URANIUM ENRICHMENT

Guidelines for Assessment and Planning

Prepared by
WINB Committee on Uranium Enrichment

Edited by
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PREFACE

One of the significant requirements in processing of nuclear fuel for the atomic power industry is the "enrichment" of the fissionable isotope U-235 from its content of only 0.71% found in natural uranium to the 2-5% U-235 required in most current power reactors. The rapid growth of the nuclear power industry is expected to create accelerating demand for additional uranium enrichment facilities in the United States and in several foreign countries.

Since it is possible that one or more enrichment plants may be built in the Western States, the Western Interstate Nuclear Board (WINB) decided in August, 1972 to undertake a study of uranium enrichment and its implications in the WINB Region. The Board appointed a committee composed of Lawrence B. Bradley, Executive Director, Washington State Office of Nuclear Energy Development; Dr. Gene P. Rutledge, Executive Director, Idaho Nuclear Energy Commission; and Wyatt M. Rogers, Jr., Associate Director, WINB, to coordinate the study.

The principal objective of the study was to develop background information and guidelines concerning the expected future siting and development of uranium enrichment facilities and their impact at the State and local levels.

WINB submits this report with the hope that it will prove useful to government officials and others in the evaluation and planning of uranium enrichment projects.

Dr. Alfred T. Whatley
Executive Director

ACKNOWLEDGMENTS

The Committee hereby wishes to express its appreciation to its consultants and advisors who were:

John C. Bellamy, Ph. D., Professor of Engineering, University of Wyoming; Craig Bigler, Associate State Planning Coordinator, State of Utah; Edwin Fast, Ph. D., consultant; Dwight Neill, Director, Colorado Division of Commerce and Development; Glen Kissinger, Colorado Division of Commerce and Development; W. B. Lewis, consultant; John McCurry, Manager of Business Programs, Exxon Nuclear Company; and Robert D. Siek, Director, Colorado Division of Occupational and Radiological Health.

The Committee also wishes to acknowledge the cooperation of the U.S. Atomic Energy Commission which provided considerable information and arranged for tours by Committee members to the Oak Ridge Gaseous Diffusion Plant.

The cooperation and information supplied by Bechtel Corporation, Exxon Nuclear Company, General Electric Company, Westinghouse Electric Company, and Reynolds Metals Company is also hereby gratefully acknowledged.

WINB Committee on Uranium Enrichment

Lawrence B. Bradley
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TABLE OF CONTENTS

REPORT SUMMARY:

OVERVIEW, FINDINGS, AND RECOMMENDATIONS

Introduction

Among the nation's pressing socio-economic problems is the so-called "energy crisis": how to provide adequate supplies of electricity, fossil fuels, and other forms of energy to a growing, technology-oriented society with minimum adverse effects on the natural and human environment and in view of finite fossil and other energy resources. As a partial answer to the problem, the electric power companies, other private industries, and the federal government have made major financial and technological committments to nuclear power plants and their supporting systems. As of October 1972, some 152 nuclear power plants with a combined electric output of 132,000 megawatts (Mwe) were in operation, under construction, or planned. Forecasts by the U. S. Atomic Energy Commission indicate that nuclear-electric power generation will grow from about 132,000 Mwe in 1980 to 1,200,000 Mwe by the year 2000 and will constitute almost 60 per cent of total installed generating capacity in 1990.

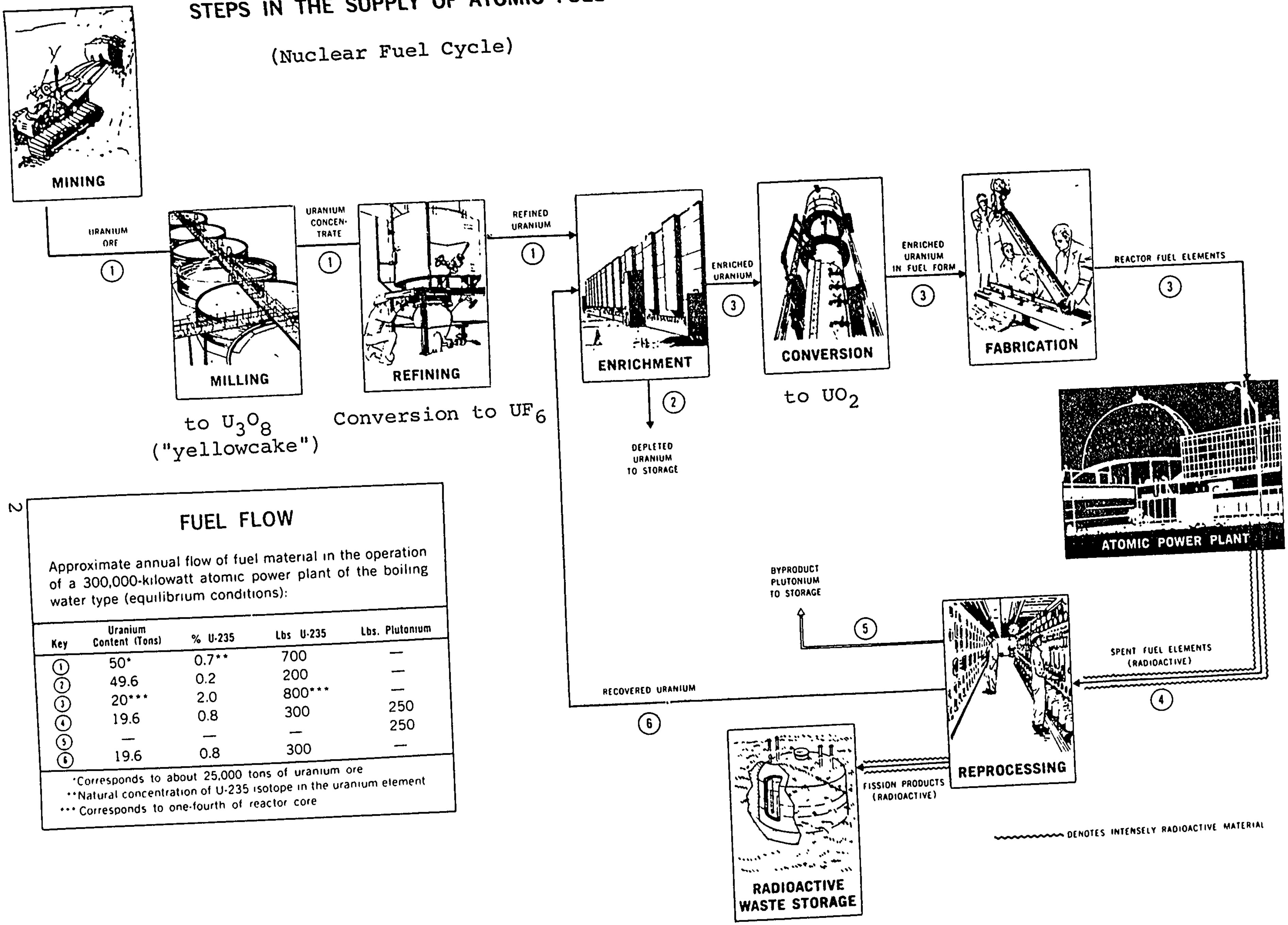
To support this growth, considerable expansion of the nation's "nuclear fuel cycle" industries is expected in the next two decades. This includes such steps as uranium mining and milling, conversion of "yellowcake" (beneficiated ore) into uranium hexafluoride (UF6), enrichment, fuel fabrication, spent fuel reprocessing, and by-product and waste storage and conversion disciplines.

Since virtually all of the civilian nuclear power plants in the United States utilize enriched uranium fuel, the "enrichment" step in the overall nuclear fuel cycle is essential to a viable nuclear power industry. Enrichment accomplishes the task of increasing the content of the fissionable isotope Uranium-235 from its natural state of 0.71% in "yellowcake" to values of 2-5% required in most nuclear power reactors. It is also the single most expensive step in the fuel cycle. To achieve such enrichment, isotopic separation must be performed through one of several processes: gaseous diffusion, centrifuge separation, electro-magnetic separation, among others. To date, the gaseous diffusion method has been employed almost exclusively in the United States and elsewhere. However, research and development is under way in the nation and abroad on the centrifuge and other enrichment processes.

A typical gaseous diffusion plant (GDP) of 8750 metric tons annual capacity requires facilities employing approximately 900 skilled employees, an electric power supply of about 2,500,000 kilowatts,

STEPS IN THE SUPPLY OF ATOMIC FUEL

(Nuclear Fuel Cycle)



FUEL FLOW

Approximate annual flow of fuel material in the operation of a 300,000-kilowatt atomic power plant of the boiling water type (equilibrium conditions):

Key	Uranium Content (Tons)	% U-235	Lbs U-235	Lbs. Plutonium
①	50*	0.7**	700	—
②	49.6	0.2	200	—
③	20***	2.0	800***	—
④	19.6	0.8	300	250
⑤	—	—	—	250
⑥	19.6	0.8	300	—

*Corresponds to about 25,000 tons of uranium ore
**Natural concentration of U-235 isotope in the uranium element
***Corresponds to one-fourth of reactor core

Table A

BREAKDOWN OF FUEL CYCLE COSTS
AND "BUS-BAR" POWER PRODUCTION COSTS
IN A TYPICAL 1,000 MWE NUCLEAR POWER PLANT
(Based on 1973 costs)

Fuel Cost Breakdown

	mills per Kwh
Uranium mining and milling -	.39
Conversion to uranium hexafluoride -	.07
Enrichment to 2-5% U-235 -	.69
Reconversion and fuel fabrication -	.33
Spent fuel shipping -	.03
Reprocessing -	.12
Plutonium recycle (credit) -	(.22)
Uranium recycle (credit) -	(.10)
Waste disposal -	.06
Sub-total -	1.37
Fuel inventory carrying charge -	.60
Total -	1.97

Electric Power Generation Costs
(80% plant factor)

Capital costs -	8.57	mills/Kwh
Fuel costs -	1.97	" "
Oper., maint. -	.55	" "
Total -	11.09	

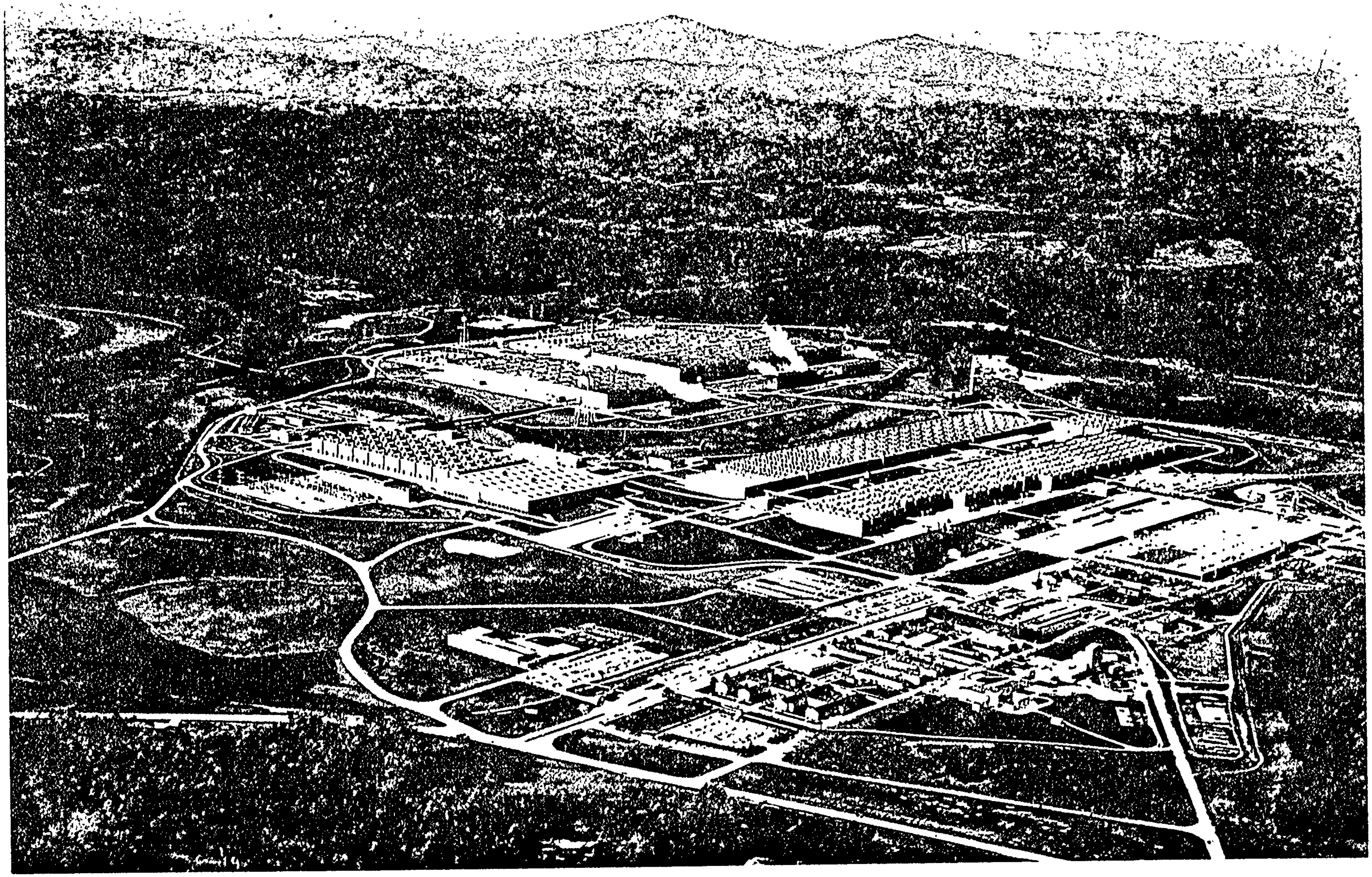


Figure 1
Oak Ridge (Tennessee) Gaseous Diffusion Plant, one of three such enrichment plants in the United States owned by the USAEC.

and capital investment of about $1.5 billion dollars, not including the requisite power generation facilities. A chemical-mechanical process, gaseous diffusion involves large quantities of only slightly radioactive chemicals and is essentially low in hazards.

Currently, all enriched uranium in the United States is processed at the three USAEC enrichment plants located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. These plants were built in the 1944-1956 period primarily to furnish enriched uranium for the nation's atomic arsenal. They continue to perform this vital function; however, due to declining national defense needs, the majority of their current and future output is for the nuclear power industry. These enrichment facilities utilize the gaseous diffusion process.

As indicated earlier, the expansion of nuclear power generation in the 1975-2000 period is expected to necessitate construction of new facilities throughout the nuclear fuel cycle. Of critical importance is the expansion of uranium enrichment capacity by the early 1980's. Although USAEC enrichment plants will be expanded and modernized to accommodate a part of this increased requirement, it appears that, for the first time, private industry will be encouraged to enter this remaining segment of the nuclear fuel cycle still under federal monopoly. Recent policy statements by President Richard Nixon and AEC Chairman James R. Schlesinger indicate that federal policy will be developed soon to facilitate private participation in uranium enrichment.[1] Under its new program to foster private industry participation, AEC has permitted some seven (7) domestic firms to gain access to certain classified information concerning enrichment technology.[2]

Several of the participating companies have recently announced plans for undertaking extensive studies toward possible commercial enrichment ventures. One of these, Reynolds Metals Company, has announced plans for a very large enrichment facility in Wyoming. Other proposals are expected to be developed in the near future.[3]

Principal Findings of the Study

The WINB Ad Hoc Committee on Uranium Enrichment and its consultants have undertaken studies of the uranium enrichment industry, its expected market and supply requirements, its siting problems, and its socio-economic and environmental impacts. While its primary orientation was toward the potential implications in the Western States, the Committee also investigated some of the national and international issues involved in expansion of the uranium enrichment industry. The following are the major findings of the Committee:

1. Considerable and rapid expansion in uranium enrichment capacity will be required during the period 1980-2000.

Current expansion and modernization plans, the "Cascade Improvement Program" (CIP) and "Cascade Up-rating Program" (CUP), at USAEC enrichment plants should be able to provide adequate supply capability until about 1982-83.

Beginning in 1981-82, a continuous expansion of enriching capacity will be required to serve the rapidly-growing nuclear power industry in the United States and abroad. Assuming a typical annual capacity of 8750 metric tons of "separative work"* for each plant, new facilities should become operational at about yearly or biannual intervals during the late 1980's and early 1990's. The new plants built in the United States are expected to be privately-owned, although there is some possibility of further expansion of USAEC facilities particularly if the private sector is unable to meet projected demand.

Due to the long "lead" time required for planning and construction (8-10 years), investment and siting decisions for the first new plants must be made in 1973-74.

2. The gaseous diffusion process (GDP) and the gas centrifuge process appear to be probable choices of enrichment technology for new plants.

GDP, a well-established technology, seems to have a slight edge for the first new plants; however, the centrifuge is undergoing development and could achieve "commercial" status in a few years. Key components and process equipment for GDP are well-developed; manufacturing capacity for barrier material, compressors, etc. already exists in AEC and industry and can be expanded with little foreseeable difficulty. Critical equipment for the centrifuge process, on the other hand, is not readily available at present and may represent a constraint on early commercial use of the centrifuge method of enrichment.

3. Siting of an enrichment plant is critically dependent upon adequate and highly reliable supplies of low-cost electricity.

A typical GDP plant of 8750 MTSWU** annual capacity requires about 2,500 megawatts (Mwe) of electricity at very high load and reliability factors. Thus, new electric generating facilities must be built in close proximity to serve the enrichment complex.

For centrifuge-type plants, approximately one-seventh (1/7) to one-tenth (1/10) as much electricity would be involved for an annual output of 8750 MTSWU. This lower electrical energy demand (250-300 Mwe) would permit more flexibility in siting.

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*"Separative work" is a measure of isotopic separation effort in an enrichment plant. It includes measures of product assay of 235 U and/or volume of material processed.

**MTSWU-metric tons of separative work units: a metric ton is 1000 kilograms.

4. The Western Region of the United States holds considerable potential for enrichment plant siting.

The vast fossil fuel resources and water supply in many areas, coupled with many potential sites for nuclear power stations, indicate that a number of enrichment plant locations in the WINB Region may be economically feasible and thereby warrant detailed evaluation.

Centrifuge enrichment plants, with their much lower electric power requirements and greater orientation to subsequent steps in the "nuclear fuel cycle" (i.e., fuel fabrication plants and reactor locations), would tend to locate in reasonable proximity to the nuclear reactor "market". Gaseous diffusion plants would tend to be sited where large supplies of low-cost electricity could be generated via fossil or nuclear fuels or hydro-electric facilities.

5. Economic impact of an enrichment/power generation complex on a typical small community will be dramatic.

Direct employment in enrichment, power generation, and related mining/extractive industry operations is expected to range from 1,000 to over 2,500 and a total permanent population increase of 5,000-10,000 would be generated.

During the construction phase, an average of about 2,600 workers would be involved, peaking at about 6,000. Influx of such numbers of people during the 8-10 year development phase would impose substantial challenges to local and State governments in terms of providing the requisite "social overhead capital" - roads, housing, schools, and other public facilities.

Substantial public outlays will be required prior to receipt of tax revenues from the operating plants, necessitating the development of some system of advance cash payments by the plant owners, in lieu of normal taxation.

6. Environmental impact of a typical enrichment plant, aside from the electric power generating facilities, would be relatively mild.

A typical gaseous diffusion or centrifugation plant is considered to be a relatively clean, safe industrial process involving well-contained toxic chemicals (fluorides, chiefly) and only slightly radioactive materials requiring no radiation shielding for occupational protection. Due to the diffuse nature of the fissionable materials in the uranium hexafluoride (UF6) product, there is virtually no chance for criticality accidents. Plant effluents dispersed to the environment consist mostly of process heat removed through heat exchangers or low-profile cooling towers. Small amounts of toxic chemicals used in demineralizing and cleaning operations are intermittently discharged after treatment. UF-6 product, depleted uranium ("tails"), and other slightly radioactive substances are tightly contained throughout the process.

The electric power generation systems required to furnish energy to the enrichment plant offer potentially adverse environmental impact. Fossil-fueled power plants produce large quantities of sulphur dioxide, oxides of nitrogen and carbon, and particulate matter (including small amounts of radon, radium, and trace metals) which must be removed to the extent possible prior to atmospheric release. Enormous amounts of cooling water are desired to dissipate heat prior to discharge into the environment. In the case of coal-fired plants, large areas of land may be disturbed for coal mining operations, necessitating well-executed land reclamation measures.

Recommendations

In view of its findings summarized above, the Committee submits the following recommendations for consideration by public officials, private industry, and the general public. In offering these suggestions, the Committee is mindful of the very complex nature of the uranium enrichment industry and the many public issues and proprietary interests involved in the policy formulation- planning-decision-making process.

1. Federal government

At the federal level, policies must be formulated immediately to provide a firm basis for long-range planning of enrichment operations. Such policies should provide clear-cut responsibilities for private and public participation in the uranium enrichment field.

Federal policies should include incentives for private participation through such measures as: (1) adoption of a timetable for limiting further expansion of government-owned enrichment facilities beyond the current CIP/CUP programs; (2) providing technical information and assistance for developing the necessary expertise in qualified private firms; (3) preparing any special antitrust guidelines that may be necessary for possible multi-company (and perhaps international) ventures; and (4) developing regulations and guides concerning protection of government and private patents for enrichment-related technology.

Contingency plans for further expansion of AEC enrichment plant capacity beyond CIP/CUP should be developed to provide reasonable assurance that adequate enriching capacity is available in the event that the private sector is unable to meet market requirements. The CIP and CUP programs at existing AEC enrichment plants should be given priority status to assure completion on schedule.

Other topics which should be included in such policies are: price competition; toll enrichment services; utilization of government enrichment technology by the private sector; and international safeguards.

Since State and local governments will have a large stake in the socio-economic impact and the continuing viability of enrichment plants, co-operation among the various levels of government and industry should be encouraged through information exchange and other means of communications. Federal agencies should make their expertise available to State and local governments, upon request, concerning such areas on community planning and development and assessment of environmental impact in the vicinity of enrichment plants.

Federal policies should encourage participation by State and local governments and the general public in the evaluation of applications for enrichment plant licensing.

2. State and local governments

State planning and development agencies should conduct advance reconnaisance studies as to physical attributes relating to sites, community and regional development problems, and environmental factors in preparation for evaluation and actual development of specific projects.

