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UNITED STATES ATOMIC ENERGY COMMISSION

APPLICABILITY OF GAS CENTRIFUGE TO
ISOTOPE SEPARATION FOR ELEMENTS
HEAVIER THAN TITANIUM

By
J. J. Barker

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September 30, 1956

Walter Kidde Nuclear Laboratories, Inc.
Garden City, New York

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NYO-7348

Walter Kidde Nuclear Laboratories, Inc.,
975 Stewart Avenue
Garden City, New York

APPLICABILITY OF GAS CENTRIFUGE TO ISOTOPE SEPARATION

FOR

ELEMENTS HEAVIER THAN TITANIUM

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Classification cancelled (or changed to) *Memorandum for Declassification Branch*
by authority of *dated 10-27-59 & 2-1-60*

Prepared by

by *J. J. Barker* Approved by TISOR, date *2/12/60*

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Final Report on Task VI-A
Contract No. AT(30-1)-1374
with the
United States Atomic Energy Commission

September 30, 1956

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by *J. J. Barker* TIE, date *11/3/59*

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FOREWORD

Since early 1953 Walter Kidde Nuclear Laboratories, under Contract No. AT(30-1)-1374 with the United States Atomic Energy Commission, has been studying the application of high-speed gas-centrifuges to the separation of isotopes. Previous reports on this program are:

- NYO-3925 (WKNL-21), Interim Report on Centrifuge Study, G.B. Webb, Dec. 15, 1953.
- NYO-3928 (WKNL-38), Gas Centrifuge Economics, G. B. Webb, Aug. 6, 1954. Supplement - Recovery of Plutonium from Power Plant Waste, G. B. Webb, Sept. 21, 1954.
- NYO-3929 (WKNL-44), Quarterly Progress Report Jan. 1 - March 31, 1955, G. B. Webb, April 11, 1955.
- NYO-3930 (WKNL-45), Report on Trip to West Germany and France, April 2-19, 1955, Part I, K. Cohen, May 26, 1955.
- NYO-3931 (WKNL-47), Report on Trip to West Germany and France, April 2-19, 1955, Parts II and III, K. Cohen, Sept. 13, 1955.
- NYO-3932 (WKNL-48), Report on Isotope Developments in Europe, K. Cohen, Sept. 20, 1955.
- NYO-7347 (WKNL-60), Design and Cost Estimate for a Flexible Plant with Ten Long-Bowl Gas-Centrifuges, J. J. Barker May 18, 1956.

The present document is the final report on Task VI-A, under Contract Modification No. 13, and completes the work on this contract.

The scope of Task VI-A is defined in a letter from K. Cohen to Dr. George A. Kolstad, Chief of the Physics and Mathematics Branch of the Division of Research, dated January 19, 1955, which is incorporated as Modification No. 3 to Appendix B of the contract, dated as of January 1, 1955. This scope is:

"A. Construction and Testing of Prototype Machine:

1. Determine process specifications; bowl dimensions; seal clearance, pump diameter, material corrosion requirements; speed, shaft size, end-cap heat transfer and flow slots, temperature control.
2. Liaison during mechanical design, construction and testing.

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B. Experimental Cascade:

1. Listing and analysis of possible isotope mixtures.
2. Determination of optimum centrifuge and cascade parameters for each case.
3. Layout of experimental centrifuge cascade which will permit as close approximation as possible to each case by minor alterations; e.g., altered hookup, pressure, temperature, etc.
4. Engineering design and cost estimate for pilot plant.

C. Multicomponent mixture separation theory.

D. General liaison with the Commission, University of Virginia, and Argonne National Laboratory on other phases of program: high L/D centrifuge, chemistry of plutonium".

Most of the effort for Task VI-A was required under Item B, above, and the bulk of the present report accordingly deals with this portion of the work. The disposition of the remaining items is given in the following paragraph.

For item A, visits were made to the General Electric Company, Westinghouse Electric Corporation, Sharples Corporation, and Sperry Gyroscope Company to acquaint them with the problem and to ascertain their interest in building and testing centrifuges. Specifications for the machines to be built were determined and a draft of an invitation for proposals from the manufacturers (to be solicited by the Government) was prepared. General liaison was maintained with these manufacturers while they were preparing their proposals. The job did not reach the design stage, and therefore further liaison was unnecessary. For item C, following literature searches for information on the subject of multicomponent separation theory, a recommendation was made that the development of a theory could be accomplished most economically at a university. Item D involved various trips, letters, telephone calls, meetings and other efforts to keep abreast of developments during the period of this work.

