February 26, 1960

S.A. Levin, D. E. Hatch, and E. Von Halle, 'Production of Enriched Uranium for Nuclear Weapons by Nations X, Y, and Z by Means of the Gas Centrifuge Process,' Operations Analysis Division, Union Carbide Nuclear Company

Citation:

Summary:

A Union Carbide Nuclear Company study to determine how quickly and easily foreign countries could develop and utilize gas centrifuges with the goal of creating nuclear weapon facilities. The study determines that, due to the cheap cost and relatively small size of the centrifuges, even un-industrialized countries such as Cuba could achieve this technology within 8 years if helped by a larger nation.

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PRODUCTION OF ENRICHED URANIUM FOR NUCLEAR WEAPONS BY NATIONS X, Y, AND Z BY MEANS OF THE GAS CENTRIFUGE PROCESS

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UCC

POST OFFICE BOX P
OAK RIDGE, TENNESSEE

February 26, 1960

United States Atomic Energy Commission
Post Office Box E
Oak Ridge, Tennessee

Attention: Mr. S. R. Sapirie, Manager
Oak Ridge Operations

Gentlemen:

Transmittal of Centrifuge Study

The accompanying report presents the results of a study on the production of enriched uranium for nuclear weapons by nations X, Y, and Z by means of the gas centrifuge process. It contains the information requested in your letters of February 15 and 19, 1960.

We wish to stress that we claim no special qualifications for translating U. S. requirements into the requirements of foreign nations. The limitation of time precluded a thorough investigation of the problem. Nevertheless, the correlation which was developed in the report appears reasonable.

We shall be glad to provide any additional information which you may require.

Very truly yours,

UNION CARBIDE NUCLEAR COMPANY

L. B. Emlet

L. B. Emlet
Manager of Production

LBE:SAL:h

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51. A. E. Cameron
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PRODUCTION OF ENRICHED URANIUM FOR NUCLEAR WEAPONS BY NATIONS X, Y, AND Z BY MEANS OF THE GAS CENTRIFUGE PROCESS (U)

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Operations Analysis Division
G. A. Garrett, Superintendent

Distribution

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UNION CARBIDE NUCLEAR COMPANY
UNION CARBIDE AND CARBON CORPORATION
Oak Ridge, Tennessee

[redacted]

PRODUCTION OF ENRICHED URANIUM FOR NUCLEAR WEAPONS BY NATIONS X, Y, AND Z BY MEANS OF THE GAS CENTRIFUGE PROCESS (u)

I. INTRODUCTION

The nations of the Western Alliance have been engaged in a series of sporadic negotiations with the Soviet bloc on the subject of nuclear disarmament spanning the last several years. In order to provide valuable background material for future disarmament conferences it was deemed desirable to conduct a study for the purpose of assessing the feasibility of producing a small number of nuclear weapons, either overtly or covertly, in a country currently not known to have a nuclear weapons program.

Two approaches to the problem of producing nuclear weapons on a small scale have already been studied: a) the natural uranium reactor for the production of plutonium and b) the high speed gas centrifuge process for the production of isotopically enriched uranium.* It was concluded, as a result of this study, that the gas centrifuge plant was the shorter and probably the more economical path to a nuclear weapon. It also became apparent that, in general, it would not be too difficult to build a relatively small clandestine gas centrifuge plant capable of producing sufficient enriched uranium for a small number of nuclear weapons.

The gas centrifuge process lends itself to clandestine operation for the following reasons. Most important is the fact that the power requirement for the centrifuge plant under consideration is relatively small: only about 3 megawatts are required for its operation. Secondly, one can obtain a relatively large separation in a single centrifuge: thus, the number of centrifuges required for the plant, particularly if they are of an advanced design, is less than the number of gaseous diffusion stages which would be required for this small production goal. Since centrifuges are mounted vertically and are less than one foot in diameter, they take little floor space and a small centrifuge plant can be contained in a building of modest dimensions. Due to both of these properties of centrifuge plants, such a plant would be difficult to detect, especially in an industrial country.

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* The results of this centrifuge study are presented in Report KB-789, "Small Centrifuge Plant for Producing U-235 Weapons," L. B. Emlet, Union Carbide Nuclear Company, Oak Ridge, Tennessee, December 14, 1959.

[redacted]

In this report an attempt is made to correlate the probability of some country (an n^{th} power) successfully producing a nuclear weapon by means of a clandestine program involving the construction and operation of a hidden gas centrifuge plant with the industrial capability of that country. For this purpose the countries of interest have been divided into three groups designated by X, Y, and Z. Group X countries are those which possess a relatively high degree of technological competence and which have a high level of industrial activity. West Germany and Sweden are two countries which would come under this classification. Group Z countries are those which possess relatively little technological skill and which have relatively little industrial activity. Egypt and Cuba are two of the countries in this category. Group Y countries are those which lie between and which have limited internal industrial activity. Brazil and Israel are both considered as group Y countries.

The production facility which will be considered is one capable of producing 50 kilograms per year of highly enriched U-235 which should be a sufficient amount of fissionable material for the fabrication of at least one nuclear weapon per year. The production facility may be considered as consisting of three separate processes. These are:

1. The feed plant in which the ore concentrate is converted to process gas.
2. The isotope separation plant itself in which the concentration of U-235 is raised from that of the feed (0.71 weight percent) to that required for a nuclear weapon ($>$ 90 percent).
3. The metal reduction plant in which the enriched UF_6 from the isotope separation plant is converted to uranium metal and then machined to make finished metal parts for the nuclear weapon.

Two different isotope separation plants are considered. Both are gas centrifuge plants. One plant is assumed to utilize centrifuges which experiment has shown should be operable without the necessity of further development work. These centrifuges are 3 meters in length and rotate with a peripheral velocity of 300 meters per second. The other plant is assumed to utilize centrifuges of an advanced mechanical design which are 1.1 meters in length and which rotate with a peripheral velocity of 450 meters per second. It is postulated that centrifuges of this type can be developed within three years. The sizes of the feed plant and of the metal reduction plant are not affected by the type of centrifuge in use and are the same for both cases.

Estimates are made of the total length of time necessary to construct and place in operation each of the two types of centrifuge plants in those countries categorized by X, Y, and Z. Estimates of the variations in manpower requirements and over-all costs of building a complete plant in the various countries are also presented. The special problems which are peculiar to each class of countries are discussed separately.

II. SUMMARY

It is felt that it is feasible that the countries described in this report which do not now have a nuclear weapons program could produce enriched uranium by means of a small gas centrifuge plant. A class X country would need no outside assistance. A class Y country would probably have to import some of the hardware necessary to fabricate the centrifuges and also some of the auxiliary equipment. A class Z country would probably have to purchase prefabricated centrifuges and almost all of the auxiliary equipment from foreign vendors. In addition a class Z country would need technical advisors from the outside to aid in the construction and operation of the centrifuge plant.