State and local governments should encourage full, prompt disclosure of information concerning proposed projects and should provide for public participation in decision-making and planning.

Some equitable method of financing essential new public facilities during the enrichment plant construction period should be devised. Perhaps a fee or advance payment system in lieu of conventional property taxes could be developed to provide revenues and/or a "tax base" to permit issuance of revenue or general obligation bonds for public facilities financing. Maximum use of federal assistance programs for community development, housing, school construction, etc. should be made.

3. Private industry

Private companies planning enrichment ventures should, to the extent possible, make early, full disclosure of their proposals to State and local, as well as federal, agencies. Companies should make special efforts to involve all relevant public agencies and citizens groups during the preliminary planning and actual construction stages.

4. <u>Western Interstate Nuclear Board</u>

WINB should continue to monitor developments in the uranium enrichment field and to keep key state officials apprised of such developments. The Board should offer to conduct or to co-sponsor with USAEC special briefings and tours on the subject for Governors and other key officials.

Chapter I

URANIUM ENRICHMENT: PROJECTED SUPPLY AND DEMAND

The projected growth of the nuclear-electric power industry in the United States and abroad is expected to require substantial increases in uranium enrichment capabilities over the next two decades. Currently, production capacity of the three (3) AEC enrichment plants is considerably greater than domestic demand. A similar situation exists in the foreign enrichment plants in England and France. Over-capacity of AEC plants resulted from the sharp curtailment of production devoted to national defense during the past few years. However, this over-capacity is expected to be short-lived in view of the enriched uranium requirements for the rapidly-developing civilian nuclear power industry.

Based on domestic and "free-world" forecasts as depicted in Figure 3, the equivalent of about 15-18 plants, each providing enrichment services equal in capacity to one of AEC's current gaseous diffusion plants, will be required by the year 2000. If the gaseous centrifuge process is employed, it is conceivable that 50 to 150 plants would be needed. It appears likely that a "mix" of both gaseous diffusion and centrifuge plants will be built during the forecast period.

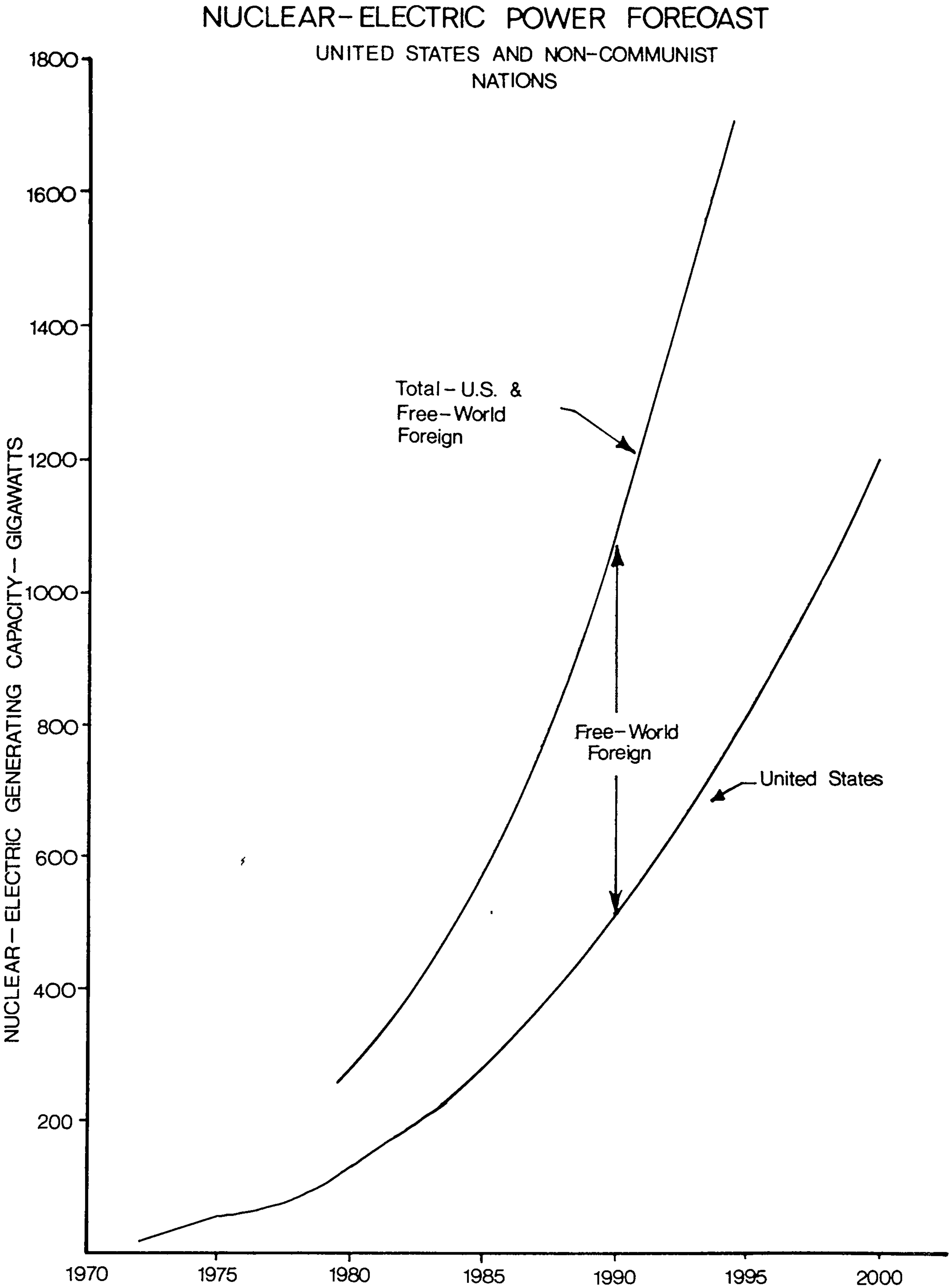
To meet the increased demand, USAEC has active plans for increasing the output of its gaseous diffusion plants from their current combined capacity of 17.5 million "separative work units" (SWU)* per year to about 27.7 million SWU annually by 1981. Annual production from these facilities is planned to increase steadily from a 1973 level of 10.4 million SWU to the 27.7 million design capacity in 1983. Including separative work in pre-production inventories, the cumulative supply available is expected to be surpassed by demand by around 1982-83. Since no plans have been announced for additional expansion of AEC plants beyond the current "cascade improvement" (CIP) and "cascade up-rating program" (CUP), additional output is expected to be supplied by: (a) expansion of foreign enrichment plants; or (b) new plants, domestic and/or foreign.

Government's Role in Enrichment

Recent policy statements by President Nixon and subsequent actions by the USAEC have set forth some incentives for participation by private enterprise in providing uranium enriching services.[4] In 1971, USAEC initiated a program wherein a number of domestic industries have gained, under proper security measures, access to some of USAEC's classified uranium enrichment technology. Under this program, private firms are being allowed to pursue research and development in a number of enrichment processes with a view toward possible entry into commercial enrichment ventures.

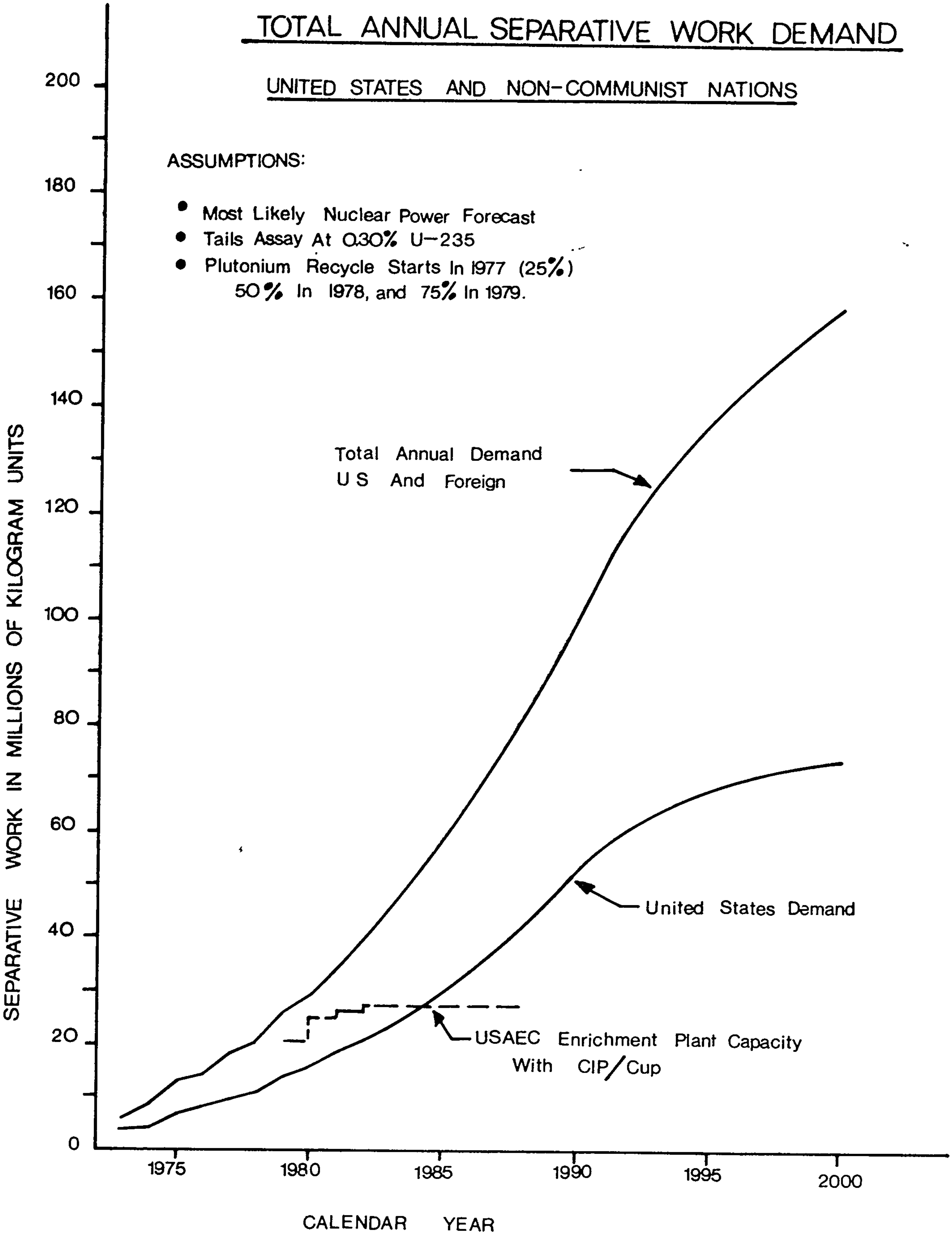
*In this report, "metric tonnes" (1000 kilograms) is a term frequently used in describing SWU.

Figure 2



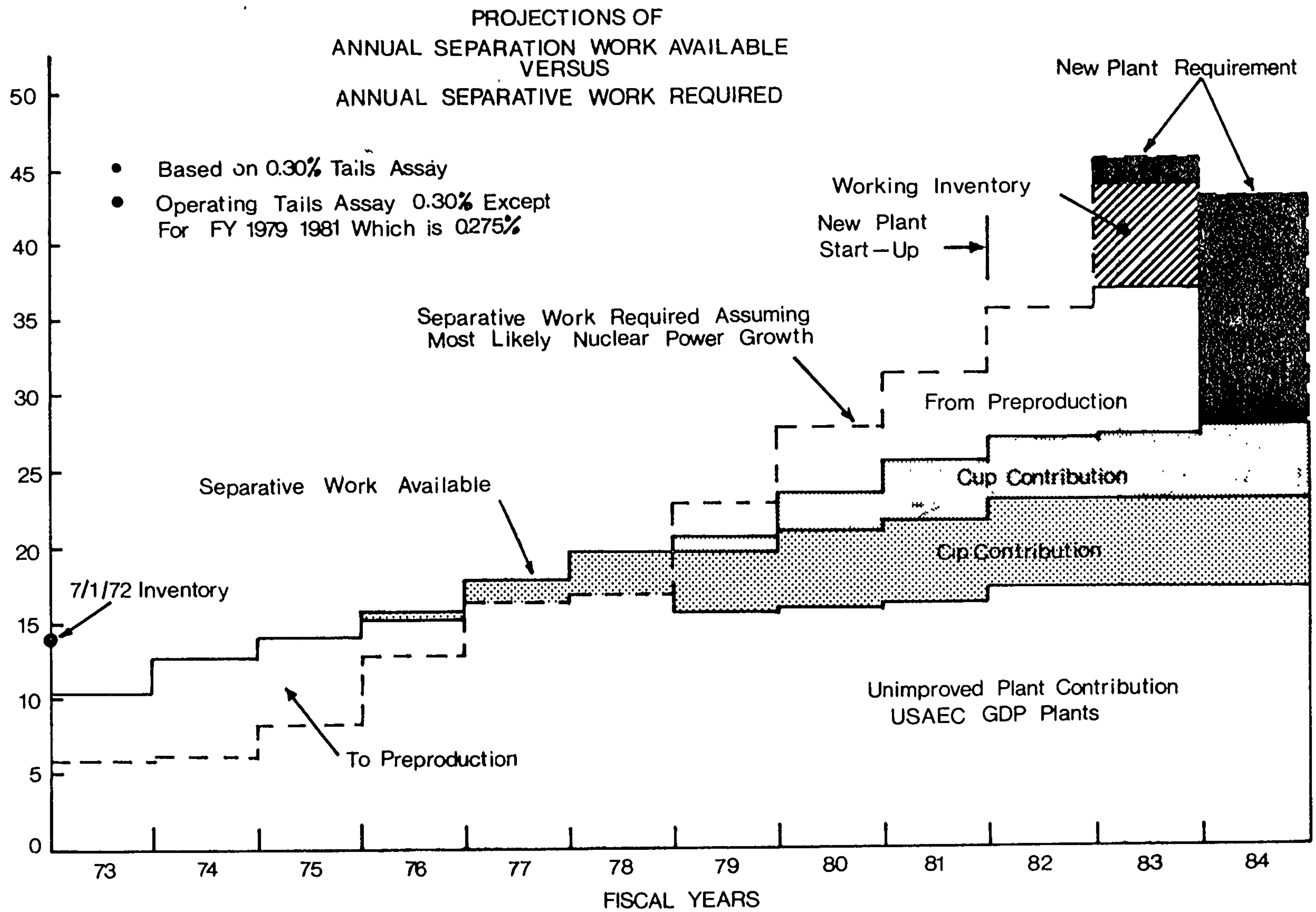
Source: USAEC - WASH-1139 (72)

Figure 3



Source: U.S. Atomic Energy Commission, Wash-1139(72)

Figure 4



Source: US Atomic Energy Commission, March 1973.

In addition, USAEC and some domestic firms, it is understood, have held exploratory discussions with officials of Western Europe and Pacific Basin nations concerning possible multi-national ventures in future enrichment operations.

From the foregoing actions, it appears that the United States government is taking definite steps to end its monopoly position in the uranium enrichment segment of the nuclear fuel cycle. At this early stage, however, it is uncertain as to the long-term (i.e., beyond about 1990) role of USAEC's three enrichment plants. Many basic policy issues must be resolved to permit a sound, long-range basis for private industry investment decisions. For example, will AEC enrichment plants be operated on a "commercial" basis, permitting full cost recovery and realistic pricing? To what extent will new privately-owned plants be allowed to compete freely in international as well as domestic markets? What new security and other regulatory mechanisms at the state and federal levels will be required? Numerous other questions must be resolved in the very near future to facilitate sound planning.

The above problem areas notwithstanding, federal monopoly in providing enrichment services will probably end within the decade, leading the way toward development of several domestic uranium enriching plants in the 1980's. The vast capital investment required has no doubt weighed heavily in the federal government's decision to encourage private industry participation. Another factor bearing on the decision is the current development efforts by several foreign countries to perfect their own enrichment technology primarily for internal needs.

Recognizing that adequate enriching capacity should be provided via government plants until private industry participation is assured, USAEC is proceeding with CIP and CUP programs to be completed in 1981. The agency recently announced plans for continued operation of its enrichment plants at a "tails assay" of .30% U-235, except for fiscal years 1979-1981. It will also "pre-produce" from its stockpile considerable quantities of enriched uranium over several years. The combined effect of these actions is to: (1) delay until about 1981-82 the time when new enrichment facilities will be required; and (2) reduce the government's uranium stockpile while simultaneously avoiding direct competition by the government in the private uranium market.

Opportunities and Problems for Private Enterprise

From the supply-demand situation depicted in Figure 4, it can be seen that new enrichment capacity should be operational by 1981-82. Additional new plants, assuming annual out-put of 8750 metric tonnes each, are indicated at about annual intervals thereafter.

At current prices of $36-38 per kilogram of "separative work", an annual international market volume for enriched uranium may reach \$2.2 billion in 1985, and could be an important factor in the "balance of payments" among trading nations. Thus, there are strong incentives among industrialized and "developing" countries to enter the international enrichment competition.

On the other hand, many economic, technological, and other constraints may affect the long-term growth of enrichment operations. First, the long-term outlook for enriching is clouded by uncertainties as to the impact of the "fast breeder reactor", the development of which is currently being vigorously pursued by USAEC and the utility industry. Fast breeders, when operating in a "steady state" mode, have virtually no requirement for enriched uranium. If current development schedules are met, commercial introduction of the breeder is expected around 1986. Since the breeder will not, however, constitute a substantial share of the reactor economy until well after the turn of the century, the enriched uranium market will grow dramatically until about 2000. Will the market remain profitable long enough for investments in new enrichment plants to be fully amortized?

Secondly, the economics and profitability of enrichment plants are largely a function of the technology involved. The gaseous diffusion process currently used in USAEC plants is based on a technology some 25 years old. While some technical improvements are being made, it would appear that the "limits" are in sight. Competing technologies, such as the ultra-centrifuge, could achieve "breakthroughs" rendering them economically attractive within the next few years. A number of large domestic companies and several foreign nations are, in fact, experimenting with the centrifuge method of uranium enrichment.

Thirdly, problems associated with siting of enrichment plants (particularly those using the gaseous diffusion process) are formidable. Very large (2000 to 3000 Mwe) power plants must be built adjacent to enriching facilities. In some locales, it may be feasible to utilize nuclear power plants for the electric energy source. Cooling water requirements for the power plants and, to a much smaller degree, for the enrichment plant are considerable, dictating a site with ample water resources. Proximity of enrichment facilities to markets and sources of feed material is only a minor consideration in siting, since transportation costs are relatively insignificant in overall production costs.

Siting an enrichment plant employing centrifuge technology is expected to be much more flexible due chiefly to the signficantly lower electric energy requirements (about one-seventh (1/7) to one-tenth (1/10) of that needed for the gaseous diffusion process) and economics of operation which permit much smaller plants. Thus, it would be possible to locate centrifuge-type plants closer to sources of supply or customers. For a centrifuge plant of 1000-3000 MTSWU/year capacity, perhaps only 30-80 Mwe of electric load would be required. At some locations, it may be possible to obtain this amount of energy from local electric utilities, reducing the need for construction of new electric power plants. Of course, the large water requirements for electric power plant cooling would also be reduced.

The availability of key process equipment (diffusion barrier material, centrifuges, compressors, special pumps, motors, etc.) may be an important factor in the long-term growth of the enrichment sector. While existing supply sources appear to be adequate for the first one or two new enrichment plants, it will probably be necessary to construct new manufacturing capacity for production of key components during the early 1980's.

Another important consideration is the extent of community development, "social overhead" capital, and supporting services required for a large enrichment complex located in a remote, sparsely-populated area. Whereas the federal government built new towns for its existing enrichment plants under wartime circumstances, new private plants will not have such government resources at their disposal. Clearly, new cooperative arrangements between the plant owners and state and local governments must be devised to provide such resources.

The Enrichment Outlook

As discussed earlier, the demand for enriched uranium will probably exceed projected capacities by as early as 1981 or as late as 1984, depending upon:

1. The rate of growth of conventional nuclear power plants in the United States and the "free world";
2. The operating modes, including the "tails assay", of existing government plants;
3. Completion of the CIP and CUP programs at existing USAEC enrichment plants;
4. That portion of new capacity supplied by foreign sources;
5. Extent to which "plutonium recycle" is utilized in light water reactors; and
6. The timing and rate of commercial development of the fast breeder reactor.

Because of the very large capital investments required, multi-company consortia are expected to be created to undertake enrichment financing and operations. It is possible that one or more such consortia will involve equity participation by "free world" foreign companies, although in a minority position and with some government-imposed restrictions as to access to U. S. classified information and imports of foreign feed materials.

USAEC's enrichment plants are expected to be operated for at least the next two decades, providing toll enrichment services for the civilian power industry and enriched material for national defense needs. Therefore, private firms contemplating entry into the enrichment field can probably rely on some degree of government competition for the foreseeable future. In view of emerging federal policy which is expected to provide for private participation in the uranium enrichment industry and the large public outlays required, it appears unlikely that AEC plants will be expanded much beyond the currently-planned 27.7 million SWU/year capacity. A large potential market, therefore, is predicted for private enrichment ventures during the 1980's and beyond. On the other hand, reluctance by private industry to commit itself to timely production schedules would probably necessitate considerable expansion of government enrichment capacity by around 1983-84.

Chapter II

CHARACTERISTICS OF ENRICHMENT FACILITIES

A. TECHNOLOGY

Natural uranium is made up of about 0.711% U-235 and the remainder U-238, except for a trace of U-234. It is possible to design and build a nuclear reactor that will burn natural uranium as a fuel. In fact, this is done to a great extent in foreign countries, especially England. However, in the United States, light water reactors have been developed which require an enrichment in the isotope U-235 of approximately 2-4%. Also, one commercial type reactor developed in the United States utilizes an enrichment greater than 90%.

During the war years three enrichment plants were constructed on an emergency basis in Oak Ridge, Tennessee. Two of these three plants, namely the electro magnetic plant and the thermal diffusion plant, were not able to compete with the economics of the third plant, which was based upon gaseous diffusion technology. The military need for enriched uranium was so great following the war that additional gaseous diffusion facilities were built at Oak Ridge, Tennessee, and a new plant was built at Paducah, Kentucky, and then a third plant was built near Portsmouth, Ohio.