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SUMMARY

This report examines the applicability of the gas centrifuge to the separation of the isotopes of the elements from titanium through uranium. The suitable elements are determined and their effects on required centrifuge characteristics are surveyed. The performance of cascades of various sizes with different gases is explored and the cost of a pilot-plant program to develop basic separation data is estimated.

Only 15 of the 71 elements from titanium through uranium appear to be suitable to separation by the gas-centrifuge: titanium, chromium, zinc, germanium, selenium, molybdenum, cadmium, tin, tellurium, xenon, tungsten, mercury, thallium, lead, and uranium. The breakdown of the unsuitable elements is as follows: 21 with no volatile compounds; 18 with only one isotope; 9 with only radioactive elements; 8 with no apparent utility. Presumably these limitations apply to the gaseous-diffusion method of isotope separation as well, but the elements with no volatile compounds might be separable by other methods. All of these elements have four or more stable isotopes, excepting thallium and uranium, each of which has two main isotopes. Data are lacking on the physical properties of most of the compounds that would be used.

Regardless of the gas being processed, weight flow rates through a given centrifuge tend to be about the same and axial pressures are approximately inversely proportional to the molecular weight of the gas. Desired flow rates can be obtained by adjusting the inventory of the centrifuge, since the volumetric pumping rate stays constant. Figure 2.1 shows the flow pattern through a centrifuge in a cascade and Figure 2.2 shows how the flow rate varies with axial pressure. A sealing system that is adequate for uranium hexafluoride will be satisfactory, with minor changes, for any other gas. Compression in the end-caps must be as nearly isothermal as possible, to minimize separation inefficiencies from radial flow, which increase with molecular weight, ratio of specific heats and speed of rotation.

Vibration at critical speeds is the major problem in the design of the centrifuge. Balancing techniques perfected by the large turbine manufacturers should prove useful in the manufacture of long-bowl centrifuges. Gas bearings along the bowl may contribute significantly to the successful operation of a slender bowl, but considerable development would be necessary to establish a workable design and to define power requirements, tendency to flutter, and effects on separation performance. The drive for the centrifuge is no problem; induction motors of small and large capacity are operable at speeds up to 120,000 RPM at present. Movable or intermittent bearings may be useful in bringing the rotor through its critical speeds, but experiments are necessary to establish their utility.

A given centrifuge cascade appears to be efficiently operable with any gas that is compatible with its materials of construction, chiefly because the process piping is small and easily rearranged. A plant with 10 long-bowl centrifuges similar to those used during the war could produce

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uranium enriched sufficiently (3.4 mol per cent U-235) to form a critical lattice with ordinary water, but about 50 years would be required to produce enough uranium. A 25-machine plant could do this in 14 years. A 100-machine plant could produce the fuel loading of a Geneva Reactor in about 3 years. A small nation that wanted an independent source of enriched uranium might find such a plant of interest.

Monochlorotrifluoromethane, manufactured by DuPont and sold under the trade name "Freon-13" would be an excellent test gas for a centrifuge pilot plant. Other "Freons" could be used to study the effects of molecular weight or to obtain the bromine isotopes.

Stiff-rotor centrifuges manufactured in Germany by Sartorius-Werke could be used to obtain accurate separation data while American industry focused its efforts on development of a reliable long-bowl machine. A pilot plant program involving 6 stiff-rotor machines 0.75 meter long plus 3 machines 1.2 meters long, and a staff of ten people to design, procure, construct and operate the plant over a period of 2.5 years would cost about \$750,000.

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INTRODUCTION

Centrifugation of gases was first suggested as a method of isotope separation in 1919, but the process was not successfully demonstrated until 1939, when Beams and Skarstrom changed the abundance ratio of the chlorine isotopes with an evaporative centrifuge (1)*. During World War II, development work on countercurrent gas centrifuges for the separation of U-235 from U-238 was carried out at Columbia University, the University of Virginia, Westinghouse Research Laboratories, and the Standard Oil Development Co. (1, 2). Before terminating this work early in 1944 in favor of the gaseous-diffusion method of separation, feasibility of the countercurrent method had been demonstrated with a number of short-bowl machines, with a research-model long-bowl machine, and with a commercial-model long-bowl machine. Nothing further was done in this country until 1953, when the current series of studies was started with investigations of the suitability and economics of the countercurrent centrifuge method to the separation of Pu-240 from Pu-239, of U-236 from U-235, and of U-235 from U-238. These studies indicated that the centrifuge method might show important cost advantages for the heavier elements and that a thorough review of the potentialities of the method was in order. Consequently, the studies reported here, which examine the applicability of the centrifuge method to the elements with atomic number greater than 20, were undertaken.