A summary of the over-all time, investment, and work force required for construction of the nuclear weapon facility and the cost and manpower required for its operation is presented in Table I for the X, Y, and Z nations. A detailed cost, time, and manpower breakdown of the nuclear weapon facility into its three separate processes - isotope separation plant, feed plant, and metals plant - is presented in Tables II through IV based on U. S. experience. Estimates are given both for centrifuge plants containing 300 meter-per-second and 450 meter-per-second machines. A correlation which is used to obtain factors for converting U. S. requirements into requirements of other nations is presented in Figure 5.

It can be seen that the time required to produce the first atomic weapon in an X, Y, or Z nation is about 5, 6.5, and 8 years respectively. These times may be compared with 4 years in the case of the United States. The construction of the 450 meter-per-second centrifuge plant, however, can not be undertaken prior to 1963 since it has been assumed that this advanced design will not be developed before that date.

The total capital investment which amounts to about $62,000,000 and the operating cost of about $7,000,000 per year for a 300 meter-per-second centrifuge plant in the case of a class Z country would be a burden on the economy of the country. A class Z country would have to be highly motivated to undertake such a project. However the lower construction cost of about $12,000,000 and operating cost of $2,500,000 per year in the case of a 450 meter-per-second centrifuge plant for the class Z country would make the project more feasible.

In converting the U. S. requirements for manpower into requirements for class X, Y, and Z nations the manpower conversion factor was applied to both technical and total manpower. However the proportion of technical manpower to total manpower actually may very well be different, especially for a class Z nation.

The physical concealment of the centrifuge plant should present no problems because of the relatively small size of the plant. The ground area of the 300 meter-per-second centrifuge plant is about one-half acre and the ground area of the 450 meter-per-second plant is about one-fourth acre. While the centrifuge plant might be about three stories high for conventional construction, this would not be especially noticeable in industrial areas of X and Y nations. The building height could be lowered by using a less convenient layout of the plant equipment. This may be desirable in the case of class Z countries in which a large three-story building could not be easily camouflaged. The feed and metal processing are relatively small operations which could be performed within the centrifuge separation plant.

The power requirement for the plants is very small, about 3 megawatts for the 300 meter-per-second centrifuge plant and 1 megawatt for the 450 meter-per-second centrifuge plant. The power could be easily supplied either through conventional power lines or if desired by diesel engine-generator sets which would be self-contained.

The effluents from the plant could be handled easily. The waste stream from the plant over a period of one year, which is essentially the same amount as the feed, could be stored in three 10-ton UF_6 cylinders. These cylinders are 10 feet long and 4 feet in diameter and are of standard steel construction. Thus they could be stored conveniently anywhere within the plant. The off-gases from the feed and metal plants are neutralized with caustic and easily disposed of.

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TABLE I

GAS CENTRIFUGE PLANT SUMMARY FOR CLASS X, Y, AND Z NATIONS

	Class X		Class Y		Class Z	
	300 m/sec.	450 m/sec.	300 m/sec.	450 m/sec.	300 m/sec.	450 m/sec.
Capital Investment, Dollars:						
Centrifuge plant	42,000,000	7,000,000	50,000,000	8,400,000	60,000,000	9,900,000
Feed plant	1,300,000	1,300,000	1,500,000	1,500,000	1,800,000	1,800,000
Metals plant	240,000	240,000	290,000	290,000	340,000	340,000
Total	43,540,000	8,540,000	51,790,000	10,190,000	62,140,000	13,040,000
Peak Construction Work Force:						
Total no. of men	1,300	400	1,500	500	1,800	600
Technical	66	30	78	36	93	43
Construction Manpower, Man-Months	25,000	6,000	42,000	10,000	65,000	15,000
Over-all Construction Time, Years	3.9	3.9	5.4	5.4	7.2	7.2
Operating Cost, Dollars Per Year:						
Centrifuge plant	5,900,000	1,900,000	6,200,000	2,000,000	6,400,000	2,100,000
Feed plant	300,000	300,000	320,000	320,000	330,000	330,000
Metals plant	115,000	115,000	120,000	120,000	125,000	125,000
Total	6,315,000	2,315,000	6,640,000	2,440,000	6,855,000	2,555,000

	Class X 300 m/sec.		Class X 450 m/sec.		Class Y 300 m/sec.		Class Y 450 m/sec.		Class Z 300 m/sec.		Class Z 450 m/sec.	
Operating Work Force:	Tech.	Totl	Tech.	Totl	Tech.	Totl	Tech.	Totl	Tech.	Totl	Tech.	Totl
Centrifuge plant	52	430	26	140	62	500	31	170	73	600	37	200
Feed plant	2	14	2	14	3	17	3	17	3	20	3	20
Metals plant	2	6	2	6	3	7	3	7	3	8	3	8
Total	56	450	30	160	68	524	37	194	76	626	43	228

	Class X 300 m/sec.	Class X 450 m/sec.	Class Y 300 m/sec.	Class Y 450 m/sec.	Class Z 300 m/sec.	Class Z 450 m/sec.
Time to Produce First Weapon, Years	4.9	4.9	6.4	6.4	8.2	8.2

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III. PLANT DESCRIPTIONS

Estimates of the capital investment, operating cost, time schedule, and manpower requirements for each of the processes of the production facility are presented in Tables II through V.

A. Gas Centrifuge Plant

In our previous study, KB-789, in making the estimates for the gas centrifuge plant it was assumed that a prototype of the centrifuge was available, similar to the one described as "Presently Proposed German" in Report K-1368.* This centrifuge is 300 cm. in length, 20 cm. in diameter, and has a peripheral velocity of 300 meters per second. The separative capacity of the centrifuge at an assumed 60 percent efficiency is 3.6 kilograms U per year. This machine has been developed under the direction of Dr. Groth of the University of Bonn. This machine is illustrated in Figure 1.

Recently a new centrifuge design, developed by Dr. Zippe, an Austrian, at the University of Virginia has received considerable attention. The work was done under an AEC contract and is based on previous work which Dr. Zippe performed while associated with the Russian centrifuge project. This new high-speed subcritical centrifuge is relatively very simple in design and has, to a great extent, removed the problems associated with the bearings and process gas handling. At present this machine has attained only an efficiency of approximately 20 to 30 percent. For the purpose of this report it is assumed that development work would take place over a three-year period which would result in an improved Zippe type centrifuge operating at a higher efficiency and also at a higher speed due to newly developed materials of construction. The centrifuge would be 110 cm. in length, 20 cm. in diameter, and have a peripheral velocity of 450 meters per second. The separative capacity of the centrifuge at an assumed 60 percent efficiency is 7.2 kilograms U per year. This machine is illustrated in Figure 2.

Therefore in this report two centrifuge plants have been considered: one plant containing 300 meter-per-second centrifuges which could be started in a relatively short time and the other plant containing 450 meter-per-second centrifuges which could be started three years hence. The centrifuge plant description given below is essentially the same as that previously presented for the 300 meter-per-second centrifuge plant in KB-789. In the case of the 450 meter-per-second centrifuge plant based on the Zippe type centrifuge, some of the process control and auxiliary items may not be necessary depending on future developments.

