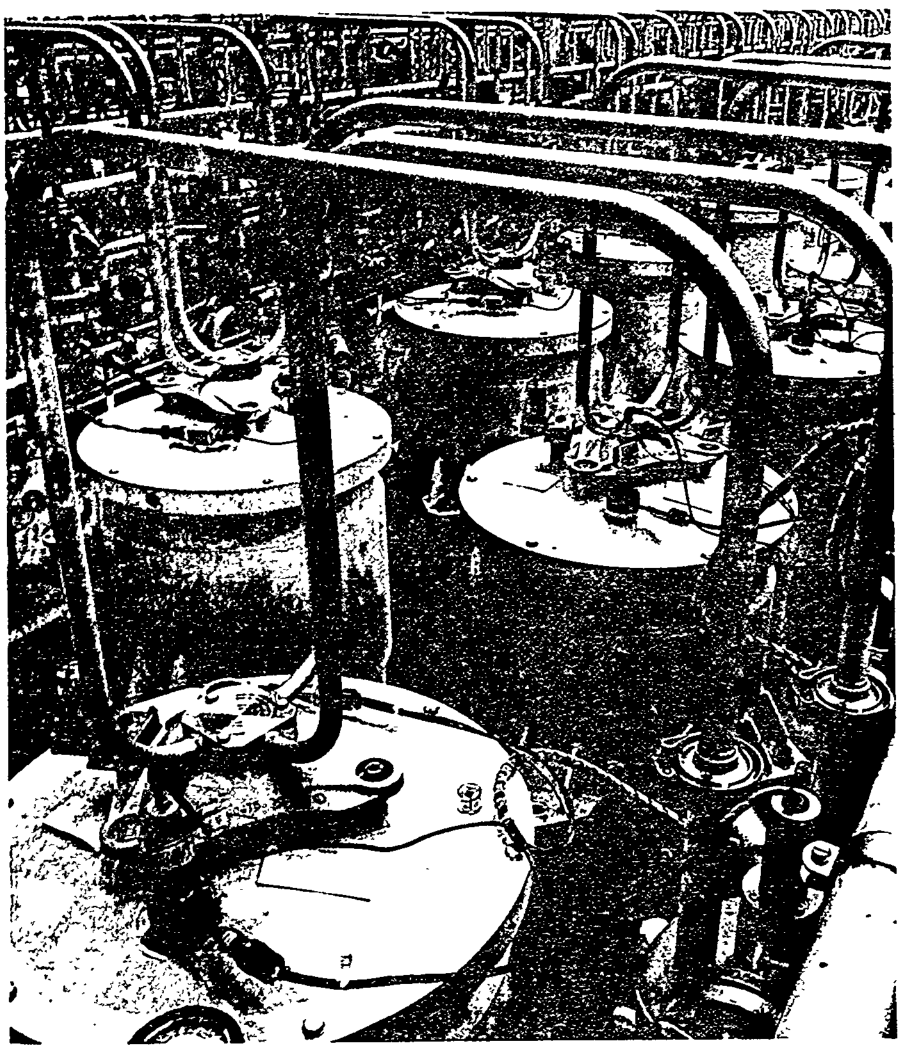
University of Virginia, Charlottesville, Virginia

The Advanced Machine Development Laboratories (AMDL), for improving and testing centrifuges, are located at both Oak Ridge and Torrance.

The Advanced Equipment Test Facility (AETF) is expected to begin operation in the spring of 1978. This facility will be used primarily to test the reliability of the production centrifuges that will be used in the Centrifuge Plant Demonstration Facility (CPDF) and the full-size Gas Centrifuge Enrichment Plant (GCEP). The facility will also be operated to test plant subsystems.

