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ATOMIC ENERGY COMMISSION · UNITED STATES OF AMERICA

A Study of GAS CENTRIFUGE as it RELATES to the PROLIFERATION of NUCLEAR WEAPONS

UNITED STATES ATOMIC ENERGY COMMISSION

WASHINGTON, D.C. 20545

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AUTHENTICATED January 4, 1967

U. S. ATOMIC ENERGY COMMISSION

BY [signature]

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FOREWORD

The United States has consistently maintained that the development of peaceful nuclear power should proceed only under the protection of a reliable system of safeguards to prevent the spread of nuclear weapons. Immediately after World War II the United States took the initiative in the United Nations to establish international control of atomic energy under the Baruch Plan.. After a decade of unsuccessful effort to achieve international control through the United Nations, the United States in 1955 began negotiating with individual countries bilateral agreements with incorporated safeguards against diversion of nuclear materials to weapon uses while assisting these nations in civilian nuclear power programs. The United States also took the lead in establishing the International Atomic Energy Agency.

In January 1961, the United States supported the principle that the IAEA should have the right to inspect and control the uses of the nuclear fuel and technical assistance provided by the agency. During the same year the creation of the Arms Control and Disarmament Agency as an independent unit in the Executive Branch demonstrated the growing concern of the President and the Congress over the potential spread of nuclear weapons.

In an effort to discourage other nations from acquiring nuclear weapons -- and to allow time for acceptance of international safeguards -- the United States has attempted to limit the dissemination of sensitive technical information which could assist other nations in building a nuclear weapons capability. The most sensitive information of this type relates to the design and fabrication of weapons and to the production of uranium 235. For many years, when gaseous diffusion appeared to be the only practical method of separating the uranium isotopes, the Commission's efforts could be concentrated on protecting the technology of gaseous diffusion plants. Today, U. S. gaseous diffusion technology is still considered more advanced than that possessed by other nuclear powers, thus attesting to the apparent success of protecting the technology for 24 years.

In 1960 technical advancements in materials research and in component design suggested that another method of isotope separation, the gas centrifuge process might someday be economically feasible and meanwhile could offer an "n^{th}" power an alternative - albeit an expensive one - to gaseous diffusion. The Commission took steps in 1960 to prevent the dissemination of gas centrifuge information by determining that all advances beyond those published as of August 1, 1960, were Restricted Data. On December 13, 1960, then AEC Chairman John A. McCone issued a public statement and report on the status of gas centrifuge technology. (A copy of Chairman McCone's statement is included as Appendix H.)

About the same time the State Department and AEC began negotiating an agreement with three Western European nations to adopt similar classification policies to protect gas centrifuge information being developed in those countries. The result was a formal agreement with the United Kingdom, and informal arrangements with The.Netherlands and the Federal Republic of Germany, under which the parties agreed to limit access to gas centrifuge information in accordance with a common classification guide prepared by the U.S. Atomic Energy Commission.

Work on gas centrifuge technology has continued in these countries. In addition, other nations, such as Japan, now have embarked upon what appears to be modest efforts in gas centrifuge research and development, ostensibly aimed at low-enrichment fuel for their power reactor programs. In this country, classified work has continued under AEC auspices and, commencing in 1961 certain privately-funded classified research and development has been permitted in a limited number of U.S. industrial concerns.

There have been other significant developments since 1960, the most sobering of which has been the testing of nuclear devices by Red China. This development -- coupled with Red China's bellicosity, the unrest within her borders, and the weight which must be given to her influence in the Viet Nam escalation equation -- has added new urgency to the need for anti-proliferation measures.

Still another development, hopeful and encouraging in and of itself, has been the upsurge in the demand for nuclear electrical power and a concurrent evaluation of the requirements for and availability of future enriching services for the nuclear fuel cycle. Abroad, and especially in Europe, nations are assessing their future national requirements for fuel and enriching services.

The United States is seeking to assure those nations dedicated to a peaceful-uses program -- and who are willing to accept international safeguards -- of a long-term, low-cost, guaranteed supply of fuel from the United States. The Atomic Energy Commission has made clear in its testimony before the Congress and in other public issuances that U.S. gaseous diffusion capacity is ample to meet all foreseeable free world demands through 1976, and through 1981 with some modernization. In August, 1966, the Joint Congressional Committee on Atomic Energy held extensive hearings on a proposed plan whereby the Atomic Energy Commission would "toll-enrich" foreign ore in its diffusion plants, as a means of further dissuading nations from building indigenous uranium separations plants.

It is possible that these assurances from the United States, no matter how sincerely offered, may not be sufficient to dissuade nations with strong nationalistic tendencies from seriously considering their independent need for an indigenous enriching capability, even though it might mean a higher cost for product. Because the gas centrifuge appears to offer a relatively low initial capital investment and low electrical power demands for modest production requirements, its potential application to these estimated needs apparently is being considered. In this connection it should be observed that 50% of the work of producing weapons grade (93%) uranium takes place in enriching the product to about 2% or 3% (fuel grade U-235). No significant additional technology is involved in the higher enrichment steps once a workable process for enriching product up to 2% or 3% has been achieved. It may well occur to a potential "n^{th}" power that a respectable approach to an ultimate separations capability for weapons would be a modest, low-cost, gas centrifuge plant justified as part of an indigenous nuclear electric power program. The credibility of the latter approach may be somewhat enhanced by the potential application of the centrifuge process to the separation of non-fissionable isotopes or other substances of commercial interest.

During the past year the pleas of world leaders to halt the spread of nuclear weapons have intensified. "Nuclear proliferation" appropriately has been the subject of extensive discussion in the public press and on the floor of the Congress, and it has continued to be a matter of grave concern to the President. A number of studies have been undertaken to analyze and to reduce to formula the combination of political, military, economic and scientific-technical factors which must be present as preconditions to the acquisition of a nuclear weapons capability. While these studies have recognized that a source of fissionable material either in the form of man-made plutonium derived from the operation of reactors (whether designed for the purpose or produced incidental to electric power generation) or from the fissionable isotope U-235 is central to such a capability, relatively little attention has been devoted specifically to the proliferation potential of the gas centrifuge process per se. Accordingly, at the suggestion of AEC Commissioner, James T. Ramey, in November 1965, the Atomic Energy Commission directed the AEC staff to update the technical potential of the gas centrifuge and to reassess its potential contribution to the proliferation of nuclear weapons. On January 18, 1966, AEC General Manager Robert E. Hollingsworth appointed a Task Force to carry out the Commission's directive.

The study has been timely. It has coincided with the renewed efforts on the part of President Johnson and leaders in the Congress to check the proliferation trend. On May 17, 1966, the United States Senate adopted a resolution introduced by Senator John O. Pastore, Vice Chairman of the Joint Congressional Committee on Atomic Energy, which urged every effort be taken to prevent nuclear proliferation. President Johnson wrote Senator Pastore on June 13, 1966, commenting on the Senate's unanimous adoption of the resolution, observing that: "...This overwhelming expression of sentiment is more than an indication of the support of the American people for our unremitting efforts to stop further proliferation of nuclear weapons."

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The Task Force Report which follows is intended to provide the :essary technical data, analyses and discussion to assist the Commission updating its assessment of the proliferation risk of the gas centrifuge, l in making the necessary policy decisions with respect to classification, itrol and development of the technology in a manner consistent with the)liferation concern.

Task Force Chairman

* * * * *

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The Task Force acknowledges with gratitude the technical assistance and counsel provided by Mr. George F. Quinn, Assistant General Manager for Plans and Production; Brig. General Delmar L. Crowson, Director of the Division of Military Application and his staff; Admiral John A. Waters, Jr., Director of the Division of Security and Mr. Earl F. Lane, Assistant Director for Administration, Division of Security; the AEC Oak Ridge Operations Office including Dr. Russell E. Leed, Deputy Director of the Division of Production, OR; the many key personnel throughout the AEC contractor organizations participating in the AEC funded and directed program; also, the assistance of the Office of the Secretary to the Commission for performing valuable research into the official policy history of the program; Mr. John A. Harris, Director, Division of Public Information for editorial assistance; and especially the teams of valiant secretaries who worked countless nights and weekends in the preparation of this report.

SUMMARY

I. THE TECHNICAL POTENTIAL

As a result of advances made in the AEC gas centrifuge development program over the past six years, in particular the successful operation of the experimental centrifuge cascade, the technical feasibility of the gas centrifuge process for the separation of uranium isotopes has been established. As of today, gas centrifuge units operating in an experimental cascade with up to 35 units for over two years have demonstrated a separative capacity whereas in 1961, only 12 machines having a separative capacity of DELETED in the cascade. Data have also been accumulated on groups (up to 6 units) of machines of unit capacities ranging vidual machines having separative capacities DELETED operated for periods ranging from several hours to over a year (the DELETED operated only several hours).

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Projections made to estimate the possible future relative economic competitiveness of the gas centrifuge process with the gaseous diffusion process, and based on the successful trend of the current development program, indicate that in the mid 1970's the gas centrifuge process could become competitive with new gaseous diffusion plants at total plant separative capacities of about 500,000 kg/yr. However, this estimate represents a considerable extrapolation from currently available gas centrifuge performance and, therefore, there is considerable uncertainty associated with its realization. In general, however, the economic characteristics of the two processes are such that as smaller plant capacities are considered, the gas centrifuge process appears progressively more favorable relative to gaseous diffusion. Therefore, the process could be economically attractive to nations having low separative work requirements.

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The gas centrifuge process theoretically offers the potential for considerable further improvement in performance beyond that projected for the mid 1970's. Achievement of such further extrapolations of machine separative capacity is, however, considerably more uncertain. Assuming significant advances would continue to be made in both machine size and speed, examples of possible centrifuge models for the 1980's have been postulated. These increases in capacity are dependent on development of improved materials of construction and on reliable mechanical performance.

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II. THE PROLIFERATION RISK

Chapter II of the report recognizes that a number of technical, economic, and political factors must be present to bring about a situation favorable to nuclear weapons proliferation. It also recognizes that there are inherent features in the gas centrifuge that lend themselves to the small "nth" power situation: relatively low capital investment, low electrical power requirements and easy concealment. Assuming that these elements of the proliferation syndrome are present, the prolifera-tion potential of the gas centrifuge may be summed-up as follows:

For the nation willing to pay a high price for a few weapons, it is believed that there are enough technical data in the published unclassi-fied literature, patents, and patent applications, to enable a competent group to begin an effective development program toward the building of a workable gas centrifuge. The availability of information on more ad-vanced machines, i.e., information which is now classified, would improve the economics.

Nations having appreciable industrial capability and strongly seeking to acquire a nuclear weapons capability could probably develop and con-struct gas centrifuge machines suitable for separating weapons grade uranium. Depending upon their industrial capability and assuming access to technology comparable to AEC's, it is estimated that this could take them anywhere between 5 and 9 years. Without such access, it is believed it would then take at least 7 to 12 years.

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Chapter II also discusses the current international arrangements with the U.K., the Netherlands and West Germany to classify gas centrifuge development as well as other known foreign activities in this field.

Appendix A contains an extensive discussion of classification considerations, and patent and export controls.

Appendices D, E, F, and G contain specific information relating to the proliferation issue.

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CHAPTER I

TECHNICAL STATUS AND POTENTIAL OF GAS CENTRIFUGE

A. STATUS OF TECHNOLOGY - AEC SUPPORTED

The AEC, by contracts, has supported work on the gas centrifuge since 1953. Until 1960 this effort ranged between approximately \$60,000 and \$300,000 per year. The present AEC program, which is under the direction of the Oak Ridge Operations Office, is being conducted by the University of Virginia, the du Pont Company, Union Carbide, AiResearch and Yale University. These contractors, working as a team, have substantially advanced all phases of the gas centrifuge technology. 1/

The objectives of the AEC's gas centrifuge program are:

1. To significantly reduce the uncertainties and the predictions of the ultimate potential of the process for the separation of uranium isotopes in an attempt to determine if the process can become economically competitive.

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3. To investigate the applicability of the process to separate isotopes of other materials such as tungsten, sulfur, etc.

4. To evaluate the Nth power capability based on our progress in the centrifuge field.

5. To maintain United States leadership in the isotope separations field.

Expenditures on the program since November 1960 have been approximately \$2.3 million per year. The current dollar expenditure for the AEC contractors and the private industrial firms together with a breakdown of the personnel cleared for gas centrifuge work is shown in Table I.1a/ Their work has been divided roughly as described below.

a. University of Virginia - Basic research and development studies in the areas of internal flow, separation, applied mechanics, and materials, with special emphasis on separation efficiency, materials and the aerodynamics of scoops.

1/ Appendix C shows the major factors generally considered in evaluating progress in gas centrifuge development.

1a/ Throughout the report, Tables and Figures follow immediately the page on which they are first referenced.

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TABLE I

AEC CONTRACTOR AND PRIVATE INDUSTRIAL PERSONNEL WITH CURRENT ACCESS TO GAS CENTRIFUGE INFORMATION

NAME	CURRENT ANNUAL $ LEVEL	CATEGORIES: ADMINISTRATIVE, CLERICAL & SUPPORT	PLANT PROTECTION	TECHNICAL, MAINTENANCE & INSPECTION	TOT.
1. Union Carbide	$ 835,000	18	0	51	69
2. AiResearch	700,000	17	2	28	47
3. University of Virginia	325,000	9	4	32	45
4. du Pont	525,000	26	0	6	32
TOTAL	$2,385,000	70	6	117	193
Private Industry					
1. W. R. Grace	$ /	6	0	10	16
Electro-Nucleonics	750,000 /	5	0	9	14
SUBTOTAL	$ 750,000	11	0	19	30
2. GE	112,500	7	0	22	29
Allied	112,500	2	0	5	7
SUBTOTAL	$ 225,000	9	0	27	36
TOTAL	$ 975,000				66 3/

2/ The number of personnel in this Table does not reflect the current technical effort. The figures are for personnel with full access, either continuously or periodically, to gas centrifuge data. Personnel with only limited access, such as part-time consultants, etc., are not shown. The numbers of such additional personnel would be as high as 75% of the above number or a total of approximatel 340 individuals.

3/ This figure includes all individuals that have access to some degree including lawyers, secretaries, etc.

b. Flow Theory Study Group (Yale University) - Basic internal flow theory studies in collaboration with the University of Virginia. These include (1) studies on wider classes of boundary conditions; (2) finding significant parameters affecting scoop chamber flow; and (3) studies of radiation heat transfer, wave-like phenomena, feed flow, higher order separation, and other important areas as they develop. Several newly proposed methods will be developed for verification of internal flow theory as more experimental data become available; these will be used to refine the understanding of the gas hydrodynamics and the mechanism of the separation process within the rotor.

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c. Union Carbide Corporation - Development of versatile machines suitable for cascade operation for use in a number of different separation DELETED Experimental data on the cascade performance of these new and improved centrifuges are analyzed as they become available and applied to the evaluation of the potential of the process. Emphasis will continue to be directed toward improving reliability, reducing process gas losses, reducing costs, and increasing the separative capacities 4/ and separation efficiencies 5/ of the machines. The cascade will continue to be operated for life tests to determine machine reliability and to perform requested small-scale isotopic separations.

d. AiResearch Division of the Garrett Corporation - Concentrates its efforts on the development of supercritical 6/ machines of sufficient reliability for testing in the experimental multi-unit test facilities. The effort includes analytical and experimental programs in the areas of applied mechanics, bearing development, aerodynamics, corrosion, rotor dynamics, and electric motor development.

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e. du Pont Company at the Savannah River Laboratory -

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4/ Separative capacity is the ability of a device to separate isotopes. It is proportional to the product of the flow rate and the square of the enrichment factor minus one (a factor of one indicates no separation). Separative capacity is expressed in units of mass flow of a specific material, e.g., kg/yr.

5/ Separation efficiency is the ratio of the actual (or expected) separative capacity of a device to the maximum theoretically obtainable.

6/ A supercritical machine is one that passes through one or more flexural critical frequencies during acceleration or deceleration. A subcritical machine is one that does not pass through a flexural critical frequency. In general, subcritical centrifuges have an L/D (length to diameter) ratio equal to or less than 4, while the supercritical centrifuges have an L/D ratio greater than 4.

has been developed and demonstrated on UF_6 (uranium hexafluoride) at other sites.

A summary of the significant progress made during the past five and one-half years in machine development is given in Table II. A summary of the PuF_6 separation experiments is given in Table III.

It is clear that since the inception of the AEC's expanded experimental gas centrifuge development program in November 1960, significant advances have been made in several areas of centrifuge and cascade design and operation. For example, the subcritical centrifuge development program has included work on machines of 3, 6, 10, 14, and 20-inch diameters.

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A 35 unit gas centrifuge cascade has been in operation for approximately three years DELETED length, filling most of the spaces. Fiberglass epoxy composite bowls, lined and unlined, have also been tested in the cascade for extended periods. The cascade has provided machine reliability data as well as valuable information in establishing the practicability of arranging and operating the centrifuge units in various cascade configurations. Such information has been extremely useful in the preparation of economic studies on enriched uranium separation and Nth power evaluation.

Supercritical machine development effort has been directed toward (1) learning to negotiate flexural criticals, (2) applying development experience on machines of one diameter and length to design and development of machines of larger diameter and length, and (3) improvement of reliability and general cascadeability of the development machines.

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A 35 unit gas centrifuge cascade has been in operation for approximately three years with fiberglass overwrapped aluminum bowls, 6" diameter x 23" length, filling most of the spaces. Fiberglass epoxy composite bowls, lined and unlined, have also been tested in the cascade for extended periods. The cascade has provided machine reliability data as well as valuable information in establishing the practicability of arranging and operating the centrifuge units in various cascade configurations. Such information has been extremely useful in the preparation of economic studies on enriched uranium separation and Nth power evaluation.

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TABLE II

CENTRIFUGE UNITS DEVELOPED IN GAS CENTRIFUGE PROGRAM 1960 - 1966

Type	Rotor Diameter (Inches)	Rotor Length (Inches)	Peripheral Speed (m/s)	Separative Capacity (kg/yr.)	Separation Efficiency %	Maximu Operat Time w (one u
Subcritical Units						
Original, Zippe (Base)	3.0	13.0	350	0.30	28.0	1 yr

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B. STATUS OF TECHNOLOGY - U. S. INDUSTRY SUPPORTED

Following the removal of AEC classified gas centrifuge information from the Access Permit Program, the work of only two of the private industrial firms which had had access under this Program was continued on a limited basis in this field. The status of that work and of the work of two firms which had not been given access to AEC classified gas centrifuge data is reviewed below.

General Electric and Allied Chemical - The General Electric Company and the Allied Chemical Corporation had access to Category C-24 data through June 1964 and have been working together in the gas centrifuge field on a cost sharing basis for a two year period which expires at the end of 1966. At that time, the relationship and the course of the future program will be evaluated. Their major effort is at the General Electric Plant, San Jose, California, on both mechanical and theoretical development, with specialized development work being done at the General Electric Missile and Space Division, Valley Forge, Pennsylvania; the General Electric Specialty Motor Division, Fort Wayne, Indiana; and the General Electric Research and Development Center, Schenectady, New York.