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* D. A. Hayford and S. A. Levin, "Competitive Economic Status of the Gas Centrifuge," Union Carbide Nuclear Company, Oak Ridge, Tennessee, December 19, 1957 (K-1368).

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ROTATING SYSTEM
01 Upper hollow shaft
02 Rotor
03 Lower hollow shaft
04 Drawing off nozzle
05 Motor shaft
06 Armature
07 Tachometer assembly and anchoring clamp

UPPER GAS SEAL
A Gas chamber
B Trap chamber
10 Housing of the upper gas seal
12 Gas inlet
16 Evacuation conduit
18 Oil drain

MOTOR
M Motor chamber
20 Motor base plate
21 Upper bearing
22 Stator assembly
23 Cooling jacket of the stator
24 Pressure chamber of the oil piston pivot bearing
25 Packing of the oil piston pivot bearing
26 Lower cellar bearing
27 Oil collecting main
28 Upper damping bearing
29 Detector choke of the oscillation measuring device

SAFETY CASING
D Casing chamber
30 Oil catcher
31 Safety casing
32 Cooling coil
33 Screwing ring
34 Seal ring
35 Protective lining
36 Guard ring
37 Gliding plane for anchoring clamp 38
38 Anchoring clamp for the connection of the lower gas seal with the safety casing
39 Oil collecting main

LOWER GAS SEAL
E Blocking chamber
F Gas chamber
40 Lower lid of the safety casing
41 Connection for the gas trap
43 Evacuation conduit
45 Oil drain
47 Oil drain

FOUNDATION
51 Apparatus support
52 Counter-nut of the lower gas seal
53 Concrete foundation