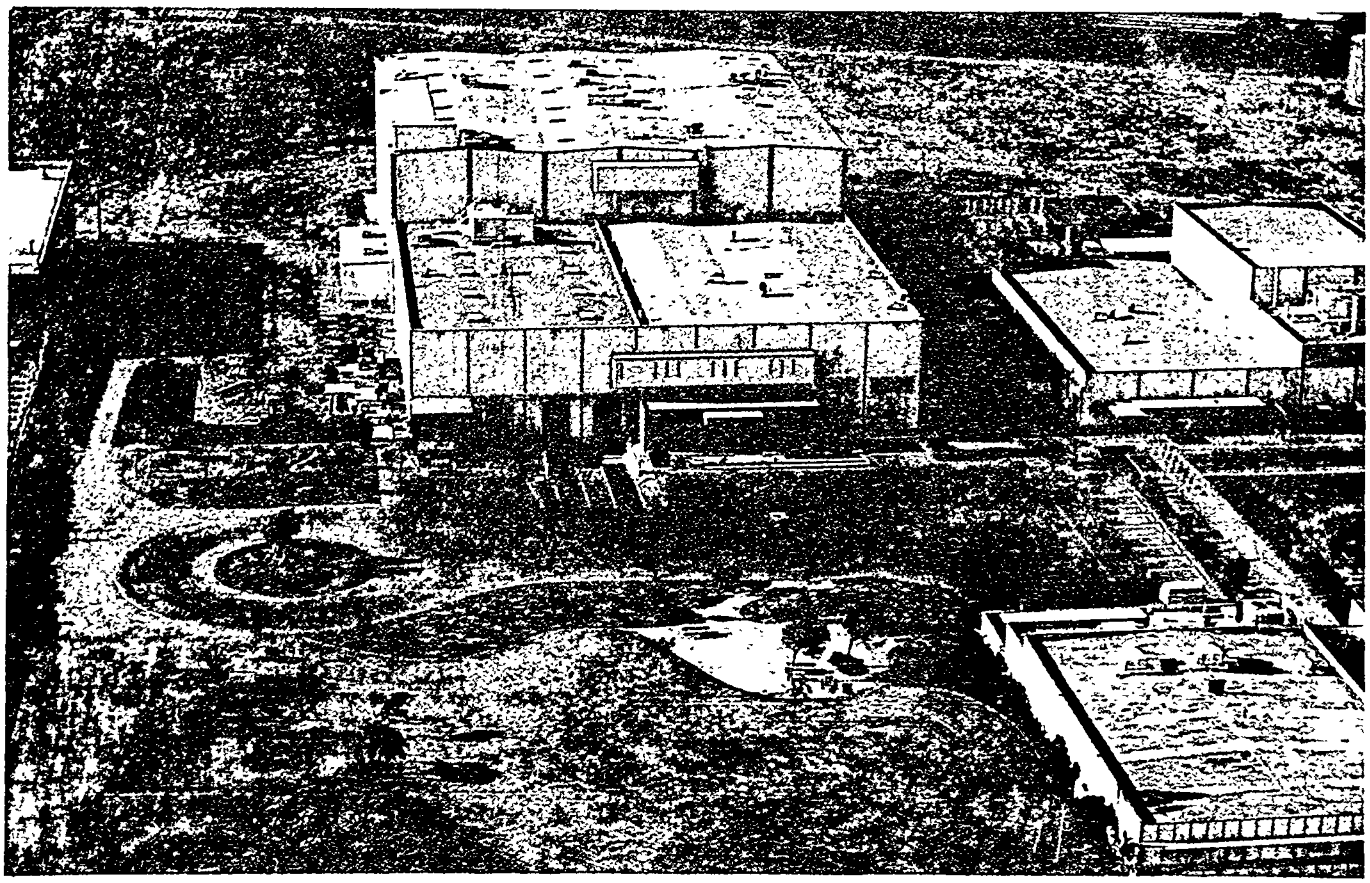
The Centrifuge Plant Demonstration Facility (CPDF) will be in operation by early 1982 and is estimated to cost $60 million. This facility will be used to test not only centrifuges but also other cascade equipment and systems. Much equipment, including all centrifuges for this project, will be procured from industry. The facility will be used to obtain information to show that producible machines and the necessary industrial vendors are available, and that the design, construction, and operating criteria are satisfactory for use in the full-size plant.

As testing of machine and cascade auxiliary equipment in the CPDF proceeds, further extensive evaluation and qualification of industry-produced machines and plant components will be conducted to achieve cost and performance goals. These activities, identified in the ten-year development plan, will demonstrate machine producibility and operability by the manufacture and testing of machines and plant components in Government facilities and by early operation of the first GCEP production train, which consists of six cascades. Machines and plant components beyond the CPDF will incorporate improvements from the development program.