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GE made and tested their first aluminum-bowl machines in 1963. DELETED This efficiency is in agreement with results obtained by Carbide and the University of Virginia on similar machines.

Since late 1964, the GE and Allied effort has been directed toward determining the feasibility of operating a gas centrifuge DELETED and verifying experimentally that the postulated theoretical efficiency curve is accurate During 1966 the feasibility of mechanically operating a centrifuge DELETED and additional empirical points were determined in their efforts to verify the theoretical efficiency curve. DELETED The manufacturing process for a new double

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tapered end high speed epoxy-fiberglass rotor 4.5" in diameter and 13.5" long, has been developed and a number of complete rotors manufactured. Development work has progressed on a promising new rotor liner made of Aclar 22A, an Allied Chemical Corporation polymerized fluorohalocarbon film. High speed drive disc development has been completed and a new high speed, high torque motor is being manufactured.

W. R. Grace and Electro-Nucleonics - The W. R. Grace Company at Pompton Plains, N. J., and Clarksville, Maryland, and Electro-Nucleonics, Inc., at Caldwell, N. Y., also are working as a team. These companies, working under an AEC no-fund contract, have not been given access to AEC classified development information.

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Electro-Nucleonics, Inc., is developing and individually testing the gas centrifuge machines and is currently working with aluminum rotors with

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The stated goal of this company is to produce a workable centrifuge machine that can be mass-produced at an economic price.

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The W. R. Grace Company is installing, operating and testing, at their Pompton Plains facility, multiple-unit assemblies of 4.25" x 13" aluminum rotors which are fabricated by Electro-Nucleonics. At the present time, 25 units are installed and operating **DELETED** a cascade arrangement. The company is evaluating and interpreting, through the use of computer analysis at Clarksville, Maryland, the data generated at Pompton Plains. Technical and administrative direction of the experimental program is handled at Clarksville.

Westinghouse Corporation - The Westinghouse Electric Corporation, Atomic Power Division, has requested access to Category C-24 classified technology pertaining to isotope separation - gas centrifuge method, through June 30, 1964. The reported purpose of this request is to assist the company in its consideration of possible further active development of the process and to alleviate what it regards as a possible competitive advantage afforded General Electric and Allied Chemical Companies through their access to such information.

The Westinghouse Corporation describes Phase I of its program as encompassing research and development studies in three main areas:

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In addition, by correspondence dated May 5, the company stated that it believes the following techniques have possible application to uranium enrichment:

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1. Electrochemical Diffusion - The efficiency of systems involving aqueous solutions of $UO_2(NO_3)_2$ or UCl_4 appears high. Separation factors are being calculated and will be measured experimentally.

2. Gas Chromatography - Experimental data on separation of other isotopes (Ne and Ar) suggest that good efficiencies can be obtained using uranium isotopes. Appropriate chemical systems are being evaluated in order that separation factors may be predicted more precisely for uranium.

3. Electromagnetic Separation - Reductions in separative cost appear possible if a device designed specifically to produce large quantities of fuel having 5% enrichment is developed.

The company indicates it may also wish to explore other more "esoteric" separation methods, including molten salt distillation and laser excitation.

CAUTION

It must be observed that, whereas, Electro-Nucleonics, Inc., and W. R. Grace Company, as one team, and the General Electric Company and Allied Chemical Company, as another team, are authorized to develop and to communicate their own privately developed classified gas centrifuge information to authorized individuals within their own group, they are specifically prohibited from transmitting classified information between groups. That is, the General Electric-Allied team is not entitled to the W. R. Grace-ENI team's classified gas centrifuge data and vice versa.

W. R. Grace-ENI is not authorized access to any AEC classified data on gas centrifuge.

GE-Allied is authorized access to AEC classified information only up through June 30, 1964.

In addition to the different levels of private and government classified information contained in this report, the report also contains proprietary information belonging to the private companies working in the two teams.

Therefore, readers of this report must exercise particular care not only to protect the sensitive classified information contained herein, but to recognize and protect the various levels of classified and proprietary information.

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D. FUTURE ADVANCES

As a result of advances made in the AEC gas centrifuge development program over the past six years, in particular, the successful operation of the experimental centrifuge cascade, the technical feasibility of the gas centrifuge process for the separation of uranium isotopes has been established. A remaining major question is its economic feasibility, and, of particular interest, its competitive position with the diffusion process for enriched uranium production. Continued development will provide more advanced technology from which to gauge the future expectations for the process.

Experimental results to date from AEC's classified program tend to confirm the theoretical predictions of separative capacity (Figure 1) and separative efficiencies (Figure 2) as a function of the peripheral speed of the centrifuge bowl. Figure 3 shows the machine improvements, in terms of separative work, which have been attained, since the beginning of the AEC's expanded program in 1960. From Figure 3 on page 32, and the photograph on page 21, it can be seen that considerable progress has been made since 1961, when the modified Zippe 3" x 13" units were running at 370 m/s with a separative capacity of 0.35 kg/yr, up to the present time where DELETED This chart is not intended to reflect any degree of machine reliability since the various centrifuge models shown have operated over different time spans, ranging from a few hours to several years.

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On the basis of past work, the promise of better materials, the availability of many good alternative design approaches, and not yet having reached theoretical limits on performance, the prospects for continued progress in centrifuge technology are very good. The primary purpose of the AEC program is to develop centrifuge units with high separative work capacity at low separative work cost. While increases in separative capacity may be significantly enhanced by increasing the peripheral speed, increases may be obtained also by increasing the length of the centrifuge unit.

Short-term tests in the AEC program, such as those already made at impressively high speeds, have added confidence to projections involving high-performance units. However, much more development work and advance of technology is required to determine whether the long-term performance and reliability, essential for the economic operation of projected high performance units, can be achieved.

The performance estimates of gas centrifuges for the early 1970's, shown in Figure 4, represent significant extrapolations from currently available performance, and as such there is considerable uncertainty associated with realization of these estimates. The estimates indicated for the 1980's in Figure 4 represent, of course, further extrapolations and are correspondingly more uncertain. It is not presently known whether the performance of the centrifuge types projected for the 1980's can be realized; e.g., it is not possible to predict at which point operating levels will be limited by mechanical performance rather than material strength. The ability to operate large bowls DELETED range depends upon improvements in existing materials or advancements in new high strength materials, and in the application of these materials to centrifuge configurations. The AEC program depends on efforts to develop for other purposes materials such as high strength fiberglass; the rate of progress in materials technology, therefore, will be affected by national efforts independent of centrifuge program needs. Also, it is expected that the success of efforts to fabricate rotors with near-perfect balance

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FIGURE 1

COMPARISON OF EXPERIMENTAL SEPARATIVE CAPACITY DATA WITH THEORETICAL PREDICTION

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FIGURE 2

THEORETICAL SEPARATIVE EFFICIENCY vs SPEED COMPARED WITH MEASURED VALUES

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[redacted]

FIGURE 3

IMPROVEMENTS IN SEPARATIVE CAPACITIES OF GAS CENTRIFUGES

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FIGURE 4

SEPARATIVE CAPACITIES OF GAS CENTRIFUGES PAST AND PROJECTED FUTURE

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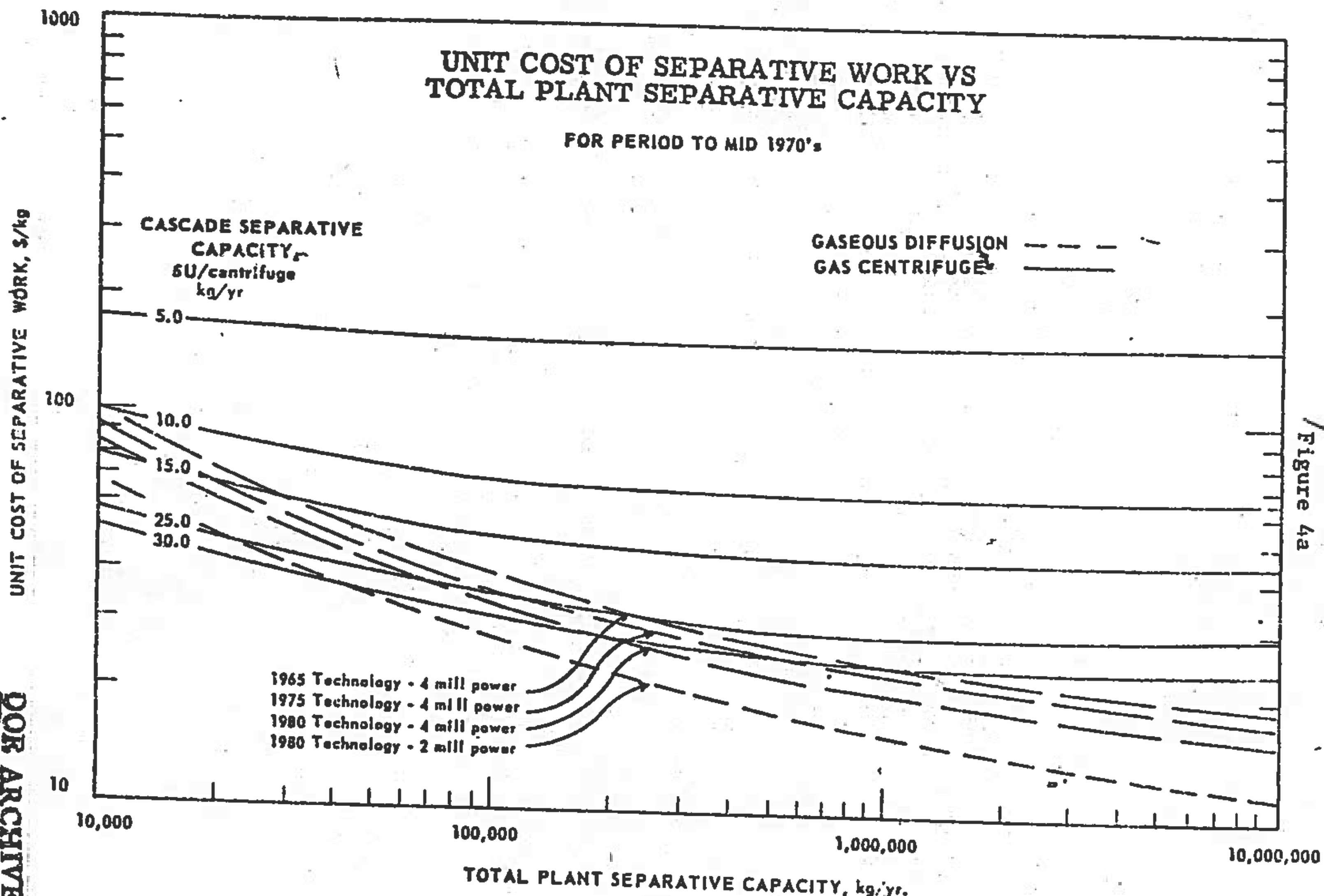
UNIT COST OF SEPARATIVE WORK VS
TOTAL PLANT SEPARATIVE CAPACITY
FOR PERIOD TO MID 1970's
CASCADE SEPARATIVE CAPACITY, SU/centrifuge kg/yr
GASEOUS DIFFUSION
GAS CENTRIFUGE
5.0
10.0
15.0
25.0
30.0
1965 Technology - 4 mill power
1975 Technology - 4 mill power
1980 Technology - 4 mill power
1980 Technology - 2 mill power
UNIT COST OF SEPARATIVE WORK, $/kg
1000
100
10
10,000
100,000
1,000,000
10,000,000
TOTAL PLANT SEPARATIVE CAPACITY, kg/yr.

Figure 4a

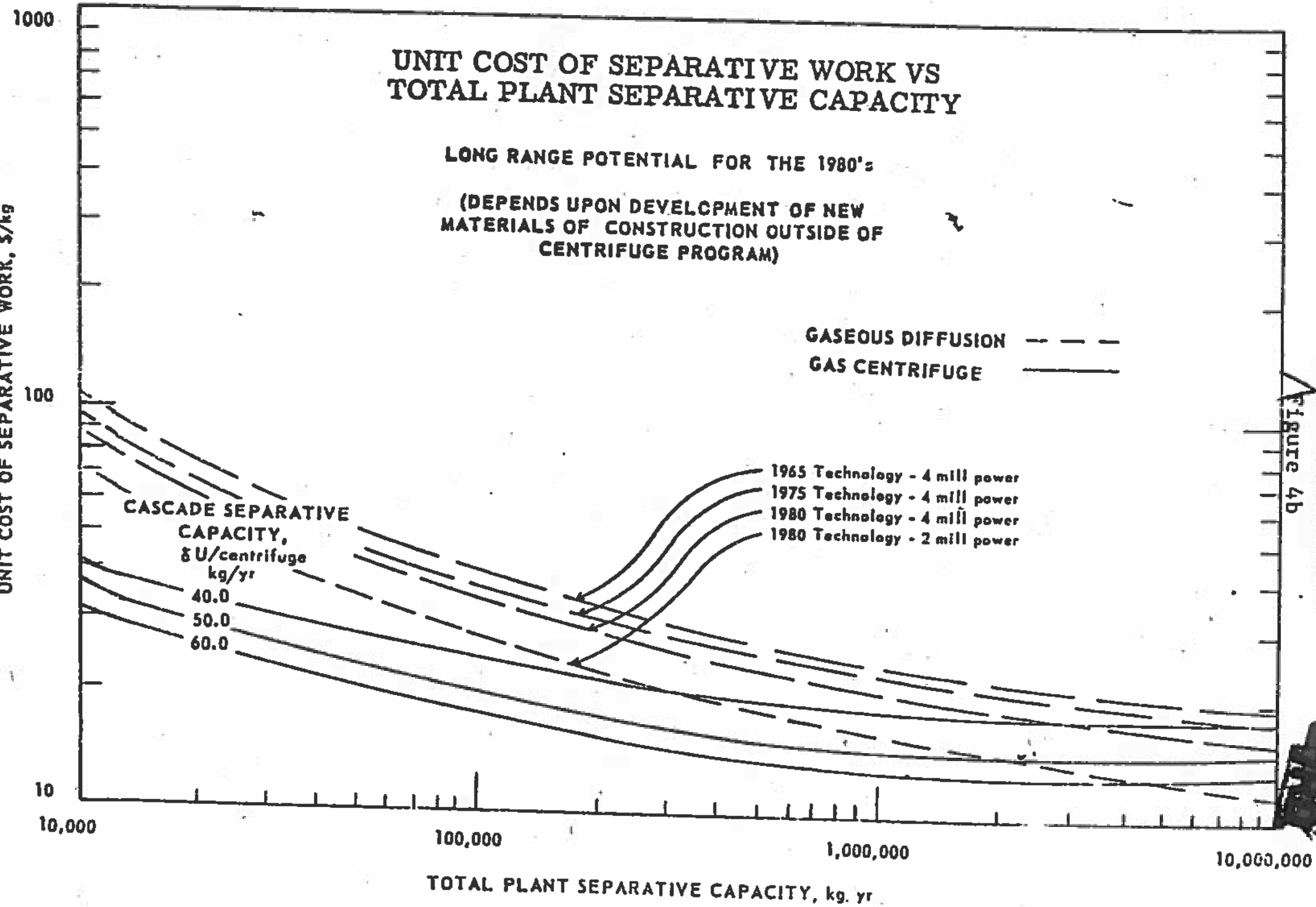
UNIT COST OF SEPARATIVE WORK VS
TOTAL PLANT SEPARATIVE CAPACITY
LONG RANGE POTENTIAL FOR THE 1980's
(DEPENDS UPON DEVELOPMENT OF NEW MATERIALS OF CONSTRUCTION OUTSIDE OF CENTRIFUGE PROGRAM)
GASEOUS DIFFUSION
GAS CENTRIFUGE
1965 Technology - 4 mill power
1975 Technology - 4 mill power
1980 Technology - 4 mill power
1980 Technology - 2 mill power
CASCADE SEPARATIVE CAPACITY, δU/centrifuge kg/yr
40.0
50.0
60.0
UNIT COST OF SEPARATIVE WORK, $/kg
1000
100
10
10,000
100,000
1,000,000
10,000,000
TOTAL PLANT SEPARATIVE CAPACITY, kg. yr

Figure 4b

DOE b.3(a)

FIGURE 4c.

COST OF SEPARATIVE WORK
PAST AND PROJECTED ESTIMATES

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will have a significant effect on the ability to achieve high speeds with the desired machine reliability and life expectancy. The continued development of the technology over the next five years should provide a good basis for reassessing possible further gains in the process.

Figures 4a and 4b present estimates of the unit cost of separative work as a function of plant capacity for both gas centrifuge and improved gaseous diffusion plants, and illustrate the effects of the extent of advancement in technology. It is evident from Figure 4a that if the projected range of capability of gas centrifuge units by the early 1970's is achieved

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additions for new capacity if no further advances are made in the diffusion process) the gas centrifuge process would appear to be favored. The estimates indicated in Figure 4b for the 1980's represent, of course, further extrapolations and are, as noted earlier, correspondingly more uncertain. Achievement of the machine performances postulated for the 1980's would make the centrifuge process economically competitive with diffusion for large scale production plants. Figure 4c provides estimates of the uncertainty range on unit costs of separative work for these projections for the gas centrifuge process.

DOE 6.2(a)

Although the projected unit cost of separative work for gas centrifuge plants built with models postulated for the long-term (1980's) decrease significantly and tend to approach, for the higher capacity plants, the projected unit costs for new gaseous diffusion plants, it should be noted that, from the standpoint of proliferation or assistance to foreign military or nuclear power programs, the comparisons between U.S. gaseous diffusion and gas centrifuge economics cannot be simply extrapolated to situations abroad.

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DOE 6.2(a)

The experimental cascade has been operated with both uranium and tungsten hexafluoride. Research quantities of tungsten isotopes produced in the experimental cascade were supplied to NASA and to the Lawrence Radiation Laboratory.

Studies have indicated that the gas centrifuge process may be the most economical method for the separation of pound quantities of various isotopes. This production level would fill the gap which now exists between gram quantities from the electromagnetic facilities, and ton quantities from gaseous diffusion plants. A semi-quantitative comparison of the centrifuge process

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with other isotope separation processes is presented in Table IV[16/]. A centrifuge cascade would have small gas inventories and the equilibrium time would be short. Thus a single centrifuge facility could be used for the production of a wide variety of isotopes since the cascade can be evacuated, recharged with a new gas, and reach equilibrium operating conditions again within a short time. Table V[16/] summarizes several isotope separations for which the gas centrifuge would be well-suited. The unit costs are based on a 500-centrifuge facility DELETED DELETED DELETED to produce research and development quantities of the desired isotopes. Installing future improved centrifuge model in the 500-centrifuges would have the effect of reducing the unit cost of the product.

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E. OTHER ADVANCED APPLICATIONS

The specialized and unique capabilities of the gas centrifuge has led to the development of a neutron velocity selector for the NASA Lewis Laboratory. The neutron velocity selector, which is classified, is a high speed rotor that operates on the principles of the subcritical gas centrifuge. DELETED It is used to measure the velocity spectrum of thermal and epithermal neutrons through liquid-metal interfaces in reactor research, and can produce a source of monochromatic neutrons.

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16/ These Tables are taken from the Gas Centrifuge Appraisal Report dated 2/4/64. The Task Force has made no independent verification of the information.