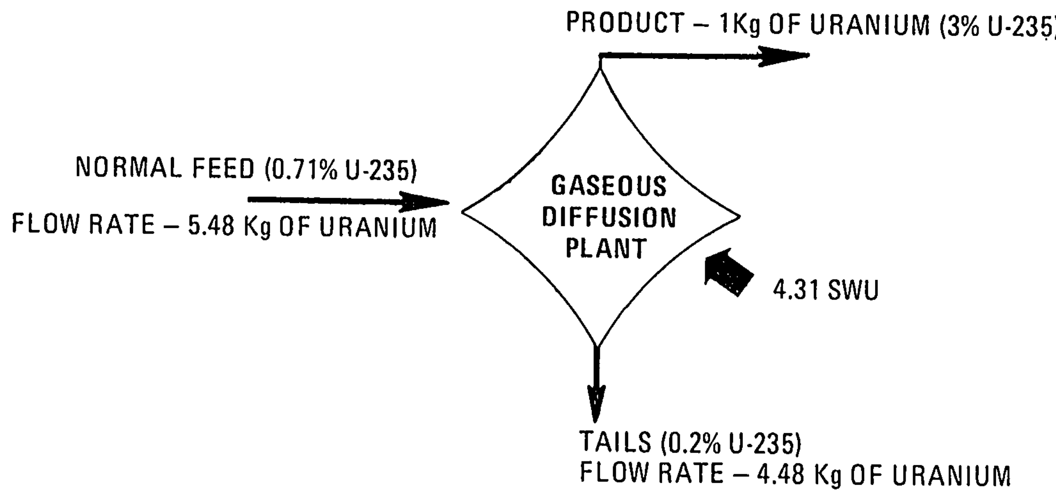
The enrichment processes of commercial significance are discussed briefly below.

1. Gaseous Diffusion

In this process uranium as UF_6 is allowed (or forced) to diffuse through a material having very small holes of diameters small compared to the path length between successive collisions of the gas molecules. The lighter molecules get through slightly faster than the heavier ones resulting in enrichment in the lighter isotope in the initial product coming through the porous barrier. The maximum theoretical enrichment that can be obtained in a single step is 1.0043, which means an increase of about 0.4% in the amount of U-235 present in the feed material. In practice the value is somewhat less. The small amount of enrichment in one step is of little value; however, using this as the feed for the next step, and its product for the third step, etc., almost any degree of enrichment may be obtained by using a sufficient number of stages. To obtain a 99% U-235 product, about 4000 steps would be needed. This type of operation is referred to as the cascade principle. Thus, the reason why a very large plant is required for uranium enrichment becomes obvious. Large compressors are required to increase the volume of material processed and to move the products to the next units, hence the large power requirements of a diffusion plant.

Figure 5

EXAMPLE OF SEPARATIVE WORK REQUIREMENTS

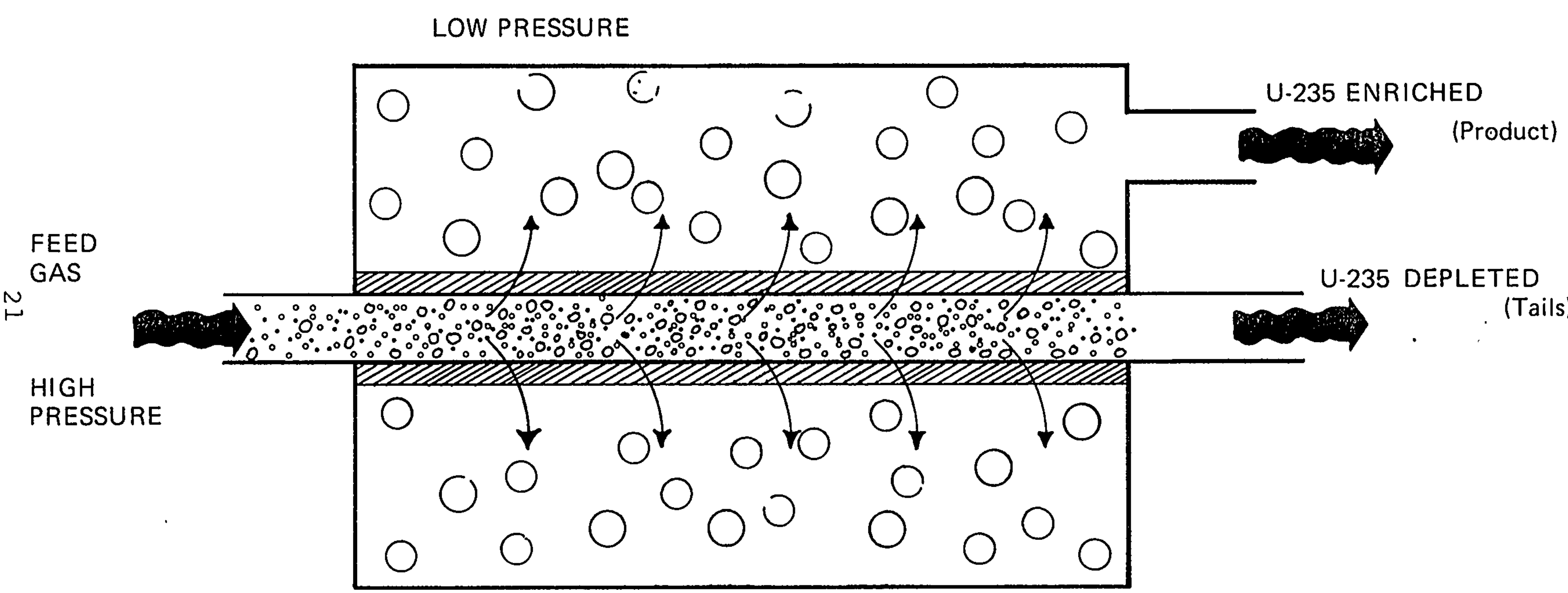


THE MEASURE OF THE REQUIREMENT FOR PERFORMING A SPECIFIED JOB IS SEPARATIVE WORK.

FOR THE CASE SHOWN 4.31 UNITS OF SEPARATIVE WORK ARE REQUIRED FOR EACH Kg OF PRODUCT.

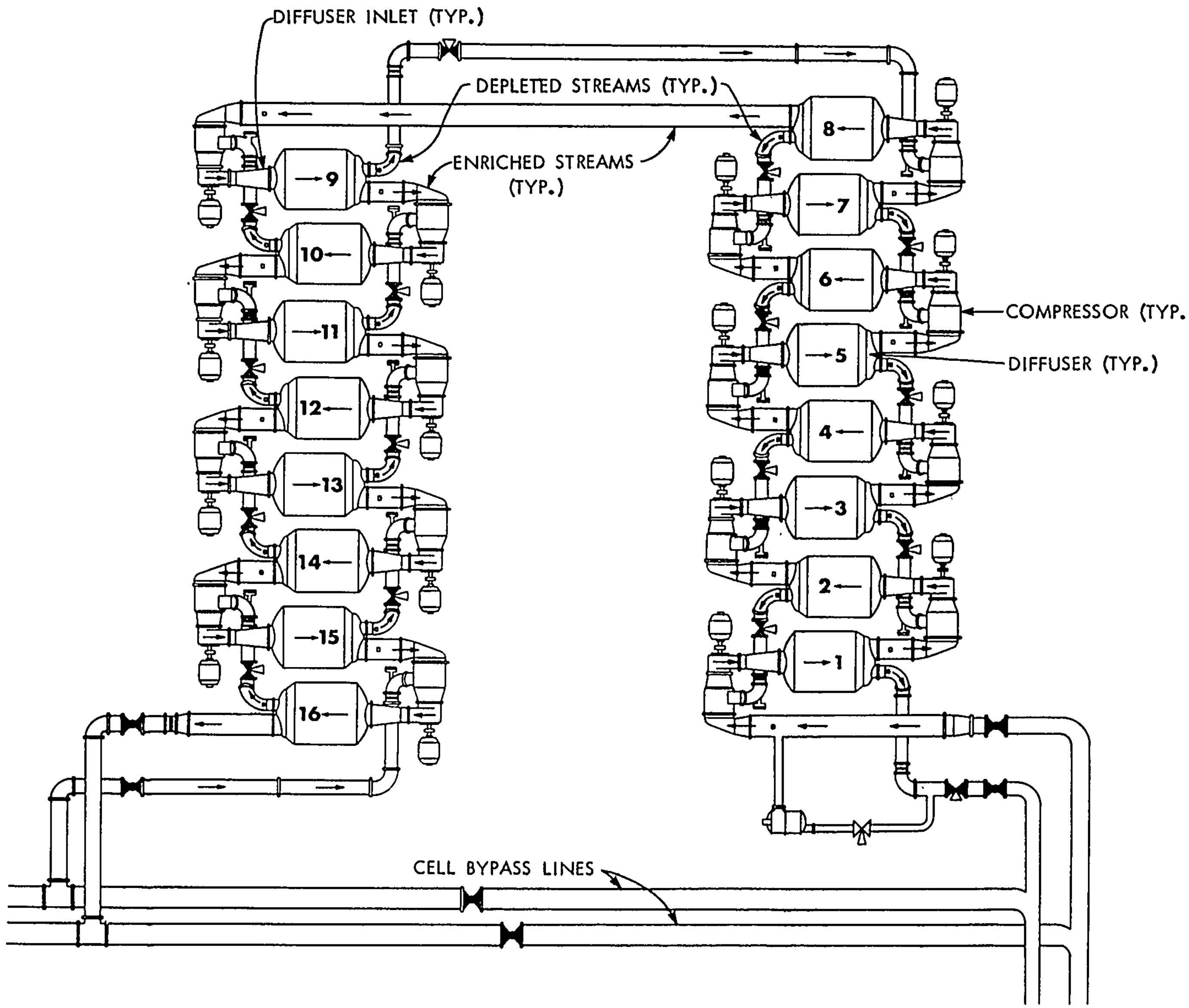
Figure 6

GASEOUS DIFFUSION STAGE



MAXIMUM THEORETICAL SEPARATION PER STAGE = 1.00429
APPROX. 1200 STAGES NEEDED FOR COMMERCIAL PLANT

Figure 7



16-STAGE PROCESS CELL

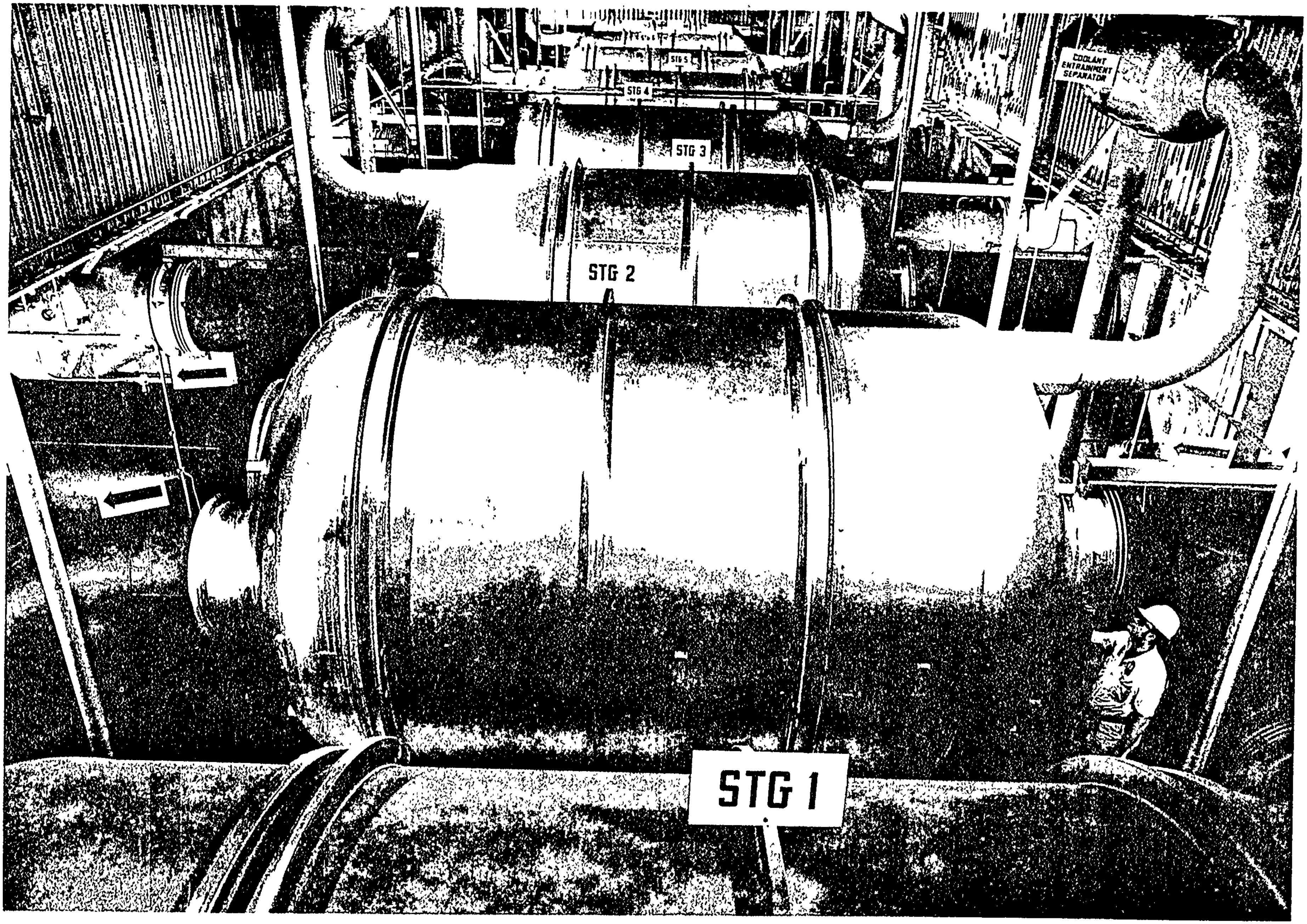


Figure 8
One of numerous process cells and stages at the USAEC Oak Ridge Gaseous Diffusion Plant.

2. Centrifuge

Another enrichment process of growing commercial interest is the gas centrifuge. The principle here is that heavier (more dense) molecules tend to go down due to gravitational pull displacing (forcing up) the lighter molecules. Practically, it would be impossible to observe any separation by normal gravitational forces because of the continual thermal agitation of the molecules. But in a high speed rotator, the effective "gravity" may be increased thousands of times through centrifugal force, making the process practical. Although the separation factor per stage is higher than that possible via the diffusion method, it is still small (about 1.2 - 1.6), necessitating numerous stages in a cascade system.

In a typical stage, normal UF-6 gas is fed into the center of the centrifuge and is spun via very high speed rotators. The heavier U-238 isotope tends to be forced toward the outside of the container via centrifugal action, leaving the lighter U-235 isotopes near the center.

Currently, USAEC and several multi-national consortia in European nations are reportedly conducting research on gas centrifuges capable of long operating lives (10 years or more) at very high rotational speeds (50,000 to 100,000 r.p.m.).

Much of the operating details of the centrifuge are highly classified.

3. Other Enrichment Processes

Several other methods of isotopic separation are technically feasible, but due to various economic considerations have not been utilized on a large scale basis. In the electromagnetic process, a beam of ionized uranium atoms, accelerated uniformly, enters a magnetic field and consequently is deflected in a circular path. The radius of the circular path is dependent upon the mass of the ion. The larger mass will describe the circle of larger radius. Thus, if a receptor is inserted in the path of an ion it can be collected. For uranium, one receptor is positioned in the path of U-235 and the other where the U-238 atoms come. Hence, each isotope of an element may be collected if the resolution (separation) of the beams is sufficiently great. The relative abundances of isotopes are obtained from measured electrical currents registered as the ions strike the collector. The principle is that of the mass spectrograph, widely used in industry and research for analytical purposes. The amount of material needed in a mass spectrograph is extremely small. Conversely the amount of enriched material produced by this process is small and requires enormous electromagnets and electric power for the process to give sizable quantities. However, with proper focusing the product beams can be made to give a high degree of separation and hence purity of isotopes.

Efficiency of the process and amount of U-235 produced can be greatly improved if a partly enriched feed is used. Low enrichments can be readily obtained by other processes. Historically a thermal diffusion process produced feed material for the calutrons at the Manhattan Project near Oak Ridge.

Another process, thermal diffusion, has undergone some experimentation. In principle, it operates as follows: In fluid containers having a temperature gradient the lighter species tend to concentrate at the higher temperature and the heavier at the lower temperature side. The development in the early 1940's used two long vertical concentric tubes with the gaseous uranium product UF_6 in the annular region. High temperature steam passed through the center tube while the outer tube was kept cold. The lighter U-235 fraction tended toward the center (hot) tube and by convection rose to the top. Hence an enriched fraction could be drawn off at the top.

The nozzle method proposed in 1955 separates isotopes by passing the gaseous mixture through an expanding air nozzle at below atmospheric pressures. The lighter molecules tend to concentrate at the outside of the gas steam because of their faster motion.

Use of the laser has recently been reported for enrichment purposes. The process depends on differences of absorption of light of a given wavelength by various isotopes or molecules containing these isotopes. For example $U\text{-}235F_6$ isotope is processed so that it is separable from its matrix material.

4. Discussion of Processes

In the all-out effort to produce the atomic bomb in the early 1940's three methods of isotopic separation primarily were pursued by the military: (1) gaseous diffusion, (2) centrifuge, and (3) electromagnetic separation. Another one (4) thermal diffusion was investigated independently at the naval laboratories and used by the Army later to produce the low enrichment feed for the electromagnetic separation.

The gaseous diffusion method proved the best method initially for large scale production of uranium of various enrichments. The key was the development of an efficient and durable barrier material in large quantity and of uniform quality, coupled with the availability of large blocks of electrical power needed to operate the pumps for the UF_6 gas.

The centrifuge method was not developed initially because of the lower production potential compared to the gaseous diffusion method. However, since the war, centrifuge development has proceeded with considerable success. Much higher rotational speeds have become available, leading to increased research and development in the process by both domestic and foreign interests.

Advantages of the centrifuge process are much lower electrical power requirements than those of gaseous diffusion. The centrifuge process, by virtue of smaller unit components, lends itself to smaller and more flexible plant designs. Maintenance costs, however, are believed to be higher than those of gaseous diffusion. This is due to the relatively short life-span of the high-speed centrifuge equipment. Current research emphasis is understood to be placed on development of more durable, reliable equipment.

A comparison of the number of stages required for enriching uranium to 2.9% U-235 is shown in Figure 9. In this illustration, a diffusion cascade would need 1500 to 2500 stages, a jet nozzle cascade would require 400-500 stages, and the centrifuge would involve 10-30 stages.

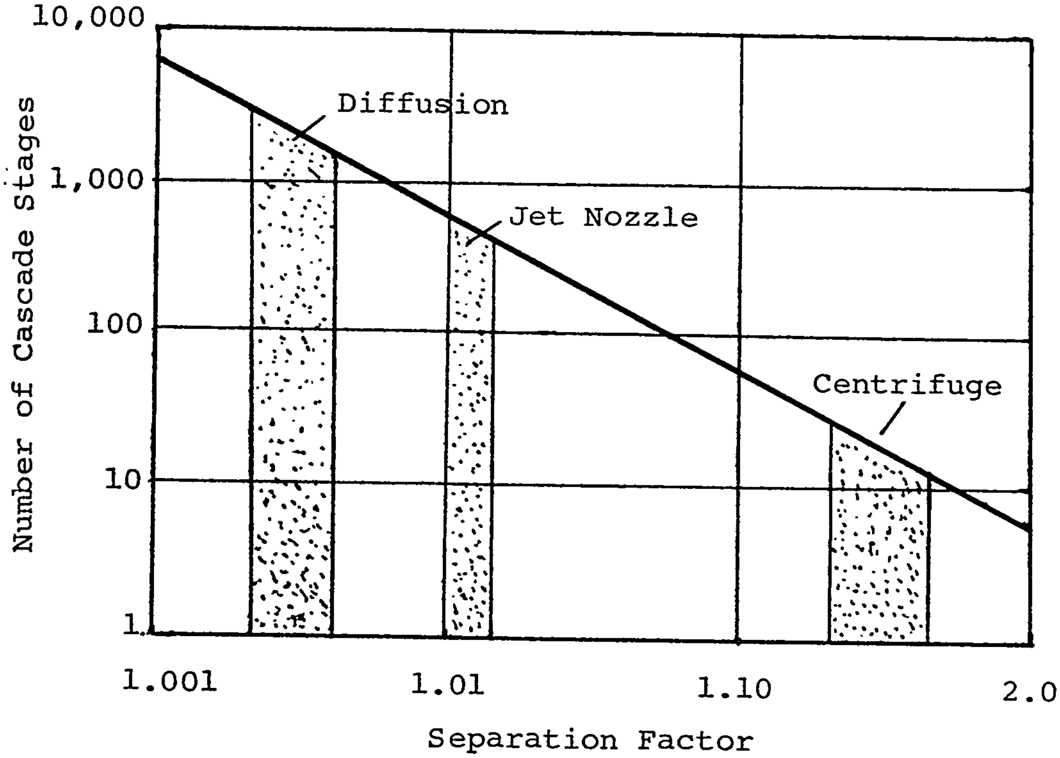
At present, a "Cascade Improvement Program" (CIP) and "Cascade Uprating Program" (CUP) is being carried out in the AEC gaseous diffusion plants. Expected gain in efficiency via CIP is about 28%. That is, almost a third more enriched uranium will be produced in the present plants after improvements without any additional electrical power requirements. The uprating would enlarge the present plants by about 25% with corresponding additional power requirements.

Concurrently, AEC is expanding its program of developing a competitive gas centrifuge system. In its recent announcement on the subject, AEC stated that it will concentrate its development efforts on specific centrifuge machines capable of becoming potentially competitive with the gaseous diffusion process by the early 1980's.[5] Its program will include new demonstration and pilot plant fabrication facilities at Oak Ridge, Tennessee. Among its program goals, AEC will seek to verify the potential competitiveness of the gas centrifuge with the best diffusion technology at power costs of about 7 mills/kwh.[6]

Several foreign organizations have recently initiated expanded programs for developing the centrifuge process. Great Britain, West Germany, and the Netherlands are jointly pursuing a centrifuge demonstration venture with a view toward building commercial enrichment facilities in the late 1970's and early 1980's. The tripartite enrichment consortium, Urenco, is involved with several private European industries in building pilot centrifuge enrichment facilities at Alemo, Holland and

Figure 9

NUMBER OF STAGES NEEDED TO ACHIEVE
2.9 PER CENT U-235 ENRICHMENT LEVEL
USING THREE MAJOR SEPARATION METHODS



For the example shown, about 1500 to 2500 stages needed for gaseous diffusion process, some 400 to 500 stages for the jet nozzle, and 10 to 30 for the gas centrifuge method.