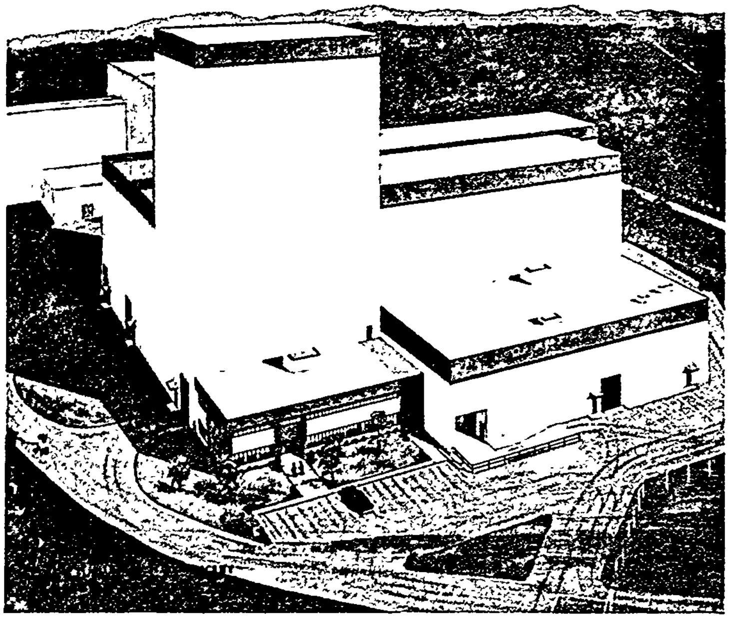
*COMPONENT TEST FACILITY*
*OAK RIDGE, TENNESSEE*

AiRESEARCH GAS CENTRIFUGE
DEVELOPMENT FACILITIES
TORRANCE, CALIFORNIA

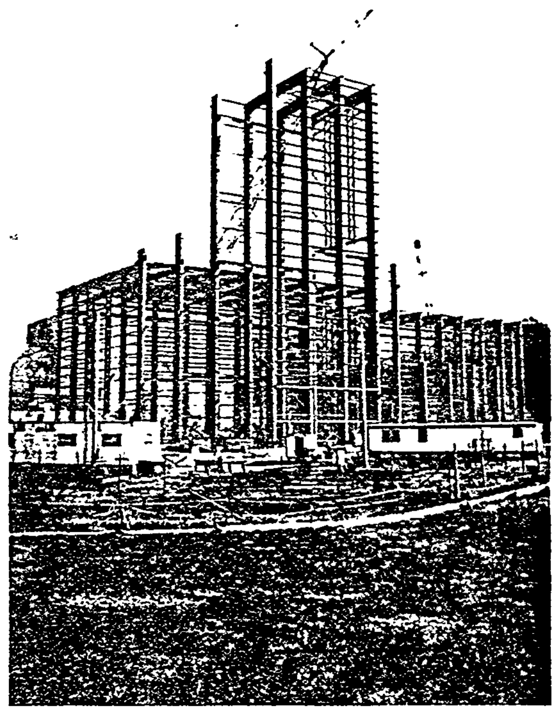


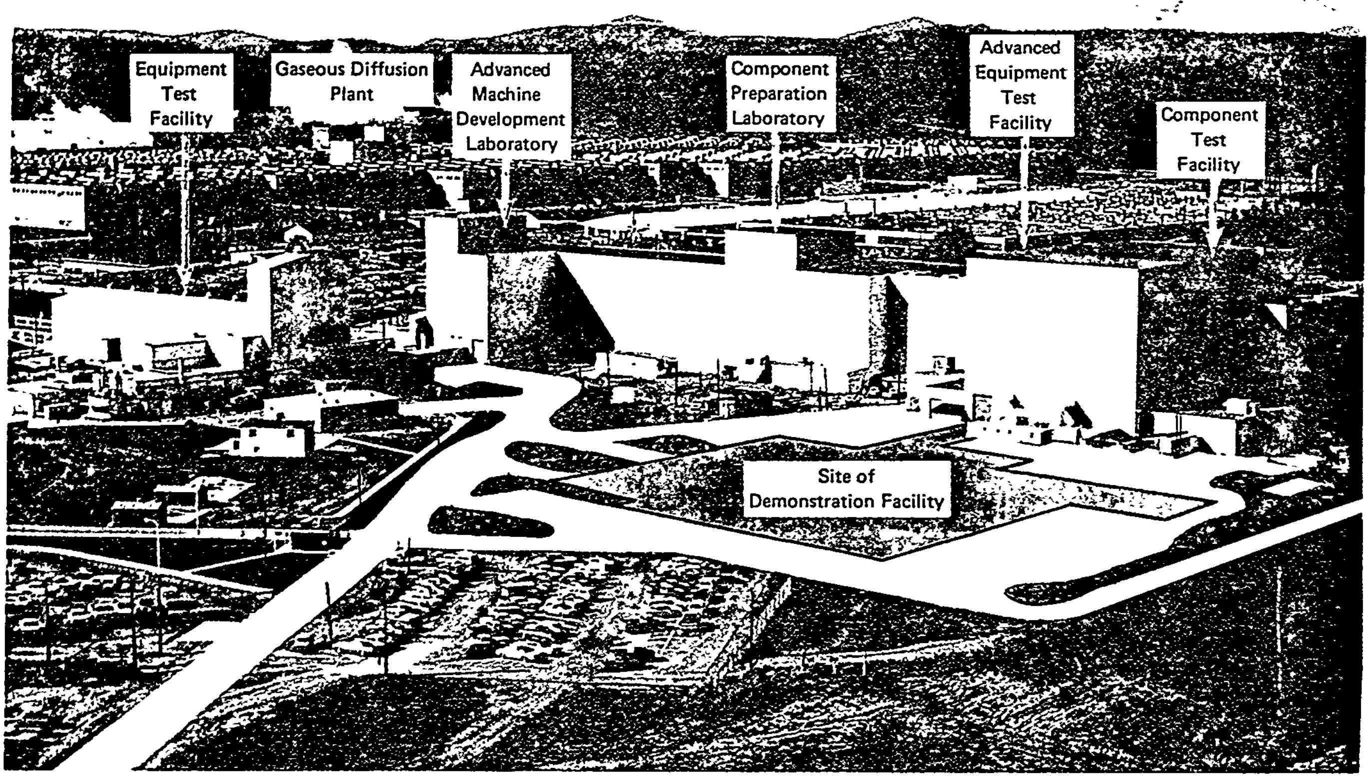
*CENTRIFUGE PLANT DEMONSTRATION FACILITY*
*OAK RIDGE, TENNESSEE*

*Artist's Sketch*



*Under Construction*






*GAS CENTRIFUGE DEVELOPMENT FACILITIES*
*OAK RIDGE TENNESSEE*

# The Gas Centrifuge Enrichment Plant

The Gas Centrifuge Enrichment Plant will be a large construction project. It is designed to provide a nominal 8.8 million SWU per year of separative capacity and will consist of eight process buildings, plus additional auxiliary, administrative support, test, and service facilities as required. The total area under roof is about 90 acres, and each process building would conveniently hold four football fields. The project will require new industrial manufacturing capacity as well as the talents of a number of architect-engineers and construction contractors.

## Site

The Department of Energy directs extensive uranium enrichment operations at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. Locating the centrifuge enrichment plant at one of these existing sites provides advantages of shared facilities, administration, and overhead. These considerations entered into the selection of the Portsmouth site, which is operated for the DOE by Goodyear Atomic Corporation. The construction site at Portsmouth consists of about 300 acres of relatively level land lying approximately west and south of the existing diffusion plant.