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TABLE IV

THE MOST PROMISING METHODS OF ISOTOPE SEPARATION FROM THE POINT OF VIEW OF ECONOMICS FOR VARIOUS SEPARATION TASKS

	Light Isotopes (M < 40)	Intermediate Weight Isotopes (40 < M < 150)	Heavy Isotopes (M > 150)
Small Scale Production Rates, mg/day	1. electromagnetic[18/] 2. distillation, chemical exchange 3. thermal diffusion 4. molecular distillation 5. electromigration[17/]	1. electromagnetic[18/] 2. thermal diffusion 3. molecular distillation 4. electromigration[17/]	1. electromagnet 2. thermal diffu 3. centrifuge 4. molecular distillation
Intermediate Scale Production Rates, g/day	1. distillation, chemical exchange 2. thermal diffusion 3. sweep diffusion[17/] 4. molecular distillation 5. centrifuge	1. centrifuge 2. thermal diffusion 3. sweep diffusion[17/] 4. molecular distillation 5. electromagnetic	1. centrifuge 2. sweep diffusio 3. molecular distillation 4. electromagneti
Large Scale Production Rates, kg/day	1. distillation, chemical exchange 2. molecular distillation	1. gaseous diffusion 2. centrifuge 3. sweep diffusion	1. gaseous diffus 2. centrifuge

17/ Processes requiring appreciable development effort.

18/ For small scale production the electromagnetic process is most economical due the fact that a separation facility is already in existence and costs can be p rated to each separation job.

[redacted]

TABLE V

CENTRIFUGE SEPARATION OF ISOTOP[redacted]INTEREST 19/

500 Centrifuges

Isotope Desired	Product Concentration Desired, %	Estimated Unit Cost,20/ $/gram	Interest Expressed By	Statement of Use
Molybdenum-92 -94	90-99	8-25	LRL ORNL	Structural material in nuclear ram jet engine and as membrane in a molten salt reactor.
Nickel-64	10	10	Westing-house Corp.	Obtain estimates of depletion rates of boron-10 in reactors.
Silicon-29 -30	9.4 6.4	12 2.50	Rice Univ. ORNL	Research experiments related t neutron energy measurements. Feed for calutrons.
Tungsten-182 -184 -186	90 90 90	30 45 10	NASA	Development of advanced nuclea rocket engines.
Vanadium-50	2.5	100-150	ORNL	Neutron cross section measurem and mass spectrometer standard Feed for calutrons.
Sulfur-36	1.6	250	Biology Div. ORNL	For use in biological research
Uranium-234	3.7	5	Isotope Div. ORNL	Pre-enriched feed for calutror and basic research studies.
Xenon-134	1 barn	1.00	LASL	Isotopically altered xenon.

19/ Partial listing of materials is shown. In general, calutron operating personne are interested in pre-enriched materials such as Te-120, Se-74, etc. LASL is also interested in mercury-201 and osmium-187, 189, all enriched to 80% concentration.

20/ Costs include full cost recovery on labor, overhead, material, and plant write-off based on 10-year straight line depreciation. 75% utilization factor is assumed. No allowance is made for AEC charges or feed material cost.

[redacted]

CHAPTER II

POTENTIAL OF GAS CENTRIFUGES FOR CONTRIBUTING TO PROLIFERATION OF NUCLEAR WEAPONS

Proliferation of nuclear weapons has been the subject of widespread interest in recent months. A number of studies have been undertaken[21] most of which have sought in some manner to identify the factors which must be present to bring about a condition of political "criticality." The present study, however, is the only one of which we are aware which deals primarily with the proliferation potential of the gas centrifuge.

It is recognized that the possession of gas centrifuge technology and capability would not alone be sufficient to cause or permit an Nth power to embark upon a nuclear weapons program. Other political, economic and technological factors must also be present. This chapter explores the elements of proliferation, the technical choices of plutonium or U-235, and the extent to which gas centrifuge technology and its special features might tip the political scales in certain countries in favor of a modest nuclear weapons program.

A. Prospects and Motivations

The late President Kennedy is reported to have said, "...I see the possibility in the 1970's of the President of the United States having to face a world in which 15 or 20 or 25 nations may have these nuclear weapons. I regard that as the greatest possible danger and hazard."[22] This was in March of 1963. At that time, 4 nations possessed nuclear weapons. Today, 3 years later, 5 nations possess nuclear weapons.

Many nations in addition to the present five nuclear powers have a potential to develop nuclear weapons. Plutonium production from the operation of nuclear electric power reactors is generally well understood. Some nations already have or could easily acquire chemical separations plants. Nuclear electric power plants are essential if the world's growing power demands are to be met. Nations have been encouraged to develop nuclear power technology as being important to man's future welfare

21/ The Rand Corporation is currently making a broad study on proliferation for the U.S. Air Force and the Assistant Secretaries of Defense -- International Security Affairs (ISA) and Systems Analysis.

Stanford Research Institute is currently studying proliferation problems for the Department of the Army.

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22/ CBS Reports, March 21, 1963

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The natural consequence of expanding nuclear power production is increased plutonium availability. With increased production of plutonium, expanded knowldege of its characteristics, and broadened capability to work with it one can expect reduction in the incremental costs of plutonium produced incident to electric energy production and thus reduction in the net cost of material which might go into a weapons production program.

Inventory of Potential Nth Powers23/ - There are a number of countries not now possessing nuclear weapons which do have the technical and industrial capability to make nuclear weapons. Even more could do it with varying amounts of outside help. The time that would be required to produce the first weapon varies, and the incentives or motivations for or against a decision to embark on a nuclear weapons program also vary. The passage of time can only reduce the relative economic burden of a nuclear weapons program. Changes in motivations and incentives that will occur in the future are more difficult to predict.

Of the nations not now possessing nuclear weapons, Canada probably could do so in the shortest time. Within a few months to a year, Canada could, without outside assistance, test a first device, and could produce weapons relatively shortly thereafter. Incentives to do so are considered to be relatively weak because of the special relationship between the USA and Canada.

The following countries are examples of those which could produce a few weapons in the next 10 years, either alone or with some outside assistance; but whose balance of motivations and restraints make it appear unlikely that they would decide to do so: Belgium, Denmark, Italy, The Netherlands, Norway, Portugal, Spain, Argentina, Brazil, Czechoslovakia, and East Germany.

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Motivations - The factors which determine whether or not a nation will seek to acquire nuclear weapons differ widely from country-to-country and may not be fully apparent to observers outside the country since they can be based rather heavily on personal judgments or feelings of individual government officials. What may appear to the U.S. as critical deficiencies in the basis for a projected nuclear weapons program may not appear as such to the government considering the Program; the latter may feel, for a

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mixture of political, military, and other reasons, that a given program would be a good investment even though by our standards it would be costly relative to other economic needs of the country.

The rationale for seeking independent nuclear weapons capability generally can be expected to include arguments relative to national security which, in turn involve judgments of long term reliability of alliances and psycological arguments on the importance of national indigenous independence from outside sources. Underlying motivations behind published rationale may be even more varied and more difficult to identify.

B. Elements of Proliferation

1. Economic Base - Even a modest weapons program (say, one weapon the first year of production with an objective of stockpiling 25 weapons in a 5-7 year period) would require an initial investment for the first weapon of approximately $140-180,000,000 through the first detonation, and $20 million to $30 million a year thereafter. However, the cost increases markedly for more than a minimum program. For example, a program to produce about 20 plutonium fission weapons per year would probably cost about $500 million to $600 million through the first test in order to develop the production base to support the larger quantity, with subsequent annual operating expenses of about $75-$100 million. All Figures in this paragraph are exclusive of delivery systems. India, Sweden, Japan, West Germany, Israel, and Australia would appear to be able to meet this level of expenditure.

2. Industrial Base - The industrial base required for a nuclear weapons program depends to some extent upon the specific course chosen for supplying materials for that program; for example, plutonium from reactors as a by-product of power generation suggests emphasis on chemical processing technology with needs in metal fabrication and large power equipment dependent upon choice of domestic manufacture or import. Extensive imports presumably require foreign exchange to be available from other industrial, agricultural or mining activities. Isotope separation, whether by gaseous diffusion, gas centrifuge, or electromagnetic separation, suggests the need for a industrial base of advanced materials technology, mechanical engineering, and chemical processing.

Industrial skills required for developing and producing nuclear weapons, having the fissionable material in hand, also are somewhat dependent upon the material chosen but, in general require abilities in metals fabrication electronics and instrumentation, and explosives.

Whatever the choice in weapons material, the industrial base must offer not only the particular skills in personnel and capabilities in equipment needed but also must be of sufficient total capacity that the diversion to this end is acceptable in terms of total national economy.

The acceptable level of diversion, of course, depends upon political decisions, the urgency of the motivation, and upon other resources available to the country.

3. Scientific Base - Scientific and engineering skills in fields such as physics, metallurgy, chemistry, and mechanics must be available, at least in part, in connection with the industrial complex of a nation, if industry supports reasonably extensive research and development activities. These skills, however, could be supplied from one or more educational or research institutions of high quality. While physical sciences and advanced engineering are vital, medical sciences play an important supporting role. It is unlikely that a successful program could be carried out, even with the current general availability of much of the needed technology, without the participation of at least a small group of capable scientists with experience in nuclear science and technology supported in turn by a larger group of technically trained personnel, preferably with experience in the nuclear field.

4. Materials Base - Finally, there would need to be available sufficient raw materials, including source or special nuclear material legitimately acquired or diverted from peaceful uses to support the nuclear program.

If all of the foregoing general elements are present at a given time, together with strong political motivations, and if strong external military or international political restraints are absent, another Nth power may well be conceived.

C. Sources of Special Nuclear Materials

Only three nuclear materials (U-233, U-235 and Pu-239) have all the characteristics which make them useful in producing an explosive fission reaction. Other fissile materials have such short half-lives and are so strongly radioactive that they have little or no practical value in weapons, and in addition, they are more costly to produce. No basic processes, isotope enrichment and transmutation of materials, offer alternate routes to production of materials for nuclear weapons. Each process has several variations with attendant risks in costs, time, and assurance of success. The degree of assurance of success is determined largely by the extent to which a country uses technology which has proven to be successful. The production of plutonium and U-233 can be carried out in nuclear reactors with separation of the nuclear materials in fuel reprocessing plants. Both reactors and processing plants can be and, in fact, are being built using readily available unclassified technology. In encouraging the peaceful uses of nuclear energy for production of power it was necessary to make available technical information which unavoidably could be used for the production of nuclear weapons material. Plutonium can be produced in reactors fueled with natural uranium, which require no isotope enrichment facility. In fact, all central station nuclear power plants, whether fueled with natural uranium or slightly enriched uranium, automatically make plutonium as a by-product of their operation. If thorium is present in the reactor U-233 is automatically produced. There are technical difficulties in using U-233 in a weapons program, but they are surmountable.

Some appreciation of the extent to which special nuclear material will be produced in connection with central station power plants is pertinent. AEC Chairman Glenn T. Seaborg has projected[24/] that if the estimates for free world nuclear power generation by 1980 are correct (about 100,000 MW electrical in the U.S. by 1980 and a comparable amount in other countries, exclusive of the Soviet Bloc and Communist China) the plutonium produced will be at the rate of more than 100 kilograms per day.

Isotopic separation is required to produce uranium enriched in the isotope U-235. There are several processes by which this may be accomplished, including gaseous diffusion, gas centrifuge, electromagnetic, and thermal diffusion processes. Electromagnetic and thermal diffusion processes were declassified years ago based on judgments that neither held promise of economical production of weapon grade U-235 in quantities large enough to be of military significance. Gaseous diffusion technology has been most widely used for separation of U-235 and has been controlled very restrictively by each nation which has developed the technology and applied it to production plants.

The non-nuclear countries which might initiate a weapons program in the next decade would probably regard the gaseous diffusion process as an overly long and expensive road to a modest capability. Built on a large scale, an electromagnetic separation plant would be considerably more expensive than a gaseous diffusion plant. However, an electromagnetic plant is technologically somewhat easier to construct, and it can be built on a smaller scale. Communist China may have obtained its U-235 through a combination of the gaseous diffusion and the electromagnetic processes or gas centrifuge topping.

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D. Proliferation Potential of the Gas Centrifuge

Note: (In discussing the proliferation potential, certain assumptions are made that need to be explained. First, it is initially assumed that

24/ Speech before the National Association of Manufacturers' Conference On Industrial Science & Technology, Washington, D. C., June 7, 1966.

the potential Nth power is a nation seeking only a modest weapons program, say, one weapon the first year of production with an objective of stockpiling about 25 weapons in five to seven years. Secondly, initial yearly production rates of

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The proliferation of nuclear weapons has occurred independently of the gas centrifuge, and it appears that without strong military or international political restraints (safeguards), nuclear weapons capability will almost certainly continue to spread.

The gas centrifuge, especially with AEC's current advanced technology could serve both to increase the number of Nth powers and to accelerate the rate of entry into the "club." Table VI illustrates the economic advantage of the gas centrifuge over plutonium produced from reactors built specifically for weapons purposes. 25/ For production rates of 50 kg a year of weapons grade uranium, the cost per weapon is less than for a weapon fabricated from plutonium produced in a production reactor.

The cost of fissile material per weapon for a device fabricated from weapons grade uranium produced by a gas centrifuge cascade based on 1965 technology would DELETED as compared with fabricated from weapons grade plutonium produced in a production reactor.

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Using 1966 AEC gas centrifuge technology and based on bowl speeds DELETED

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It is significant that even by using 1961 technology with bowl speeds of DELETED as compared per weapon fabricated from production reactor produced plutonium. The higher cost for one weapon using 1962 gas centrifuge technology, could for a particular Nth power, be preferable if elements of concealment and prospects for improvement in centrifuge technology entered into the consideration.

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25/ Plutonium production reactors referred to have and generally throughout the report are envisioned to be relatively small and of the type an Nth power might build and not the large production facilities found within the AEC.

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TABLE VI

ESTIMATED COSTS OF FISSILE MATERIALS TO PRODUCE ONE NUCLEAR WEAPON*

FOR AN ADVANCED NTH POWER

Enriched Uranium Produced Using Gas Centrifuge/ Technology Level As Measured by Peripheral Speed	PLUTONIUM PRODUCTION	Total Estimated Fissile Material Cost, $/Weapon
	DELETED	
	Pu Via Production Reactor Route	$6.5 MM ($650/g Pu).
	Pu Via Early Discharge of Power Reactor Fuel	$1.0 MM ($100/g Pu)

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Note: It is emphasized as pointed out in the text that these estimates do not include the total resource requirements needed to produce a nuclear weapon.

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firm drawing only upon information in the unclassified literature.26/ Obviously gas centrifuge technology beyond 1966 with bowls DELETED DELETED would reduce the costs per weapon still further.

Table VI also makes it apparent that from the standpoint of economics an Nth power might find it advantageous to embark on the more respectable course of acquiring plutonium incidental to the production of nuclear electric power. Under this choice the cost would drop to about $200 thousand per weapon. This is because the civilian nuclear power program could be charged with the capital investment and the operating and chemical separation costs, whereas the weapons program would be charged only for fabrication costs and fuel value of the Pu.27/ It should be noted, however, that this presupposes an ability on the part of a particular Nth power to use "dirty" plutonium. (See footnote on page 44.) While the physical principles of using plutonium with a high 240 content material are known, the use of "dirty" plutonium requires a higher degree of sophistication in handling and fabrication techniques, and limits the weapons designer in achieving desired goals. It would require considerable experience in the handling of plutonium and it would be desirable to actually test at least one to assure a reliable weapons design. (An Nth power would probably want to test at least one weapon regardless of the design to announce entry into the "club.") In addition, more "dirty" plutonium would be required per weapon over that containing a higher ratio of Pu-239 (weapons grade plutonium). Therefore, the apparently lower dollar costs for plutonium produced incidental to a nuclear electric power reactor program may not be as attractive as at first blush.

26/ A review of the published unclassified literature, patents and patent applications by AEC and contractor personnel knowledgeable in the gas centrifuge field has led to the conclusion that enough technical data is contained in those documents to enable a competent individual or group to begin an effective development program toward the building of a workable gas centrifuge machine. The success of the program would, however, depend on the quality of the individual or group, and on the direction selected for the thrust of their development. In regard to the direction taken it has been noted that Electro-Nucleonics, Inc. chose a direction which yielded good results in a reasonable period of time. There is no guarantee that a country beginning work in the gas centrifuge field might not make comparable progress starting with information in the unclassified literature.

27/ A number of countries' funds have been spent for research and for development of facilities not directly related to weapons production. The additional amount which each of these countries would have to spend if it wished to produce weapons would depend on the size of the weapons program desired. With the exception of weapons fabrication and test facilities, all facilities essential to weapons production can be justified as necessary for a peaceful nuclear research and power program. By deferring a decision to manufacture weapons until after completion of all facilities required for production of fissionable materials, a country can limit the incremental cost of undertaking weapons production to the expense incurred for research, development, fabrication, and testing of actual weapons.

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Therefore, based on technical progress, gas centrifuge technology appears to offer the following advantages to a potential nuclear power:

1. Small production rates of U-235 - equivalent to a few weapons per year - could be provided with gas centrifuges at both a lower capital investment and a lower unit cost than with a relatively small gaseous diffusion plant.

2. Physical concealment of plants using gas centrifuges should present no problems because of their relatively small size (even including feed and metal processing and waste storage) and because of relatively small power requirements.[28]

3. Gas centrifuge technology appears to have considerable development potential which should result in technology which will further reduce resource requirements for production of weapons material by this route.

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Some of the emphasis on relatively low production rates - 50 to 500 kg of U-235 per year - in discussing gas centrifuge derives from the substantially greater efficiency of the gaseous diffusion process for production rates in the thousands of kg per year, and the high

28/ Photographs on pages 46 through 50 show the K-25 gaseous diffusion complex and the small building requirement of the gas centrifuge work at Oak Ridge (including a photograph of the 35-unit cascade) and at Electro-Nucleonics, Inc., Caldwell, N. J.