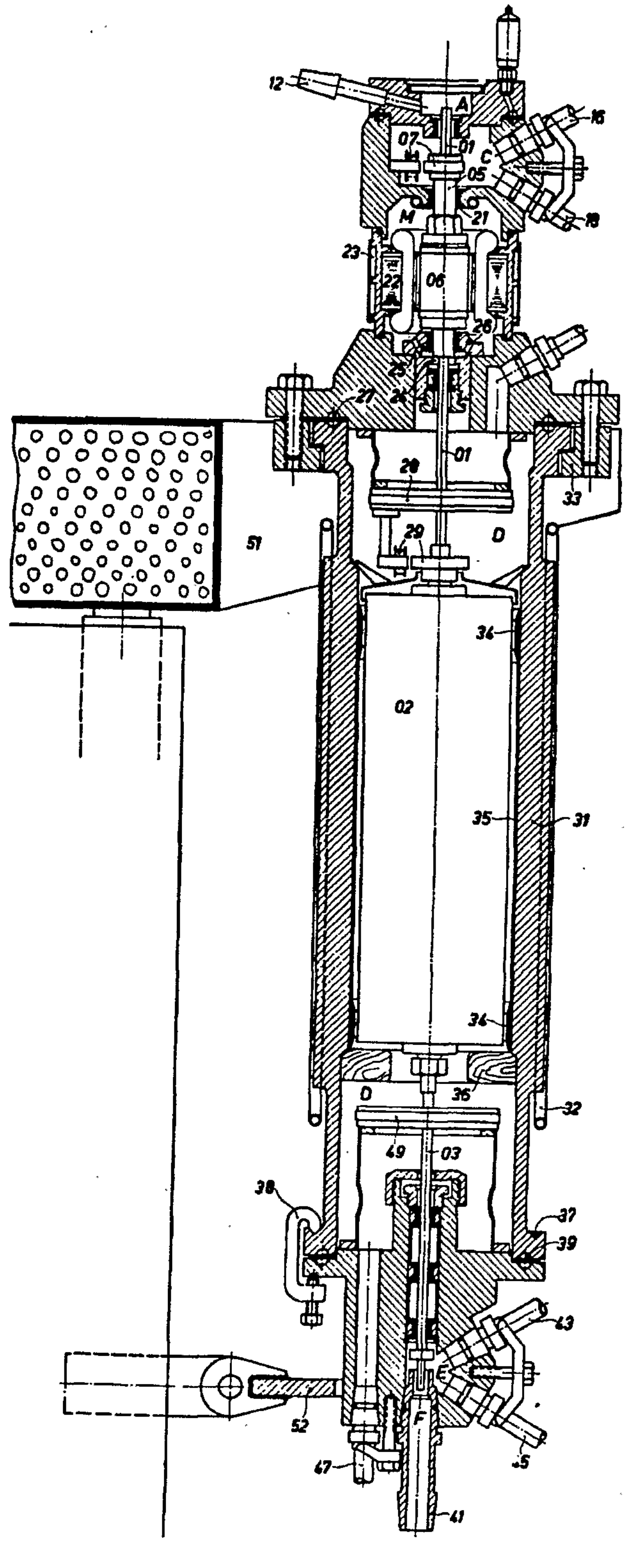

Figure 1
The Present German 300 Meter-Per-Second Gas Centrifuge

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A. Flexible steel needle

B. Upper bearing

C. Magnet mounting

D. Steel tube

E. Feed tube

F. Gas withdrawal scoop

G. Gas withdrawal scoop

H. Baffle

K. Molecular pump

L. Molecular pump

M. Electric motor

N. Armature

O. Centrifuge rotor

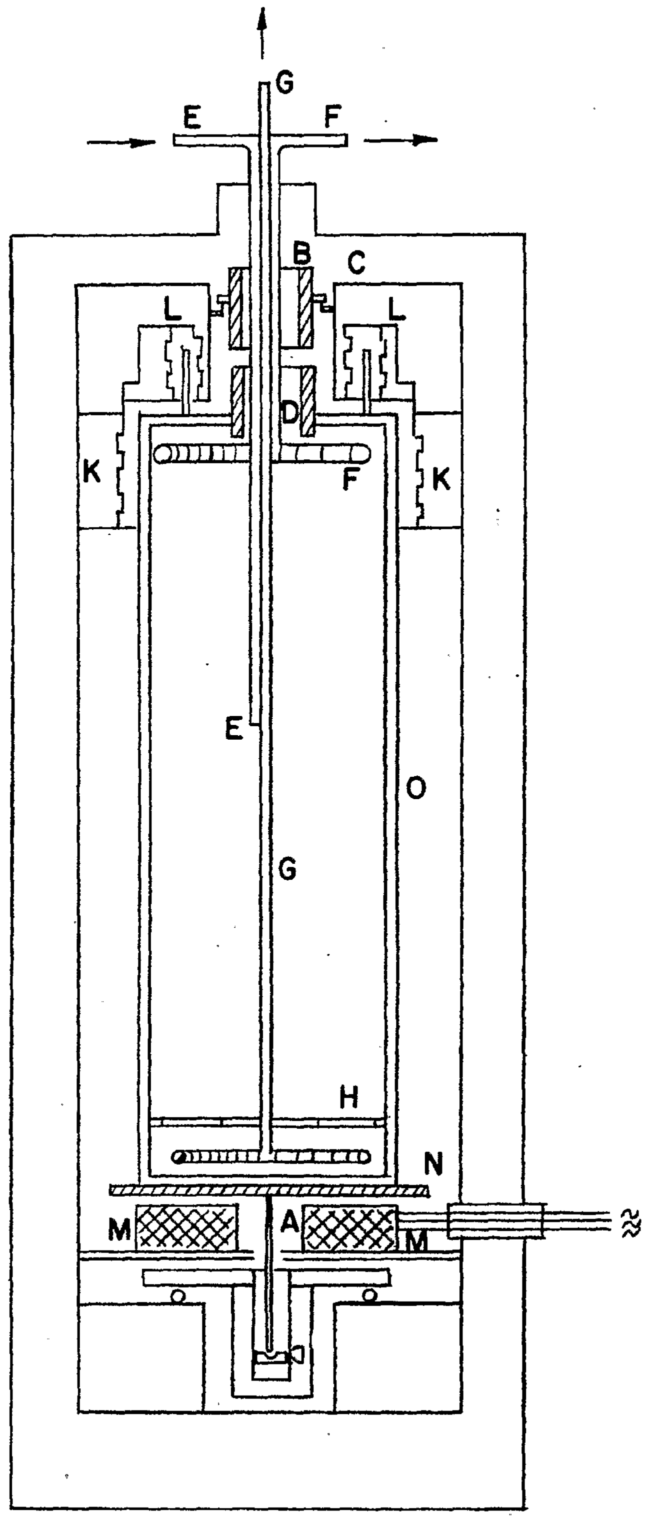

Figure 2
The 450 Meter-Per-Second Gas Centrifuge
(to be developed within three years)

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The separation in the centrifuge depends on the countercurrent flow of gas relatively near the core to gas relatively near the periphery. The centrifuges are connected in series to attain the desired enrichment and in parallel to get the desired throughput. The 300 meter-per-second centrifuge plant would require 2400 centrifuges and the 450 meter-per-second centrifuge plant would require 1200 centrifuges. Ideal plant tapers for these plants are shown in Figures 3 and 4.

The centrifuge itself consists of the following components:

(1) a drive motor

(2) a bowl and end caps

(3) bearings and shafts

(4) process gas seals

(5) vacuum jacket, blast shield, fittings, and frame.

In addition to the centrifuge itself a certain amount of auxiliary equipment, instruments, piping, and other items must be installed. These items may be divided into the following groups:

1. Electrical Equipment

Even though the operating power requirement of the process is small, about 3 megawatts for the 300 meter-per-second centrifuge plant and 1 megawatt for the 450 meter-per-second plant, the following equipment is necessary:

a. Step-down equipment, main switchgear, switchyard and switch house.

b. High frequency motor-generator sets for normal operation with the required frequency control equipment.

c. Variable frequency motor-generator sets for acceleration of the centrifuges, instrumentation for controlling the frequency, and startup control equipment.

d. Direct current motor-generator sets for braking of the centrifuges.

e. Distribution system to individual centrifuges including automatic controls for starting, operating, and stopping of each unit.

f. Distribution system for process auxiliaries.

2. Process Controls

The controls needed for the operation of the centrifuge plant are those required to maintain steady process gas flows and pressures and those required to insure reliable mechanical operation of the centrifuges as follows:

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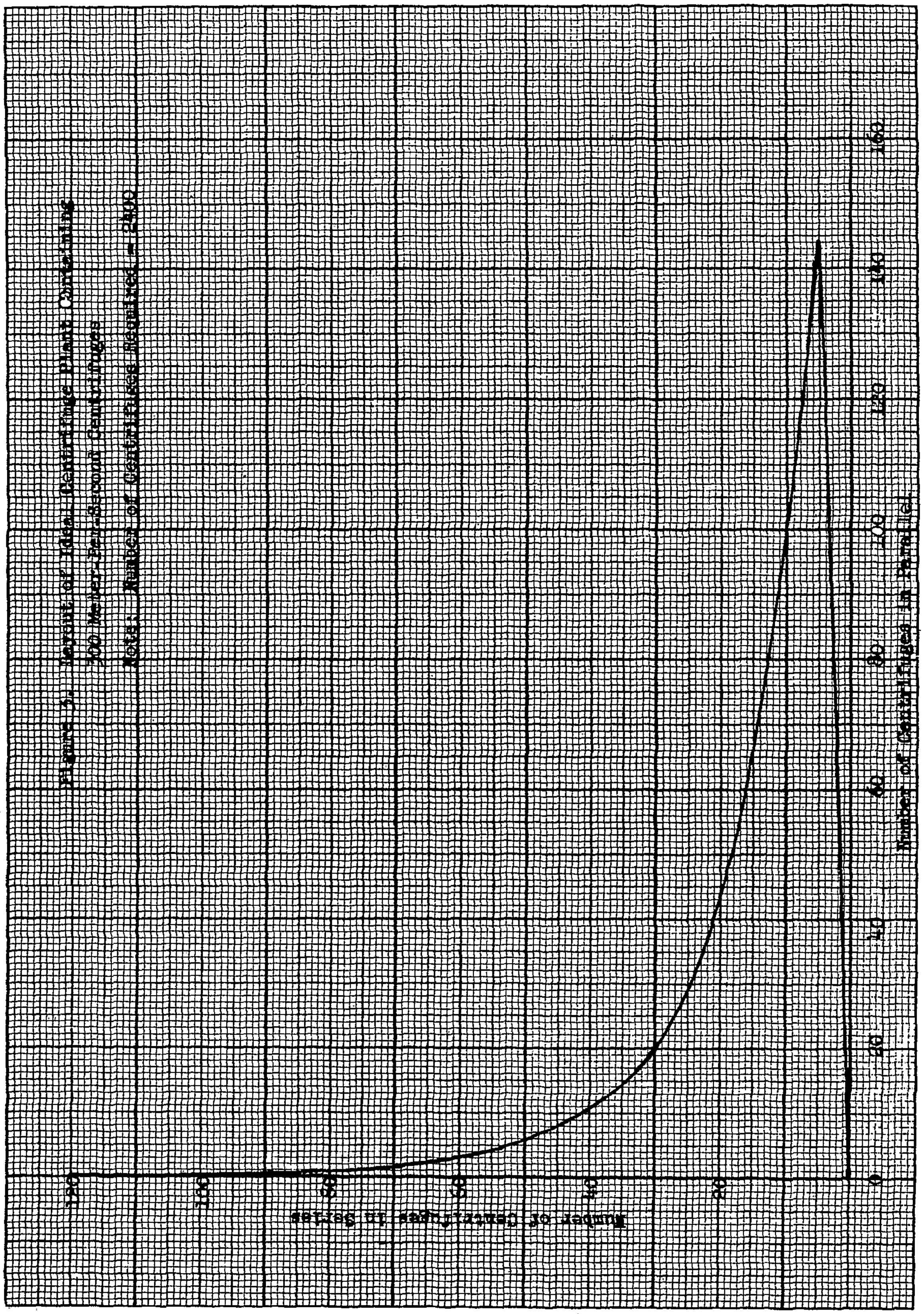