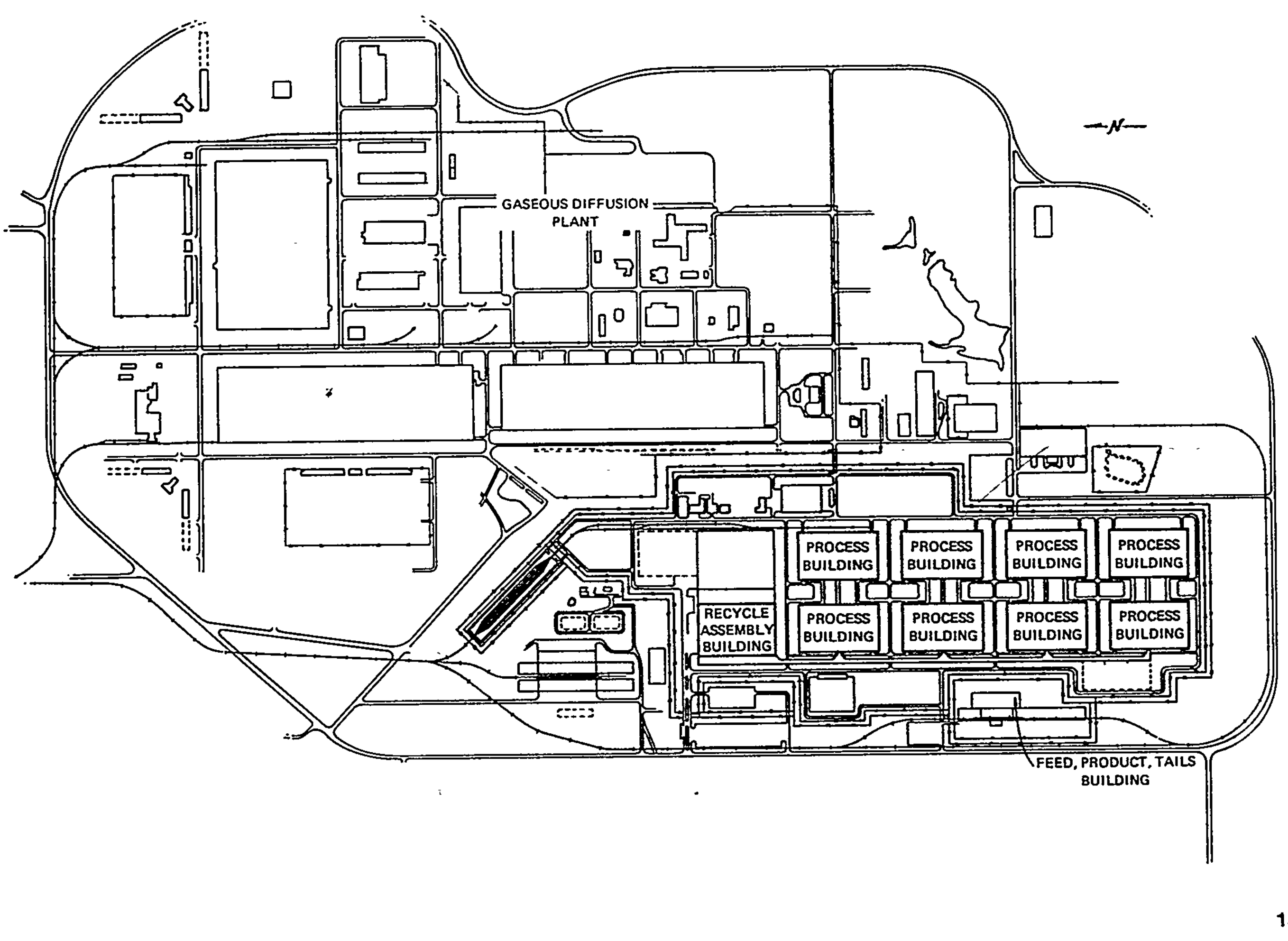
## GCEP Design

Design of the Gas Centrifuge Enrichment Plant is the outgrowth of conceptual engineering design studies which began in 1973 as an enrichment planning contingency measure.

The conceptual studies have been performed by Union Carbide Corporation–Nuclear Division and two architect-engineering firms, Catalytic, Inc. (Philadelphia), and Commonwealth Associates (Jackson, Michigan), with contributions by AiResearch, the University of Virginia, and industry. This effort has provided conceptual design of buildings, equipment and support systems, improved design for major pieces of equipment, construction schedules, and estimates of construction and operating costs. In December 1975 a complete conceptual design and cost estimate of a full-size gas centrifuge plant (about nine million SWU per year) was completed. As a measure of the detail and magnitude of this effort, the final design report included 21 volumes containing 3,800 pages of text and 1,100 drawings. The cost estimate is contained in five volumes consisting of approximately 3,000 estimate sheets.