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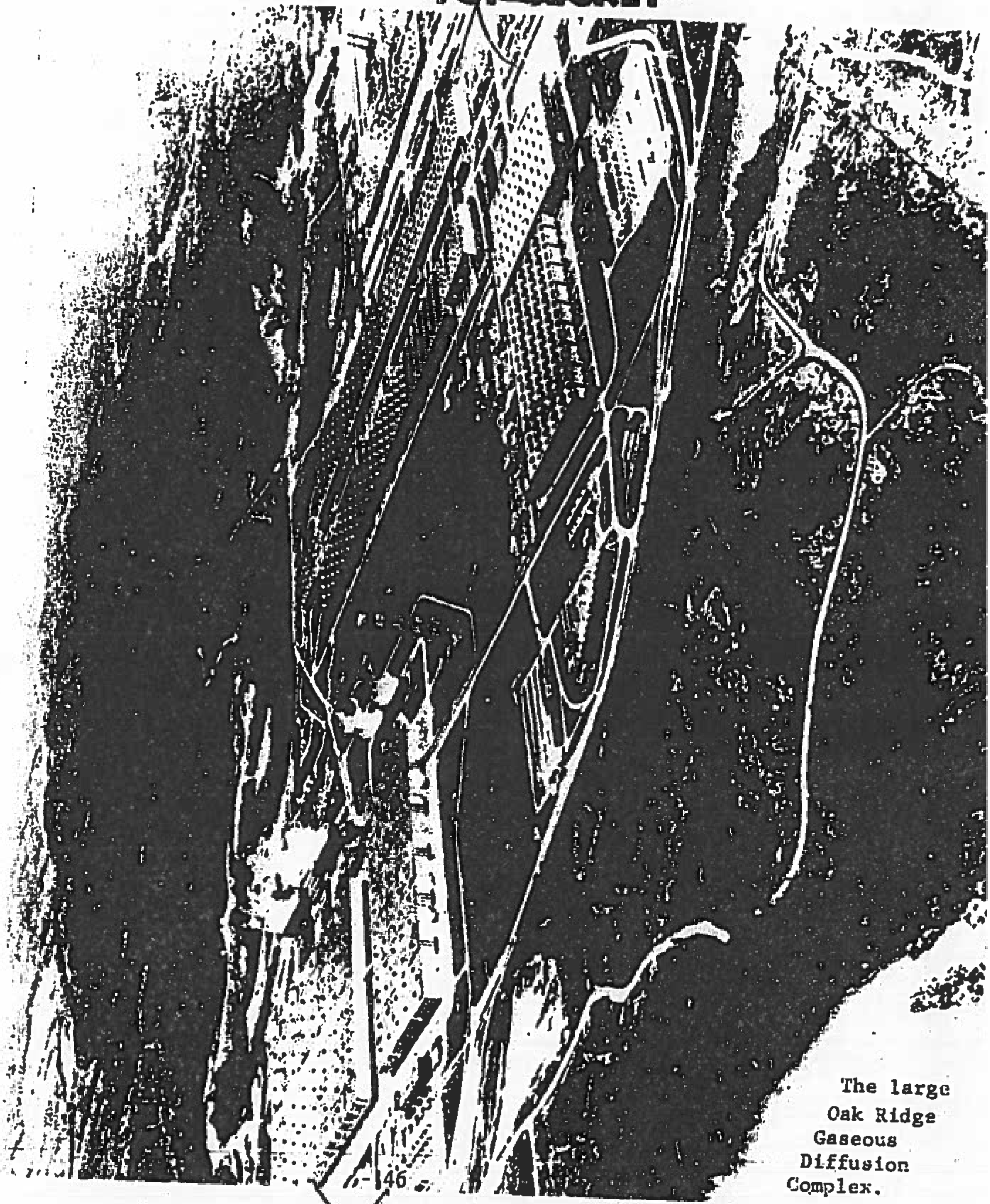

The large Oak Ridge Gaseous Diffusion Complex.

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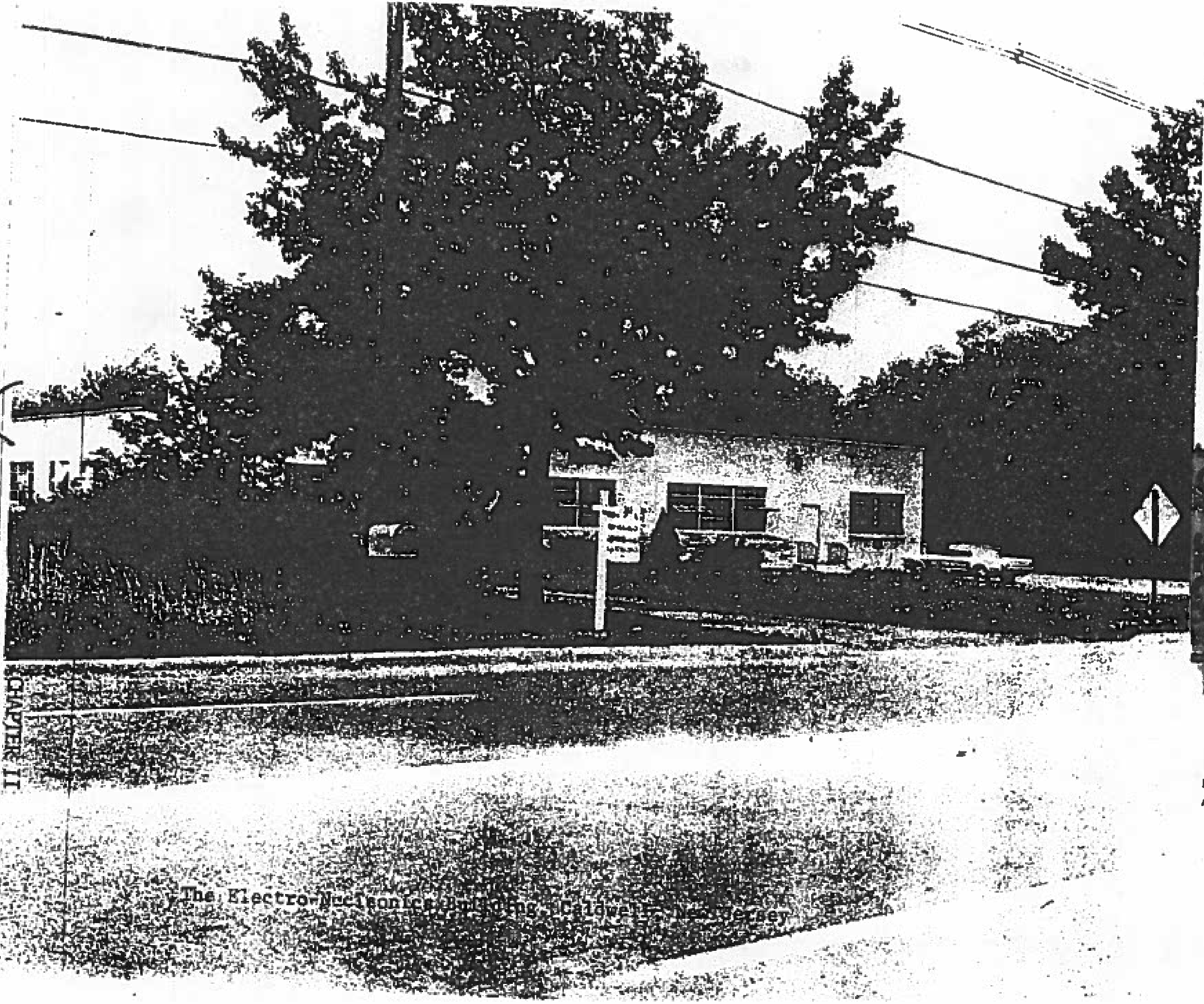
CHAPTER II



The Electro-Nucleonics Building, Caldwell, New Jersey

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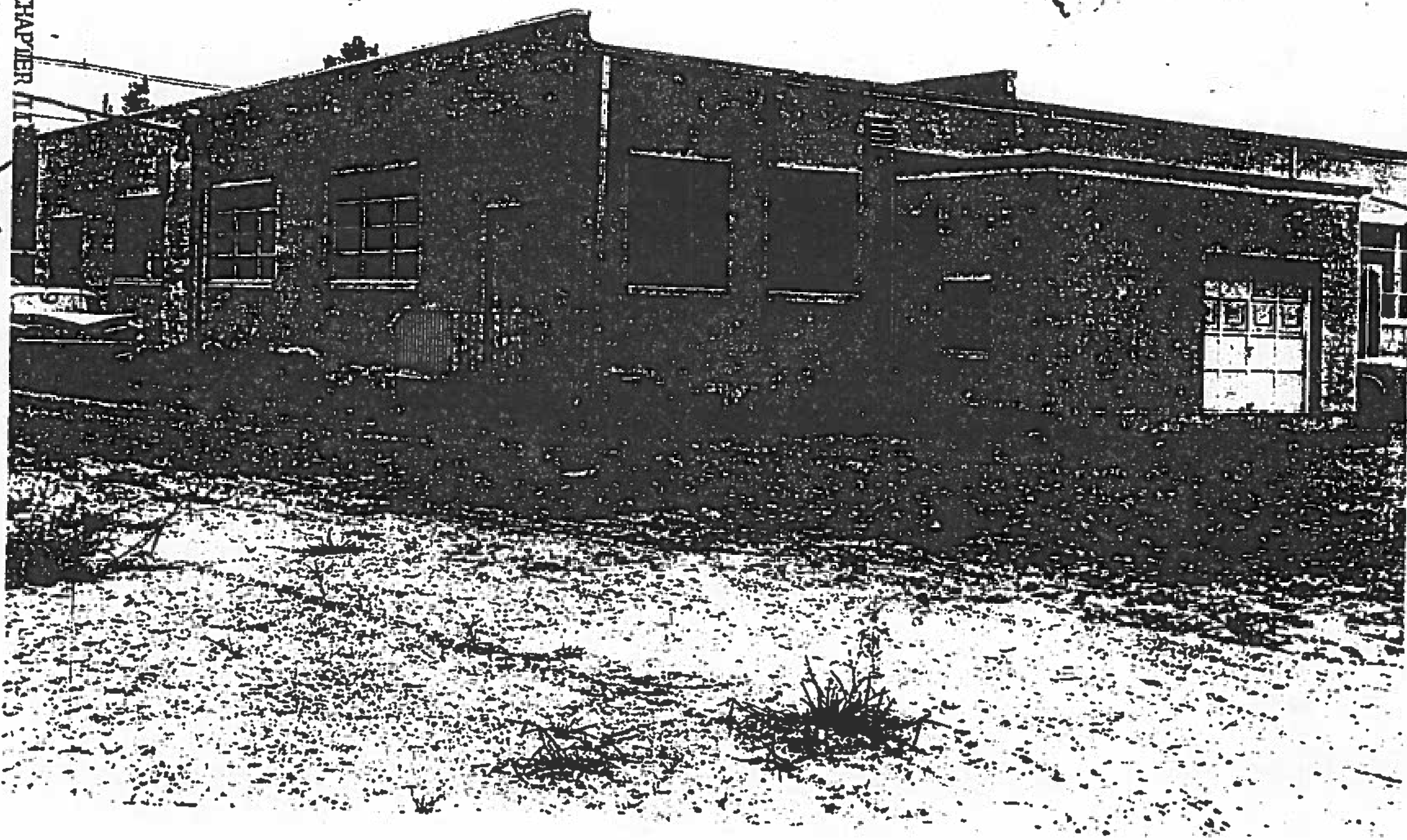
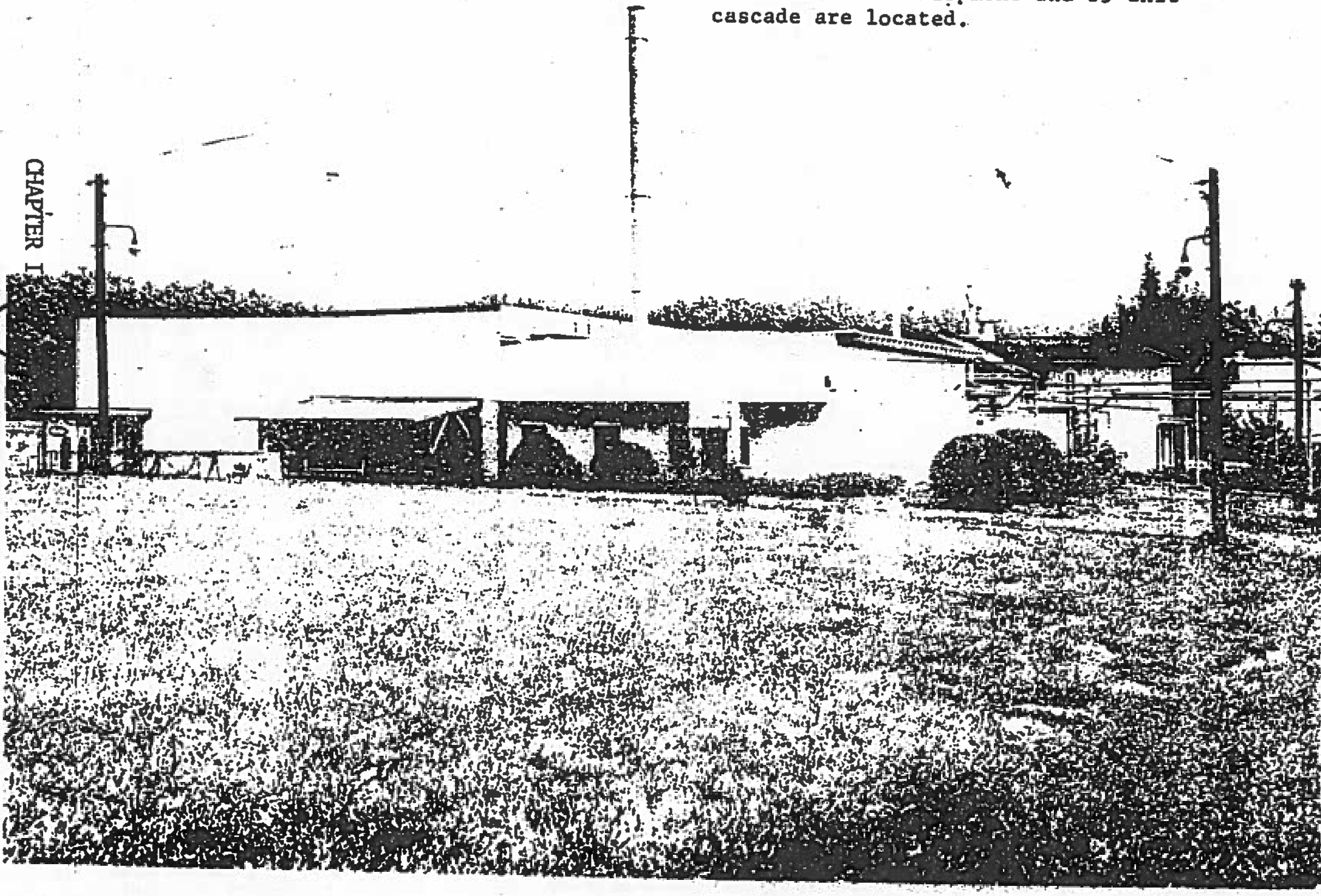
Rear view of Electro-Nucleonics
Building, Caldwell, New Jersey



Building in which Oak Ridge gas centrifuge research and development and 35 unit cascade are located.



CHAPTER I

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degree to which the process has been perfected in the United States. However, the reader's attention is invited to Figures 4a and 4b, on pages 33a and 33b, on which foreseeable advances in gas centrifuge technology have been projected and compared with gaseous diffusion for comparable amounts of production.

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In summary, it can be postulated that:

1. Proliferation of nuclear weapons can and has occurred without gas centrifuge technology.

2. Gas centrifuge technology could accelerate or increase proliferation. In addition, the gas centrifuge offers special features for a small weapons program, especially when coupled with the ease of concealment.

3. There is no guarantee that a country beginning work in the gas centrifuge field might not make significant progress starting with information in the unclassified literature.

4. Advanced gas centrifuge technology if available to the potential Nth powers could greatly influence a decision to embark on a nuclear weapons program; and would be of great interest to some of the present nuclear powers in improving their weapons materials production processes.

E. Controls and Safeguards Against Proliferation

It is apparent from the preceding discussion that the proliferation of nuclear weapons has occurred independently of gas centrifuge technology and that there is no absolute assurance, taking into account the susceptibility of the gas centrifuge to clandestine development, that proliferation of nuclear weapons through this technology might not continue despite such classification and security controls as may be applied domestically. Therefore, it is imperative that we continue to foster effective international safeguards in general.

No occasion has yet arisen requiring the application of international safeguards to any significant isotope separation facility. The technique for safeguarding such a facility will be complicated by the necessity to avoid dissemination of the technology through the inspectors while providing acceptable assurance that all the product of the facility may be accounted for. This problem has not been studied in detail for the case of an isotope separation facility, either of gaseous diffusion or the gas centrifuge type, in a non-nuclear weapon country, where one must be concerned with the possible diversion or clandestine production of small amounts of highly enriched uranium.

Meanwhile, there appears to be little choice but to continue the policy of classifying and controlling gas centrifuge technology. Appendix A contains an extensive discussion of classification, patent and export controls and formal and informal arrangements with the U.K., the Netherlands, and West Germany to protect gas centrifuge at the level of Secret, using the AEC classification guide OC DOC-73. Appendix B describes the history, purpose, and legal distinctions in relation to the gas centrifuge of the Access Permit Program and the no-fund contract.

APPENDIX A

CLASSIFICATION AND CONTROLS

1. Domestic Control

(a) Classification Policy - Classification and associated restrictions, including penalties, offer the only practical method for control of information. Information covering the gas centrifuge process for separating isotopes was classified by the U. S. effective August 1, 1960. Current centrifuge classification policy as expressed in OC Doc-73, and in CG-PGC-2, provides that credible technical information in the public domain as of August 1, 1960, is unclassified. Developments and improvements developed since that time are classified.

(b) Limitation on Number of People Having Access to Centrifuge Technology - In a general sense, the possibility of inadvertent disclosure in any control system is in part a function of the number of people - and particularly the number of organizations - who have access to the information being controlled. In dealing with this aspect of controlling gas centrifuge information, it is perhaps helpful to perspective to recognize the size of the access groups in alternative or supplemental areas of the chain of essential information.

Below is a table reflecting the number of U. S. nationals that presently have and those that have had access to classified technology in the gas centrifuge, gaseous diffusion, and weapons fields.

		Number Presently Having Access	Number Who Have Had Access to Date
Gas Centrifuge - AEC		340	495
	Industry	60	105
	Total	400	600
Gaseous Diffusion		4,800	20,000
Weapons		@200,000	@500,000

Although the number of individuals in private industry that have and have had access to gas centrifuge technology (including AEC technology) can be determined with a fair degree of accuracy, it is more difficult to determine the number of AEC (including contractor employees), DOD and others that have and have had access to gas centrifuge, gaseous diffusion and weapons technology.

It should also be pointed out that not all of the individuals noted above had access to the more sensitive information. For example, in gaseous diffusion only approximately 3,000 individuals had access to information related to seals, barrier, converter assembly and conditioning of converters. Access to this type of sensitive information is controlled through physical or administrative means.

With respect to gas centrifuge classification it can best be described as a "tricky" informational situation in the U. S. programs: there are three "compartments" of classified information: (1) privately-generated classified information without access to AEC classified data; (2) partial access to AEC classified data up to June 1964 in addition to privately-generated classified data; and (3) the classified, advanced AEC data, some of which may be patentable. The requirement that one be ever conscious of the several boundaries and to avoid breach of containment is burdensome and risky.

(c) Patents - When a patent application is filed in a specific field or National Defense interest, e.g., atomic energy, the U. S. Patent Office refers the application for review to the AEC pursuant to the Secrecy Order Act (35 USC 181). If a patent application is in other National Defense interest, it is referred to areas of the Defense Department or NASA for similar secrecy review. If any of the agencies to which an application in a specific field is referred deem secrecy necessary, a recommendation is made by the agency and the Commissioner of Patents automatically issues a Secrecy Order as to the application under 35 USC 181. The Secrecy Order prohibits the dissemination of any information pertaining to the subject matter of the patent application under penalties (35 USC 184-186 inclusive) and requires the Applicant and his counsel to notify any recipients of the information of the U. S. Patent Office Secrecy Order. This Secrecy Order is not rescinded without the approval of the agency that requested the imposition of the Order, and no U. S. patents are issued until the Secrecy Order is rescinded.