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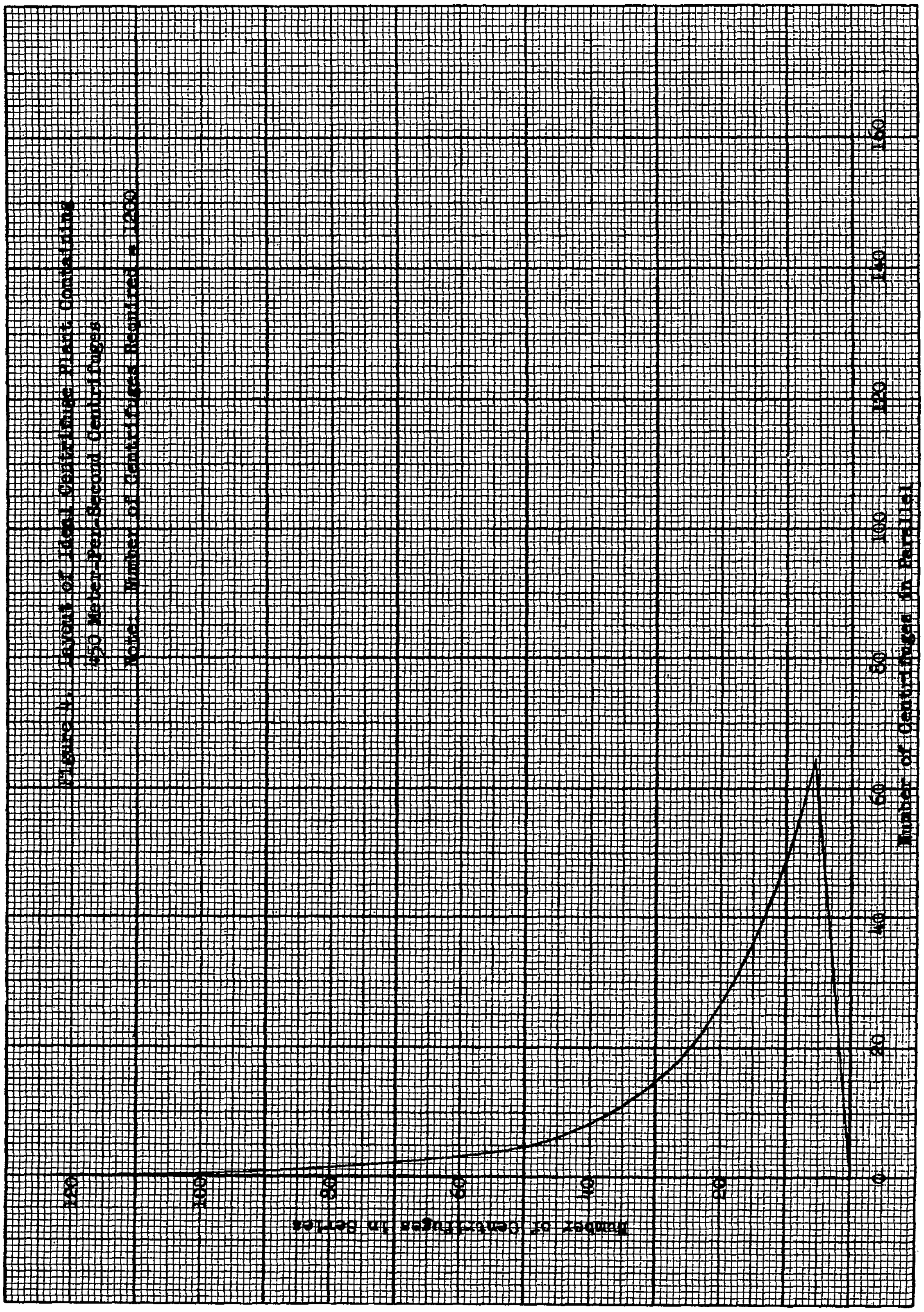

Figure 4. Layout of Ideal Centrifuge Plant Containing
450 Meter-Per-Second Centrifuges
Note: Number of Centrifuges Required = 1200

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a. Process gas flow and pressure controllers.

b. Bearing oil pressure and temperature monitors with cell shutdown controls.

c. Vibration level monitor with cell shutdown controls.

d. Process gas mass spectrometer leak detectors.

3. Uranium Hexafluoride Handling and Process Auxiliaries

a. Seal gas system

b. Casing gas system

c. Lube oil system

d. Cooling water and coolant system

e. Vacuum system

f. Process gas feed, waste and product system

g. Refrigeration system

h. Instrument air and building auxiliary systems

i. Process gas purge system

4. Process Gas Piping

The process gas piping for the centrifuge plant consists of the process gas headers and control valves, the process gas header compressor, the interheader transfer lines, the centrifuge unit-process gas lines and control valves, the by-pass headers and valves, and the heated header jackets.

5. Process Building

The centrifuge process building would be of a type similar to the gaseous diffusion plants. The building would have a floor for auxiliaries, a floor for an operational area, a floor as a pipe gallery, a main centrifuge floor and an overhead gallery for reaching the centrifuges. The 300 meter-per-second centrifuge plant would be in a four-story building with about 24,000 square feet of ground area. The 450 meter-per-second centrifuge plant would be in a three-story building with about 12,000 square feet of ground area.

6. Outside Auxiliary Systems

The outside auxiliary systems include such items as the recirculating water system and cooling tower, steam plant, maintenance shops, laboratory, etc.

Centrifuge Operating Cost. The principle items that make up the operating cost for a centrifuge plant are as follows:

(1) centrifuge and auxiliary systems direct operating labor

(2) maintenance labor and materials

(3) plant utilities cost

(4) plant overhead

B. Feed Plant

A rough optimization of the combination of plant and feed required for the 300 meter-per-second centrifuge plant resulted in a feed rate of 25 tons U per year. Since a relatively small facility is required to process this feed and since the cost of the ore concentrate is unknown, the same feed rate was used for the 450 meter-per-second centrifuge plant.

Briefly, the process can be described as follows:

The ore concentrate, assaying approximately 60 percent uranium, is treated with HNO_3 and the uranium is dissolved. The following chemical reactions occur:

$$U_3O_8 + 8\ HNO_3 \rightarrow 3\ UO_2(NO_3)_2 + 2\ NO_2 + 4\ H_2O$$

$$3\ U_3O_8 + 20\ HNO_3 \rightarrow 9\ UO_2(NO_3)_2 + 2\ NO + 10\ H_2O$$

The uranium is purified by solvent extraction using TBP in kerosene as the solvent. Extraction and stripping are accomplished in two 4-inch diameter glass columns, each approximately 20 feet in height; either agitated or pulse type columns will suit. Tankage, piping, valves, pumps, and the internal liquid contacting mechanisms of the columns are of stainless steel. The rejected aqueous nitric acid streams (raffinate) are neutralized with caustic potash and discarded. The purified uranyl nitrate solution is evaporated to remove all free water and the hexahydrate of the uranyl nitrate is calcined in an agitated vessel to produce uranium trioxide. Stainless steel equipment and process piping are required for all phases of this step. The off-gases from the calciners, which contain primarily nitrogen dioxide, oxygen, and water are piped to the waste handling area and treated with caustic potash.