*PORTSMOUTH, OHIO, URANIUM ENRICHMENT PLANT*

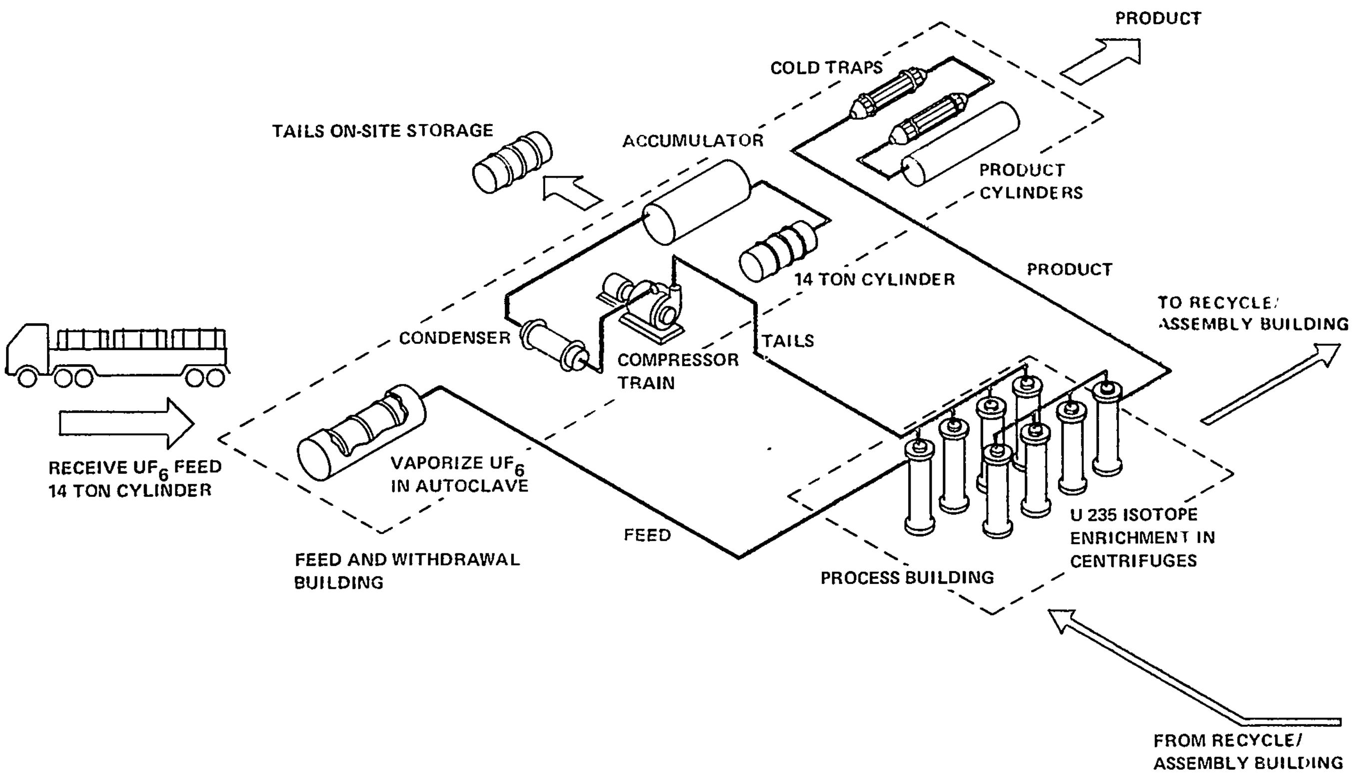
***The gas centrifuge plant is highlighted in the bottom right.***