An inventor whose patent application is placed under secrecy may recover damages and compensation resulting from the imposition of the Secrecy Order (35 USC 184). In determining the amount of such compensation, the inability to promote domestically or promote in foreign countries are factors, among others, that are taken into consideration.

It should be recognized that even though no Secrecy Order is issued on a U. S. patent application, all U. S. pending patent applications are deemed confidential by the U. S. Patent Office and not examinable without the consent of the Applicant, his assignee, or his attorney, except by patent examiners and other Government representatives as provided for by special law.

2. International Controls

(a) Classification Arrangements - In 1959 it was learned that at least two countries, West Germany and the Netherlands, were vigorously pursuing studies in the gas centrifuge field and were freely publishing their information. From their publications, it seemed that there technology was at least equal to that developed in the United States. Because any classification action taken by the Commission could be vitiated if the German and Dutch activities were to proceed on an unclassified basis, the Commission consulted with the Department of State early in 1960 with respect to the feasibility of discussing with the German, Dutch and U. K. governments, the possibility of inducing them to classify their work on the gas centrifuge.

At AEC's request, arrangements were made by the Department of State to discuss the matter with representatives of the Federal Republic of Germany (FRG), the Netherlands and the U. K. during the period of July 13 through 20, 1960. A United States' team consisting of representatives of the Department of State and of the AEC participated in these discussions.

These nations agreed with the U. S. assessment that the gas centrifuge process offered the possibility for additional nations to acquire nuclear weapons material. In the interest of minimizing the proliferation of gas centrifuge information and recognizing the desirability of achieving uniform classification policies and practices within the four countries on gas centrifuge research and development programs, the countries agreed to classify their work in accordance with guidance to be provided by the U. S. Accordingly, the United States prepared and furnished to the West German, Netherlands and U. K. governments copies of a "Classification Guide for the Gas Centrifuge Program", dated August 1, 1960 (OC Doc-73). This guide is now used in these countries in classifying gas centrifuge data. A more detailed guide, CG-PGC-2, using the same principles of OC Doc-73 is used in the U. S.

It is important to note that the German and Dutch agreement to classify their programs is an informal one; neither government has formally agreed to classify their research and development work to date because, as they have both advised us, formal classification of German and Dutch work might raise serious psychological and political problems with respect to their Euratom partners if these countries formally classify their work and this action became known. However, they advised that although classification of their programs might present difficult internal problems because of limitations which might be placed upon industrial participation in or commercial exploitation of the gas centrifuge program, they felt that classification ought to be applied. To date the informal arrangement with the FRG and the Netherlands has worked well. The U. K. through the common use of the Commission approved "Classification Policy Guide" (CG-C-1) follows classification criteria identical to those of the U. S.

Since 1960, two additional meetings have been held. The first took place during March 1962. The classification guide was reviewed and reaffirmed. Also discussed was the matter of the filing of classified patents in other countries. In line with the U. S. suggestion, the Germans agreed that where time permits each of the four would notify the others in advance of permitting the filing of foreign patent applications by their nationals. The Dutch agreed to consider the U. S. suggestion.

The second meeting was held on March 2, 1964. In summary, the meeting resulted in the preservation of the current status under which the four governments are classifying gas centrifuge information according in the common classification guide. The United States again urged the position that filing of classified patent applications should be limited to the four countries. However, the Netherlands and German governments again made clear their intention to remain free to file such applications in countries with which they had arrangements enabling the filing of patent applications on a classified basis. The Netherlands government indicated that it would not file such applications outside the NATO membership if any of the four countries represented at the meeting were to object to such filings.

At the March 1964 meeting there were indications that, because of the internal pressures previously referred to the German and Netherlands governments are becoming reluctant partners to the classification arrangements. For example, a U. S. Embassy official in Bonn was informed that the German Ministry for Scientific Affairs had intended to propose a termination of the classification understanding, but that this step was overruled by the German Foreign Ministry. The Netherlands representative at the meeting attempted to secure a termination of the arrangements by proposing that all classified information in the field be automatically declassified after two or three years.

If it is desired to maintain the security of gas centrifuge technology, it would seem to be important that the U. S. take no action which would give indications of a weakening of U. S. position since this could be the deciding factor in losing the cooperation of the Germans and Dutch.

(b) Patents - International - Most of the industrialized countries of the world have a system of maintaining patent applications in secrecy for reasons of national defense and in the field of atomic energy. In those countries with which there have been classified Agreements of Cooperation, the secrecy arrangements and provisions of the Patent Office of such countries have been reviewed and where deemed adequate, patent applications have been filed by the U. S. Atomic Energy Commission in secrecy in such countries, e.g., in the United Kingdom and Canada under certain classified Bilateral Agreements.

The NATO Agreement as respects technical exchange provides for the filing of patent applications where the classified defense information is the subject of the NATO Agreement. Atomic Energy patent applications have been deemed outside the scope of the NATO Agreements and procedures. Under NATO the member countries have set up procedures for the issuance of Secrecy or Prohibition Orders at the request of the initiating country. Any claims for damages and compensation resulting from the secrecy request are usually borne by the originating country.

As noted earlier an informal classification arrangement was initiated with the Netherlands, Germany, and the United Kingdom. The participants at the last Conference in March 1964 agreed that each would consider the common Classification Guide in maintaining classification, including the classification of inventions and patent applications. This informal arrangement included an understanding as to the imposition of Secrecy Orders by the four respective countries on applications filed from one of the countries where secrecy was deemed necessary.

At the March 1964 Conference, U. S. representatives suggested that it be agreed that no patent applications be filed outside of the four countries, except possibly Canada. The Dutch and German representatives believed that classified filings should be permitted in NATO countries. The delegation of the Netherlands felt that it could not reasonably deny an inventor the possibility of applying for protective patent rights in any country of the free world, but that as to filing in countries outside of NATO, they would consult with the other three and be prepared to consider withholding of filings if any of the three objected. The U. K. delegation stated they would not file outside of the four countries. It was recognized that the United States would not file outside the United States in the absence of some arrangement under which the classified information originating in the United States was the subject of a classified Cooperative Exchange Agreement.

The Netherlands delegation noted that they believed they would have to disclose the information of a Dutch application to any member of Euratom, pursuant to paragraph 1 of Article 25 and paragraphs 1 and 2 of Article 16 of the Euratom Treaty. The U. K. delegation observed that under paragraph 5 of Article 16 of said Treaty, the referenced provisions were not necessarily applicable if an agreement were consummated with a third party or with an international organization that precluded communication.

The Office of the Assistant General Counsel for Patents has, with the Division of International Affairs and the Department of Defense, requested the imposition of Secrecy Orders on U. S. patent applications that have been filed by the other participants where classification was in accordance with the Guide.

Annex I shows the Patents and Patent Applications filed in the U. S. by the Dutch, Germans, and British in the gas centrifuge field. The notation "S.O." indicates that the applications are under secrecy in the United States Patent Office and the "No S.O." indicates those cases where secrecy was not necessary according to the Division of Classification. In

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ANNEX I

GAS CENTRIFUGE APPLICATIONS

NETHERLANDS

Dutch Filing Date & No.	Inventor	Title	S.O. Status	U.S. Filing Date & No.	Other Filings if known
6-17-57 218,181	J. Los H. W. Baron	Gas Tight Seals for High Speed Rotary Shafts	No S.O.	6-17-58 742,607(48)(ab)	
12-27-57	J. Wind	Ultra-Centrifuges for the Separation of a Gas Mixture in Two Components (c-i-p)	No S.O. No S.O.	12-22-58 782,004(48)(ab) 2-13-61 88,862(60)	
12-27-57	J. Wind J. Los	Continuously Operating Ultracentrifuges U.S. Pat. 3,216,655 Ger. Pat. 1,080,931	No S.O.	2-13-61 88,862(60)	GER. 12-19-58 R 24637III/82b
3-17-60 249,508	J. Los F. Kelling	Centrifuges, E.G. Ultracentrifuges for the Separation of Gases U.S. Pat. 3,219,265 Fr. Pat. 1,298,342	No S.O.	3-14-61 95,683(60)	French
3-17-60 249,506	J. Wind	Damping Devices for the Support or the Suspension of a High-Speed Rotatable Rotor	S.O. ASPAB	3-15-61 96,036(60)	
3-21-60 249,633	J. Los J. Wind	Centrifuges, E.G. Centrifuges for the Continuous Separation of Gaseous Mixtures (c-i-p)	S.O. ASPAB S.O. ASPAB	3-15-61 96,037(60)(ab) 1-25-63 254,821(60)	
3-19-60 249,611	J. Wind	Centrifuges for the Separation of Gaseous Mixtures	S.O. ASPAB	3-15-61 96,038(60)	
3-19-60 249,612	J. Los	Devices for Supporting a Body Rotating with Super-Critical Speed	S.O. ASPAB	3-15-61 96,039(60)	
4-20-60 250,654	J. Kistemaker E.J.J. Veldhuyzen	Apparatus for the Separation of a Mixture of Gases or Gaseous Isotopes (c-i-p)	S.O. ASPAB S.O. ASPAB	3-15-61 96,040(60) 9-5-63 308,924(60)	

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Metherlands cont.

6-14-61 265,924	J. Wind H. W. Baron G. B. Beeftink	Suspension System for Centrifuge Rotor	S.O. ASPAB	6-13-62 202,336(60)	
9-27-61 267,598	G. B. Beeftink	Ultracentrifuges for the Separating of Gaseous Mixtures	S.O. ASPAB	7-19-62 211,135(60)	
9-14-61 269,268	J. Los	Ultracentrifuges & Methods for the Separation of Gas Mixtures	S.O. ASPAB	9-12-62 223,586(60)	
9-8-61 269,111	J. Los	Ultracentrifuge	S.O. ASPAB	11-6-62 235,887(60)	
11-28-61 271,927	J. Kistemaker	Apparatuses for Centrifugation and Sublimation of Gases	S.O. ASPAB	11-15-62 238,828(60)	
3-21-60 249,633	J. Los J. Wind	Centrifuges for the Separation of Gaseous Mixtures	S.O. ASPAB	1-25-63 254,821(60)	Can. 3-21-61 Eng. 3-17-61 Ger. 3-21-61 Fr. 5-5-61 It. 6-5-61 Belg. 5-12-61
2-28-62 275,355	G. B. Beeftink	Ultracentrifuges for Continuous Operation and the Separation of Gas Mixtures of Gaseous Isotopes	S.O. ASPAB	2-28-63 262,298(60)	
5-11-62 278,330	H. W. Baron H. C. Wentzel	Ultracentrifuges for Separating in Continuous Operation Gas Mixtures or Mixtures of Gaseous Isotopes	S.O. ASPAB	5-9-63 279,635(60)	
5-20-60 250,654	J. Kistemaker E.J.J.Veldhuyzen	Separation Apparatus for Gas and the Like	S.O. ASPAB	9-5-63 308,924	
12-11-62 286,545	J. Van den Brink	Ultracentrifuges for the Continuous Separation of Gases or Gaseous Isotopes	S.O. ASPAB	12-5-63 328,429(60)	

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Netherlands cont.

12-18-62 286,861	G. B. Beeftink H. C. Wentzel	Ultracentrifuges for the Continuous Separation of Gases or Gaseous Isotopes	S.O. ASPAB	12-11-63 329,922(60)	
3/29/63 290,861	H. W. Baron J. Los	Ultracentrifuges	S.O. ASPAB	3-25-64 354,799(60)	
5-30-63 293,396	N. Dekkers	Ultra-Centrifuge Bowls	S.O. ASPAB	5-27-64 370,729(60)	
8-7-63 296,355	J. Los	Ultracentrifuges for the Separation of Gas Mixtures	S.O. ASPAB	8-5-64 387,810(60)	
9-1-64 64.10182	J. Los	Ultracentrifuges for the Continuous Separation of a Gas Mixture Consisting	S.O. ASPAB	5-5-66 548,363	Belg. 8-24-65 17090 Ger. 8-20-65 R 41368 III/82b Fr. 8-23-65 29173 It. 8-65 22/133
6-21-56 208,223	J. Y. Wiarda	High-Speed Centrifugal Machines and Methods of Manufacturing Such Machines Dutch Pat. 87,740 - U.S. Case Abandoned U.S. Translation is AEC-TR-4822	No S.O.	6-18-57 666,356(48)	
3-17-60	J. Wind	Point Bearings for the Support of a Rotor Rotating with High Speed (U.S. Pat. 3,052,504	No S.O.	3-14-61 95,742(60)	
3-22-60 249,680	J. Schutten P.J. Van Deeneen	Rotary-Field Motors for Driving a Rapidly Rotating Body Abandoned	No S.O.	3-14-61 95,743(60)	

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GAS CENTRIFUGE APPLICATIONS
GERMANY

German Filing Date & No.	Inventor	Title	S. O. Status	U.S. Filing Date & No.	Other Filings if known
2-20-57 43594 III/82b 1-23-58 47553 III/82b	K. Beyerle	Damping Bearing for the Shafts of a Gas Centrifuge U.S. Pat. 3,097,167	No S.O.	2-20-58 716,332(48)	
3-27-57 B 44072 XII/47f	K. Beyerle	Shaft-Seal for Gas-Centrifuges Abandoned	No S.O.	2-24-58 717,465(48)(ab)	
	K. Beyerle	Gas Centrifuge Abandoned	No S.O.	9-1-59 837,414(48)	
11-14-57 D 26831 11-28-57 A 7728/57 12-28-57 D 27109	G. Zippe R. Scheffel M. Steenbeck	Centrifugal Separators	No S.O.	11-14-58 845,584	
11-28-57 A 7726/57 11-28-57 A 7729/57	G. Zippe R. Scheffel M. Steenbeck	Vacuum Pump U.S. Pat. 3,117,713	No S.O.	11-24-58 845,585(48)	
8-28-59 54605 III/82b	K. Beyerle	Gas Centrifuge with Rotating Drum	No S.O.	8-29-60 52,430(60)	
11-10-59 D 31855 III/82b	R. Scheffel	High Speed Gas Centrifuge Abandoned (c-i-p)	S.O. AEC S.O. ASPAB	11-7-60 67,854(60) 10-23-64 406,196(60)	

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Germany cont.

6-29-60 D 33597 III/82b	G. Zippe R. Scheffel	High Speed Gas Centrifuge	S.O. ASPAB	6-29-61 122,608(60)
6-29-60 D 33598 III/82b	R. Scheffel	High Speed Gas Centrifuge	S.O. ASPAB	6-29-61 123,075
7-2-60 D 33596 IVc/12e	G. Zippe	Separation of Mixtures of Gases or Isotopes	S.O. ASPAB	6-29-61 123,076(60)
10-25-60 D 34602 III/82b	R. Scheffel	High Speed Gas Centrifuge	S.O. ASPAB	10-19-61 146,373(60)
		(c-i-p)	S.O. ASPAB	10-23-64 406,195(60)
11-5-60 D 34725 III/82b	R. Scheffel	High Speed Centrifuge	S.O. ASPAB	11-3-61 150,096(60)
1-21-61 D 35224 II/82b	G. Zippe	Method for the Production of a Self-Cascading Circular Flow in a Rotating Centrifuge	S.O. ASPAB	1-22-62 167,975(60)
10-25-60 D 34602 III/82b	R. Scheffel	High Speed Gas Centrifuge	S.O. ASPAB	10-23-64 406,195(60)
11-10-59 D 31855 III/82b	R. Scheffel	High Speed Gas Centrifuge	S.O. ASPAB	10-23-64 406,196(60)
4-4-64 D 44083 III/82b	R. Scheffel	High Speed Centrifuge	S.O. ASPAB	4-5-65 445,800(60)

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GAS CENTRIFUGE APPLICATIONS
UNITED KINGDOM

Br. Filing Date & No.	Inventor	Title	S.O. Status	U.S. Filing Date & No.	Other Filings if known
2-4-57 3841/57	T. Barrett D. English K. J. Williams	Shaft Seal U.S. Pat. 3,109,658	No S.O.	2-4-58 713,267(48)	
10-18-57 32543/57	S. Whitley	Journal Bearings U.S. Pat. 3,039,830	No S.O.	10-16-58 767,623(48)	
11-7-58 35901/58	S. Whitley D. S. Allen	Journal and Journal Bearing Assemblies U.S. Pat. 3,079,203	No S.O.	11-2-59 850,324(48)	
1-28-59 3046/59	S. Whitley D. S. Allen	Devices for the Sealing of a Rotatable Shaft in Passage Through a Casing	No S.O.	1-14-60 2,381(60)	
2-4-59 3930/59	L. G. Williams	Thrust Bearing	S.O. AEC	1-29-60 5,585(60)	
5-22-59 17494/59	S. Whitley D.S. Allen	Gas Lubricated Journal and Journal Bearing Assemblies	No S.O.	5-12-60 28,564(60)	
5-20-59 17231/59	A. Barker J. Ashton	Fluid Operated Pump Systems U.S. Pat. 3,168,046	No S.O.	5-17-60 29,600(60)	
12-2-60 41651/60	A. Barker	Bearing Systems	S.O. AEC	12-1-61 156,542(60)	
12/16-60 43490/60	S. Whitley D. S. Allen A. J. Bowhill	Rotor Systems	S.O. AEC	12-18-61 160,357(60)	
12-21-61 45935/61	D. S. Allen P. J. Stokes S. Whitley	Locating Arrangements	S.O. AEC	12-19-62 247,447(60)	

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United Kingdom cont.

4-9-62 13657/62	S. Whitley P. Dunn A. J. Bowhill	Centrifuges	S.O. AEC	12-19-62 247,448(60)
12-21-61 45936/61	D. S. Allen P. J. Stokes S. Whitley	Locating Arrangements	S.O. AEC	12-19-62 247,449(60)
6-29-62 25162/62	A. J. Bowhill	Centrifuges	S.O. AEC	12-19-62 247,450(60)
4-9-62 13658/62	S. Whitley L. G. Williams	Centrifuges	S.O. AEC	12-19-62 247,451(60)
5-8-62 17727/62	S. Whitley D. S. Allen	Glands	S.O. AEC	5-8-63 279,026(60)
4-10-63 14325/63	M. W. Boothroyd	Separation Systems for Fluids	S.O. AEC	3-31-64 356,695(60)

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those instances where patents have been issued in the United States, the application either was not classified at any time, or, if one time classified, had been declassified in accordance with established procedures, and the Secrecy Order was rescinded prior to the issuance of the patent.

The Dutch have made four (4) filings in the United States since March 1964 but three (3) of these applications were filed in the Netherlands in 1963 and only one (1), which was filed in the Netherlands on September 1, 1964, was filed in the United States on May 5, 1966. Although the Dutch advised on February 9, 1965, that they were going to file in the U. S. two (2) other applications that had been filed July 1964 in the Netherlands, no such filings have yet been made, so far as the U. S. Patent Office records indicate.

The British have made only one (1) filing in the United States since March 1, 1964, on an application filed in Great Britain in April 1963.