Source: Hans Mohrhauer, "Enriching Europe with the gas centrifuge", <u>New Scientist</u>, Oct.5,1972.

at Capenhurst, England. Urenco has announced plans to build commercial centrifuge plants which would provide 3,000 metric tonnes of separative work capacity by 1980.[7,8]

Britain and France are also pursuing further development of gaseous diffusion technology. Japan has announced new joint ventures with Urenco and other nations in investigating possible multi-national enrichment ventures.

The European interest in the centrifuge process stems largely from the comparatively high-cost electric power situation in most of Europe, making gaseous diffusion process economics difficult to achieve.

Briefly, the advantages and drawbacks of the two processes are as follows:

<u>Gaseous Diffusion Technology</u>

1. Well-proven process with over 22 years of actual production experience;
2. Process components and equipment are available;
3. Requires large plants (6,000-9,000 MTSWU per year output) to achieve economical operation;
4. Requires very large quantities of low-cost electricity at high load factors (2,000-2,500 Mwe for a 8750 MT/year plant at load factor of 95 + percent);
5. Heavy total capital investment for enrichment and electric power generation facilities;
6. Potential for process improvements beyond current "state-of-the-art" is limited;
7. Siting dependent upon power and water resources;
8. Construction time of about six years (excluding power plants).

<u>Gas Centrifuge Technology</u>

1. Potential economic competitiveness appears to justify a large-scale development program;
2. Lower electric energy requirements (about 10% of that for a comparable gaseous diffusion plant);
3. Economies of scale permit building of small (1,000-3,000 MTSWU/year) plants;
4. Process equipment with economic operating lifetimes not yet perfected;
5. Construction time of 3-4 years;
6. More flexibility in plant siting.

Comparative advantages of the two major processes are, as mentioned above, undergoing intensive study by domestic and foreign organizations. As of this writing, there has been no clear consensus among nuclear officials as to which process will become the "mainstay" for the enrichment industry. Of course, from a national energy conservation standpoint, it would be desirable for the centrifuge process (with its lower power needs) to achieve competitiveness with gaseous diffusion as soon as possible. However, much research and development must be performed before such determinations can be made.

It is projected that AEC gaseous diffusion plants will be operating at full capacity in the late 1970's and thereafter. Additional plants, employing either of the processes, will be required to meet expected demand beginning in the early 1980's.

A recent announcement by the USAEC indicates that government enrichment technology will be made available to companies deemed qualified on technical and financial grounds as potential participants in the production of uranium enrichment. With this important policy decision of the USAEC, it is believed that economic evaluations will be made by knowledgeable commercial organizations and that in the near future a determination will be made with respect to the appropriate method to be pursued.

An earlier policy decision by the USAEC permits what is known as "Phase II" of AEC's enrichment access program. As of this writing, seven companies have elected to request participation in this program, which involves permission to do research and development in the enrichment field at their own expense. The companies that have requested to participate in this effort are General Electric, Westinghouse, Goodyear Tire & Rubber, Electro-Nucleonics, United Aircraft, Exxon Company, and Reynolds Metals.[9]

Additionally, a joint venture to study the feasibility of a commercial enrichment facility has been initiated by Union Carbide, Westinghouse, and Bechtel Corporation.[10] As previously discussed, Reynolds Metals Company has announced a proposal for building a large gaseous diffusion plant in Wyoming.[11]

B. ECONOMICS OF OPERATION

1. Net Energy Balance

Both the gaseous diffusion and centrifuge processes require very large quantities of electrical energy. In the GDP, electricity is used to drive motors for large compressors. In the centrifuge process, the energy is consumed in a large number of high-speed rotators (centrifuges).

In a GDP, for example, the energy fuels required for enriching U-235 to 3% product and the energy equivalents of enriched product are discussed briefly. For an oil-fired power plant, some 8,000 barrels of oil are consumed to produce one barrel of enriched UF-6, which has an energy equivalent of 200,000 barrels of oil, or a ratio of 1/25. By a similar calculation, 2,000 tons of coal can produce one barrel of UF-6 which is equal to 56,000 tons of coal, or a ratio of 1/28.

Also, 48 million cubic feet of natural gas can be consumed to process one barrel of UF-6, equal in energy to 1.24 billion cubic feet of natural gas, for a ratio of about 1/26. (See Appendix A for detailed discussion.)

A nuclear reactor fueled with uranium (3% U-235) can also provide the energy to drive the compressor in an enrichment plant. Hence, the energy in 1/22 of a barrel of UF_6 will provide the electrical power to obtain a full barrel of UF_6. This appears to be a conservative estimate; USAEC estimates show ratios of 1/24 to 1/45.

Comparable energy "input-output" data were not developed for the centrifuge process; however, such analysis would undoubtedly show a distinct improvement in net yield via the centrifuge.

(The Appendix to this report provides additional information on energy input-output calculations for the GDP.)

2. Operating and Capital Costs

Costs of construction and operation of gaseous diffusion plants are well-established by virtue of AEC GDP plant experience. Considerable studies on costs for new GDP facilities have been conducted by AEC and industrial firms. The economics of the centrifuge process, however, have yet to be demonstrated on a near-commercial scale. Moreover, much of the data on the centrifuge process is still classified by USAEC. Nevertheless, some information on comparative economics of the two processes has been published and are shown in Table B.

Data for new GDP facilities are shown in Table C. Cost figures are based on 1971 dollars. Capital investment for a typical 8750 MTSWU/year plant is estimated at $1.05 billion (1971 dollars). Industrial sources have estimated capital costs of around $1.5 billion for such new facilities based on completion of construction in the 1980's.

In addition to the capital costs for the enrichment plant, new GDP facilities would require outlays for new electric generating systems. At 1973 costs of about $300 per kilowatt for fossil-fueled power plants and $400/Kw for nuclear power reactors, capital investments for a 2,500 Mwe power station would be around $750 million to $1.0 billion. These figures would no doubt be considerably higher in the 1980's.

3. Utility and Manpower Requirements

The process support system and manpower requirements for new GDP plants and the existing enrichment plants at Oak Ridge, Paducah and Portsmith are given in Tables D and E taken from the AEC reports, ORO-684 and ORO-685.[12,13]

Table B

ENRICHMENT PROCESS ECONOMICS

	Gaseous Diffusion	Gas Centrifuge
Minimum capacity for optimum economics (annual MTU)	8,750	1,000
Construction time (years)	6	3
Electric power req'd. (megawatts)	2,050+	30
Specific investment ($ per kg. of separative work)	120-140	150-170
Production costs (per kg SW):		
Capital costs	$ 8.50-19.50	$17.00-30.00
Power	12.50-21.60	2.30- 3.60
Operation, and other	1.50- 7.30	4.00-12.50
Totals	22.50-48.40	23.30-46.10
URENCO estimates	28.30	31.80
AIF estimates	35.90-43.10	30.40-39.60

Sources: Uranium Enrichment, Atomic Industrial Forum, 1972.
Hans Mohrhauer, "Enriching Europe with the gas centrifuge", New Scientist, October 5, 1972.

Note: Power costs are based on rates ranging from 6 mills to 9 mills per kilowatt hour.

Table C

NEW GASEOUS DIFFUSION PLANT ESTIMATES

(Located in the U.S., Assumed Product Assay of 3-4% U-235, Assumed Tails Assay of 0.25% U-235)

(Costs in June 1971 Dollars)

Technology	1970	1970	Projected Advanced
Separative Capacity, Millions of SWU/yr	8.75	17.5	8.75
Capital Investment, $ Million*	1200	1900	1050
Specific Investment, $/SWU/yr	137	109	120
Power, Mw	2430	4730	2050
Specific Power, kw/SWU/yr	0.278	0.270	0.234
Operating Cost (Excluding Power Costs), $ Million/yr	14	16	15
Manpower Requirement	900	925	960

*Excludes the capital cost of the barrier production and test facilities. In the case of U.S. plants, facilities required for the Cascade Improvement Program are projected to be adequate for construction of plants of the sizes shown. New facilities sized for the assumed construction schedule for an 8.75 million-SWU/yr plant are estimated to cost about $80 million.

Source: Data on New Gaseous Diffusion Plants, ORO-685, U.S. Atomic Energy Commission.

C. LOGISTICS AND TRANSPORTATION

The feed material to an enrichment plant is unenriched uranium hexafluoride (UF-6), usually shipped in the solid state in protective cylinders by truck from the UF-6 conversion plants. The enriched product of the process is also UF-6, and it is usually transported by truck or rail in protective cylinders to fuel fabrication plants. (See accompanying photos.)

Uranium by-product ("depleted UF-6" or "tails) is stored temporarily in protective containers on-site and is subsequently sold to industrial firms for uses in radiation shielding and other applications.

Due to the very high energy and product values of enriched UF-6 per unit weight and volume, transportation costs of feed material and product constitute a very small fraction of total production costs. AEC estimates for ocean transport of 5000 miles transit, are about $0.6/SWU, and about $0.2/SWU for shipment of product only. Rail shipments of 1000 miles are estimated to have corresponding values of about $0.35/SWU and $0.15/SWU.

Converting these values to equivalent energy production costs, transportation costs are as follows:

Table D
PROCESS SUPPORT SYSTEMS
(Maximum Capacity)

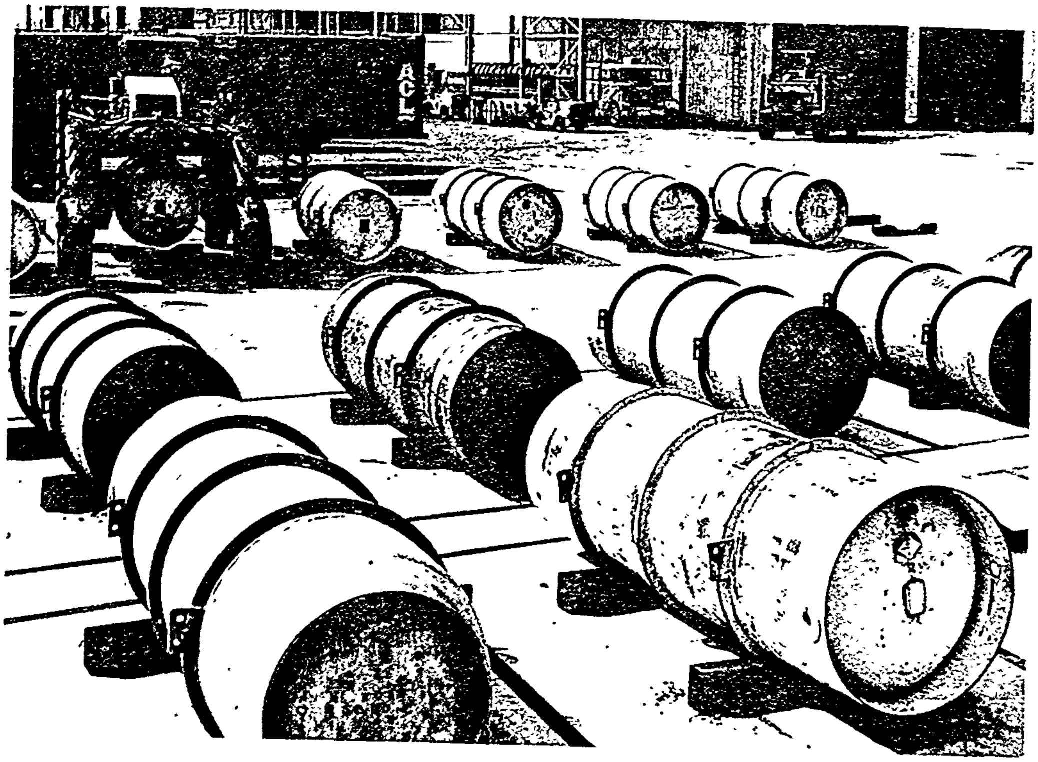
Facility	Oak Ridge	Paducah	Portsmouth	New GDP Plant (8750 Mt/y
Recirculating water system (gpd)	400,000,000	500,000,000	450,000,000	450,000,000
Fire water system (gpm at 85 psi)	16,500	20,000	16,500	16,000
Water treatment plant (gpd)	25,000,000	30,000,000	30,000,000	20,000,000
Steam plant (pounds/hr)	270,000	330,000	375,000	350,000
Nitrogen plant (scfm)	180	195	65	N.A.
Dry air system (scfm)	22,000	15,000	22,000	12,000

Table E
GASEOUS DIFFUSION OPERATIONS PERSONNEL
(1971)

Function	Oak Ridge	Paducah	Portsmouth	New 8750 MT/yr GDP Plant
Production	256	240	286	177
Maintenance & Plant Engr.	376	368	404	439
Technical	100	38	213	67
Other	174	243	279	217
	906	889	1182	900

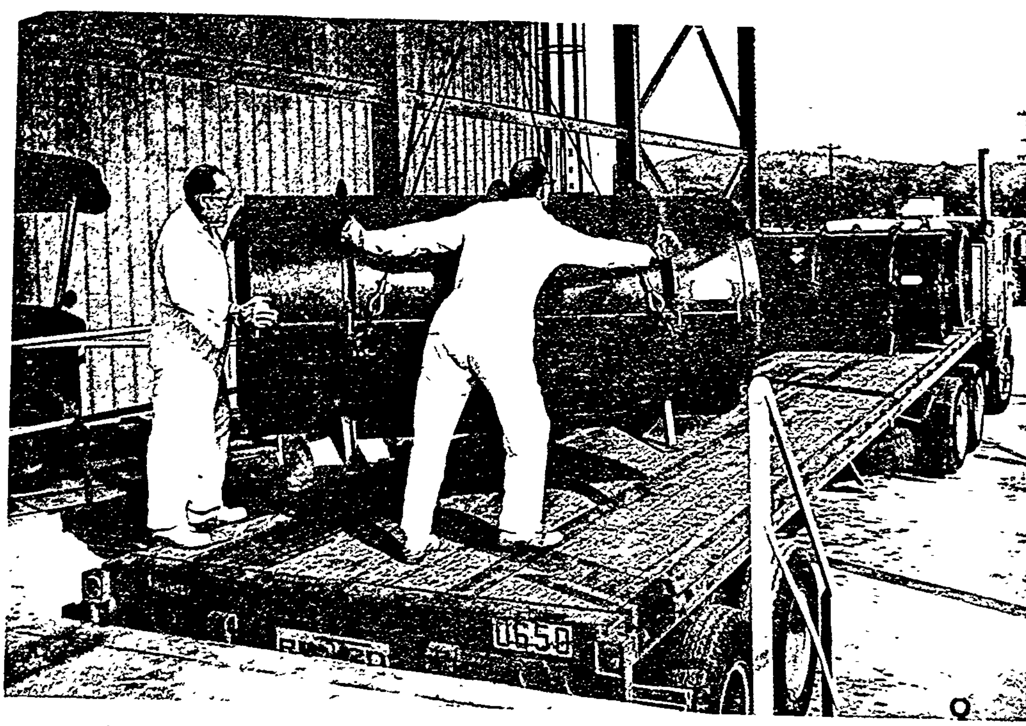
Source: USAEC, Report No. ORO-684, 1972.

Figure 10



UF-6 Feed Material in Storage Awaiting Enrichment at Oak Ridge Gaseous Diffusion Plant.

Figure 11



Enriched UF-6 Product Being Loaded for Shipment at Oak Ridge Gaseous Diffusion Plant.

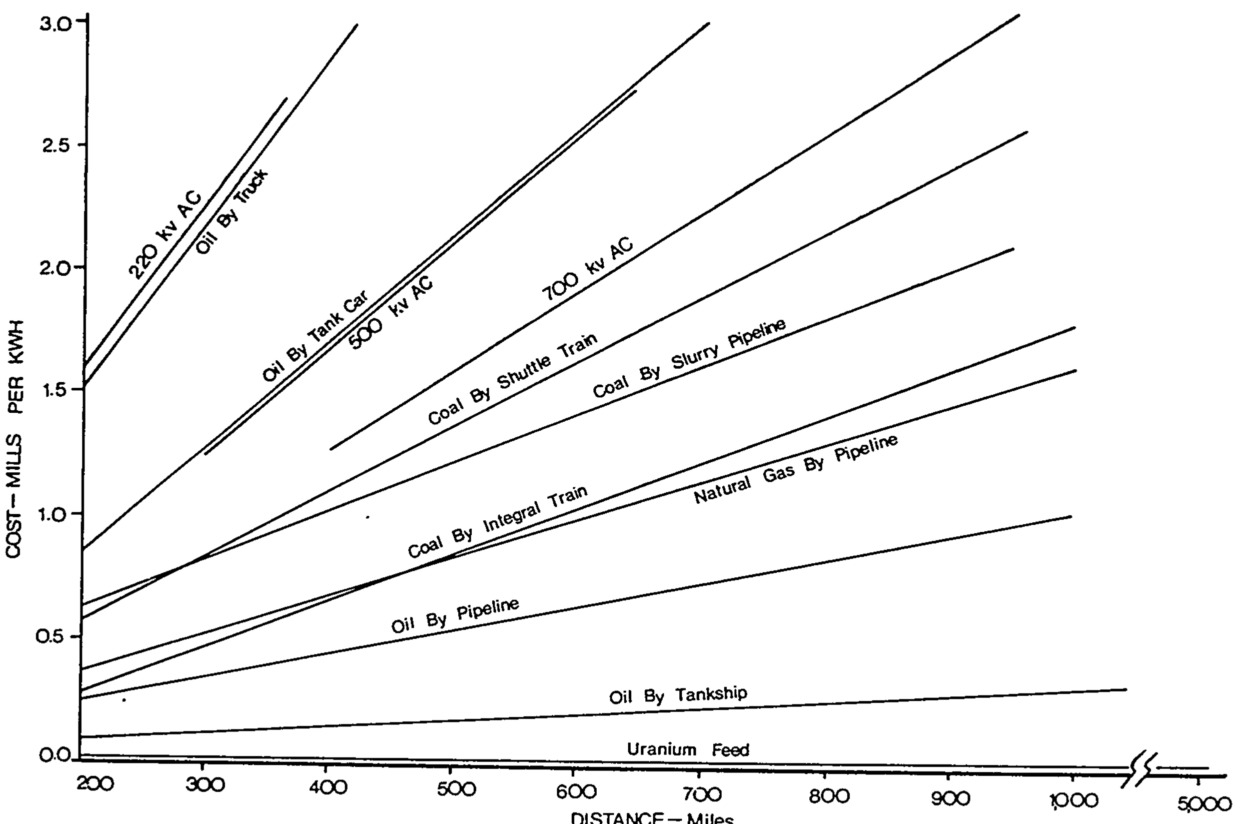
	5000 miles (Mills/Kwhr)	1000 miles (Mills/Kwhr)
UF-6 Feed	.00363	.00211
UF-6 Product	.00121	.00091

Comparative energy transportation costs for several types of common fuels is shown in Figure 12.

From the foregoing, it can be concluded that siting of an enrichment plant will not be greatly influenced by transportation costs of feed material or product. On the other hand, shipping costs for fossil fuels are relatively high per unit value. Thus, if fossil fuels are to be used in the attendent power plants, enrichment plant siting should be in reasonable proximity to fossil fuel sources.

Figure 12

AVERAGE ENERGY TRANSPORTATION COSTS



Source: National Power Survey, 1970,
Federal Power Commission

Chapter III.

SITING AND DEVELOPMENT CONSIDERATIONS

Owing to their mammoth size, energy requirements and a host of other critical locational factors, uranium enrichment plants of the gaseous diffusion type pose unique challenges in siting and development. Great care must be exercised in selecting sites which facilitate economical operation with minimal impact on the environment.

Table F summarizes the major siting factors for typical gaseous diffusion and centrifuge enrichment plants of 8750 MTSWU annual capacity. Of paramount importance is the availability of large quantities of low-cost electricity. Water supplies for enrichment processes and for cooling of power plant condensors are another significant requirement. Labor availability, transportation facilities, and various supporting services are also of major import. The following are discussions of these criteria.

Electric energy

As is pointed out elsewhere in this report, about 50-70% of the production costs of a gaseous diffusion enrichment facility are for electric power. Additionally, electric energy at very high load factors (over 90%) is required for efficient, "round-the-clock" operation. These requirements, coupled with the very high power demand (2000 to 3000 Mwe), necessitate siting in close proximity to electric generation sources.

For gaseous diffusion plant requirements, it is unlikely that such large amounts of electric energy could be purchased from existing power systems; therefore, the construction of new power plants appears to be essential. Since the delivered cost of electricity is sensitive to transmission distances, it is highly desirable to locate power plants as near as possible to the enriching facilities.

To permit economically competitive operation, electric power costs should probably not exceed about 10 mills per kilowatt hour (Kwh). Currently, coal-fired power plants in the 1,000 Mwe size range equipped with state-of-the-art pollution abatement equipment produce electricity in the range of 7 mills to 15 mills/Kwh. Plants located at the "mine-mouth", of course, generally operate at the lower end of this range. Power costs for oil or natural gas-fired plants produce power at "bus-bar" costs of about 8-25 mills/Kwh, depending upon location.

Nuclear power plants may be another potentially attractive power source in some locales. Present-day reactors of the "light-water" or "gas-cooled" types generate electricity in unit capacity sizes of 800 to 1,200 Mwe at costs of about 6-12 mills/Kwh. The Hanford-2 nuclear power plant under construction in the State of

Washington, for example, is expected to produce 1,135 Mwe at around 5.27 mills/Kwh.

Table F
MAJOR SITING CONSIDERATIONS
(Enrichment Plant of 8750 MTSWU Annual Capacity)

	Gaseous Diffusion	Centrifuge
Electric energy (demand in MWe)	2,000-3,000	200-300
Water-enrichment plant (gal. per day)	22,000,000	N.A.
Water-power station (acre-feet/year)	40,000-63,000	N.A.
Land area - enrichment plant (acres)	400-700	300-500
Land area power station (acres)*	200-900	N.A.
Labor Availability		
Construction work force	6,200 peak	5,000 peak
Permanent work force*	1,000-1,300	1,100-1,400
Transportation facilities	truck + rail	truck + rail
Proximity to markets	Not significant	Moderately important
Proximity to feed materials	Not significant	Not significant
Environmental impact		
Enrichment plant	Minor	Minor
Power station	Major**	Minor
Socio-economic impact	Major	Major

N.A. - not available

* Does not include possible coal-mining operations for power plants.