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The uranium trioxide is fluorinated directly to uranium hexafluoride with elemental fluorine using a flame reactor similar to design to the enriched assay processing unit in K-1420:

$$2\ UO_3 + 6\ F_2 \rightarrow 2\ UF_6 + 3\ O_2$$

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Unreacted material is caught in an ash receiver bolted to the bottom of the tower.

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The uranium hexafluoride is separated from the product gas stream by batch cold traps mounted vertically in trichlorethylene baths. The bath liquid is cooled by coils in which Freon-22 is evaporating. The refrigeration system is a 5-ton, 2-stage (Freon 12-Freon 22) refrigeration unit. The uranium hexafluoride is transferred out of the traps as a vapor.

All items of equipment and piping in contact with uranium hexafluoride are constructed of Monel. The oxide hopper and the rotary dispersers are made of steel.

Fluorine is produced from two 6,000-ampere Monel fluorine cells and hydrogen fluoride is removed from the fluorine stream by sodium fluoride. The fluorine is compressed to 40 psig. by a Worthington piston compressor. The compressed gas is stored in a 200-cubic foot Monel tank and withdrawn as required. Fluorine piping can be of steel. Hydrogen from the generator is pumped to the waste disposal system by a rotary lobe compressor. Fluorine disposal is accomplished by means of a potassium hydroxide spray tower. Provision is also made in the fluorination system for evacuation. General decontamination facilities are also available.

C. Metal Component Facility

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DOE
4 CWI
6.2(a)

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Casting skulls will be burned to oxide, leached, extracted, and returned to wet chemistry for precipitation. Machining chips will be briquetted and recycled to reduction. All massive metal will be returned to casting. The wet chemistry and reduction salvage will be discarded.

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TABLE II

300 METER-PER-SECOND GAS CENTRIFUGE PLANT

(U. S. Experience)

Capital Costs	
Centrifuges, installed	$14,304,000
Piping	2,400,000
Instrumentation and controls	5,400,000
Electrical system	816,000
Process auxiliaries	4,200,000
Utilities	480,000
Building	1,200,000
Direct construction costs	$28,800,000
Engineering, design and inspection	2,200,000
Indirect construction costs	5,000,000
Total	$36,000,000

Construction Manpower and Scheduling	
	Men
Peak Manpower:	
Engineering	50
Non manual	150
Manual	800
	Man-Months
Total Manpower:	
Engineering	900
Non manual	3,000
Manual	11,000
Time Required:	3 years

Operating Manpower and Costs, Dollars Per Year		
Direct operating labor (96)	at $3/hr.	$ 576,000
Maintenance labor (200)	at $3/hr.	1,200,000
Auxiliary systems labor (12)	at $3/hr.	72,000
Direct labor		$1,848,000
Overhead		1,848,000
Works laboratory technician, 8 at $3/hr.		48,000
Technical supervision, 24 at $6/hr.		288,000
Technical and scientific staff, 20 at $6/hr.		240,000
Total labor		$4,272,000
Maintenance material		1,200,000
Utilities and auxiliary system material		120,000
Power, 2400 kw at 5 mills/kw		105,120
Total material		$1,425,120
Total		$5,697,120

1250
570
1820

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TABLE III

450 METER-PER-SECOND GAS CENTRIFUGE PLANT

(U. S. Experience)

Capital Costs

Centrifuges, installed	$2,200,000
Piping	500,000
Instrumentation and controls	990,000
Electric system	110,000
Process auxiliaries	230,000
Utilities	70,000
Building	430,000
Direct construction costs	$4,530,000
Engineering, design and inspection	400,000
Indirect construction costs	960,000
Total	$5,970,000

Construction Manpower and Scheduling

	Men
Peak Manpower:	
Engineering	20
Non manual	60
Manual	200
	Man-Months
Total Manpower:	
Engineering	400
Non manual	800
Manual	2,000
Time Required:	3 years

Operating Manpower and Costs, Dollars Per Year

Direct operating labor (32)	at $3/hr.	$ 192,000
Maintenance labor (60)	at $3/hr.	360,000
Auxiliary systems labor (4)	at $3/hr.	24,000
Direct labor		$ 576,000
Overhead		576,000
Works laboratory technician, 4 at $3/hr.		24,000
Technical supervision, 12 at $6/hr.		144,000
Technical and scientific staff, 10 at $6/hr.		120,000
Total labor		$1,440,000
Maintenance material		300,000
Utilities and auxiliary system material		40,000
Power, 1200 kw at 5 mills/kw		53,000
Total material		393,000
Total		$1,833,000

100
183
283

72 x 365

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TABLE IV

FEED PLANT

(U. S. Experience)

Capital Costs

Installed Equipment:	
Dissolver	$ 5,600
Extraction columns	38,500
Evaporator and calciner	28,000
Fluorinator	42,000
Fluorine system	112,000
Auxiliary chemistry systems	51,800
	$ 277,900
Piping	126,500
Instrumentation	45,900
Utilities	30,000
Maintenance facility	20,000
Administrative, laboratory	25,000
Building	250,000
Direct construction costs	$ 775,000
Engineering, design and inspection	100,000
Indirect construction costs	215,300
Total	$1,090,600

Construction Manpower and Scheduling

	Men
Peak Manpower:	
Engineering	6
Non manual	8
Manual	45
	Man-Months
Total Manpower:	
Engineering	108
Non manual	144
Manual	360
Time Required:	18 months

Operating Manpower and Costs, Dollars Per Year (40-Hour Week Operation)

Labor:

6 chemical operators, 2 maintenance, 1 laboratory technician, 1 clerk	at $3/hr.	$ 60,000
2 supervisors at $6/hr.		24,000
		$ 84,000

TABLE IV (CONTINUED)

Operating Manpower and Costs, Dollars Per Year (40-Hour Week Operation) (continued)

Overhead	$ 84,000
Chemicals	90,520
Maintenance materials	17,520
Other materials	4,380
Utilities	9,490
Total	$289,910

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TABLE V

METAL COMPONENT FACILITY
(U. S. Experience)

Capital Costs

Installed Equipment:	
Wet chemistry process	$ 33,000
Reduction bombs	3,000
Casting equipment	26,000
Machining and testing facility	28,000
	$ 90,000
Piping	10,000
Instrumentation	2,000
Utilities	22,000
Building	24,000
Direct construction costs	$148,000
Engineering, design and inspection	20,000
Indirect construction	34,000
Total	$202,000

Construction Manpower and Scheduling

	Men
Peak Manpower:	
Engineering	2
Non manual	1
Manual	4
	Man-Months
Total Manpower:	
Engineering	18
Non manual	18
Manual	48
Time Required:	12 months

Operating Manpower and Costs, Dollars Per Year (40-Hour Week Operation)

Labor:		
2 operators, 1 maintenance	at $3/hr.	$ 18,000
1 engineer, 1 supervisor	at $6/hr.	24,000
		$ 42,000
Overhead		42,000
Materials		25,000
Total		$109,000

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IV. DISCUSSION

A. Feasibility of Clandestine Operation

As indicated above, any nation in groups X, Y, and Z could, if sufficiently motivated, build a gas centrifuge plant which would produce sufficient fissionable material for the construction of a nuclear weapon.