The Germans have made three (3) filings in the United States since March 1964. Two (2) were on applications filed in 1959 and 1960 in Germany and one (1) in April 1964 in Germany.

It might well be that in the light of the United States position on classification and appreciating that the U. S. was not filing abroad, the three participants have deemed it inadvisable to file in the United States.

(c) Export Controls - Gas centrifuges are subject to both international embargo control to the Sino-Soviet bloc and U. S. unilateral export control to all destinations except Canada.

U. S. Department of Commerce export regulations require a specific validated export license for any shipment of gas centrifuges "capable of the enrichment or separation of isotopes", and specifically designed parts, to any destination of the world except Canada, if the value of the shipment is in excess of (a) $500 to consignees in North and South America, and (b) $100 to consignees in the rest of the world except the Sino-Soviet bloc. Identical licensing coverage is also provided by Commerce regulations for the following commodities which could include liquid as well as gas centrifuges:

Other centrifuges - power-driven, bowl type, with all product surfaces of aluminum, nickel, or alloy containing 60% or more nickel; and parts.

Centrifuge bowls - wholly made of or lined with aluminum, nickel, or alloy containing 60% nickel; and parts.

In addition to Commerce export controls, the Office of Munitions Control (OMC), U. S. Department of State requires specific licenses for the export of any arms, ammunition, implements of war and miscellaneous and auxiliary

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equipment. Although gas centrifuges are not specifically identified in their regulations, two categories set forth in the OMC statute would appear to extend export controls to this equipment and its technology. Category XIX states that OMC licensing controls extend to "any article not enumerated herein having significant military applicability..."; and Category XVII controls the export of "all articles including technical data, not enumerated herein, containing information which is classified as requiring protection in the interests of national defense."

Internationally, gas centrifuges "capable of the enrichment or separation of isotopes" are embargoed to the Sino-Soviet bloc by COCOM. Any technology relating to an item on the COCOM embargo list is also automatically embargoed to the bloc pursuant to the administrative procedures of COCOM. If a government at its own discretion determines that the gas centrifuge to be exported is specifically designed for industrial use and not suitable for atomic energy production use, a note to the COCOM embargo definition permits such governments of COCOM to export gas centrifuges to the bloc without prior authorization from COCOM. During the recent COCOM list review, the U. S. proposed that this Note to the definition be deleted since we believed any gas centrifuge, regardless of the fact that it might be specially designed for industrial use, is suitable for atomic energy production use, or its technology could be used in the fabrication of gas centrifuges for atomic energy applications. The purpose of the U. S. proposal was to further tighten the embargo on this type of equipment. The proposal was defeated because of French and British insistence that gas centrifuges had potentially wide applications in the civil sector (biological and medical research; industrial uses) and should not be totally embargoed. The French Delegate to COCOM indicated that a French company was at present completing the development of a gas centrifuge system intended for the extraction of solid particles from gases, and that this system, which was more economically sound than the cyclone-type device used at present, would be marketed shortly. As a result of British and French objections to the U. S. proposal, the embargo definition and note will remain unchanged.

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APPENDIX B

HISTORY AND PURPOSE OF INCLUSION OF GAS CENTRIFUGE TECHNOLOGY IN ACCESS PERMIT PROGRAM, AND OBSERVATIONS RESPECTING DISTINCTION BETWEEN CONTROL UNDER THE ACCESS PROGRAM AND UNDER THE NO-FUND CONTRACT

The Access Permit Program was established in 1955, based on the Atomic Energy Act of 1954, to permit industrial organizations to obtain access to Restricted Data pertinent to civilian applications of atomic energy. The program provides for the controlled dissemination of portions of atomic energy information required by private industry in peaceful atomic energy applications.

Private work in the gas centrifuge area on an unclassified basis became impermissible after the Commission's determination in August 1960 that future gas centrifuge developments would be Restricted Data. Prior to 1961, several U.S. industrial firms had expressed interest in exploring, with private funds, the possible commercial potential of the gas centrifuge process to provide fuels for nuclear reactors. AEC amended its regulations, 10 CFR Part 25, on April 20, 1961, to include in its Access Permit Program Category C-24, Isotope Separation -- Gas Centrifuge Method. This amendment permitted industry, through investment of private funds, to work in the gas centrifuge field on a classified basis provided certain qualifying criteria were met. These included the following:

1. §25.15(b)(1) "An application for an access permit authorizing access to Secret Restricted Data will be approved only if the application demonstrates that the applicant has a need for such data in his business, trade or profession and has filed a complete application form."

2. In addition, §25.15(b)(3) "An application for an access permit authorizing access to Secret Restricted Data in Category C-24, Isotope Separation -- Gas Centrifuge Method, will be approved only if the application demonstrates also that the applicant:

(i) Possesses qualifications demonstrating that he is capable of making a contribution to research and development in the gas centrifuge method of isotope separation and is directly engaged in or proposes to engage in a substantial research and development program in the centrifuge field or a substantial effort to develop, design, build or operate a gas centrifuge plant; or

(ii) Is furnishing to a permittee having access to Category C-24 under the subdivision (i) of this subparagraph substantial scientific, engineering or other professional services to be used by said permittee in carrying out the activities for which said permittee received access to Category C-24."

[redacted]

In order to determine whether an applicant qualified for access to C-24 data, the staff developed the following guidelines:

a. "Capable of making a contribution" shall be assumed if a group or company employes in its centrifuge activities one or more professional level scientists or engineers who will devote the equivalent of full time to investigation of one or more of the scientific or engineering aspects of the advanced centrifuge field.

b. "Proposes to engage" shall be accepted of an applicant if he certifies that he does so propose, gives acceptable evidence that he has reason to be in the field, that is, he owns or has available ore deposits, produces or processes UF_6, processes enriched materials, or otherwise has a direct and identifiable interest in the commercial utilization of the centrifuge, and affirms that he will mount a "substantial research and development program" or "substantial effort to develop, design, build or operate" a plant, providing the facts he ascertains during his term of access warrant such a program.

c. "Substantial" research and development program in the centrifuge field or "substantial" effort to develop, design, build or operate a plant shall be construed as involving an annual expenditure for personnel, plant, equipment, operations or contract work in excess of $50,000 per year.

The inclusion of gas centrifuge technology in the Access Permit Program was predicated on the Commission's conclusion that in the interest of the common defense and security no dissemination of classified gas centrifuge information for private purposes would be permitted except under the Access Permit Program. The qualifying companies who were permitted to disseminate private classified gas centrifuge information were also given access to AEC's information in this field.

The AEC announcement of the inclusion of the gas centrifuge category in the Access Permit Program emphasized "that the granting of an access permit under the following amendment will impose no obligation on the Commission to grant any license for a production facility or otherwise facilitate the commercial use or sale of any invention or development which may result therefrom."

Each gas centrifuge access permittee was required by the conditions of the AEC regulation, among other things, to:

1. submit reports to the AEC covering the results of its work in the gas centrifuge field during the term of the Permit and for one year after expiration of the Permit;

2. make available for AEC inspection all technical data and experimental equipment developed during the term of the Permit and for one year thereafter;

DOE ARCHIVES

3. grant to the Government upon request, for reasonable compensation, a non-exclusive, irrevocable license to use for Government purposes, any patent on any invention or discovery made or conceived during the term of the Permit or one year thereafter in the course of the permittee's work in the gas centrifuge field; and

4. grant to the AEC, upon request, for reasonable compensation, the right to use for AEC programs, any of the Permittee's proprietary data developed in the course of its work in the gas centrifuge field during the term of the Permit or one year thereafter.

The following five firms were given access to AEC's classified gas centrifuge information:

Company	Date Permit Issued	Status
Dow Chemical Co.	8/18/61	Expired 9/26/62
Allied Chemical Corp.	4/11/62	*
General Electric Co.	5/2/62	*
Bendix Corp.	8/15/62	Expired 3/5/64
United Nuclear Corp.	5/28/62	Expired 5/28/63

* These Companies have been permitted to continue to work in the gas centrifuge field with no access to AEC classified technology beyond June 30, 1964.

On June 30, 1964, AEC announced that access to its own Restricted Data in the Gas Centrifuge field would no longer be made available under the Access Permit Program. This was indicated to be an interim measure, pending the Commission's consideration and decision as to whether a new regulation, Part 26, should be issued to specify the conditions under which privately developed Restricted Data, including such data in the gas centrifuge field, could be disseminated and received for private purposes. GE's and Allied's access to AEC data theretofore made available was not withdrawn, but GE and Allied were no longer provided access to subsequently generated AEC classified information in this field. GE and Allied were permitted to have access to their own information subsequent to the withdrawal of AEC's information from the Access Permit Program.

On January 3, 1964, AEC entered into a no-fund contract with Electro-Nucleonics, Inc., of Caldwell, New Jersey, which would permit that company to perform research and development work in the gas centrifuge field. The contract stated that no access to AEC classified information, or that of access permittees, in this category would be provided. The period of the contract was, initially, two months, but the contract has been continuously extended and, presently, its stated expiration date is November 30, 1966, subject to AEC's option to accelerate the date by written notice to that effect to the company. In December, 1964, W. R. Grace & Co. was added as a co-contractor.

[redacted]

The terms of the Electro-Nucleonics-Grace contract are similar in substance to the regulatory requirements of gas centrifuge permittees in effect under the Access Permit Program. The essential differences are the contract feature stating that AEC would arrange for processing up to 10 individuals for security clearances at Government expense and the use in the contract of "boilerplate" (covenant against contingent fees, nondiscrimination in employment, officials not to benefit, assignment and subcontracting prohibitions, convict labor, and Work Hours Act of 1962). Common in all contracts but not included in the Access Permit Program.

The Access Permit Program was developed to implement the provisions of the Atomic Energy Act of 1954 favoring the participation of private industry in the development and use of atomic energy for peaceful purposes and the general welfare.

The Access Permit Program was affirmative and encouraging in tone, although it clearly specified conditions and terms predicated on considerations of the common defense and security and it related to private needs for purposes other than AEC's own nuclear programs.

AEC contracts are, of course, principally related to AEC's nuclear programs and AEC's needs. The no-fund contract that could be employed as the mechanism for permitting and controlling access to private Restricted Data in the gas centrifuge field, however, would not be an arrangement to advance AEC's scientific or technical needs but, rather, one to advance the private aims and purposes of the contractor. For this reason, a covering regulation explaining that no access to Restricted Data in the gas centrifuge field for private purposes will be permitted except under a special no-fund AEC contract will helpfully label this type of arrangement as one different from AEC's usual contracts. Also, to minimize any appearance of bias or special treatment not based on considerations of the common defense and security, and to assist in establishing a legally sturdy platform in support of AEC's control of access to private Restricted Data, the regulation should specify the general criteria for eligibility to become an AEC contractor under the special no-fund contract system.

If the foregoing measures are taken, the differences between access under the no-fund contract and access under the Access Permit Program would, in one sense, not be very significant in substance; the only difference might well be the inclusion in current contract "boilerplate" which, of course, wasn't used in the Access Permit Program. In another sense, and as alluded to above, the use of the no-fund contract would not convey an attitude of encouragement by AEC for private utilization of gas centrifuge technology.

[redacted]

[redacted]

APPENDIX C [redacted]

MAJOR FACTORS GENERALLY CONSIDERED IN EVALUATING PROGRESS IN GAS CENTRIFUGE DEVELOPMENT

General areas of technical information used to note progress in the gas centrifuge development program are as follows:

A. Machine Designs

Data on rotor dimensions, end cap design, baffle design and placement, materials of construction, types of bearing and damping systems, feed and product removal systems, power drive systems.

B. Mechanical Tests

Number of test stands, general results of test runs, dimensions of rotors tested, peripheral speeds obtained, duration of test runs, duration of life tests, causes for failures if known, and results of individual tests on components.

C. Separation Tests

Items covered in B as they specifically relate to actual tests with additional data on the process gas used, feed and product rates and assays, separative capacities obtained, machine efficiencies, and loss rates.

D. Cascade Data

The number, type, and general operating characteristics of machines, general layout of units, and general experimental results similar to those in item B and C above.

[redacted] [redacted]

The significance of some of these major factors is given below:

ITEM	SIGNIFICANCE
Machine Separative Capacity	High separative capacity per machine is desired to reduce unit cost of product; fewer machines would be required to perform given separation task.
Separative Efficiency	Since the unit cost of separative work will vary inversely with the overall centrifuge and cascade efficiencies, it is desirable to have both of these efficiencies as high as possible. The centrifuge efficiency is dependent upon the flow pattern within the centrifuge bowl; the magnitude of the countercurrent flow, the design and placement of the feed and scoop system; the departure of the centrifuge from an ideal cascade; and on other phenomena such as turbulence and end effects. The cascade efficiency is dependent upon the losses due to the fact that the machines in the cascade in practice will not perform precisely identical; and the time that individual units are actually on stream and operating.
Rotor Dimensions	Separative work available from a centrifuge is directly proportional to the rotor length, other factors being unchanged. The rotor diameter affects the enrichment factor, the process gas inventory and throughput, the decay of countercurrent flow and the equilibrium time. The length-to-diameter (L/D) ratio of the rotor gives an indication whether the unit is subcritical or supercritical. (A subcritical machine operates at speeds less than that at which the first flexural critical occurs while a supercritical unit operates at speeds equal to or greater than that of the first flexural critical. In general, supercritical machines have an L/D greater than 4.)
Peripheral Speed	The separative capacity of a centrifuge machine varies theoretically as the fourth power of the peripheral velocity. Even though the overall separation efficiency decreases with increasing peripheral velocity, the separative capacity increases sharply.
Reliability	Centrifuges should be capable of operating trouble-free for extended periods (2-3 years) in order to achieve low operating and maintenance costs, and to assure high cascade efficiency.

[redacted]

ITEM	SIGNIFICANCE [redacted]
Process Gas Loss Rate	Low process gas loss rates are necessary to permit attainment of high enrichments in a cascade, and are desirable for economic and contamination reasons.
Capital Costs	Important from an economic viewpoint, but not necessarily from an Nth power regard. A low centrifuge unit manufacturing cost may be essentially worthless unless the unit performs efficiently and reliably.
Operating Costs	Important from an economic viewpoint, but not necessarily from an Nth power regard.
Bearings and Damping Systems	The suspension system is important if the machines are to have a low power consumption. Long life bearings with associated damping mechanisms which will support the rotor as well as damp the system critical modes, assist in improving machine operation.
Feed and Product Removal System	A major objective of feed insertion is to find an arrangement that will minimize interference with established flow patterns. Violent mixing or reduction of the gas rotating speed will cause a loss of separative work. With product and tails removal scoops, the number, the diameter of the tubing, the length, and the tip design are of paramount importance in determining the magnitude of the disturbance of internal circulation, and consequently the separative work of the machine.
Feed and Product Rates and Assays	Feed rates and product and tails removal rates affect the overall machine efficiency; assays of product and tails indicate the separation factor of the centrifuge, i.e., the degree of enrichment attained, and depend on the operating mode of the machines.

i.

[redacted]

APPENDIX D

[redacted]

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3.3(b)
(1)(6)

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[redacted]

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CIA
3.3(b)
(1)(6)

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6.2(a)

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6.2

DOE ARCHIVES

CIA 3.3(b)(1)(6)

DOE 6.2(a)

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DOE ARCHIVES

TABLE 1

DOE 6.2(a)

DOE 6.2(a)

CIA 3.3(b)(1)(6)

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DOE 6.2(a)

DOE 6.2(a)

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CIA 3.3(b)(1)(6)

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[redacted] [redacted]

APPENDIX E

PROJECTED WORLD NUCLEAR POWER GROWTH & SEPARATIVE WORK REQUIREMENTS

The projected free world growth of nuclear power for plants to be fueled with enriched uranium from the U.S., together with the associated separative work requirements, are as follows:

	Domestic		Foreign*		Total World	
	MWe	Separative Work 10^3 kg/Yr	MWe	Separative Work 10^3 kg/Yr	MWe	Separative Work 10^3 kg/Yr
1970	10,000	2,800	4,500	1,500	14,500	4,300
1975	40,000	8,300	26,000	5,700	66,000	14,000
1980	95,000	16,200	84,000	12,700	179,000	28,900
1985	212,000	21,000	190,600	15,500	402,600	36,500

Additional estimates were also projected (Tables 2,3,& 4) out to the year 2010 for U.S. requirements using three different mixes of reactor types.

The maximum U.S. separative capacity of the existing plants (not improved) is about 17,000,000 kg/Year at full power. The separative capacities of other existing and potentially competitive plants are:

USSR	-	6,000,000 kg/Yr.
France	-	525,000 kg/Yr.
United Kingdom **	-	150,000 kg/Yr.

From the above it is apparent that existing U.S. capacity would be adequate to supply estimated domestic requirements until about 1981 on the assumption of very little preproduction. If the U.S. were to supply the potential domestic and free world requirements, our existing capacity would be exhausted in the 1975-1981 time period depending upon the percent of the free market that the U.S. captures:

% Foreign Market	Year U.S. Capacity is Exhausted
20	1979
40	1978
60	1977
80	1976
100	1975

It is difficult at this point in time to determine with any degree of confidence the amount of additional separative capacity that will be needed. However, improvement of the gaseous diffusion plants in the late 1970's, to incorporate the latest technology, would add approximately 10,000,000 kg/yr (for a total of 27,000,000 Kg/yr) of separative work, and extend the above

*Exclusive of U.K.

** Current unimproved capacity. Announced modification program indicated UK capacity may increase to a total of 450,000 kg/Yr.

[redacted] [redacted]

times before U.S. capacity would be exhausted by about 5 years. Preproduction of material prior to 1972 would extend the period that the U.S. could satisfy all requirements (domestic and foreign) to approximately 1983. It may also be that the gas centrifuge process will reach a state of development by 1980 that would make it economically competative with the gaseous diffusion process, and added separative capacity could be attained by the construction of a gas centrifuge plant. The following Figures and Tables portray various aspects of the projected nuclear power growth and separative work requirement to meet the future demands.

Figure 1 shows the predicted "most likely" annual separative work requirements (both foreign and domestic) of the gaseous diffusion plants through 1980. Normal feed and a tails assay of 0.2% were assumed. The "total" curve shows that the present, unimproved, diffusion plants would run out of capacity by 1976; but with improvements installed (1975 technology), the plant could meet demands through about 1980 (assuming no preproduction) at which time new plant would be required. Maximum and minimum separative work requirements for foreign and domestic reactors were estimated ± 20% of the "most likely" curve, respectively.

Figure 2 shows that with preproduction in the early years, prior to 1972, improved gaseous diffusion plant would be able to satisfy demands to about 1983, at which time a new plant might be required. This curve represents one of the U-235 cases presently under consideration in the long-range preliminary studies. It is not considered to be the optimum plan of operation.

Figure 3 shows the marginal cost of separative work due to power from the existing 3-plant complex, with 1965 improvements installed, as a function of plant separative capacity, with power costing 4 mills/KWH. (Solid line) The dotted curve shows the marginal cost of separative work for an unimproved plant. It can be seen that new plant construction would be advisable when the saturation value reached $24.58/kg U. This would be at approximately 6080 megawatts at which the separative work would be 21,200 MT/Yr. for the improved plant with 1965 technology.