The present report has four chapters. Chapter 1 establishes the elements to which the centrifuge method is most applicable. Chapter 2 describes the studies on the design of the centrifuge itself to determine the effects of operation with various gases on the performance of the machine. Chapter 3 reviews plant versatility and examines the performance of plants of various sizes on two separations of interest. Chapter 4 presents a design and cost estimate for a pilot plant that would use stiff-rotor machines of German manufacture as an interim approach until long-bowl American machines could be procured.

Most of the work reported here is based on the use of a long-bowl type centrifuge similar to that tested during the war. Many of the calculations consider operation at higher speeds than were thought possible during the war. Table i gives the centrifuge specifications used as the basis for most of the calculations in this series of studies. For a description of the various types of centrifuges, see references (1) and (2).

* Numbers in parentheses refer to bibliography.

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Table 1

Centrifuge Specifications (1)

	<u>Wartime</u>	<u>Present</u>
Bowl Length, Inches (Inside)	126	126
Bowl Diameter, Inches (Inside)	7.2	7.2
Rotational Speed, RPS	470	520
Peripheral Speed, cm/sec	27,000	30,000
Axial Pressure, mm Hg	8	4
Gas Temperature, °C	75	75
Separative Power, gm mol UF ₆ /day	0.0285	0.0435
Gas Holdup per Centrifuge, gm UF ₆	220	226
Power Requirement, KW	5	6.2
Lubricating and Cooling Oil, gal/hr	50	62.5
Casing Water Circulation, gal/hr	100	125
Cooling Water, gal/hr	30	37
Seal Nitrogen, SCF/day	6	4
Casing Hydrogen, SCF/day	17	17
Vacuum Exhaust, CFM	2.6 (6 mm Hg)	4.8 (3 mm Hg)

- (1) For use with UF₆. See reference (2) (NNES-X-1) for description of wartime machine. See Table 2.6 for additional specifications.

Corrosion has not been considered in detail, because of the specific nature of this problem. However, materials that are capable of resisting uranium hexafluoride would probably be satisfactory for most other process gases. If a particular gas should be incompatible with the bowl material (which is the critical item), it has been assumed that suitable inserts or coatings could be used to protect the surface of the bowl. Other items in contact with process gas are not subject to the high centrifugal stress that is an added complication in the case of the bowl material, and therefore these materials can be selected on the basis of optimum corrosion resistance, if necessary. Process piping, for example, is small enough so that it could be made of highly resistant alloys and still not represent a significant portion of the investment in a cascade of centrifuges.

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Chapter 1

ISOTOPES AMENABLE TO CENTRIFUGAL SEPARATION

A preliminary survey (3) of operating conditions and costs for various separations indicated that the isotopes of a dozen or so elements might be economically obtained by a cascade of countercurrent centrifuges. These results stimulated interest in the more thorough survey described in the present report. Chapter 1 covers the following phases of the survey: the elements suitable to the centrifuge process; the compounds to be used as the feed materials; and the operating conditions for a representative group of the suitable elements.

Suitable Elements

Table 1.1 lists all the elements considered; they range from titanium (atomic number 22) to uranium (number 92)(4). The isotopes of elements below atomic number 22 can be separated more easily by other means (such as chemical exchange). For those elements for which isotope separation by the centrifuge appears practical, the most suitable compound, together with its normal boiling point, is listed under the heading "Practical". Unsuitable elements have the reason for their rejection listed in the column marked "Rejected".

Elements were rejected for any of the following reasons:

1. The element occurs in nature either as a single isotope, or, if more than one isotope exists, the isotopic abundance of all but one is so small as to render separation impractical. These elements are marked "s.i.".
2. No advantage can be realized in separating the isotopes of an element, considering such reactor applications as structural components and fuel element constituents. Elements were rejected whose naturally occurring isotopes all had thermal-neutron absorption cross-sections of equal magnitude, or whose products (produced in neutron-capture processes in a reactor) have short half-lives. Also rejected were elements where no utility exists in reactor technology. The notation for this category is "n.u.".
3. No compound of sufficient volatility could be found. Only compounds whose normal boiling point is below 200°C and whose vapor is sufficiently stable were considered. Where more than one volatile compound exists, the one with the lowest boiling point and/or the simplest molecule was chosen. These elements are marked "n.v.c.".
4. The isotopes of the element are radioactive. Such elements are designated by the symbol "r".