** Depends largely on type of electric generating plants involved.

Water requirements

Dissipation of heat produced in enrichment plant processes and attendant electric power plants involves use of vast quantities of water. Cooling water for enrichment processes amounts to some 450,000,000 gallons per day, the great majority of which is recirculated through heat exchangers. Consumptive losses involve about 22,000,000 gallons daily.

Water supplies for cooling spent steam in power plant condensers depends upon the size and type of power plant and several other factors. It is estimated that fossil-fuel power plants of 40% thermal efficiency, producing 2,500 megawatts of electricity, would require about 2 billion acre-feet of cooling water annually through the condensers. By comparison, nuclear power plants require approximately 3.4 billion acre-feet per year. Except at oceanside sites or other locations where "once-through" cooling may be feasible, it is usually necessary to employ large cooling towers or reservoirs to dissipate heat prior to discharge of effluents into local watersheds. Net consumptive use of water via cooling towers amounts to some 62,500 acre-feet per year for a 2,500 Mwe nuclear power station and about 40,000 acre-feet annually for a fossil-fueled power plant of comparable output.

Table G provides comparative data on the cooling water requirements for several types of power plants.

From the foregoing, it is obvious that the availability of water for cooling purposes and the "sensitivity" of the local environment to water utilization are major determinants in siting an enrichment-power station complex.

Transportation and logistics

Location of an uranium enrichment plant with respect to raw material sources and markets is not a critical factor in plant siting. Uranium feed, in the form of uranium hexafluoride (UF_6), is shipped to the enrichment plant from commercial conversion facilities (domestic plants are in Illinois and Oklahoma). Estimated costs of shipping and interest costs of inventory in transit are as follows:

	1,000 miles rail transport	5,000 miles ocean freighter
Uranium feed (UF_6)	\$0.20/SWU	\$0.40/SWU
Enriched product	\$0.15/SWU	\$0.20/SWU

Due to its more concentrated form, "product" shipping costs per unit are lower than that for feed material. This would tend to favor plant locations in reasonable proximity to feed material sources. However, since transportation plays such a relatively unimportant role in total production costs, nearness to raw materials and customers is not essential to economical enrichment operations.

Transportation facilities, on the other hand, are quite essential. Access to railroad and truck transport is of major consideration in siting. A desirable, but not essential, additional factor is the availability of commercial air freight service. It may be quite feasible to transport enriched product via air freighters in some instances.

Labor availability

The supply of skilled and/or "trainable" labor during both the construction and production phases is another important factor in plant development. Since it is unlikely that new enrichment plants will be located within major metropolitan communities (requisite power plant operations largely dictate non-metropolitan sites), a considerable portion of the construction labor force must be imported from outside the local labor market.

Labor importation during the construction phase may impose additional costs in the form of temporary housing and other facilities not readily available in small communities. Likewise, the permanent work force, although considerably smaller, may require some partial subsidization by the enrichment plant operators in the form of grants or loans for housing acquisition, moving expenses, etc.

TABLE G

HEAT CHARACTERISTICS OF MODERN ELECTRIC PLANTS

(Heat values in BTU per kwh)

Plant Type	Thermal Efficiency (per cent)	Required Input (heat rate)	Total Waste Heat (Input minus heat equivalent)	Heat Lost to Boiler, Stack, etc.	Heat Discharged to the Condenser	Cooling Water Req'd (Cubic ft. per second per megawatt of capacity
Modern plant-fossil fuel (coal,oil, or natural gas)	40	8,600	5,200	1,300	3,900	1.15
Light water reactor	33	10,500	7,100	500	6,600	1.90
Breeder reactor	42	8,200	4,800	300	4,500	1.35

Notes: 1. Heat equivalent of one kilowatt-hour of electricity (kwh) is 3,413 British thermal units (BTU).

2. Based on inlet temperature in the 70^{o} s F. and a temperature rise across the condenser of 15^{o} F.

Source: The Water Use and Management Aspects of Steam Electric Power Generation, Consulting Panel on Waste Heat, National Water Commission, May 1972.

Community attributes and area development

Since enrichment facilities are likely to be built in small to moderate-sized communities (for reasons cited previously), the socio-economic impact is expected to be of dramatic proportions. The great influx of construction and operating personnel, new construction, demands on existing community facilities, and requirements for large committments for new roads, schools, cultural and recreational pursuits, and other "social overhead" to support the enrichment complex are expected to offer unusual challenges to the plant ownership and local citizens. Cooperative, "open" planning of a high order must be undertaken and continued during the entire planning, construction, and initial operational phases to facilitate orderly development of both the enrichment complex and the entire community.

Of course, public acceptance is of utmost importance in decisions as to siting and development. After preliminary evaluation has narrowed the choices to two or three feasible locations, preliminary plans should be discussed at length with state and local leaders prior to a final siting decision. Such discussions should include full disclosure of the expected economic, social, and environmental impacts of the venture on the state and local economy.

Environmental factors

Siting studies must include extensive evaluation of environmental conditions affecting plant operation and, conversely, environmental effects stemming from plant operations. Such analyses are necessary for a proper assessment of local environmental factors which could significantly affect internal economics and profitability. The second type of studies are needed to assure compliance with all local, State, and federal regulatory requirements.

Being a "production and utilization facility" as defined by the U. S. Atomic Energy Act, an enrichment plant must meet all applicable USAEC standards as to safety and health. Applicants for an AEC license must file a "preliminary" and "final" "Safety Analysis Report" (PSAR and SAR, respectively) as well as an "Environmental Impact Statement" as required by the National Environmental Policy Act (NEPA).

The following is a partial listing of environmental factors to be evaluated in the siting and planning of enrichment facilities. Two cases are shown: Case A is for an enrichment complex supplied with electricity by a coal-fired power plant; Case B is for a facility supported by a nuclear power plant of equivalent electrical output.

Case A: Coal-fired power plant-enrichment complex

a. Climate and meteorology - with respect to prevailing winds, site should be "downwind" of population concentrations. Areas subject to temperature inversions should be avoided where possible. Power plant stack gas emissions should enter atmosphere at sufficient height to permit proper plume geometry and dispersion.

If cooling towers or reservoirs are used for heat dissipation, careful attention should be given to local meteorological conditions (e.g., fog, icing, etc.) in the choice of cooling methods.

b. Hydrology - local and regional surface and underground water supplies should be charted as to their interactions with plant operations. Hydrological studies should include an inventory of water resources and water use patterns, fish and wildlife associated with water supplies, ambient water chemistry, and potential effects of consumption and discharges by the plant.

c. Seismology - sites in proximity of active fault zones should be avoided. The seismic history of potential sites should be carefully assessed.

d. Fuel storage - the large coal storage piles should be situated so as to minimize their unsightly appearance, wherever possible.

e. Waste disposal

(1) Gaseous airborne wastes - combustion by-products from power plants should be removed to the maximum possible extent through use of electrostatic precipitators, "scrubbers", and other air pollution abatement equipment. Special attention should be given to such pollutants as particulates, sulphur dioxide (SO_2), nitrogen oxides, radium, and trace metals.

(2) Liquid wastes and water discharges - power plant liquid wastes are of two types: relatively unpolluted cooling water discharged to the environment after heat dissipation via various cooling systems; and other liquids such as chemical additives, corrosion products, spilled lubricants, cleaning agents, water treatment materials, and furnace washings. Segregation of in-plant drainage systems as to types of liquid wastes should be an important element of effluent control systems.

(3) Solid wastes - of primary concern in a coal-fired power system is disposal of residues from the combustion of coal. These residues, "bottom ash" and "fly ash", may amount to 250,000 tons per year and are stored in "slurry" form in lagoons or as solids in huge waste piles. Careful design and plant layout must be undertaken to minimize dispersion of ash and other solids in the environment and to offset to the extent possible the unsightly appearance of residue piles.

f. Coal mining operations. An estimated 7 to 10 million tons of coal per year is required to fuel the 2,500 to 3,000 Mwe of power plant capacity. It will probably be necessary to site the power plant-enrichment complex at or near coal deposits, necessitating development of a major coal mining facility. Environmental effects of surface ("strip") mining or underground "room and pillar" mining will vary greatly, depending upon the terrain, vegetation, wildlife habitat, water resources, and numerous other factors. Strip mining would probably be favored wherever feasible due to economic considerations; however, this extraction method usually has the greater potential adverse environmental impact. Very careful evaluation of the local ecology should be undertaken to determine ways of minimizing detrimental consequences of stripping and to plan appropriate land reclamation measures.

Case B: Enrichment plant-nuclear power station

As in Case A described above, environmental factors for a nuclear powered enrichment complex are numerous and complex. Nuclear-electric power offers certain environmental advantages in many locations; however, siting is simultaneously more flexible and more stringent. It offers greater flexibility in siting in that the complex is not "tied" to its source of fuel, in this case enriched uranium fuel elements. Since fuel costs and fuel transportation costs, in particular, comprise only a small fraction of total nuclear power costs, it is possible to site nuclear power plants near the customers or load centers. The "customer" in this instance would be the enrichment plant.

On the other hand, siting is a somewhat more demanding task due to the stringent health and safety regulations imposed on nuclear reactors by the U. S. Atomic Energy Commission. To comply with State and federal requirements, detailed analysis of the following is essential:

a. Climate and meteorology - siting must provide for minimal possible dispersion of low-level airborne radioactive effluents over populated areas.
b. Seismology - siting should avoid seismically active areas; and reactor design usually must withstand earthquakes of 0.5-0.75 "g" acceleration.
c. Hydrology - power plant should be situated well above underground water tables to reduce the likelihood of groundwater contamination from plant effluents. Siting in flood plains, of course, is to be avoided.
d. Demography - power plant site should avoid areas of high population concentrations so as to provide for the lowest possible radiation exposures to the off-site citizenry, including provision for an "exclusion zone".
e. Geology - surface and underground geological conditions should permit "high load" construction.
f. Waste management - radioactive wastes should be disposed of at licensed burial sites. Chemical wastes should be neutralized

prior to discharge into local watersheds or concentrated and shipped to approved burial sites. Additionally, siting of both nuclear and coal-fired power plants should include consideration of local scenic and other aesthetic values, historical sites and landmarks, archeological resources, and other unique land features.

Enrichment plant only - environmental considerations

In both cases above, the environmental factors associated with the electric power production component of an enrichment complex were considered. The following is a brief analysis of environmental factors related to only the enrichment plant.

a. Background radiation - naturally-occurring radioactivity in soils, vegetation and from extraterrestrial sources (cosmic rays, etc.) should be sufficiently low to assure compliance with applicable State and federal radiation exposure guidelines for both plant employees and off-site residents. Incremental radiation via enrichment operations should not add more than about 3 to 5 millirems (MR) annually to natural background radiation.

b. Heat dissipation - as described earlier, process heat removal requires approximately 450,000,000 gallons of water per day, most of which is recirculated in the plant after passing through cooling apparatus. Some 22,000,000 g.p.d. of "make up" water is needed.

c. Waste and by-product materials management - "Depleted" uranium, in the UF_6 form, should be stored in sealed metal casks and maintained in a protected area to prevent introduction of the slightly radioactive substance into the environment and to ward off possible theft or sabotage. While the possibility of a criticality accident is extremely remote, even without normal precautions, great care should be taken in design of product and waste materials handling and storage systems to assure proper "geometry", spacing of containers, and materials concentration so as to avoid possible criticality.

d. Toxic chemicals management - uranium hexafluoride (UF_6) is a quite toxic compound which could cause serious illness or death if ingested in large amounts by plant workers or off-site residents. Process design should incorporate adequate safety and monitoring features to prevent large-scale escape of fluorine chemicals into the working and off-site environments.

e. Aesthetics - while gaseous diffusion plants may be considered "low-profile" designs in terms of height requirements, the very large amount of plant area involved (60-70 acres under roof) poses some serious architectural challenges. Plant exterior design should be compatible with surrounding terrain and existing structures.

Land area requirement

Approximately 60-70 acres of enclosed plant building area is required for a nominal 8750 MTSWU/year gaseous diffusion plant. This includes space for process, maintenance, storage, support facilities, and offices but does not include electric power plant buildings. Typical power plant land area requirements are as follows:

Plant fuel	Land Area for 2,500 Mwe Power Plant Acres of land	Remarks
Coal	900-1,200	Assumes on-site coal storage and ash disposal.
Nuclear	200-600	Includes exclusion area around plant.
Gas	100-200	Assumes pipe line delivery and modest on-site fuel storage capability.
Oil	150-350	Assumes adequate on-site fuel storage.

Total land area for the enrichment plant and power generation facilities are shown below.

1. Enrichment Plant: 60-70 acres (plant buildings)
   400-600 acres (parking, expansion, support facilities area)
   460-670 acres
2. Power Plant: 200-900 acres
3. Total Land Area: 660-1,570 acres

(Note: Does not include coal mining and related operations.)

Supporting industrial facilities

Due to the specialized equipment and classified nature of gaseous diffusion plant operations, much of the normal maintenance and service functions must be performed by "in-house" support facilities. Nevertheless, siting of an enrichment plant should include consideration of available machine shops and other service facilities within reasonable distances of potential sites.

Opportunities for Ancillary Industrial Development

The development of an enrichment-power generation complex may offer some unique possibilities for secondary or related industrial development. Under certain conditions, it may prove economically and environmentally attractive to develop "multi-purpose agro-industrial complexes" for more efficient utilization of land, heat, electrical, and other resources, products, and by-products. Some examples that might be considered in the siting and development phases are:

1. Agricultural complexes in arid or semi-arid regions which would utilize thermal discharges from power plants to irrigate some 25,000 to 100,000 acres of cropland or would employ heat in greenhouses, hydroponic farming, and other agricultural and horticultural applications. Food processing facilities might also be developed in the complex.
2. Desalting and related operations at coastal locations where desalted seawater might be utilized in municipal, residential, and commercial applications.
3. Aquaculture in coastal, estuarine, or inland fisheries where warm water might be used to enhance fish culture.
4. Manufacturing complexes, in which power plants would supply the process heat and electric energy needs for various energy-intensive industries such as aluminum reduction, chlorine and caustic production, and petro-chemicals. The symbiotic relationships among industries sharing common energy sources might facilitate conservation and economics in the utilization of energy, land, water, and other resources.
5. "Power parks" that would produce, at one large site, sufficient electrical energy to supply both regional load requirements and enrichment plant needs.

Construction Options and Schedules

Figure 13 depicts the normal schedules for construction of a typical GDP enrichment plant and related power facilities. It is noted that the "critical path" for completion of the complex is the time requirements for licensing, design, and construction of the power plants. A nuclear power plant requires about 8-10 years whereas a fossil unit would entail about 6-8 years.

Several construction options have been described by USAEC in its report, "Data on New Gaseous Diffusion Plants" (ORO-685). Among these are:

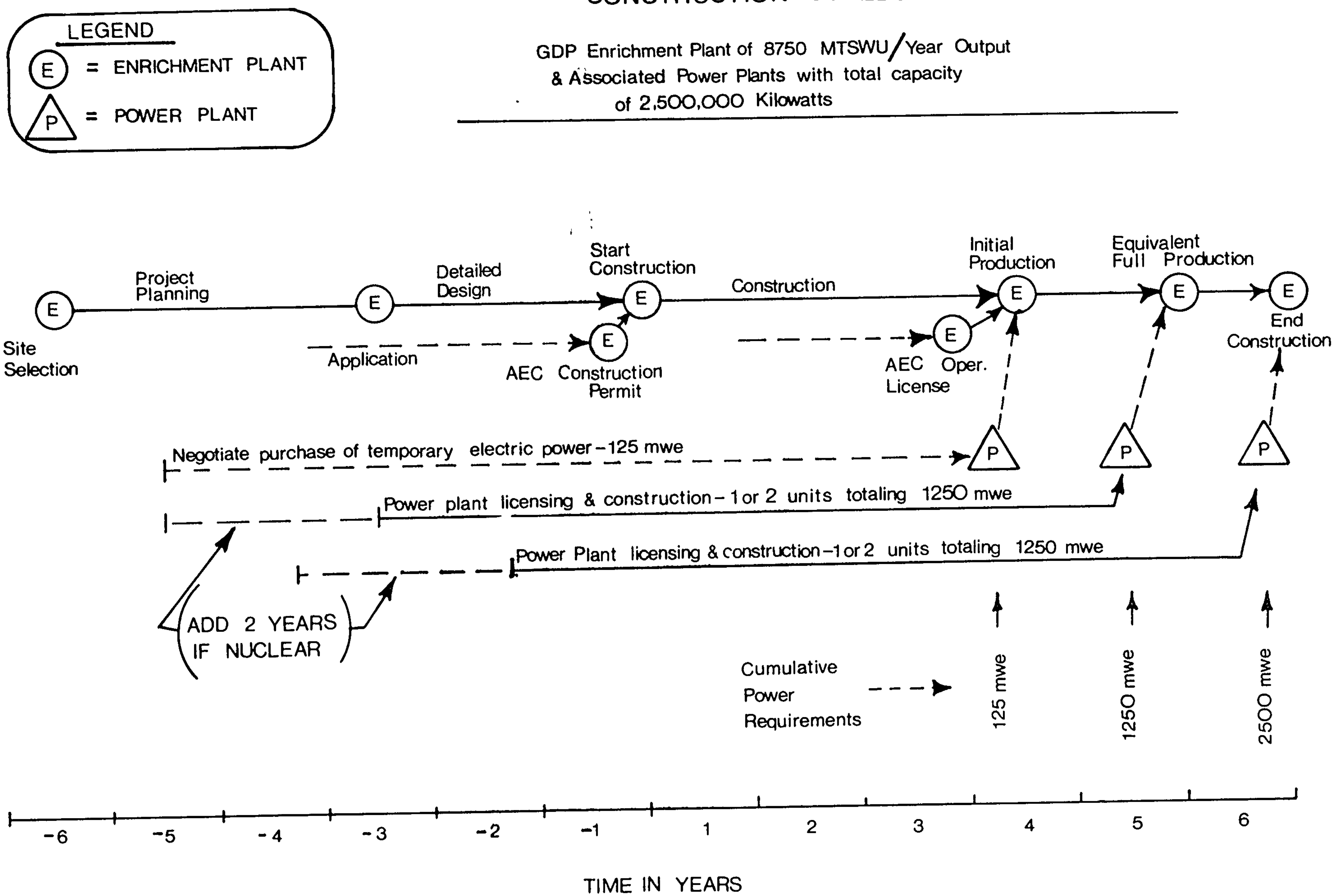
1. Development of a "full-gradient"* plant of the size ultimately desired to be completed when enriched product is first required. This strategy could permit operation at partial electrical load to coincide with market demands. Or, the plant could operate at design load with the excess production stockpiled or sold.
2. A long-term construction program could be undertaken at a rate which matches capacity and demand. In this case, the small stage section of the cascade could be brought into production some 3½ to 4 years after start of construction, with medium and large stages added later in the 6-year construction phase. This approach would require procurement of electrical power from local utilities until new generating plants are built. It would also necessitate shipment of partially enriched

* "Full-gradient" plant is one which can produce 4% product assay while stripping tails to 0.25%.

Figure 13

CONSTRUCTION SCHEDULE

GDP Enrichment Plant of 8750 MTSWU/Year Output & Associated Power Plants with total capacity of 2,500,000 Kilowatts



product to other facilities for completing the enrichment to final assay of 2 to 4% U-235.

3. A full-gradient plant of low capacity could be built and later expanded through addition of more large stages as the demand materializes.

A construction program for a gas centrifuge plant of annual processing capacity of 1000-3000 metric tonnes is projected to involve about three or four years exclusive of pre-construction siting studies and detailed design activities. The "critical path" during construction is believed to be the installation of centrifuge cascade components. Of course, it will be necessary to make pre-construction arrangements for electric power supply (30 to 100 megawatts).

Chapter IV

SOCIO-ECONOMIC AND ENVIRONMENTAL IMPACT

General

Public acceptance of any major industrial installation is largely dependent upon the comparative benefits and social costs associated with the industrial facility and a widespread public understanding of those benefits and "disbenefits". A GDP enrichment complex with its requirement for attendant electric power plants holds the potential for major impacts on a region's socio-economic as well as natural environments. These effects may vary considerably from place to place depending on local economic and environmental factors.

From an economic development standpoint, enrichment facilities would generate significant new direct and secondary employment, personal income, and tax revenues. These effects in a remote, sparsely-populated area may be quite dramatic. Such economic growth would also impose additional social costs in the form of new housing, schools, and other public facilities.

Environmental effects of an enrichment plant itself are considered to be minimal in terms of safety, radiation emissions, and other plant effluents. The addition of the requisite electric power station to the complex poses potential adverse environmental effects, depending chiefly upon the type of fuels used in the power plants. All currently available power technology suitable for enrichment operations would have some effect on local environmental conditions. Nuclear power plants would offer the advantages of virtually no atmospheric pollution, but would require larger amounts of cooling water than fossil-fueled units of the same electrical output. Among the fossil-fueled power systems, coal-fired units would pose the most serious problems in terms of atmospheric pollution, solid waste disposal, and unattractive ancillary operations. Additional environmental concerns would no doubt be raised if coal-mining facilities were constructed to serve the power plants.

Obviously, many sites would clearly be unsuitable due to possible adverse social or environmental consequences; whereas, development at other locations could contribute substantially to economic progress with minimal adverse effects. The determination of which sites should be selected must be based on extensive studies which incorporate careful consideration of local and regional socio-economic and environmental conditions and public opinion.

The following sections of this chapter are devoted to information concerning potential socio-economic and environmental factors involved in uranium enrichment and related electric generation operations.

Economic Impact

Economic implications and impacts of an enrichment power complex may be felt in varying degrees at the national, regional, as well as local levels.