A class X country could build a clandestine cascade containing either the presently developed 300 meter-per-second centrifuge or containing centrifuges of the advanced design with no outside assistance and with little drain on its economy. A class X country may be seen to have several large universities. In general, all have conducted research of varying description pertaining to problems in isotope separation. It appears quite evident that any type X country has the experienced scientists and engineers necessary to bring a centrifuge plant into successful operation. Similarly a class X country would have no problem in obtaining the services of skilled machinists for constructing the centrifuges nor in recruiting trained operators and maintenance men for running the plant. The special materials required for the construction of the isotope separation plant and related facilities would most likely be readily available in a class X country or, if not, could be purchased without arousing any suspicion, due to the high level of domestic industrial activity. For example, mass spectrometers, if needed, could be purchased by a class X country, say, through a university, for its research departments without inviting attention. Furthermore, the countries in this category already have, or may be expected in the very near future to have, nuclear power programs. Thus these countries will, therefore, have a valid requirement for uranium ore. It would not be possible to detect the small diversion of uranium necessary to provide feed to a small isotope separation cascade under these circumstances

A class Y country may be characterized as a country which possesses technological competence, but which has limited industrial activity. A class Y country could not build a centrifuge plant without some outside assistance; however, it could probably adequately disguise the nature of its activities from the outside world. A class Y country may be assumed to have a sufficient number of scientists and engineers to bring a centrifuge to successful completion. Since these men may lack specific experience of this nature, it may be assumed that it would take appreciably longer for a class Y country to achieve successful operation than a class X country would require. A class Y country would have some difficulty in recruiting the skilled machinists, operators, and maintenance men necessary to construct and operate the isotope separation plant. A class Y country would in all likelihood have to import much of the hardware necessary to fabricate the centrifuges and also some of the auxiliary equipment required for the plant. The material of construction of the centrifuge bowl would probably have to be imported. However, since further machining could be done after delivery, the use to which this material is to be put may not be evident. A class Y country would probably also have to import seals and bearings, motor-generator sets for high frequency current, process control equipment, mass spectrometers, and perhaps other items of specialized nature. These orders could be distributed among a large number of vendors, in order to prevent detection of the construction effort. Class Y countries may well have access to uranium ore either by virtue of a domestic nuclear power program or their own natural resources. If not, they would have to procure it elsewhere and this may provide a method of detection. There are, however, many countries able to export uranium ore and one should remember that 25 tons is a relatively small quantity of ore.

A class Z country would find the construction and operation of a centrifuge plant a difficult task. Such a plant would be a burden on the economy of a class Z country, but not so much as to prevent the country from undertaking the project. A class Z country would need a great deal of outside assistance both in manpower and in material in order to bring a centrifuge plant to successful completion. Countries in this category would probably need technical advisors from abroad, competent scientists and engineers, to aid in the development of an operable separation cascade. Operators and maintenance men would have to be trained for their particular jobs. A class Z country would probably not have sufficient skilled machinists to fabricate the centrifuges. It would be expected, therefore, that a type Z country would purchase prefabricated centrifuges. Their alternative would be to train the necessary machinists and to purchase the lathes, drill presses, and other shop equipment which would be required for centrifuge manufacture. In addition to the centrifuges, almost all of the auxiliary equipment required for the plant would have to be purchased from foreign vendors. The power requirement of the centrifuge plant which was of little importance in the case of class X and Y countries would be an appreciable percentage (2 to 5 percent) of the electrical power usage in a typical class Z country. Furthermore, the plant itself, which would occupy about one-half acre of ground would probably be somewhat more difficult to hide in a nonindustrial country. In short, it appears that a class Z country could not build a completely clandestine nuclear weapons facility. It could, however, with the collaboration of a class X country, build such a plant but even then it would have much more difficulty in hiding it than would an X or Y country.

B. Development Time

Although it has been assumed in this report that a 300 meter-per-second centrifuge has passed through the development stage and is currently operable, it is important to point out that this assumption should not be interpreted to mean that a cascade of such centrifuges is currently operable. Up to the present time there has been no indication that anyone has successfully run even two interconnected centrifuges, much less anything approaching a useful isotope separation cascade. It has been assumed that any country desiring to build a centrifuge cascade would, if necessary, first purchase a prototype centrifuge. The class X and Y countries could then duplicate this prototype and only a minimum of development effort on the centrifuge itself would be required. The time required for the development of the centrifuge plant refers therefore to the time required to solve the problems encountered when one attempts to connect large numbers of centrifuges together and run them in the series-parallel arrangement which constitutes the separation cascade. These problems are primarily those of plant design and process control.

The development of a successful 450 meter-per-second centrifuge depends to a large extent on the development of a suitable material of construction for the centrifuge bowl capable of withstanding the higher peripheral speed. It is felt that a development program of this nature would be carried out only in a class X country. It has been postulated that three years would be required for a class X country to achieve this goal. Thus Y and Z countries will achieve 450 meter-per-second centrifuges only after they have been developed by a class X country and then only if they can obtain either the centrifuges or the material for their construction from a class X country.

C. Process Controls

At the present time there is no reliable information about what a centrifuge separation plant control system should be like. There is no data from an experimental cascade and no particular theoretical studies on this problem. A centrifuge plant can be made hydrodynamically stable in the same sense as a gaseous diffusion plant. For instance a slight change in speed of all the centrifuges would result in a large surge of process gas that would have to be removed by proper controls on groups of centrifuges in parallel. Future developments will have to determine whether the variations in the flows and inventories between individual centrifuges are harmful enough to make it desirable to add additional controls. These variations between individual centrifuges would result in a loss in the plant separative capacity.

The amount of control that should be included in a centrifuge plant would be determined, ideally, by an economic balance between the cost of additional controls and the value of the lost production. A centrifuge plant to produce weapons should be conservatively designed because of the high value of production (that is, bombs).

D. Operation and Maintenance

Because of the lack of knowledge regarding the reliability of the centrifuge over extended periods of operation a really meaningful estimate of operating and maintenance requirements is impossible. The operating labor is determined more by the necessity of the available staff being able to handle "abnormal" periods of trouble rather than normal periods of quiet operation. Until reliable operating data is available it would be advisable to allow for an adequate staff of operators and perhaps later it may be reduced. Similar considerations apply to maintenance.

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E. Centrifuge Manufacturing Plant

It has been assumed that the development program resulting in the construction and testing of a prototype centrifuge is essentially complete at present in the case of a 300 meter-per-second centrifuge and will be complete three years hence in the case of a 450 meter-per second centrifuge. After the prototype design is accepted, manufacturing and inspecting procedures would have to be determined. A few machines may be made as pre-production models at a higher-than-production unit cost in order to test manufacturing procedures.