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Table 1.1

Element			Practical for Centrifugal Separation			Element			Practical for Centrifugal Separation		
Atomic No.	Name	Symbol	Recommended Compound	B.P. °C	Rejected ⁽¹⁾	Atomic No.	Name	Symbol	Recommended Compound	B.P. °C	Rejected ⁽¹⁾
22	Titanium	Ti	TiCl ₄	136.4		57	Lanthanum	La			s.i.
23	Vanadium	V			s.i.	58	Cerium	Ce			n.v.c.
24	Chromium	Cr	Cr ₂ O ₃ Cl ₂	117		59	Praseodymium	Pr			s.i.
25	Manganese	Mn			s.i.	60	Neodymium	Nd			n.v.c.
26	Iron	Fe			n.v.c.	61	Promethium	Pm			r.
27	Cobalt	Co			s.i.	62	Samarium	Sm			n.v.c.
28	Nickel	Ni			n.u.	63	Europium	Eu			n.v.c.
29	Copper	Cu			n.v.c.	64	Gadolinium	Gd			n.v.c.
30	Zinc	Zn	Zn(CH ₃) ₂	46		65	Terbium	Tb			s.i.
31	Gallium	Ga			n.u.	66	Dysprosium	Dy			n.v.c.
32	Germanium	Ge	GeH ₄	-90.1		67	Holmium	Ho			s.i.
33	Arsenic	As			s.i.	68	Erbium	Er			n.v.c.
34	Selenium	Se	SeH ₂	-42		69	Thulium	Tm			s.i.
35	Bromine	Br			n.u.	70	Ytterbium	Yb			n.v.c.
36	Krypton	Kr			n.u.	71	Lutecium	Lu			n.v.c.
37	Rubidium	Rb			n.v.c.	72	Hafnium	Hf			n.v.c.
38	Strontium	Sr			n.v.c.	73	Tantalum	Ta			s.i.
39	Yttrium	Y			s.i.	74	Tungsten	W	W ₆	19.5	
40	Zirconium	Zr			n.v.c.	75	Rhenium	Re			n.u.
41	Niobium	Nb			s.i.	76	Osmium	Os			n.u.
42	Molybdenum	Mo	MoF ₆	35		77	Iridium	Ir			n.u.
43	Technetium	Tc			r.	78	Platinum	Pt			n.v.c.
44	Ruthenium	Ru			n.v.c.	79	Gold	Au			s.i.
45	Rhodium	Rh			s.i.	80	Mercury	Hg	Hg(CH ₃) ₂	96	
46	Palladium	Pd			n.v.c.	81	Thallium	Tl	Tl(C ₂ H ₅) ₃	192	
47	Silver	Ag			n.v.c.	82	Lead	Pb	PbH ₄	-13	
48	Cadmium	Cd	Cd(CH ₃) ₂	105.5		83	Bismuth	Bi			s.i.
49	Indium	In			n.v.c.	84	Polonium	Po			r.
50	Tin	Sn	SnH ₄	-52		85	Astatine	At			r.
51	Antimony	Sb			n.u.	86	Radon	Rn			r.
52	Tellurium	Te	TeH ₂	2.0		87	Francium	Fr			r.
53	Iodine	I			s.i.	88	Radium	Ra			r.
54	Xenon	Xe	(2)			89	Actinium	Ac			r.
55	Cesium	Cs			s.i.	90	Thorium	Th			s.i.
56	Barium	Ba			n.v.c.	91	Protactinium	Pa			r.
						92	Uranium	U			

- (1) s.i. Single Isotope
 n.u. No utility
 n.v.c. No volatile compound

r. Radioactive

- (2) Considered previously and found to be expensive.
 (see reference 1)

- (3) Considered previously (see NYO-3928 and other reports in Foreword)

Table 1.1

Survey of Elements Suitable
for
Centrifugal Isotope Separation

Of the 71 elements from titanium through uranium, only 13, besides uranium and xenon, appear to be suitable to separation by the gaseous centrifuge. Uranium has been studied in detail previously. Xenon is expensive and of no great utility. The breakdown of unavailable elements is as follows: 18 with only one isotope; 21 with no volatile compounds; 8 with no utility; 9 with only radioactive isotopes.

Table 1.2 lists the physical-property data found for those compounds designated as practical for the centrifuge separation process.

Operating Conditions

Table 1.3 compares operating conditions of the centrifuges for five representative elements (Pb, Cr, Mo, Sn, Zn), selected from those termed practical ~~with the operating conditions~~ for uranium hexafluoride. Data on viscosities, diffusivities, or critical properties (from which the former may be estimated) were not available, and these had to be estimated to derive the proper flows, temperatures and pressures for the centrifuge. The results indicate that no unusual operating conditions will be required.