## Centrifuge Uranium Enriching Process

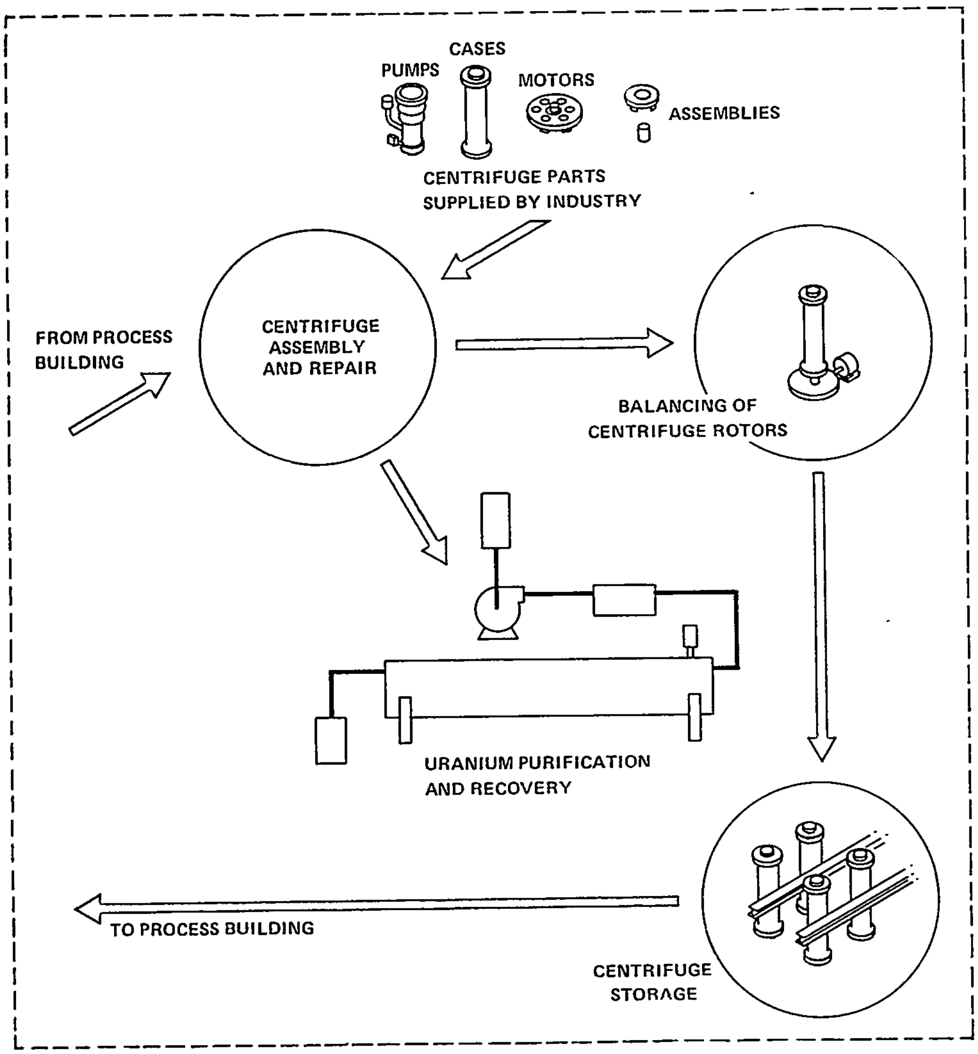
As shown in the diagram below, uranium hexafluoride ($UF_6$) is received at the enrichment plant in 14-ton cylinders. The cylinders are heated to vaporize the $UF_6$, which is then piped to the process buildings and fed to the centrifuge cascade.

The product streams of $UF_6$ enriched in U-235 are removed from the centrifuge cascade for final processing and analysis to ensure that customer specifications are met. The product is shipped to the fuel fabrication plant in 2½-ton cylinders. The stream of depleted $UF_6$ is condensed into 14-ton cylinders which are placed in an outside storage yard.



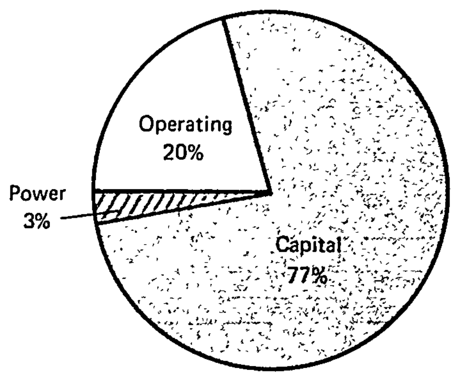
## Recycle/Assembly Facility

The Recycle/Assembly facility is one of the key areas in the plant. The facility will first be used to assemble and test the initial complement of centrifuges. When the plant is in operation, failed centrifuges are transported to the area, and the cause of failure is diagnosed. Repairs are made as necessary, rotors are balanced, and the machines are made ready for returning to service. Used parts are decontaminated, and the liquid effluent is processed to recover the uranium. In addition, spare parts are received and checked in the R/A area.



## Gaseous Diffusion and Gas Centrifuge Processes: Some Basic Differences

| Characteristic | Gaseous diffusion | Gas centrifuge |
|---|---|---|
| Enrichment by individual units | Low | High |
| Flow capabilities of individual units | High | Low |
| Process pressures | Moderate | Low |
| Inventory in cascade | High | Low |
| Cooling requirements | Large | Small |
| Power usage | Very Large | Small |
| Lubrication requirements | Large | Very Small |
| Projected equipment repairs and/or replacements | Small | Large |
| Staffing requirements | Small | Large |