Table 1 shows the effects of installing the proven 1965 technology in the three gaseous diffusion plants under several power schedules. The major cascade improvement program is estimated to cost $280 million expended over a 5-year period starting about 1972 or 1973. The capital costs are the sole additional costs which would be incurred and are based on a 10-year amortization period. Rates of return are shown for 2 cases, a 5% and a 7.5% discount. The separative work gain is in addition to the separative work from the existing plants. The anticipated gain from the use of FY 1965 technology as measured in the power utilization index (kg U/MWD) is assumed to be at one half the rate that was realized during the period CY 1956 through CY 1964 (i.e., 0.18 kg/MWD/Yr).

Tables 2, 3, and 4 reflect projected separative work requirements beyond 1980 for the U.S. only (based on a somewhat different projected near term nuclear power growth in the U.S., than used in Figure 1)

[redacted]

FIGURE 1

PREDICTED ANNUAL SEPARATIVE WORK REQUIREMENTS
FOREIGN & DOMESTIC

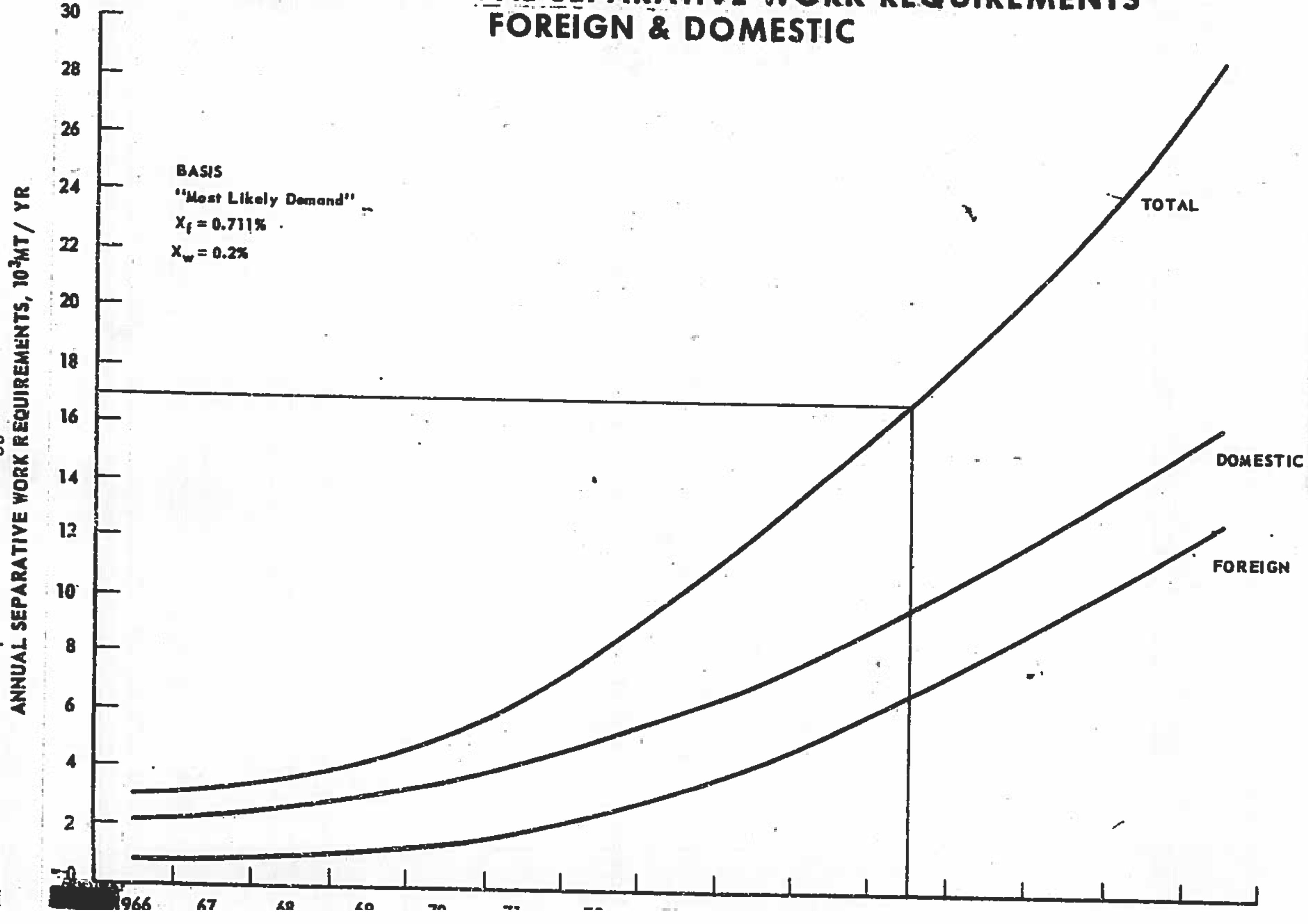

FIGURE 2

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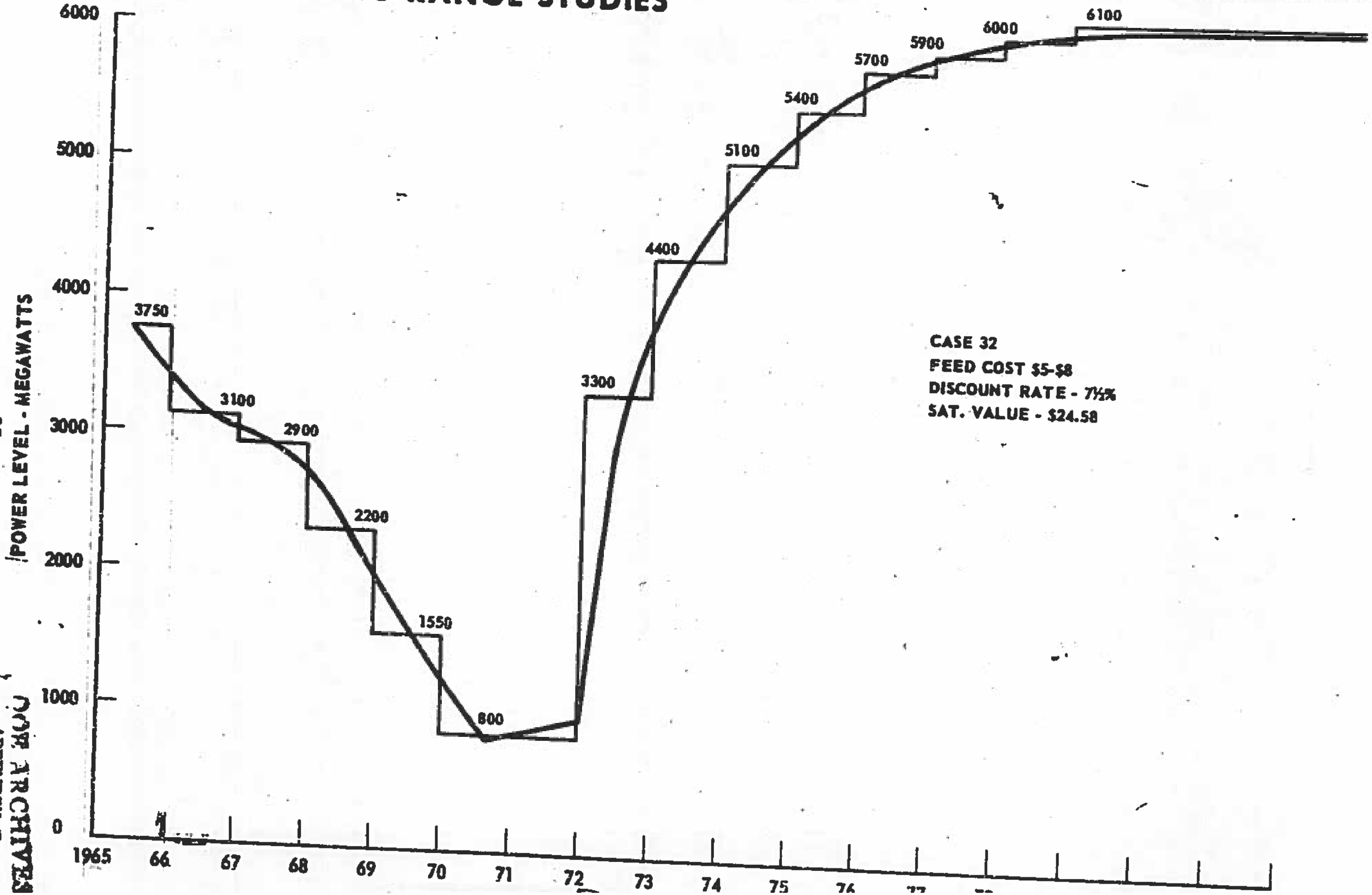
GASEOUS DIFFUSION PLANT POWER REQUIREMENTS
LONG RANGE STUDIES



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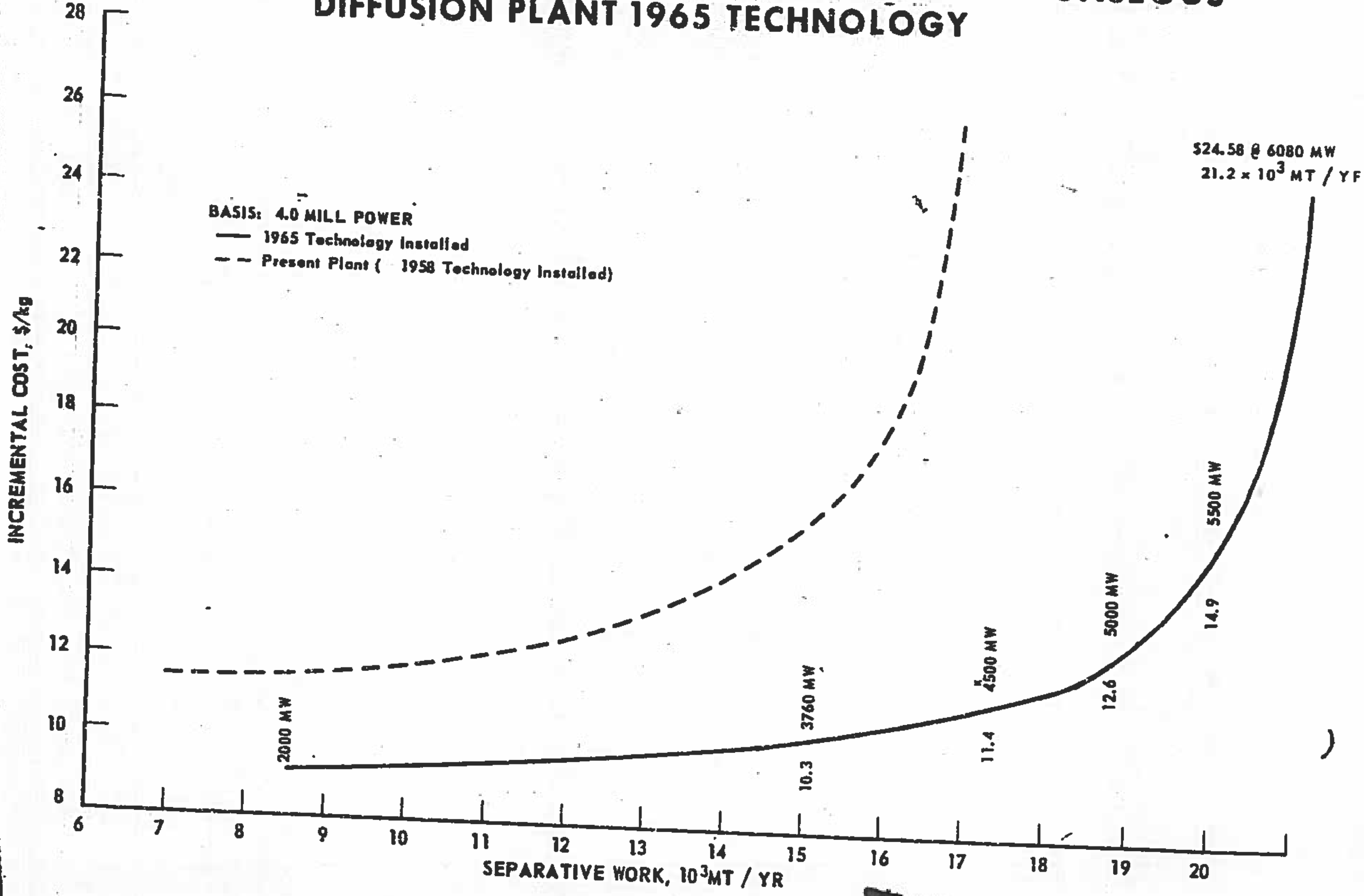
[redacted]

FIGURE 3

INCREMENTAL COST OF SEPARATIVE WORK - IMPROVED GASEOUS DIFFUSION PLANT 1965 TECHNOLOGY



[redacted]

TABLE 1 [redacted]

EFFECTS OF INSTALLING FY65 TECHNOLOGY IN THE 3 GDP'S

POWER LEVEL MW	SEP. WORK INCREASE MT/YR	UNIT COST OF ADDED SEP. WORK, $/kg 5% DISC.	7½% DISC.
2000	1607	23.29	26.20
3000	2326	16.09	18.10
4000	2975	12.58	14.15
5000	3544	10.56	11.88
6000	3984	9.39	10.57

TABLE 2 [redacted]

SEPARATIVE WORK REQUIREMENTS FOR

ONE SPECIFIC NUCLEAR ELECTRIC GROWTH PATTERN

Year Ending	Installed Nuclear Electric Capacity			Separative Work Required 32/
	LWR	FBR	Total US only	10^3 kg/yr.
	---10^3 EMW------------			
1990	252	43	295	38,000
1995	372	118	490	51,000
2000	479	251	730	59,000
2005	569	461	1,030	68,000 (peak)
2010	610	770	1,380	66,000

32/ X_w = 0.253% U235. For X_w = 0.2, the annual separation work requirements are 15% greater.

[redacted]

Table 3

SEPARATIVE WORK REQUIREMENTS

LWR ⟶ HWR ⟶ FBR

(See Figure 3B of Advanced Converter Analysis for Growth Data)

Year Ending	Installed Nuclear Electric Capacity				Separative Work Required
	LWR	HWR	FBR	Total	
	----10^3 eMW----			US only	10^3 kg/Yr.
1990	63	186	46	295	13,800
1995	63	299	128	490	16,600
2000	63	394	273	730	18,500
2005	63	469	498	1030	20,300
2010	63	491	826	1380	19,700

HWOCR	Inv. requirement	0.70 kg Δ/eMW
	Makeup requirement	0.40 kg Δ/full power eMWYr.

[redacted]

APPENDIX E

[redacted]

[redacted]

TABLE 4

SEPARATIVE WORK REQUIREMENTS [redacted]

LWR HWR FBR

(Like Figure 3B of Advanced Converter Analysis for Growth Data except that transition from LWR to HWR staged over 20 Year Interval)

	Installed Nuclear Electric Capacity				Separative Work Required
	LWR	HWR	FBR	Total US only	10^3 kg/Yr.
		10^3 eMW			
1980	64	11	0	75	12,400
1985	109	46	5	160	17,600
1990	136	113	46	295	21,000
1995	142	220	128	490	23,200
2000	142	315	273	730	25,600
2005	142	390	498	1030	26,800
2010	142	409	826	1380	25,200

HWOCR: Inv. 0.07 MT Δ/ eMW
Makeup 0.04 MT Δ/ full power eMWYr.

LWR: Inv. 0.40 MT Δ/ eMW
Makeup 0.15 MT Δ/ full power eMWYr.

X_w = 0.253%

[redacted]

[redacted] APPENDIX E

through the period when it is expected light water reactors will be phased out of new construction and replaced by heavy water and fast breeder reactors. The actual transition will, of course, depend on many factors such as the successful development of new reactors and the availability of feed to fuel them.

Table 2 is based on a reactor replacement schedule which represents the highest estimated requirement for separative capacity and reflects a peak in the year 2005 of 68,000,000 Kg/Yr. (for U. S. only).

Tables 3 and 4 also peak at about 2005 but use reactor replacement schedules which have significantly lower requirements for separative work.

NOTES:

1. For information regarding the development of the growth data, see part 3 of JCAE FY 66 Authorization Hearings, March and April 1965.

2. LWR plutonium production for FBR growth = 0.32 kg fissile Pu per full power eMWYr. Pu not recycled, except for 1980 point.

3. FBR plutonium production for FBR growth = 0.43 kg fissile Pu per full power eMWYr.

4. FBR inventory requirement of 4.2 kg fissile Pu per EMW.

5. Four year lag between production of Pu in LWR and availability to FBR; three year lag for FBR/FBR.

6. FBR growth begins 1985, rate thereafter limited only by on availability of plutonium.

7. Separative work requirements for LWR's, excluding "pipeline" requirements are:

X_w, % U235	0.2	0.25
For inventory, kg/eMW	460	400
For Makeup, kg/full power eMWYr (non-Pu recycle)	170	150

8. One year lead provided for in specifying separative work requirements (re - figures entered for year 1980 correspond with requirements in 1981).

9. Separative work requirements are for nuclear electric capacity only.

APPENDIX F

RELATIVE MERITS OF U-235 AND PLUTONIUM AS WEAPONS MATERIAL

Only three nuclear species (U-233, U-235 and Pu-239) have all the characteristics which make them useful in producing an explosive fission reaction. Other fissile materials have such short half-lives and are so strongly radioactive that they have little or no practical value in weapons. In addition, they are more costly to produce, in terms of reactor effort required, than plutonium.

Of the three useful species, only U-235 is a naturally occurring isotope. Since it occurs in nature as only 0.7 percent of natural uranium, it must be separated by an isotopic separation process. In general, the U.S. considers "weapons grade" uranium to be material enriched to 90 percent or more in U-235.

Uranium-233 can be made by neutron irradiation of thorium in a reactor. It has never been used in a practical weapon because the strong radioactivity of associated impurities introduces serious fabrication and handling problems and because its production in a materials production reactor is somewhat less efficient than the production of plutonium.

Plutonium can be made by neutron irridiation of natural uranium in a reactor. When U-238 is irradiated in a reactor to produce Pu-239, some of the resulting Pu-239 is converted by further neutron capture to Pu-240, which in turn is converted by still further neutron capture to Pu-241. In fuel elements at the end of the irradiation period, the fraction of the plutonium which is in the form of higher isotopes (Pu-240 and Pu-241) is approximately proportional to: (1) the length of time irradiated, and (2) the neutron flux present (or the power level at which the reactor was operated). "Weapons grade" plutonium from AEC production reactors in recent years has contained about 93 percent Pu-239, six percent Pu-240 and less than one percent Pu-241.

Since the prime objective in power reactor operation is the economical production of power, economics require the fuel elements to be left in the reactor as long as possible. The result is higher irradiation levels and larger fractions of Pu-240 and Pu-241 in the plutonium extracted at the end of the fuel cycle. Plutonium extracted from currently operating and advanced power reactors can be expected to contain 15 to 35 percent Pu-240 and 3 to 5 percent Pu-241.