1. National and international

As mentioned earlier, an international market for enriched uranium may reach $2.5 to $3.5 billion annually by the end of the next decade and could play a substantial role in the international balance of payments. At the national level, the economic viability of the rapidly-growing nuclear power industry will be contingent upon the availability of adequate supplies of enriched uranium fuel. Enrichment operations will have important influences in other fuel cycle industries such as uranium mining and milling, UF-6 conversion, fuel fabrication, and others.

2. State and regional

Significant tax revenues and expenditures will be related in various ways to enrichment plant operations. Tax receipts derived from new employment, personal income, increased sales of goods and services, and other induced business activity may be substantial. State-level revenues would vary depending upon tax structures in the individual states. Public outlays for support of local or state-supported educational institutions, highways and other transportation systems, and various state-level public services would also be significant.

3. Local socio-economic effects

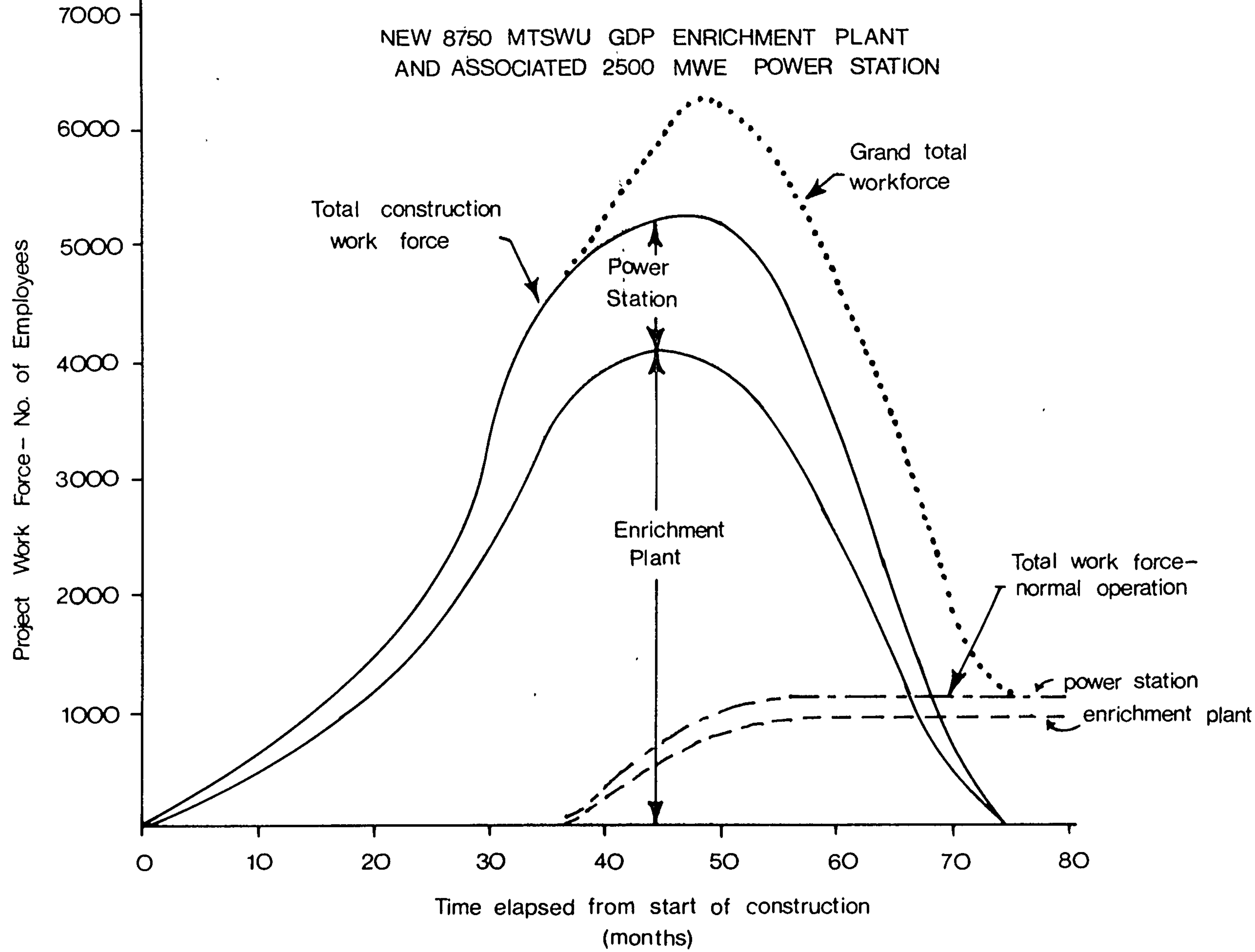
Socio-economic impact would, of course, be felt most dramatically at the local level. The combined effects of population influx, new employment, increased personal income, capital expenditure for industrial, commercial, and residential properties, and related economic activities would be quite stimulative, particularly in smaller communities. The magnitude of these economic impacts would depend upon: local population size; the size and structure of the local labor force; degree of unemployment in the area; existing economic base; and many other factors.

During the construction phase, immigration of construction workers and other "outside" personnel would impose considerable needs for temporary housing, new educational programs, and a variety of other public facilities. Some estimates of employment levels and other economic indicators are provided in Figure 14 and Tables H through L.

Upon completion of the development phase, some 1,100 to 2,500 permanent direct industrial jobs would be created,

Figure 14

EMPLOYMENT
DURING CONSTRUCTION AND NORMAL OPERATION



resulting in a total permanent population increase of about 4,300 to 13,700. Estimated annual payroll, tax revenues, and other socio-economic data are shown in Tables I and L.

To illustrate the potential economic impact, a study by the Utah State Planning Office for locations in Southern Utah indicates that some 4,500 additional jobs would be created by GDP enrichment activities. Of these, about 1,900 "residentiary" and 2,600 direct industrial jobs would be involved. Projected additional in-migration is estimated at around 10,500 persons, principally concentrated in the lower age groups.

Table H

EMPLOYMENT CATEGORIES FOR 8.75 X 10^6 SWU/YR.

GDP ENRICHMENT PLANT

Administrative, General	6
Administrative, Support	135
Engineering, Process Development	40
Laboratory	27
Security	44
Utilities	60
Maintenance	411
Operators	177
Total -	900

Source: USAEC, Report No. ORO-685, 1972.

Table I

ECONOMIC IMPACT INDICATORS
GDP ENRICHMENT AND POWER PLANT COMPLEX
CONSTRUCTION PHASE (6-8 year period)

	Average	Peak
Direct Employment at Complex		
Enrichment Plant (8750 MTSWU/year)	2,100	4,000
Power Station (2500 MWe)	500	1,200
Coal Mining (7.5 x 10^6 tons/year)	--	--
	2,600	5,200
Total Induced Employment	3,250	--
Total Population	7,800	9,000
Total Housing Units Required	2,520	2,910
School Population	2,770	3,200
Total No. Teachers Required	92	106
Annual Payroll		
a. Construction Site	$35.0 million	--
b. In Other Businesses	6.0 million	--
Total Payroll	$41.0 million	
Annual Personal Income	$53.3 million	--
Local Property Tax Revenues	$ 3.0 million	--
Other State and Local Taxes	$ 2.1 million	--

Table J

CONSTRUCTION LABOR COMPONENTS FOR

TYPICAL GDP ENRICHMENT PLANT

	Wage Rate-$ per hour*	Per Cent Total Labor
Asbestos Workers	5.65	0.1
Boilermakers	5.35	0.1
Bricklayers	5.67	0.2
Carpenters	4.85	4.2
Electricians	5.41	17.4
Ironworkers (incl. welders)	5.00	8.1
Laborers	3.25	17.5
Millwrights	5.03	4.8
Operating Engineers	3.35 - 4.65	5.9
Painters, Industrial	4.95	1.4
Pipefitters	5.90	29.5
Others	3.34 - 5.80	10.8
		100.0

*Rates for Oak Ridge, Tenn., 1970

Source: ORO-685, Data on New Gaseous Diffusion Plants, USAEC.

Table K

DIRECT EMPLOYMENT IN ALTERNATIVE

GDP ENRICHMENT & POWER PLANT COMPLEXES

(8.75×10^6 SWU and 2,500 Mwe)

I.	Enrichment Plant and Nuclear Power Station		
	GDP enrichment plant -	900	
	Nuclear power reactors (3) -	180	
	Total -	1,080	
II.	Enrichment Plant and Oil or Natural-Gas Fired Power Station		
	GDP enrichment plant -	900	
	Power station -	--130	
	Total -	1,030	
III.	Enrichment Plant and Coal-fired Power Station (Assumes nearby coal production)		
	GDP enrichment plant -	900	
	Power Station	150	
	Coal Mining (7.5×10^6 short tons/year)	325 (1)	- 1,500 (2)
	Total	1,375	- 2,550

[1]Assumes strip mining operations and productivity of 23,000 tons per man-year.

[2]Assumes underground mining methods and 5,000 tons per man-year.

Table L

ECONOMIC IMPACT INDICATORS*
GDP ENRICHMENT AND POWER PLANT COMPLEX,
NORMAL OPERATION

Direct Employment at Complex	
Enrichment Plant (8750 MTSWU/year)	900
Power Station (2500 MWe)	150
Coal Mining (7.5 x 10^6 tons/year)	325 - 1,500**
	1,375 - 2,550
Secondary (Residentiary), Other Induced Employment	413 - 1,862
Total Induced Employment	1,788 - 4,412
Total Population In-migration	4,291 -13,677
No. Housing Units Required	1,386 - 4,418
School Population	1,523 - 4,855
No. Teachers Required	85 - 270
Annual Payroll Generated	
a. At the complex	$15.1 - 28.0 million
b. Other businesses	4.1 - 7.0 million
Total Payroll	$19.2 - 35.0 million
Total Annual Personal Income	$25.0 - 46.2 million
Local Property Tax Revenues	
a. By the enrichment complex	$25.5 - 30.0 million
b. Other enterprise	$ 1.5 - 3.0 million
Other State and Local Taxes	$ 2.2 - 3.5 million

* Range of data due largely to effects of variations in mining employment resulting from different possible mining methods.

** Lower figure based on productivity of 100 tons per man-day in efficient surface mines; upper figure based on average underground mine productivity.

Environmental Impact

Effects of a typical uranium enrichment complex on the human and natural environments depend to a large extent on the type of technology employed. The gaseous diffusion process (GDP) requires approximately 2,500 Mwe of electric energy for a 8750 MT/year plant; whereas the centrifuge process would need only about one-tenth (250 Mwe) of the electric energy for a plant of equal output. Since the gaseous diffusion process is more likely to be utilized in the first one or more new plants and since it offers the more serious environmental impacts, only the GDP process will be considered in this analysis. For purpose of assessment, environmental factors are divided into two categories: (1) the enrichment plant itself; and (2) the power generation complex.

1. Enrichment plant

a. Use of natural resources

(1) Land

Approximately 500-600 acres of land would be committed during the normal 30-40 year operating life of the enrichment plant. Virtually no permanent land committments are involved since no long-lived radioactive isotopes which could not be retrieved would be disposed of at the site.

(2) Water

Some 450,000,000 gallons per day of recirculated cooling water is involved, of which about 22 million g.p.d. would be withdrawn from local supplies for make-up of evaporative losses.

b. Plant effluents

(1) Airborne

Small quantities of airborne fluoride are emitted in normal plant operations. Fluoride concentrations, based on actual experience, are well below the range in which adverse health effects have been shown. Other airborne emissions include relatively small amounts of sulfur and nitrogen oxides.

(2) Liquid

Calcium, hexavalent chromium, sodium, and sulfates are major constituents of the liquid effluents derived from process and maintenance operations. Wherever applicable, liquid effluents would be neutralized, processed, and highly diluted prior to discharge into receiving waters.

(3) Radiological effluents

Very minor releases of gaseous and liquid hexafluoride (UF-6) are involved in routine operations. Experience at AEC plants indicates that such effluents comprise less than 0.1% of the permissible limits of the federal government. No high-level radioactive materials are involved.[15]

(4) By-product and waste management

In enriching U-235 to 2-4% assay, considerable quantities of "depleted" U-235 and U-238 are generated. These "by-products" are quite valuable in various applications and are stored in sealed containers on-site for subsequent use. Other liquid and solid chemical wastes are either treated and diluted prior to release, buried on site, or packaged and shipped to approved burial grounds.

c. In-plant working conditions

The employees' working environment in most plant areas is relatively hazard-free with no significant conditions requiring radiation shielding. Criticality is avoided due to highly dilute form of uranium hexafluoride and its low (less than 5%) U-235 content. Process streams are sealed with no significant releases into the working environment. Air must be kept out of the process equipment to prevent decomposition of the compound. As a result, there is little or no routine or accidental release of material to affect employees of the environment. Only about 5% of plant employees would technically require radiation exposure monitoring, and of those, all usually receive less than 20% of the annual permissible exposure. As a precautionary measure, however, most workers wear radiation monitoring devices.

(1) Criticality control

One of the characteristics of uranium enriched in the U-235 isotope is that a self-sustaining nuclear reaction can occur under proper conditions. This is what takes place in a reactor when the uranium is caused to fission and release radiation and heat. Carefully designed equipment and controls are employed at gaseous diffusion plants to assure that conditions are never reached to cause accidental "criticality". These include control of equipment size, control of moderating impurities in the process, control of UF densities in the cascades, and carefully followed procedures. There has never been a criticality at a gaseous diffusion plant. However, the half-dozen "criticality" accidents which have occurred elsewhere since the beginning of the nuclear industry have all verified the fact that these occurrences have only localized in-plant effects. There is no "explosion" associated with such accidents. Within a few feet of these occurrences, however, the radiation exposures can be very high and even lethal. This is why careful controls are instituted to prevent them. (See Appendix C)

(2) Heat and noise

Maintenance workers are exposed intermittently to noise levels of 90-100 decibels and temperatures of 120^o - 140^o F. in some areas near compressors. When working near these localized "hot spots", maintenance crews are usually supplied with protective clothing and cool air supplies.[16]

(3) Toxic chemicals

Several toxic chemicals are used in routine process, maintenance, and cleaning operations. Some of these were mentioned above. Approximately 40-50 tons of hydrogen fluoride is stored on site and must be carefully isolated from workers.[17]

(4) Industrial safety and fire protection

In gaseous diffusion plant operations, the equipment is totally enclosed and the only moving parts seen by the operators are guarded electrical motor drives. The areas are extremely clean since no debris is created by the separation process. Compared to general industry accident experience, the three gaseous diffusion plants' last five-year average was only 0.8 disabling injuries per million man-hours. In industry, these figures were about 8.00 disabling injuries per million man-hours, and 660 days lost per million man-hours worked.[18] The building and process equipment at a gaseous diffusion plant is very costly and is, accordingly, designed to permit little or no fire hazard. The process contains non-flammable materials, and only the lubricating oil presents potential fire hazards. In view of the high plant values, specially designed sprinkler systems with very large-volume-water systems are installed. These sprinkler systems are structurally stronger than conventionally designed systems and are hydraulically designed to positively provide water over very large areas. Low loss fire experience indicates that these plants are safe and consequently are excellent insurance risks.

2. Electric Generation Complex

The major source of environmental impact related to enrichment operations is that stemming from the electric power generation needed to support the enrichment plant. In the case of a coal-fired power plant, environmental effects would be posed by: (a) gaseous effluents from coal combustion residues; (d) unsightly plant stacks, waste piles, etc.; and (e) coal mining operations. Table provides data on characteristics, emissions, and fuel requirements for a typical coal-fired power station.

As derived from Table M and actual experience, a coal-fired power station generating 2,500 MWe would produce annual quantities of air pollutants as follows:

Particulates into atmosphere:	72,250	short tons
Sulfur dioxide:	274,000	" "
Nitrogen oxides:	72,200	" "
Carbon monoxide:	1,750	" "
Hydrocarbons:	875	" "
Radioactivity: (Ra-226)	68.0×10^{-3}	Ci

Some 200,000 tons of fly ash and bottom ash created annually in coal burning must be collected and disposed of, on or off-site. Typically, ashes are mixed with water to form a slurry and placed in storage ponds on site.

Coal required for a 2,500 MWe power station is estimated at about 7.5 million tons annually. Coal production operations employing strip mining techniques would disturb about 600 to 1,000 acres of land annually. Of this total, 170 to 400 acres would be directly involved in coal production.

Depending upon local terrain and other environmental conditions, coal mining could introduce various chemical pollutants into local watersheds. A carefully designed land reclamation program would reduce significantly the permanent damage to land.

Oil or natural gas-fired power plants would offer less potential for adverse environmental effects due to reduced requirements for solid waste disposal and on-site fuel storage and elimination of local mining operations. Gaseous effluents, however, would still pose some potential atmospheric pollution problems.

A nuclear power station of 2,500 MWe output would involve potential adverse effects through:

a. Heat discharged from plant steam condensing system.

b. Controlled releases of gaseous and liquid low-level radioactive wastes into local environment.

c. Storage and handling of low-level radioactive residues and highly radioactive irradiated (spent) fuel.

Water requirements for cooling purposes amount to approximately 4.75 cubic feet per second, assuming once-through cooling. In most instances, cooling towers or ponds would be required to prevent the 12-20° F. temperature increase in the effluent from adversely affecting local receiving waters. Evaporative water losses via a cooling tower system would amount to about 62,500 acre-feet annually. A comparable fossil-fired plant would require about 38,000 acre-feet per year.

TABLE M

CHARACTERISTICS AND EMISSIONS DATA

TYPICAL COAL-FIRED POWER PLANT (1000 Mwe)

Thermal Efficiency: 40%

Heat Rate: 8,600 BTU/kwh

Total Waste Heat: 5,200 BTU/kwh

Heat Lost to Stack, etc: 1,300 BTU/Kwh

Heat Discharged to Cooling Condenser: 3,900 BTU/Kwh

Cooling Water Required: 1.15 cu. ft. per second

Fuel Required: 330 to 390 short tons/ hour, depending upon heat content of coal

Ash Content of Coal: 8 to 10%; 26 to 39 tons/hour

Emissions into Atmosphere: (average, at 100% load factor)

- Particulates*: 3.3 short tons/hour
- Sulfur dioxide**: 12.5 short tons/hour
- Nitrogen oxides: 3.3 short tons/hour
- Carbon monoxide: 0.08 short tons/hour
- Hydrocarbons: 0.04 short tons/hour
- Radioactivity***: 3.1×10^{-6} Ci/hr (Ra-226)
- Aldehydes: 2 lb/hour
- Trace metals: varies with different coals

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* Depends on efficiency of particulate matter removal systems.

** Will vary greatly depending upon sulfur content of coal, and efficiency of SO_2 removal systems at plant.

***Based on typical concentrations of radioactive elements found in coal in Western United States. Other isotopes of interest include Radon, Polonium, and Thorium.

Sources: References 19, 20, and Appendix D.

Radioactive emissions from a typical nuclear power plant are shown in Tables N and O . The example in these tables is the Trojan Nuclear Plant, a reactor of 1,130 MWe under construction in Oregon.[21] Data must be increased by a factor of about 2.5 to obtain figures for a 2,500 MWe power plant needed for the model enrichment plant. Radioactive discharges into local ecosystems would, however, be held to concentrations approximating those for a single reactor. In any event, discharges must conform to release limits (maximum permissible concentrations-MPC) promulgated by the U. S. Atomic Energy Commission. Exposures to off-site personnel must not exceed 5 millirems per year. (As a point of reference, annual exposures to the population from natural background radioactivity varies from around 100 mr to 250 mr per year in the United States, depending on location.)

Low-level radioactive solid and liquid wastes filtered out of demineralizers and other plant equipment are packaged for shipment to licensed burial sites. Spent demineralizer resins for a 2-reactor, 2500 MWe power station would amount to about 700 cubic feet annually. An estimated 200 drums of slightly radioactive rags, coveralls, filter cartridges, etc. would be disposed of annually. Each drum shipped to the burial site would contain radioactivity of about 2 Curies.

High-level radioactive discharges would consist of annual removal of spent fuel from the reactor core. Spent fuel is not "disposed of" per se due to the very high value of plutonium and unused uranium still in the fuel elements. Rather, spent fuel is placed in heavily shielded casks and shipped under close supervision to a nuclear fuel reprocessing plant where separation of the valuable constituents and waste fission products is conducted. After separation, waste products are stored underground at the reprocessing plant are eventually shipped to a government disposal site.

Table N

ANNUAL GASEOUS RELEASE BY ISOTOPE, CI/YR

Trojan Nuclear Plant
(1,130 MWe)

Nuclide	Containment Purge	Waste Gas Decay Tanks	Auxiliary Building Ventilation	Condenser Air Ejector	S.G. Blowdown Tank Vent	Total
Kr-85m			2.44	0.978	0.0006	3.42
Kr-85	2.1	2006.	7.28	2.91	0.0018	2018.
Kr-87			1.42	0.567	0.0004	1.99
Kr-88			4.30	1.72	0.0011	6.02
Xe-133	7.3	1780.	296.5	118.6	0.0748	2202.
Xe-135			25.6	10.24	0.0065	35.8
Xe-138	0.048		0.61	0.244	0.0002	0.902
I-131	0.0037		0.00003	0.008	0.0005	0.0122
I-133	0.00047			0.007	0.0004	0.0079

Source: Environmental Report, Trojan Nuclear Plant, Vol. I.