*Cost Estimate for Separative Work from Centrifuge Enrichment Plant*

**COST OF SEPARATIVE WORK**
**$86/SWU**

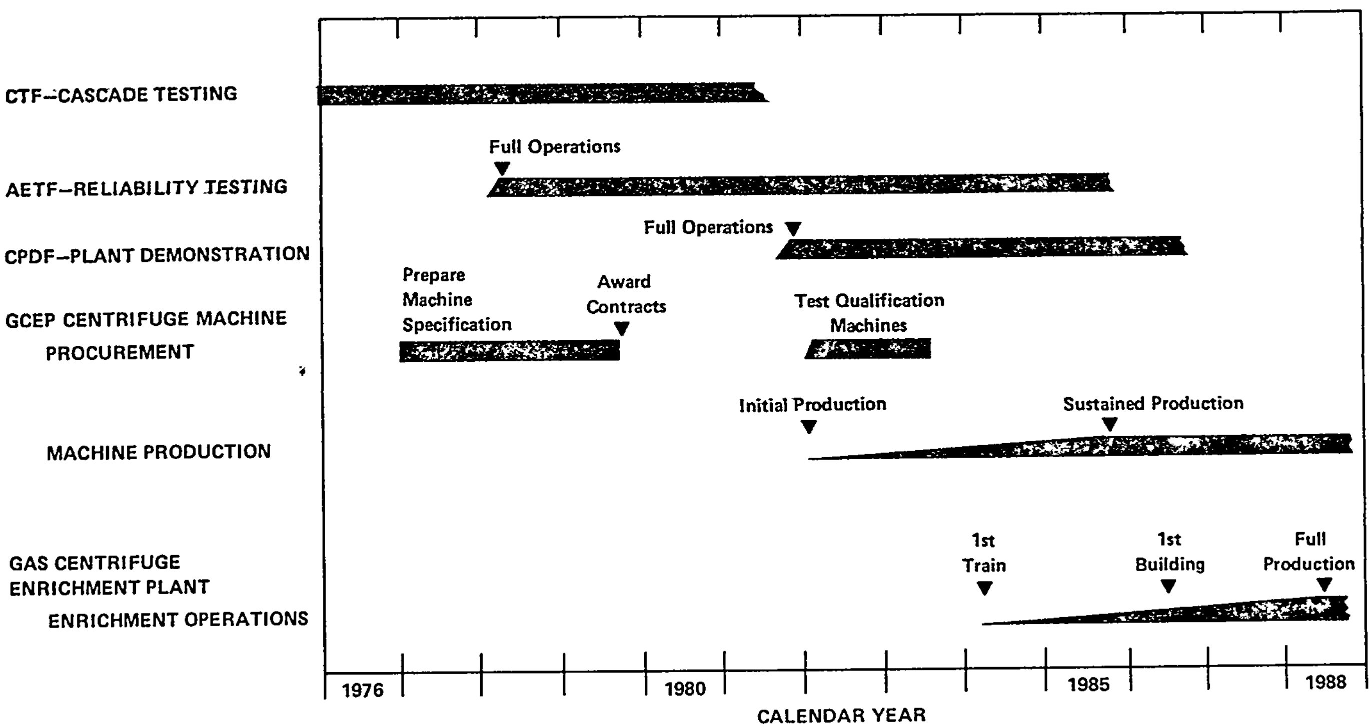
The Department of Energy has estimated the economics of uranium enrichment for the Portsmouth gas centrifuge plant. In fiscal year 1978 dollars, the capital cost for the plant is $4.2 billion. Annual operating costs and power costs are estimated to be $150 and $26 million, respectively. These costs result in a price of $86 per SWU. The above chart shows the percentage breakdown among capital, including interest during construction (estimated to be 26%), power, and other operating costs.

The current DOE calculation of separative work price is based on full cost recovery over the three-site enrichment complex. This policy provides that additional costs such as the cost of Government feed and imputed interest on (1) Government investment and (2) on the separative work component in the enriched product inventory will be reflected in the final separative work price. As construction on the Portsmouth gas centrifuge plant progresses, its costs will be factored into the DOE pricing calculation. Centrifuge research and development costs as well as early plant operating costs and interest on capital are already being included in the current price of separative work from the DOE complex.

# GCEP Milestones

*Key milestones are phased to permit an orderly and technically sound building-block approach to plant construction and initial operation. Startup of process production buildings is planned as centrifuges are installed and checked out. Initial production is planned for CY 1986 and full production in CY 1988.*

*PORTSMOUTH GAS CENTRIFUGE ENRICHMENT PLANT—KEY MILESTONES*



Today the United States supplies most of the enriched uranium used in the free world to generate electricity in nuclear power plants. Through advanced technology, research and development, and innovative engineering designs, the United States has continually improved existing plants and developed more efficient new enrichment processes to help meet the energy needs of the future.

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