Construction of a centrifuge manufacturing plant would have to be started concurrent with that of the centrifuge separation plant. Desirably, the centrifuge manufacturing plant would be finished in time to coordinate the manufacture of the first production centrifuges with the installation of centrifuges which would start about midway in the construction period of the centrifuge separation plant. The rather extensive manufacturing facilities required would, in general, have little future economic value and would have to be changed against the centrifuge. This additional cost increases the basic centrifuge cost by 25 percent.

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V. CORRELATION OF INDUSTRIAL CAPABILITY OF NATIONS

To estimate the order in which the various nations can be expected to achieve an isotope separation process and the time required for this accomplishment, it is necessary to choose some feature or features of a nation's economy which are indicative of that nation's industrial competence.

The two such features which reflect all areas of modern industrial activity are the consumption of electrical energy and the consumption of steel. Furthermore the per capita value of these quantities provides a measure of the level or relative effectiveness of application of a nation's industry, since per capita consumption is itself an empirical statement of demonstrated effectiveness.

Accordingly, the following quantities were defined:

$$\text{Relative Industrial Size, S} = \sqrt{\frac{\text{Steel Consumption}}{\text{U. S. Steel Consumption}} \cdot \frac{\text{Electrical Energy Consumption}}{\text{U. S. Elec. Energy Consumption}}}$$

$$\text{Relative Industrial Level, L} = \sqrt{\frac{\text{Per Capita Steel Consumption}}{\text{U. S. Per Capita Steel Consumption}} \cdot \frac{\text{Per Capita Electric Energy Consumption}}{\text{U. S. Per Capita Elec. Energy Consumption}}}$$

$$\text{Relative Industrial Capability} = \sqrt{S \cdot L} \; .$$

The Relative Industrial Capability (RIC) was then related to actual time, cost, and manpower requirements by correlating the industrial experience of nations for which such data were available with the computed RIC's of those nations.

The results of the correlations are shown in Figure 5, in which factors for converting U. S. requirements into the requirements of other nations are shown for man-months required for building a plant, the time which will elapse between inception and end of construction, the number of men engaged in construction or operation of the plant (applicable to peak work force in the case of construction), the construction or capital cost, and the annual operating cost. In each case an estimate made for the U. S. may be multiplied by the appropriate factor of Figure 5 to obtain the corresponding estimate for a nation for which the RIC has been computed.

The RIC was computed for a variety of nations and these are located on Figure 5. Also shown are the zones which define the X, Y, and Z categories of nations referred to in this report.

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Statistical data used in computing the RIC was obtained from "Statistical Abstract of the United States"* which contains international statistical data drawn chiefly from the United Nations Statistical Office. This agency's annual publication, "Statistical Yearbook" provides a wide variety of detailed statistical data.

ACKNOWLEDGMENT

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* U. S. Department of Commerce, Bureau of the Census, "Statistical Abstract of the United States," 79th annual edition, U. S. Government Printing Office (1958).

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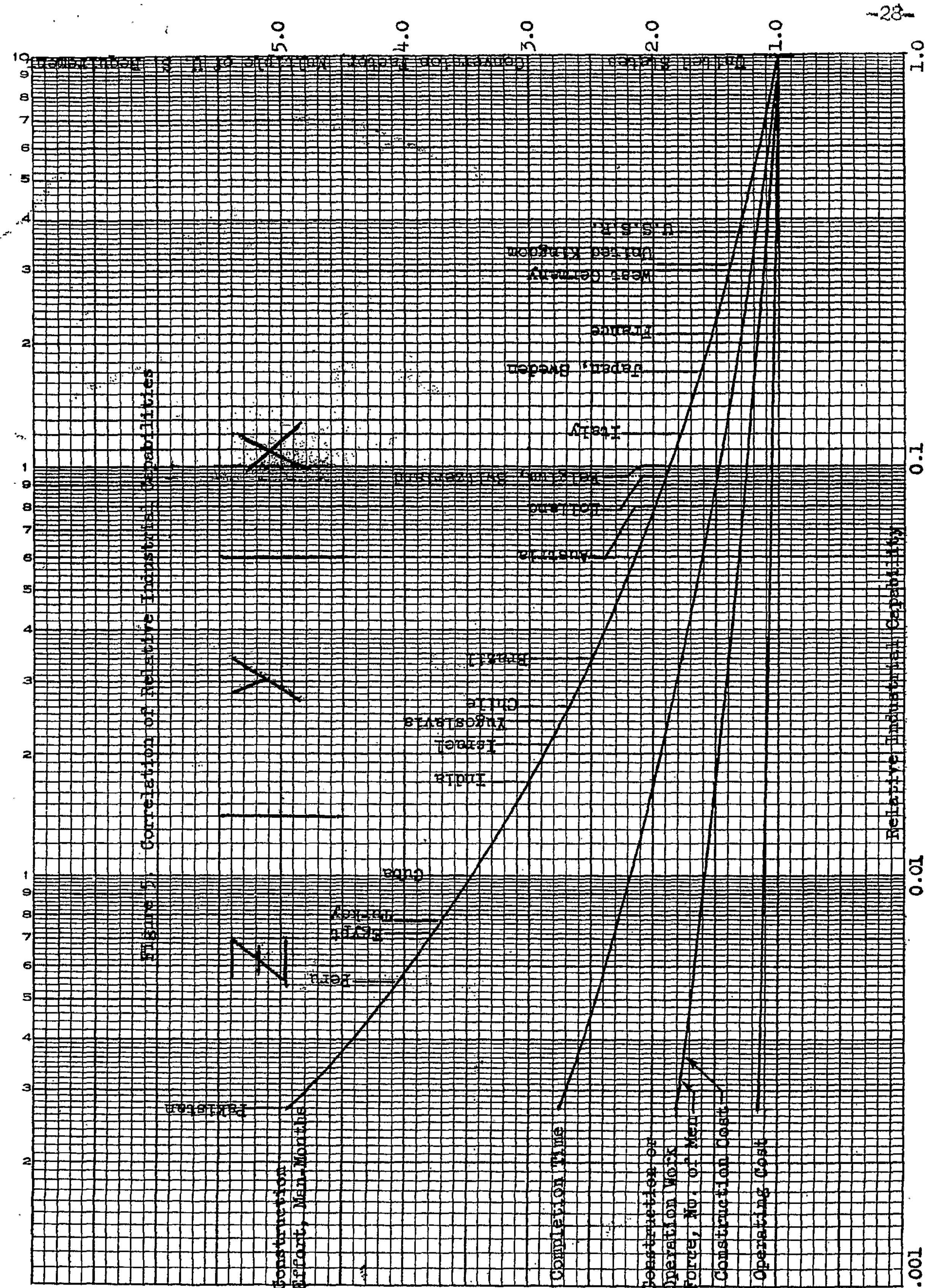

Figure 5. Correlation of Relative Industrial Capabilities

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