Table O

TROJAN LIQUID RADWASTE DISCHARGES

Isotope	Radioactive Half-Life	Primary Coolant Activity μCi/cc (120°F)	Annual Discharge, Radwaste Systems, Ci [a]	Annual Discharge, S.G. Blowdown, Ci [a]	Annual Avg. Discharge Activity μCi/cc	MPC Water Public μCi/cc
Cr-51	27.8 d	6.5×10^{-4}	4.9×10^{-8}	1.5×10^{-3}	8.7×10^{-11}	2×10^{-3}
Mn-54	303. d	5.4×10^{-4}	8.8×10^{-8}	1.3×10^{-3}	7.5×10^{-11}	1×10^{-4}
Mn-56	2.576 h	2.0×10^{-2}	$<1.0 \times 10^{-9}$	4.7×10^{-3}	2.7×10^{-10}	1×10^{-4}
Co-58	71.3 d	1.7×10^{-2}	2.1×10^{-6}	3.9×10^{-2}	2.3×10^{-9}	9×10^{-5}
Fe-59	45.6 d	7.2×10^{-4}	7.5×10^{-8}	1.7×10^{-3}	9.8×10^{-11}	5×10^{-5}
Co-60	5.263 y	5.2×10^{-4}	8.6×10^{-8}	1.2×10^{-3}	6.9×10^{-11}	3×10^{-5}
Sr-89	52.7 d	8.3×10^{-5}	8.0×10^{-8}	1.9×10^{-4}	1.1×10^{-11}	3×10^{-6}
Sr-90	27.7 y	2.4×10^{-5}	3.3×10^{-9}	5.6×10^{-5}	3.2×10^{-12}	3×10^{-7}
Y-90	64.0 h	2.9×10^{-5}	9.3×10^{-9}	5.1×10^{-5}	2.9×10^{-12}	2×10^{-5}
Sr-91	9.67 h	3.9×10^{-4}	$<1.0 \times 10^{-9}$	2.7×10^{-4}	1.6×10^{-11}	5×10^{-5}
Y-91	58.8 d	1.4×10^{-3}	3.6×10^{-7}	3.2×10^{-3}	1.8×10^{-10}	3×10^{-5}
Mo-99	66.7 h	6.7×10^{-1}	2.3×10^{-5}	1.2×10^{0}	6.9×10^{-8}	4×10^{-5}
I-131	8.05 d	5.0×10^{-1}	1.0×10^{-5}	1.0×10^{0}	5.8×10^{-8}	3×10^{-7}
Te-132	77.7 h	5.2×10^{-2}	2.5×10^{-7}	9.4×10^{-2}	5.4×10^{-9}	2×10^{-5}
I-132	2.26 h	1.8×10^{-1}	8.7×10^{-7}	3.7×10^{-2}	2.1×10^{-9}	8×10^{-6}
I-133	20.3 h	8.0×10^{-1}	6.3×10^{-8}	8.8×10^{-1}	5.1×10^{-8}	1×10^{-6}
Cs-134	2.046 y	5.3×10^{-2}	1.7×10^{-5}	1.2×10^{-1}	6.9×10^{-9}	9×10^{-6}
I-135	6.68 h	4.3×10^{-1}	$<1.0 \times 10^{-9}$	2.3×10^{-1}	1.3×10^{-8}	4×10^{-6}
Cs-136	13.7 d	8.4×10^{-3}	1.3×10^{-6}	1.8×10^{-2}	1.0×10^{-9}	6×10^{-5}
Cs-137	30.0 y	3.3×10^{-1}	1.0×10^{-4}	7.7×10^{-1}	4.4×10^{-8}	2×10^{-5}
Ba-140	12.8 d	8.5×10^{-4}	3.2×10^{-8}	1.9×10^{-3}	1.1×10^{-10}	2×10^{-5}
La-140	40.22 h	2.9×10^{-3}	1.1×10^{-8}	4.3×10^{-3}	2.5×10^{-10}	2×10^{-5}
Ce-144	284. d	1.3×10^{-4}	1.7×10^{-8}	3.0×10^{-4}	1.7×10^{-11}	1×10^{-5}
H-3	12.262 y	4.5×10^{-1}	7.2×10^{2}	1.1×10^{0}	4.2×10^{-5}	3×10^{-3}

[a] Total annual discharge without H-3 -- 4.4 Ci.
Total annual H-3 discharge -- 720 Ci.

Source: Environmental Report, Trojan Nuclear Plant, Vol. I.

Chapter V.

WESTERN RESOURCES: POTENTIAL FOR ENRICHMENT PLANT SITING

Introduction

The WINB Committee on Uranium Enrichment had among its objectives the identification of resources in the 12-State Western Region which could be important to the economic and environmentally acceptable operation of new uranium enrichment plants. This rather general overview of major energy and fuels resources in the West is intended only as a guide in identifying potential plant sites which may warrant extensive investigation.

The Committee feels that the matter of proposing and evaluating specific sites should rest with State and local governments and the plant operators. However, due to various "regional" influences involved in plant site studies and decisions (eg, the capacity of interstate electrical grid systems, and "regional" water considerations), the Committee strongly suggests regional as well as localized approaches to site evaluations.

The following provides a brief summary of principal natural and other resources of interest in enrichment plant siting.

Siting of a Centrifuge-Type Enrichment Plant

As pointed out earlier in this report, production costs for a centrifuge process enrichment plant consist of fairly high specific capital costs as well as labor and maintenance costs which are substantially greater than that of gaseous diffusion plants. Electric power costs for the centrifuge process are significantly lower than GDP plants. Thus, centrifuge plant siting would involve careful consideration of local labor and construction costs, availability and skills of the labor force, proximity to product markets and raw materials, as well as availability of low-cost electric energy at demands of 30-100 Mwe.

Unlike the gaseous diffusion process, the much lower electric energy demands for the centrifuge process would reduce the need for additional power generation facilities devoted to primarily to servicing the enrichment plant. Thus, considerably more flexibility in plant siting is possible. Many locales in the Western Region would appear to qualify for consideration as candidate sites. The West Coast and Southwest areas (Arizona, California, Nevada, Oregon, and Washington) as well as certain areas of the other Western States warrant detailed site analysis for centrifuge plants.

Potential Western Locales for a Gaseous Diffusion Plant

The gaseous diffusion process requires very large quantities of low-cost electricity, dictating plant siting near existing or potential power generation facilities. In addition, the requirement for uninterrupted electric service would suggest the need for additional "back-up" power supplies available via supplemental generators and/or connections to a highly-integrated regional electrical grid.

Electrical energy - Figure 15 indicates major electrical transmission corridors in the West for the years 1970 and 1990. Transmission lines of 230 KV or more only are shown. Estimated loads for 1970 were 54,035 Mwe and 307,759 gigawatthours. For 1990, the load is expected to quadruple to 216,420 megawatts and 1,232,800 gigawatthours (gwh). Installed generating capacity in 1970 was 66,700 Mwe. Only around 2 per cent was provided via nuclear power plants in 1970; however, by 1990 nuclear power is estimated to supply over 40% of total capacity. About 70% of the Region's load concentration is along the Pacific Coast.[22]

Resources for potential electric power generation - The Western States possess considerable water, oil, coal, natural gas, uranium, and geothermal resources which offer potential for electric power generation for uranium enrichment plants. Almost 160,000 square miles of land area in the West (mostly in the Rocky Mountain region and Alaska) is underlain by coal deposits. Oil and natural gas resources are dispersed among eight of the Compact States. Figures 16 and 17 illustrate the geographic distribution of fossil fuels in the Region.

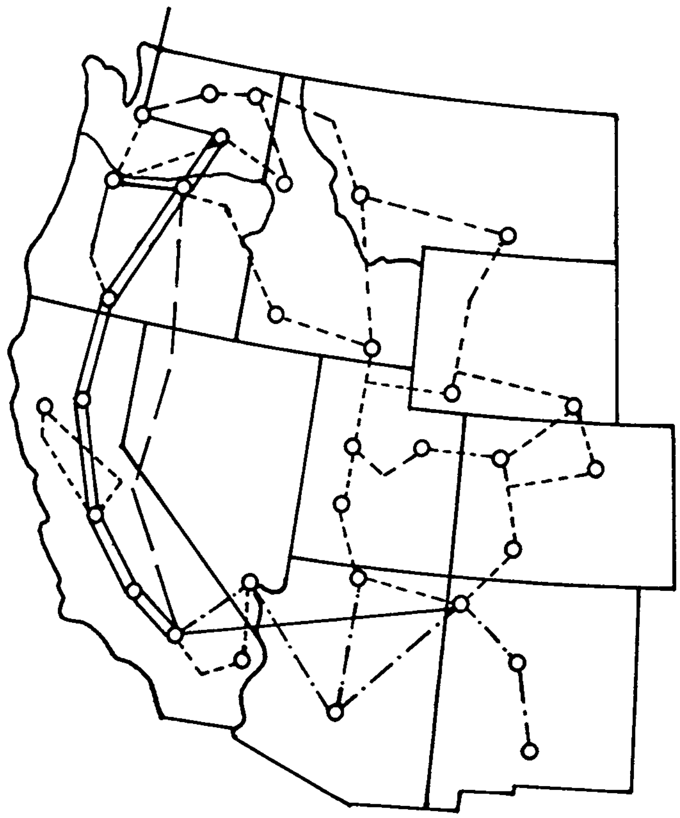
Hydro-electric power resources are well developed in California and the Northwest area. Some additional potential for hydro generation exists, but suitable sites are becoming increasingly scarce except in Alaska where significant untapped resources are available. However, due to various economic and environmental considerations (eg, migratory fish habitats, etc.), hydro-electric generation is expected to decline in importance in the future.

Alaska contains extensive coal deposits (about 35,000 square miles) in the Yentna - Beluga area, Matanuska Valley, Kenai Peninsula, the southwestern section of the State, and in the North Slope area. The southern fields are located near the Cook Inlet and Anchorage where ice-free ocean transportation and other industrial and community services are available.

Vast reserves of oil and natural gas are situated in the North Slope region. The proposed 800 mile Trans-Alaska pipeline would offer possibilities for enrichment plant siting and electric power generation, particularly in the Valdez area where the southern terminus of the pipeline would be located.

Figure 15

ELECTRIC TRANSMISSION IN THE WEST REGION



As of 1970

Planned for 1990

LEGEND

- - - - - 230 kv
-·-·-·- 287 and 345 kv
——— 500 kv and above
— — 800 kv D.C.

Figure 16

COAL FIELDS IN W.I.N.C. MEMBER STATES

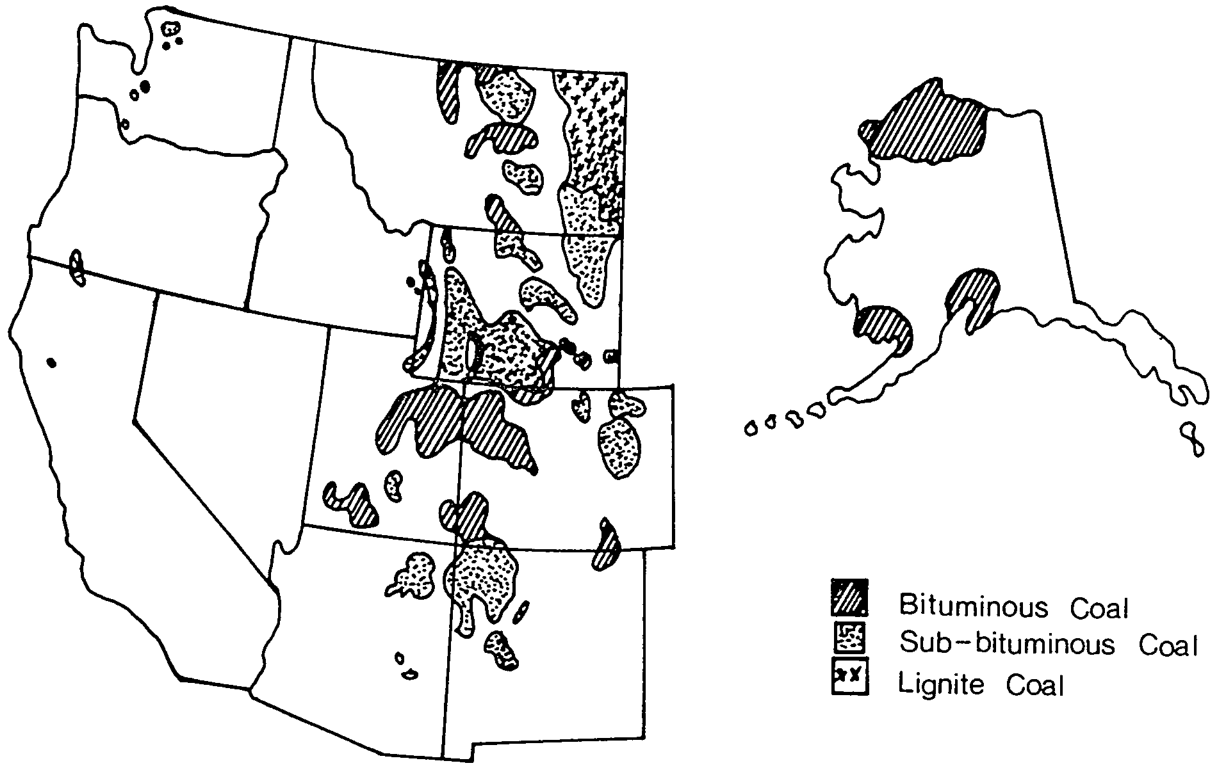
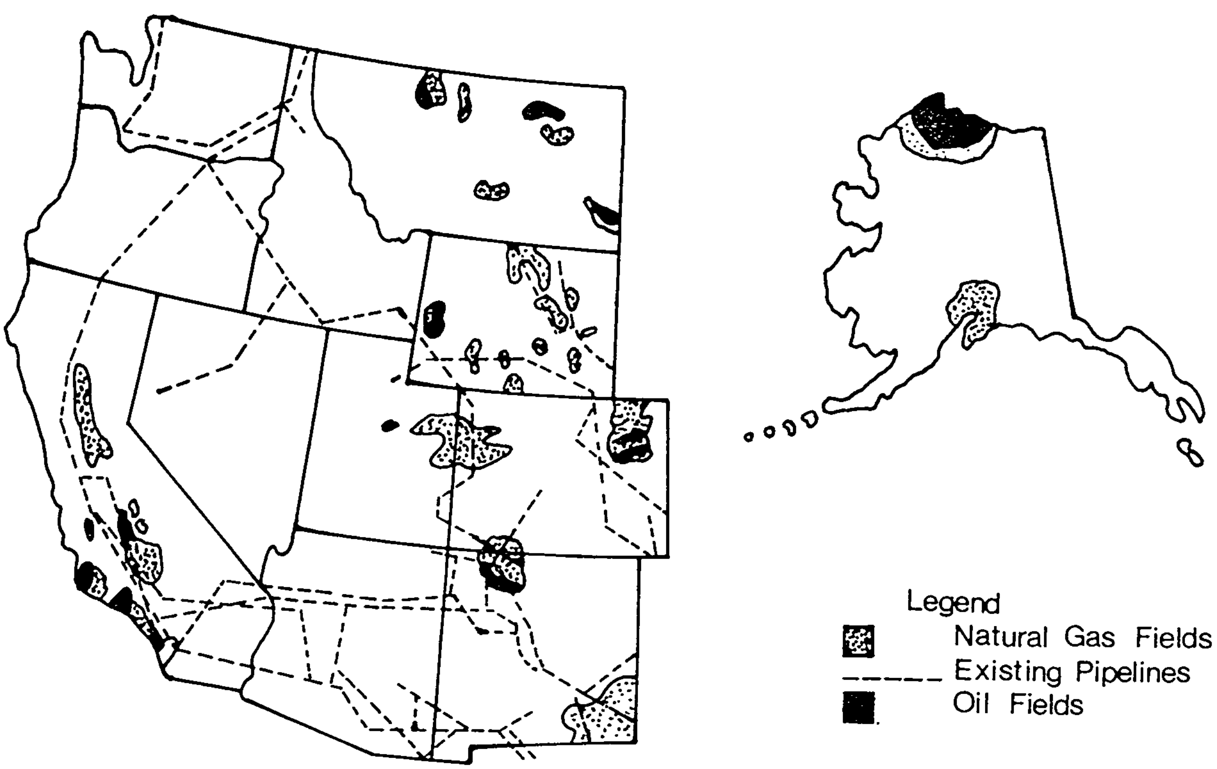


Figure 17

MAJOR OIL AND NATURAL GAS FIELDS IN W.I.N.C. STATES



Note: Alaska not shown to scale. Oil shale deposits not shown.

Considerable untapped geothermal and hydro-electric potential exists in Alaska. These resources could contribute to energy-intensive industrial development during future decades.

The Northwest region, consisting of Idaho, Oregon, and Washington, contains many favorable attributes for potential enrichment plant siting. The electrical distribution system of the Bonneville Power Administration is well developed. Although it is currently based largely on hydro-electric power, the BPA system's future expansion is expected to utilize nuclear generation.

Ample water supplies for process uses are available along the West Coast and inland along the Columbia and Snake Rivers. Commercial seaports are located at Portland, Seattle, and several other cities adjacent to the Puget Sound. Barge transportation facilities are available along the navigable portion of the Columbia River.

The large nuclear-related complexes at Hanford Reservation, Washington and Idaho Falls are among many sites in the Northwest which may be suitable for an enrichment plant location.

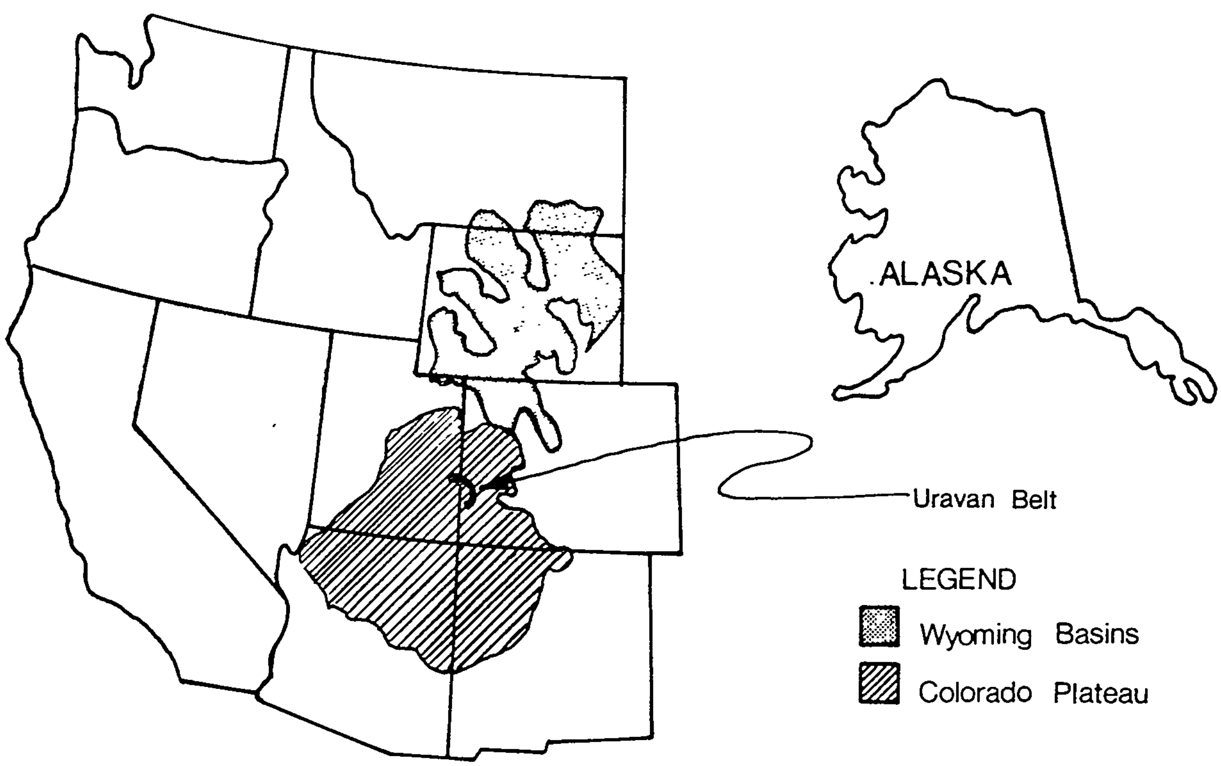
Abundant reserves of coal, oil, oil shale, and natural gas are found in many areas of the Rocky Mountain area. Suitable sites with adequate fossil fuels and water supplies are believed to exist in the States of Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Rail and motor transit facilities are well-developed in the area, and commercial air freight transport is available in the larger cities.

Although not critical to enrichment plant siting, the production of uranium "yellowcake" and ore in the region may offer opportunities for development of uranium conversion (U_3O_8 to UF_6) plants which could offer transportation economics related to enrichment operations. The region currently produces over 87% of the nation's "yellowcake". (See Figure 18.)

Figure 18

PRINCIPAL URANIUM PRODUCING AREAS

comprising over 87% of U.S. production



NOTE: Does not include areas of Alaska, Washington, and Oregon where some production has occurred, nor does it include potential uranium deposits where only limited exploration has been conducted.

Alaska shown not to scale.

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APPENDIX A
ENERGY CALCULATIONS - FOSSIL AND NUCLEAR FUELS

The following calculations and assumptions show that the energy in about 200,000 barrels of oil is equivalent to the available energy of one barrel of UF_6 (3%).

Assumption #1. The energy released per U-235 fission event is 198 MeV (ref. 4, p. 505).

Kinetic energy of fission products	167 MeV
Kinetic energy of fission neutrons	5 MeV
Prompt gamma-rays	5 MeV
Beta-decay energy	5 MeV
Gamma-decay energy	5 MeV
Neutrino energy	11 MeV
Total	198 MeV

Assumption #2. All of the above energy will generally appear as heat within the near region of the event except that due to neutrinos. Texts on (ref. 4) elementary particles will state that because of the very low probability of interaction with matter detection of neutrinos is extremely difficult. Hence, this energy is not observed near the fission event, leaving 187 MeV.

Assumption #3. Of all neutrons absorbed by U-234 only 84.4% produce fission. This is based on the relative cross sections for fission, 580 barns and for absorption, 687 barns (ref. 4, p. 490). The ratio $\frac{580}{687} = 0.844$ or 84.4%. The atoms not fissioned (15.6%) produce U-236 with gamma emission. However, the contribution of this gamma energy to the total energy is very small.

Assumption #4. The energy realized from one gram of U-235 completely "burned up" is

$$\left(187 \frac{\text{MeV}}{\text{atom fissioned}}\right)\left(0.844 \text{ fraction of fissions when U-235 absorbs neutrons}\right)\left(4.44 \times 10^{-20} \frac{\text{kwhr}}{\text{MeV}}\right)\left(\frac{6.025 \times 10^{23}}{235} \frac{\text{atoms}}{\text{gram U-235}}\right)$$

$$= 1.80 \times 10^4 \text{ kwhr heat energy/gram U-235}$$

Assumption #5. The UF_6 is enriched to 3% in U-235 (from natural 0.711%) and "burned" in a nuclear reactor to 1% U-235. This is given as a typical burnup attained in normal practice of rearranging fuel elements. Thus 2/3 of the U-235 is "burned up" to give an energy per initial gram of U-235 of

$$(2/3) \quad (1.80 \times 10^4) = 1.20 \times 10^4 \frac{\text{kwhr}}{\text{gram U-235}}$$

If instead the U-235 is burned up till the concentration is 0.711% i.e., natural uranium, the energy from one gram U-235 would be

$$\left(\frac{3.000 - 0.711}{3.000}\right) \quad 1.80 \times 10^4 = (0.763) \quad (1.80 \times 10^4)$$

$$= 1.37 \times 10^4 \text{ kwhr/gram U-235}$$

However in subsequent calculations the more conservative value of 1.20×10^4 kwhr/gram will be used.