CHARACTERISTICS OF FISSILE MATERIALS AS THEY AFFECT WEAPONS DESIGN

Fabrication and Handling

In general, U-235 is easier to work with than plutonium. It can be machined in the open and handled without remote handling equipment. Because of the health hazards associated with it, plutonium requires special precautions in fabrication.

[redacted] [redacted]

Weapons Design

Because of its greater reactivity (the required critical mass in a weapon configuration is three to five times less than for U-235), plutonium is of greater interest to a weapon designer who has relatively sophisticated design goals, such as lightweight, small-diameter, high-efficiency single-stage weapons or primaries for thermonuclear weapons. On the other hand, there are two categories of weapons, both of relatively unsophisticated design, for which only U-235 is usable

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Detailed Design Considerations

a. Uranium

In order to achieve maximum nuclear efficiency in a weapon every effort is made to prevent loss of neutrons, either by escape or by nonfission capture (absorption). U-235 is the reactive material of value to the weapon designer; while U-238 in the uranium acts as an inert diluent absorbing neutrons by nonfission capture that might otherwise be used to cause fissions. Up to a point, the effect of this dilution can be overcome by assembling a larger mass of material (or increasing its density by implosion of the material) to reduce the chance of neutrons escaping before causing fission. Thus the amount of material that must be assembled to initiate a fission chain reaction ("critical mass") increases as the proportion of U-238 in the material increases.

In order to make a uranium weapon as small, light and efficient as possible, the weapon designer needs uranium enriched to the highest percentage of U-235 possible. This need must be balanced against the effort required to obtain such highly-enriched uranium.

b. Plutonium

(1) Effect of High Plutonium-240 Content in Weapons

Plutonium-240 acts as a diluent in plutonium, much as U-238 dilutes U-235. Its presence requires a proportionately larger amount of plutonium to achieve an explosive fission reaction. Thus, its presence causes penalties in size and weight of a fission weapon.

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In addition, Pu-240 has a high rate of spontaneous fission, resulting in a large neutron [redacted] ground which could in turn cause initiation of the fission chain reaction before the fissile material has been assembled to its optimum density.

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overcome by means

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(2) Effect of High Plutonium-241 Content in Weapons

Plutonium-241, while it is a good fissile material, complicates fabrication, handling and storage because of its short half-life and the strong radioactivity of it and its daughter isotope, Americium-241.

Possible Uses of Low-Grade Fissile Materials in Weapons

a. Uranium

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All factors considered, it would seem that any country having the technical capability to develop a nuclear weapon would concentrate on production of plutonium or highly enriched uranium in preference to direct use of low-enrichment uranium.

b. Plutonium

(1) Dirty Plutonium and Types of Weapons

In view of the characteristics of the various grades of plutonium, certain observations can be made as to types of weapons in which dirty plutonium might be used.

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(2) Nth Power Use of Dirty Plutonium

It is technically feasible for an Nth power to use dirty plutonium in a weapons program, but the effectiveness of its use will depend upon: (1) the nation's weapons development objectives, and (2) the availability of certain nuclear weapons technology to the nation.

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alternative such an Nth power might concentrate on [redacted] As an ment of an isotopic separation plant for uranium. the develop-

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* * * *

On balance it appears there is no clear cut advantage from the standpoint of weapon design to using enriched uranium in preference to plutonium or vice versa to produce a simple weapon if one considers no serious limitations on size or weight of the weapon.

[redacted] [redacted]

APPENDIX G

EVALUATION OF NTH POWER CAPABILITIES

It is believed feasible for some countries which do not have a nuclear weapons program to produce enriched uranium by means of a small gas centrifuge plant. Here an attempt is made to correlate the probability that an Nth power, with a certain industrial capability, will produce nuclear weapons by means of a gas centrifuge plant. For this purpose, countries are divided into three groups; X, Y, and Z. Group X countries are those with a relatively high degree of technical competence and a high level of industrial activity. Some of the group X countries are West Germany, Sweden, Japan, U. K., and the Netherlands. Group Z countries are those which possess relatively little in technical skills and have relatively little industrial activity. Egypt, Peru, and Pakistan are a few in this category. Group Y countries are those which lie between and which have limited internal industrial activity. Brazil, Israel, India, and Yugoslavia are some of the countries considered to be in group Y.

A group X country would need no outside assistance, while a group Y country would probably have to import some of the hardware and auxiliary equipment necessary to fabricate the centrifuge plant. A country in group Z would probably have to import fabricated centrifuges and almost all of the auxiliary equipment for the centrifuge plant. In addition, a group Z country would need technical advisors from outside to aid in the construction and operation of the plant.

In a group X country the choice of whether to produce a limited amount of nuclear weapons by the centrifuge or the reactor route is not clear cut at present. The centrifuge has the potential for lower capital and operating costs, but advanced technology is not available in the unclassified literature and the centrifuge at the present time would entail a higher risk of failure than would a reactor project. A group X country will have the experienced scientists and engineers necessary to bring a centrifuge facility into successful operation; therefore, group X countries have the greatest opportunity to choose the centrifuge route for attainment of their first nuclear weapon.

In a group Y country, if the goal is primarily the achievement of a clandestine, very limited nuclear capability, the reactor-plutonium route may seem more attractive from the low risk of failure standpoint at the present time because of the availability of reactor data in the open literature.

A group Z country will find the construction and operation of either a centrifuge or plutonium facility a difficult task. These countries would need much help from a group X or Y country. Due to the nonindustrial nature of a group Z country, a completely clandestine facility could probably not be built. The choice of whether to build a centrifuge or plutonium facility in a group Z country would probably depend upon which appeared most attractive to the group X or Y country with which they were collaborating.

[redacted] [redacted]

Estimates of time and costs for countries of these groups to obtain certain quantities of nuclear weapons materials are given in Tables I through IV. For the purpose of comparison, estimates are also presented for the production of weapons grade plutonium from reactors specifically designed for such production.

The following section contains an evaluation and further analysis of the gas centrifuge capabilities of a country representative of each group. Tables I, II and III compare the costs of producing special nuclear material for a weapons program by an Nth power in each of the X, Y, and Z groups.

Group X (Japan) - Japan's technological competence and industrial capacity are well established characteristics of this country. Also it is widely known that Japan stands among the most advanced countries in mathematical competence and in basic science generally. Consequently it is not surprising that Japan was able to develop a gas centrifuge program without recourse to outside help.

The fact that Japan has purposely chosen to pursue a relatively modest program in terms of money spent and people employed, in no way detracts from her ability to attack the gas centrifuge problem more aggressively.

The progress of Japan's gas centrifuge program is commensurate with the effort expended, and there is little reason to doubt that, if Japan elects to undertake a larger gas centrifuge development program, a corresponding level of attainment will be achieved.

Group Y (Brazil) - Brazil qualifies as a class Y country on the basis of her limitations in the area of industrial skill and level of activity. Although Brazil may have a number of experts in fields pertinent to gas centrifuge development and a fairly modern industrial "plant," her overall scientific and engineering capability is such that any attempt at developing a native gas centrifuge program would be at least a risky affair. There are just too many technical problems arising during such a program for Brazil to be able to handle along with her limited means.

CIA 3.3(b)(1)(6)

The Brazilians may have recognized this when they decided to buy their machines from Germany. [redacted]

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Although the Brazilians have been operating the German centrifuges and plan to run UF_6 earlier obtained from the U.S. through them soon, the future plans are not known.

Group Z (Egypt) - Except for largely imported industrial plant and equipment, Egypt's native capacity is very low. Also Egypt lacks trained scientists and engineers of her own. Even though Egypt has higher educational facilities and competent scientists and engineers in the teaching field, trained and experienced scientists and engineers are few.

Egypt also meets requirements of a group Z country in that nearly all auxiliary equipment for a centrifuge program and the prefabricated centrifuges themselves would necessarily have to be obtained from outside. Egypt simply does not have the machinery (or of course qualified people) to make these things herself.

The Egyptians themselves are probably aware of their limitations since their one known attempt at a gas centrifuge "program" consisted of offering to have all the work done outside of their country.

All Egypt was prepared to do was pay for the work and receive an occasional progress report.

[redacted]

TABLE 1

Comparison of Plutonium and Enriched Uranium Routes by an Nth Power Group X Nation

Small Size Complex

DOE 6.2(a)

	Annual Production Rates			
	10 kg Pu	[redacted]		
		DELETED		
Capital Cost, $MM	31.7	55.1	12.4	8.1
Operating Cost, $MM	3.3	8.6	2.3	1.6
Power Requirements (MW)	—	8.4	1.6	0.9
Operating Work Force				
Total	320	620	166	118
Technical	108	35	16	15
Time to Produce* Material for First Weapon, years	7.5	5	5	5

DOE 6.2(a) DELETED

Large Size Complex

DOE 6.2(a)

	Annual Production Rates			
	100 kg Pu	[redacted]		
		DELETED		
Capital Cost, $MM	96.4	[redacted]	[redacted]	[redacted]
Operating Cost, $MM	7.5	47.2	11.5	7.5
Power Requirements (MW)	—	84.0	15.8	8.9
Operating Work Force				
Total	552	3,400	798	516
Technical	169	80	41	31
Time to Produce* Material for First Weapon, years	6.5	5	5	5

DOE 6.2(a) DELETED

*For each case it is assumed that the Nth country has knowledge (blue-prints, etc.) of the reactor and related facilities, and of the model of centrifuge involved. Time referred to, therefore, is solely the construction time required to go from demonstrated technology to the finished plant plus the time then needed to obtain enough product material for the first weapon. No judgment has been made concerning the time that would be necessary to develop the actual weapon (which might be done concurrently with the construction and operation of the production plants).

[redacted] DOE ARCHIVES

[redacted]

APPENDIX G

[redacted]

TABLE 2

Comparison of Plutonium and Enriched Uranium Routes by an Nth Power Group Y Nation

Small Size Complex

DOE 6.2(a)

	Annual Production Rates			
	10 kg Pu	50 kg U		
		DELETED		
Capital Cost, $MM	38.2	66.2	149	9.7
Operating Cost, $MM	3.5	9.0	2.5	1.7
Power Requirements (MW)	--	8.4	1.6	0.9
Operating Work Force				
Total	386	750	200	142
Technical	129	40	20	20
Time to Produce* Material for First Weapon, years	10	7	7	7

DOE 6.2(a)

DELETED

Large Size Complex

DOE 6.2(a)

	Annual Production Rates			
	100 kg Pu	500 kg U		
		DELETED		
Capital Cost, $MM	116.3	630.0	113.0	62.0
Operating Cost, $MM	7.8	49.5	12.3	8.0
Power Requirements (MW)	--	84	15.8	8.9
Operating Work Force				
Total	667	4,130	960	620
Technical	204	100	48	37
Time to Produce* Material for First Weapon, years	8.5	7	7	7

DOE 6.2(a)

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DOE 6.2(a).

*See preceding page.

[redacted] APPENDIX G

[redacted] TABLE 3 [redacted]

Comparison of Plutonium and Enriched Uranium Routes by an Nth Power Group Z Nation

Small Size Complex

	Annual Production Rates			
	10 kg Pu	50 kg U	DELETED	
Capital Cost, $MM	44.5	[redacted]	17.3	[redacted]
Operating Cost, $MM	3.6	9.3	2.6	1.8
Power Requirements (MW)	—	8.4	1.6	0.9
Operating Work Force				
Total	451	875	230	165
Technical	152	45	20	23
Time to Produce* Material for First Weapon, years	13	9	9	9

DELETED

Large Size Complex

	Annual Production Rates			
	100 kg Pu	500 kg U	DELETED	
Capital Cost, $MM	136.3	[redacted]	[redacted]	[redacted]
Operating Cost, $MM	8.1	51.0	12.9	8.4
Power Requirements (MW)	—	84	15.8	8.9
Operating Work Force				
Total	780	4,800	1,100	720
Technical	239	110	55	43
Time to Produce* Material for First Weapon, years	11.5	9	9	9

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*See preceding page.

[redacted]

APPENDIX G

DOE 6.2(a)

TABLE 4

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DOE 6.2(a)

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APPENDIX H

December 13, 1960

STATEMENT BY JOHN A. McCONE, CHAIRMAN U.S. ATOMIC ENERGY COMMISSION ON STATUS AND PROSPECTS OF GAS CENTRIFUGE TECHNOLOGY

After careful study and discussions with many qualified scientists about the gas centrifuge process, it is my conclusion that practical use of this method by any nation for producing weapons material is several years away. There is an enormous amount of development work still to be done. We foresee that the gas centrifuge ultimately can be used to separate uranium-235 from uranium-238 to produce weapons-grade materials. But this cannot be done satisfactorily with present technology. We do not think that the problems that remain are insoluble, but they certainly will take time to solve.

This process will not be simple nor cheap. Apparently, as we see the trend of future development it will take thousands of gas centrifuge machines to produce material for weapons. With auxiliaries, these machines might cost several thousand dollars each.

A country that is advanced scientifically and industrially would require a number of years - - perhaps as many as eight - - to perfect the gas centrifuge to the point where it could produce enough material for a nuclear weapon. Less industrialized countries will take much longer; the period of time depends upon how much outside assistance they receive.

We do not minimize the potential importance of this process, however. Although the gas centrifuge does not pose an immediate prospect for production of weapons material, there is no doubt in my mind it will introduce an additional complicating factor in the problems of nuclear arms among nations and our quest for controlled disarmament.

CIA 3.3(b) (1)(b)

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The attached comprehensive report by the Commission on the gas centrifuge process has been prepared to elaborate further on this matter and to place it in better perspective.

Attachment

DOE ARCHIVES

[redacted]

ATTACHMENT

ATOMIC ENERGY COMMISSION REPORT ON STATUS OF GAS CENTRIFUGE TECHNOLOGY

The following report on the status of technology on the gas centrifuge method for the separation of isotopes discusses the principle of the gas centrifuge, the possible advantages of this process and its possible use in the production of weapons material. The report also outlines the development work done by the United States and other countries and lists some of the problems which still must be solved.

I. PRINCIPLE OF THE GAS CENTRIFUGE

The theory of the gas centrifuge process is to pass uranium in gaseous form (uranium hexafluoride) through a centrifuge which spins at very high speeds. There is a slight difference in the weight of the uranium-238 and uranium-235 isotopes. Consequently, it is theoretically possible to separate these isotopes just as one can separate cream from milk by centrifugation. It must be emphasized, however, that although the same principle is involved, the gas centrifuge is a good deal more complex than the "cream separator" or other types of industrial centrifuges.

Only the uranium-235 portion of natural uranium (U-238) is fissionable and can be used for weapons purposes. Uranium-235 constitutes only .7 of a percentage point of natural uranium. The other 99.3 percent of uranium-238 is of no use for weapons. Therefore, it is necessary to separate the uranium-235 from uranium-238.

II. POSSIBLE ADVANTAGES

Two possible advantages of the gas centrifuge method, as compared with the gaseous diffusion process we now use for uranium isotope separation, are the potential lower requirement of a centrifuge plant for electric power and its potential requirement for fewer units in series in order to produce the desired enrichment of uranium-235. Further, it appears to be particularly well suited for low-capacity installations.

The centrifuge process has the interesting theoretical property that the separative work performed varies with the fourth power of the speed, all other factors being equal. This means that doubling the speed would, in theory, increase the separative work performed by the unit by a factor of sixteen. With this potential, as progress is made in materials of construction and equipment design, enthusiasm rises for the application of this process to the separation of uranium isotopes. In at least one respect this is a desirable situation since promising processes should be developed for uranium-235 separation as a step toward possible improvement in the economics of nuclear power.

[redacted]

III. USE FOR WEAPONS MATERIAL

A review by the Commission of available information on the gas centrifuge machines built both here and abroad indicates that these machines cannot now be used in a production plant without further development work. So far, centrifuge units have been operated only as single laboratory models for isotope separation. These machines are complex and expensive.

Even after substantial improvements have been made, thousands of gas centrifuges probably would be required to produce enough enriched uranium for one crude weapon per year. Including auxiliaries, a plant of this type might cost several thousand dollars per centrifuge. Compared with development by the United States, the time period would be much longer for a country not presently engaged in centrifuge research and development and not having access to advanced technical and industrial capability.

IV. DEVELOPMENT PROBLEMS

General areas in which problems still must be solved before a satisfactory process is possible with the current centrifuges include:

(1) Reliability of the present experimental machines for continuous, long-term service with uranium hexafluoride must be proved out.

(2) A model of the machine satisfactory for mass production of identical units must be developed.

(3) A method must be developed to provide for the introduction and removal of gas when the machines are grouped as would be necessary in a production plant.

(4) The auxiliary processes, services and instrumentation necessary for plant operations have to be determined.

None of these problems is simple to solve. Excellent technical and industrial talent are required.

V. DEVELOPMENT WORK BY UNITED STATES

The United States has followed development of this process for some time. The gas centrifuge was one of the methods investigated during World War II. Development work on the centrifuge method had not progressed so far as other methods when it became necessary to select the processes to be used in production plants. The United States temporarily discontinued work on the centrifuge and went ahead with gaseous diffusion, thermal diffusion and the electromagnetic methods for production of uranium-235.

Although the United States ultimately continued to employ the gaseous diffusion method as the most economical process available, the Commission has not lost sight of the gas centrifuge's possibilities. The AEC resumed research on the centrifuge method in 1953 and expanded this work gradually as the technology

[redacted]

advanced. Most of the Commission's research work has been carried out at the University of Virginia.

As the technology advances, it will be possible to make more realist appraisals of the economic attractiveness of this method for the separation of uranium-235. The Commission has recently increased the United States effor on the development of the centrifuge program. It is now expected that the tot: effort will be at a level of roughly $2 to $3 millions per year. Because of i potential significance to production of weapons materials, however, the progra is classified.

The technology of centrifuge separation is not now developed to a point where this process can produce uranium-235 at a cost competitive with the product from AEC's current gaseous diffusion plants. On the other hand, projections of possible gains in the gas centrifuge process indicate the possibili that the process may become attractive from the economic standpoint in the futu However, this would require very substantial further advances in the technology In this country, the gaseous diffusion method remains the most economical proce for large-scale production of uranium-235 at this time.

Since there has been considerable commercial interest expressed in possible industrial application of the gas centrifuge process to the developmen of economic nuclear power, the Commission has approved a program under which private industry in the United States will be permitted to work on the centrifu process with private funds, under appropriate conditions and security.

VI. WORK IN OTHER COUNTRIES

Scientists in West Germany and the Netherlands also have worked to develop the potential of the gas centrifuge process for its interesting scientif and commercial possibilities. They have been particularly interested in the potential of the centrifuge for the production of low enriched uranium for civilian research and power reactors.

In July of 1960 representatives of the Department of State and of the Atomic Energy Commission discussed centrifuge technology with the West Germa and Netherlands Governments and the United States asked that Germany and the Netherlands give consideration to the control of gas centrifuge technology. The two countries shared the concern of the United States over the possible application of the centrifuge process for weapons production.

The West German Government recently announced that it has taken steps to control the dissemination of information on the gas centrifuge process. The United States understands that the Netherlands Government is actively studyin the question of applying controls to its work.

The United States also discussed the gas centrifuge question with the United Kingdom. The United Kingdom follows classification criteria similar to those of the United States on the gas centrifuge process.

[redacted]