Assumption #6. The energy realized from U-238 fast fission and from plutonium produced from conversion of the fertile U-238 will double the energy obtained from the U-235 alone. This value is dependent on the particular nuclear reactor design and operation.

Upon contact with some engineers in this field, it has been determined that at about 30,000 megawatt days per ton, the energy from the burning of U-235 from 3% to 1% would account for about 58% of the total energy of the core and that about 42% would come from fast fission of U-238 and plutonium production. In other words, for every energy unit made available by the burning of U-235, another energy unit becomes available as the result of fast fission and plutonium production. This number must be regarded as very approximate, and if a better number is required, an appreciable engineering effort would be necessary.

Thus the total energy per gram of initial U-235 in the fuel is from Assumption #5 $(1.20 \times 10^4) \quad (2) = 2.40 \times 10^4$ kwhr/gram U-235 for burnup to 1%.

Assumption #7. One barrel is 42 gallons. This is the usual barrel used by oil companies for reporting quantities of crude oil. For a direct volume comparison of crude oil and UF_6 this is used.

Calculations of uranium and of energy per barrel of UF_6 is made as follows: The density of UF_6 is 4.68 $\frac{\text{gm}}{\text{cm}^3}$ at 21°C (ref. 5). Conversion from gallons to kilograms gives:

$$\frac{(42 \text{ gal}) \left(3785 \frac{\text{cm}^3}{\text{gal}}\right) \left(4.68 \frac{\text{gm}}{\text{cm}^3}\right)}{1000 \frac{\text{gms}}{\text{kg}}} = 744 \text{ kg } UF_6 \ (3\%)$$

Of this 503 kg is uranium calculated as follows: Since for 3% enriched product the atomic weight of uranium is

$$(0.03)(235.0439) + (0.97)(238.0508) = 237.96$$ atomic weight of this uranium and the molecular weight of UF_6(3%) is

$$237.96 + 6(19.00) = 351.96$$

The weight fraction of uranium is $\frac{237.96}{351.96} = 0.676$,

and $(0.676)(744) = 503$ kg uranium per barrel of UF_6(3%)

The fissile isotope U-235 weight is then

$(0.03)(503.) = 15.09$ kg U-235 barrels UF_6(3%).

Using the result obtained in Assumption #6 of 2.40×10^4 kwhr/g, the energy per barrel is

$$(2.40 \times 10^4)(15.09)(1000) = 3.62 \times 10^8 \text{ kwhr/bbl } UF_6(3\%).$$

Assumption #8. Crude oil has 19,300 BTU/lb., and has a density of 7.3 lbs/gallon (ref 7, p.1468). Thus a barrel of crude oil typically weighs

$$(42)(7.3) = 306 \text{ lbs/bbl}$$

and has an energy content

$$(19,300)(306) = 5.9 \times 10^6 \text{ BTU/bbl}$$

or $$(5.9 \times 10^6 \text{ BTU/bbl})\left(2.931 \times 10^{-4} \frac{\text{kwhr}}{\text{BTU}}\right) = 1730 \frac{\text{kwhr}}{\text{bbl}}$$

Thus a comparison of the energy in a barrel of UF_6(3%) and a barrel of crude gives a ratio

$$\frac{3.62 \times 10^8 \text{ kwhr/bbl } UF_6}{1730 \text{ kwhr/bbl oil}} = 2.1 \times 10^5$$

or about 200,000 barrels oil is equivalent in energy to that obtained from one barrel of 3% enriched UF_6 when burned in a nuclear water reactor.

Calculations and assumptions that show that the energy in 56,000 tons of coal is equivalent to the usable energy in one barrel of UF_6(3%).

Assumption #1. The value of 3.62×10^8 kwhr per barrel of UF_6(3%) as determined in Assumption No. 7, page A-3.

Assumption #2. Coal has an energy content of 11,000 BTU/lb. This figure is a rough average of Montana and Wyoming coals listed in reference 7.

A ton of coal then has energy in units of kwhr calculated as follows:

$$(11,000)(2,000)(2.931 \times 10^{-4}) = 6.45 \times 10^3 \frac{\text{kwhr}}{\text{ton}}$$

Thus comparison with UF_6 gives

$$\frac{3.62 \times 10^8}{6.45 \times 10^3} = 5.6 \times 10^4 \text{ tons coal per barrel } UF_6.$$

<u>Calculations and assumptions to show that 1240 millions of cubic feet of gas is equivalent to the energy in one barrel of UF_6(3%).</u>

<u>Assumption #1</u>. One barrel of UF_6 (3%) had 3.62×10^8 kwhr available energy as determined previously.

<u>Assumption #2</u>. Natural gas has 1,000 BTU/cu. ft. (ref. 7, p. 1471). This is a conservative figure since the average of 4 sources given is nearly 50% higher. The great variation in energy content depends largely on the composition. The assumed value is about that of pure methane. Converting this to kwhr

$$(1{,}000)(2.931 \times 10^{-4}) = 0.293 \text{ kwhr/cu.ft.}$$

Thus $$\frac{3.62 \times 10^8}{0.293} = 1.24 \times 10^9 \ \frac{\text{cu.ft. gas}}{\text{bbl } UF_6}$$

The value of a barrel of UF_6 (3%) is $134,000.

Calculation of the worth of a barrel of UF_6 (3%) is obtained by use of the standard table given in reference 1, page 95, which is based on $32.00* charge per kilogram unit of separative work.

The table gives a value of $266.33 per kg. for UF_6(3%). Thus per barrel the value is

$$(\$266.33)(503) = \$134{,}000.$$

<u>Calculations and assumptions to show that it takes about 8,000 barrels of oil to produce one barrel of UF_6(3%) in a diffusion plant.</u>

<u>Assumption #1</u>. 9.8 units of separative work require one megawatt day of electrical energy. Reference 6, 2.5-5 states this can now be achieved with available advanced technology. Present plants realize only 7.7 SWU/MWD. In terms of kwhr this is

$$\frac{9.8}{(24)(1{,}000)} = 4.08 \times 10^{-4} \text{ SWU/kwhr.}$$

<u>Assumption #2</u>. It takes 2.17×10^3 units of separative work to produce one barrel of UF_6(3%). From reference 1, page 95 the table shows 4,306 SWU per kg of 3% enriched uranium in the product.

*AEC proposes to increase unit charges for separative work to values of $36.00 to $38.50.

Thus $(4.306)(503) = 2.17 \times 103$ SWU/bbl UF_6(3%).

<u>Assumption #3</u>. One barrel of oil will produce 650 kwhr of electrical power (ref. 2, p. 179).

Thus $$\frac{2.17 \times 10^3}{4.08 \times 10^{-4}} = 5.3 \times 10^6 \ \frac{\text{kwhr (electrical)}}{\text{bbl } UF_6}$$

and $$\frac{5.3 \times 10^6}{650} = 8.15 \times 10^3$$ barrels of oil or about 8,000 barrels.

Note: Since we have assumed a total energy in the crude of 1730 kwhr/bbl the plant efficiency calculates to be $\frac{650}{1730}$ or 38% which is reasonable.

For each energy unit going into a diffusion plant about 25 energy units become available for the UF_6(3%) produce.

Since 8,000 barrels of oil will produce one barrel of UF_6(3%) which is equivalent in energy to 200,000 barrels of oil, the ratio of 200,000/8,000 gives a value of 25.

<u>Calculations and assumptions to show that it takes about 2,180 tons of coal to produce one barrel of UF_6(3%) in a diffusion plant.</u> The assumptions #1 and #2 of A-4, A-5 will also supply here, i.e., 4.08 SWU/kwhr and 2.17×10^3 SWU/bbl UF_6(3%).

<u>Assumption #3</u>. The energy content of coal is 11,000 BTU/lb, i.e. 6.45×10^3 kwhr/ton as was expressed in Assumption #2, Page A-3.

<u>Assumption #4</u>. Conversion in electrical generation is the same as for crude oil, i.e.,

38% App., p. A-5 Thus $(6.45 \times 10^3)(.38) = 2.45 \times 10^3 \ \frac{\text{kwhr elect.}}{\text{ton}}$

The amount of coal needed to produce one barrel of UF_6(3%) is

$$\frac{5.3 \times 10^6 \text{ kwhr/bbl } UF_6}{2.45 \times 10^3 \text{ kwhr/ton}} = 2.16 \times 10^3 \ \frac{\text{tons}}{\text{bbl-}UF_6} \simeq 2000 \ \frac{\text{tons}}{\text{bbl } UF_6}$$

<u>Calculations and assumptions to show that it takes 48 million cubic feet of natural gas to produce one barrel of UF_6(3%) in a diffusion plant.</u>

Assumption #2 of Appendix A-3 is taken to be applicable i.e. 1,000 BTU or 0.293 kwhr per cubic foot of gas. Also that a conversion efficiency of 38% is realized, i.e. $(0.293)(.38) = 0.11$ kwhr electrical per cu. ft. gas.

From App., p.A-5 it takes 5.3×10^6 kwhr(elect) to produce a barrel of UF_6(3%). Thus

$$\frac{5.3 \times 10^6}{0.11} = 4.8 \times 10^7 \text{ cu. ft.}$$

or 48 millions of cubic feet.

Using nuclear power generation about 1/22 of a barrel of UF_6(3%) is sufficient to separate one barrel of UF_6(3%).

The energy from burning UF_6(3%) in a power reactor is 2.4×10^4 kwhr heat energy per gram U-235 (App., p. A-2). From published information it takes 10,500 BTU to generate one kwhr of electricity in a non-breeder type water reactor, (Table G, p. 39), thus since 3412 BTU = 1 kwhr of energy. The efficiency of electrical energy generation is $\frac{3412}{10,500} = 0.325$ or 32.5%. Thus $(2.4 \times 10^4)(0.325) = 7.80 \times 10^3$ kwhr/gr U-235. From App., p.A-4 it takes 2170 SWU to produce a barrel of UF_6(3%) or 5.3×10^6 kwhr electrical energy. Thus $\frac{5.3 \times 10^6}{7.80 \times 10^3} =$ 680 grams U-235.

A barrel of UF_6(3%) contains 15.09 kg U-235, therefore $\frac{680}{15090} = .045 \cong 1/22$. Thus 1/22 of a barrel provides sufficient electrical energy to produce one barrel of enriched uranium UF_6(3%).

The calculation converting the diffusion plant capacity to the unit of millions of barrels of oil equivalent is as follows:

Assume the diffusion plant capacity at 8.75×10^6 kg(U)SWU (or 8750 MTSWU).

One metric ton equals 1000 Kg. (Note: For 0.2 tails 4.306 SWU is required for one Kg of product uranium, (3% enr.).) Thus

$$\frac{8.75 \times 10^6 \text{ Kg SWU}}{4.306 \text{ SWU}} = 2.032 \times 10^6 \text{ Kg of product uranium (3\%)}$$

One barrel of UF_6 contains 503 Kg of uranium, thus the yearly production is $\frac{2.032 \times 10^6}{503} = 4040$ barrels of UF_6 (3%)

or

$$\frac{4040}{365} = 11 \text{ barrels per day.}$$

If one barrel UF_6 (3%) is equivalent in energy to 2×10^5 barrels of oil the above converts to

$$11 \times 200,000 = 2.2 \times 10^6$$

or 2.2 millions of barrels per day of oil equivalent for the energy production of a diffusion plant.

Note: This is for 0.2 tails. For 0.3% value of tails the SWU value per kg uranium in the product would change, i.e. 4.306 would be something else. I have made a rough calculation based on the procedure in ORO-658, Appendix 2, and arrived at about 3.490 SWU. Following this through gives a value of about 2.7 millions of barrels per day plant production. This assumes the SWU capacity of the plant remains fixed.

Source: Edwin Fast, Ph.D., May 29, 1973

APPENDIX B

ENERGY TRANSPORTATION COSTS

Comparison of transportation costs will be made primarily by comparing relative weights, except for gas. First for equal energy content:

UF_6(3%) = 744 Kg = 1,640 lbs (App., page A-2)

(1) Crude oil 306 lbs/bbl X 2.1 X 10^5 bbls = 6.4 X 10^7 lbs.

$$\text{Ratio} \quad \frac{\text{oil wt}}{UF_6 \text{ wt}} \quad \frac{6.4 \times 10^7}{1.64 \times 10^3} = 3.9 \times 10^4$$

(2) Coal 56,000 tons or 1.10 X 10^8 lbs

$$\frac{\text{coal wt}}{UF_6 \text{ wt}} = \frac{1.10 \times 10^8}{1.64 \times 10^3} = 6.7 \times 10^4$$

Comparing weights for transportation to the diffusion plant, consider the weight of UF_6 feed material to the plant and UF_6(3%) from the plant. From reference 1, page 95, it takes 5.479 times as much feed as product. Thus the total UF_6 to be transported would be

$$(6.479)(1640) = 1.06 \times 10^4 \text{ lbs.}$$

On the other hand it takes 8,150 barrels of oil to generate the electrical power for diffusion plant enrichment of one barrel UF_6(3%). This weighs

$$(8150)(306) = 2.5 \times 10^6 \text{ lbs.}$$

The ratio: $$\frac{\text{oil weight}}{UF_6 \text{ weight}} = \frac{2.5 \times 10^6}{1.06 \times 10^4} = 236$$

With coal generation 2,180 tons is required or 4.36 X 10^6 lbs. The ratio:

$$\frac{\text{coal weight}}{UF_6 \text{ weight}} = \frac{4.36 \times 10^6}{1.06 \times 10^4} = 411$$

Although weight comparisons are given above, transportation costs of the radioactive material would doubtless be somewhat higher per unit weight because of special handling required.

From reference 2, page 164, the cost per 1,000 cubic feet to transport gas by pipeline and barge was given as \$0.50. This would calculate a total of:

$$(\$0.50)(1.24 \times 10^6) = \$6.2 \times 10^5$$

for gas of energy content the same as a barrel of UF_6(3%). Likewise for the gas to produce power for a barrel of UF_6(3%) in a diffusion plant

$$(48,000)(\$0.50) = \$24,000.$$

Based on the fuel cost only, the cost per unit energy is

For UF_6 (3%) from App. A.

$$\frac{1.34 \times 10^5}{3.62 \times 10^8} = 3.7 \times 10^{-4} \text{ or } 0.37 \text{ mills/kwhr}$$

For oil reference 2 gives a price of $1.50 per barrel. (This admittedly can vary greatly.) The unit energy cost is

$$\frac{\$1.50}{1730} = 8.7 \times 10^{-4} \text{ or } 0.87 \text{ mills/kwhr.}$$

Reference 2 likewise quotes gas at 0.70/MCF.

Thus $$\frac{0.70}{293} = 2.4 \times 10^{-3} \text{ or } 2.4 \text{ mills/kwhr}$$

The same source quotes well head price as 15 or 20 cents per MCF (no transportation charge). This would make it the same approximately as for crude oil.

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5. Handbook Lange

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8. "International Economic Implications of the Nuclear Fuel Cycle," Remarks by Commissioner Clarence E. Larson at the Symposium on Energy, Resources and the Environment, Kyoto, Japan, July 10, 1972.

APPENDIX C

CRITICALITY OF UF_6

For nuclear criticality safety, one wishes to base conclusions on data obtained from integral experiments. In such an experiment all parameters of the system being studied are kept constant except one. This parameter is varied in such a way that the system is brought from a subcritical state to a supercritical state. In this way the critical conditions are fairly well defined. By normalizing certain physical constants, an analytical model can be brought into complete agreement with an integral experiment. Such a normalized model can be used to a high level of confidence to investigate systems not too greatly different from that used in the integral experiment: (Ref. 3).

Although no data of this type are available for uranium-fluorine systems, there is a large literature for uranium-water systems (Ref. 1). Compilations of criticality data present curves showing the size of a just critical unit as a function of composition.

The absence of the desired data for fluorine systems can be circumvented by constructing an equivalent water system. One can find a mixture of uranium and water, symbolized by UW_m, which is interchangeable with UF_6 for criticality studies.

For the purposes of safety in an enrichment plant it is necessary only that the moderating properties of UW_m and UF_6 be the same. We will consider as a measure of moderation

$$Z = N_M S_M / n_M$$

where N_M is the number of moderator atoms per unit volume

S_M is the fast scattering cross section

n_M is the average number of scattering collisions required to thermalize a neutron.

The substance UW_m is essentially a slurry, with a density

$$p = \frac{\text{mass of U + mass of water}}{\text{Volume of U + volume of water}}$$

$$= \frac{A_U + mA_W}{\frac{A_U}{p_U} + \frac{mA_W}{p_W}}$$

$$= \frac{238 + 18m}{12.8 + 18\ m}$$

The molecular density of water is

$$N_W = \frac{m}{238 + 18m} \cdot p = \frac{m}{12.8 + 18m}$$

The atomic density of hydrogen is twice N_W; so $N_H = \frac{2m}{12.8 + 18m}$, hence if we attribute all scattering to hydrogen

$$Z = \frac{2m}{12.8 + 18m} \cdot \frac{S_H}{n_H}$$

For UF_6 with a solid density of 3.68

$$Z = \frac{6 \cdot 3.68}{352} \cdot \frac{S_F}{M_F}$$

Since the two values of Z are equal

$$\frac{2m}{12.8 + 18m} = \frac{6 \cdot 3.68}{352} \cdot \left(\frac{S_F}{S_H}\right) \cdot \left(\frac{M_H}{n_F}\right)$$

But $n_H = 1$, $n_F = 19.7$ and we may assume $S_F \simeq S_H$, so

$$m = 0.02$$

A slurry, $UW_{0.02}$, is equivalent, for criticality purposes to solid UF_6. The effective uranium density is only slightly less than that of solid uranium and the ratio H:U $\simeq$ 0.04. Data from reference 1 shows that unless 5% enriched uranium and water have a uranium density less than 2.1, infinitely large units are subcritical. This is equivalent to requiring the ratio H:U to be greater than 15.8. Consequently, UF_6 is undermoderated by a large factor.

Experiments on 4.5% enriched UF_6 (Ref. 2) failed to bring 7 cylinders, 30 i.d.; to criticality. Each cylinder contained 4800 lbs of solid UF_6.

An enrichment plant with a 5% upper limit has no serious criticality problems in processing or handling.

References:

1. a) UK Handbook of Criticality Data (1965)
   b) USAEC TID 7016

2. Union Carbide Inc. K-25
   Report K-1686 by Mallett & Newlon.

3. A Practical Approach to Nuclear Criticality Safety I and II, by W. B. Lewis
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W. B. Lewis

October 5, 1972

APPENDIX D

AIRBORNE RADIOACTIVITY FROM COAL-FIRED POWER PLANTS

1. Assumptions:

   3×10^6 ton coal/yr consumption

   9.1×10^5 g/T

   3×10^{12} g coal/yr consumption

   1 pCi Ra^{226}/gram coal

   3 Ci Ra^{226}/yr total available

   90% collection system efficiency

   0.3 Ci Ra^{226}/year available for distribution in the environment

2. Distribution and dose due to the above (excluding lung dose from primary distribution) Unknown variables

   Primary distribution
   - Stack velocity
   - Stack height
   - Stack effluent temperature
   - Meteorological conditions

   Reentrainment for redistribution
   - Meteorological
   - Leaching by water
   - Uptake by plants

3×10^6 tons coal/yr $\div$ (365 x 24 x 2000) = 685,000 lb. coal/hr

Assume: 10% ash content

10% of ash escapes (in collection system 90% efficient)

685,000 x 0.10 x 0.10 x 453.6 = 3,107,000 gm/hr or 6850 lb/hr

Assume 1 pCi Ra/gm coal

or 3.1 uCi ^{226}Ra/hr released

Under regulations mpc of ^{226}Ra (insoluble)

$= 2 \times 10^{-12}$ uCi/ml

$= 2 \times 10^{-6}$ uCi/m^3

Volume of air released would have to be

$$\frac{3.1}{2 \times 10^{-6}} = 1.55 \times 10^6 \ m^3$$

From Widow Creek data (see references):

Emission 32,700 lbs ash/hr

Station Distances Downwind

Station	Km	mi
1-2	2.65	1.43
3-6	5.95	3.21
7	8.2	4.41

Lung dose rates and concentrations of ^{226}Ra

Station	urem/hr	fci/m^3
1-2	0.08	0.97
6	0.0375	0.47
7	0.05	0.65

Estimated annual doses to lungs
(urem/hr x 24 hr/day x 365 days/yr)

Station	urem/hr	urem/yr
1-2	0.08	700
3-6	0.0375	329
7	0.05	439

Concentration of ^{226}Ra in Widow Creek ash
Average 231 pCi/Kg or 0.231 pCi/g
÷ 17.9% ash = 1.3 pCi ^{226}Ra/g.ash

Converting above annual long doses to our assumptions.

$$D \times \frac{6850}{32700} \times \frac{1}{1.3} = D \times 0.161$$

Distance Downwind	Annual long dose
1.4 mi	113 u rem
3.2 mi	53
4.4 mi	71

No meteorological data was given in the report.

Based on the above calculations it is estimated that the average lung dose, assuming continual exposure to fly ash, is about 75 u rem for persons within 5 miles downwind from the plant.

To convert these numbers, use the following equation to arrive at a conversion factor to correct the above numbers to the new conditions.

$$CF = \frac{\text{annual coal consumption (tons)}}{3 \times 10^6} \times \frac{\text{\% ash content}}{10\%} \times \frac{\text{\% ash escape}}{10\%} \times {}^{226}\text{Ra concentration in ash (pCi/g)}$$

NOTE: ^{226}Ra constitutes about 1/4 of the average total concentration of Ra and Th in coal.

References: RADIOLOGICAL SURVEY AROUND POWER PLANTS USING FOSSIL FUEL, EPA Document EERL 71-3, July 1970

Martin, J. E., et al. COMPARISON OF RADIOACTIVITY FROM FOSSIL FUEL AND NUCLEAR POWER PLANTS, Department of HEW, November 1969

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