Flow rates were estimated from the equation

$$L = \frac{2\pi r_2}{\sqrt{\ln \left(\frac{r_2}{r_1} \right)^2}} (m) (D, \rho) \quad (1.1)$$

Where L = upflow or downflow rate through centrifuge.

r_2 = radius of outer flow stream.

r_1 = radius of inner flow stream.

m = ratio of flow rate to ideal limiting flow rate.

D = diffusivity

ρ = density

The value of m was set at 4. The weight flow rate through a centrifuge is roughly proportional to the gas viscosity and is about the same for all gases.

Included in Table 1.3 are the suction pressures at the centrifuge pump and the pressure at the bowl for each gas. The pump-suction pressures were calculated from the following equation, which is based on constant pump-suction volumes.

$$P_{s2} = \frac{L_2}{L_1} \cdot \frac{n_1}{n_2} \cdot \frac{T_2}{T_1} \cdot \frac{M_1}{M_2} \cdot P_{s1} \quad (1.2)$$

Table 1.2

Physical Properties of Compounds Practical for the Centrifuge Separation Process

Atomic No.	Element	Compound	B.P. °C	Vapor Pressure (1)	Liquid Density, gm/cc (2)	Surface Tension dynes/cm	Latent Heat of Vaporization cal/mole	Miscellaneous
22	Titanium	TiCl ₄	136.4	log p = 7.64 - 1947.6/T	1.767 - .00162 t	°C 13 34.03 27.5 34.16 39.5 30.78 52 29.08 75 26.65		Q _p (1) = .192 cal/g C _p /Q _v (g) = 1.39
24	Chromium	CrO ₂ Cl ₂	117	log p = 7.735 - 1890/T	1.911 at 20°C			
30	Zinc	Zn(OH ₂) ₂	46	log p = 7.802 - 1560/T log p = 7.52 - 1486/T	1.386 at 10.5°C		7150	
32	Germanium	GeH ₄	-90.1					
34	Selenium	SeH ₂	-42	log p = 6.27 - 1030/T	1.961 - .00167 t	= 27.74 at -27°C Temperature Coefficient = .165		T ₀ = 411°K P ₀ = 88 atm.
42	Molybdenum	MoH ₆	35	log p = 7.407 - 1394/T	2.55 at 20°C		6360	
48	Cadmium	Cd(OH ₂) ₂	105.5	log p = 7.764 - 1850/T	2.479 - .001631 t		8468	
50	Tin	SnH ₄	-52	log p = 7.40 - 1000/T			4430	
52	Tellurium	TeH ₂	2.0	log p = 5.53 - 1005/T	2.701 - .00136 t	= 36.75 (-28 to 4.6°C) Temperature Coefficient = .246		
74	Tungsten	WH ₆	19.5	log p = 7.565 - 1361.5/T	3.44 at 20°C 12.9 g/l (gas)		6250	
80	Mercury	Hg(OH ₂) ₂	96	log p = 7.57 - 1750/T	3.069 at 20°C			
81	Thallium	Tl(O ₂ H ₅) ₃	192		1.957 at 23°C			
82	Lead	PbH ₄	-13					

(1) T = °K
p = mm Hg

(2) t = °C

Table 1.2

Physical Properties of Compounds
Practical for the Centrifuge
Separation Process.

Table 1.3

Operating Conditions for Centrifuge With Various Gases⁽¹⁾

Gas	<u>UF₆</u>	<u>Pb(CH₃)₄</u>	<u>MoF₆</u>	<u>CrO₂Cl₂</u>	<u>SnH₄</u>	<u>Zn(CH₃)₂</u>
Molecular Weight	352	267.35	209.9	154.9	122.7	95.45
Boiling Point, °C	56.5	110	36	117	-52	46
Critical Properties (2)						
Temperature, °K	518	570	497	633	386	486
Pressure, atm.	44	32	48	80.7	85	55
Viscosity, micropoises	275	442	512	948	613	386

Temperature of Gas, °C	75	110	75	90	18	75
Flow Rate, mg/sec ⁽³⁾	54.4	37.8	45.8	68.5	56.2	33.4
Pressures, mm Hg						
Pump Suction	7.15	5.8	7.95	17.3	14.3	13.1
Bowl Periphery	600	645	485	305	247	84
Vapor Pressure	1620	760	2560	385	9130	2100

- (1) 28,200 RPM for UF₆; 35,000 RPM for other gases.
- (2) Critical properties for gases other than UF₆ estimated from boiling point and vapor pressure or liquid density data.
- (3) Estimated through viscosity (derived from critical properties) and assuming $D/\rho/\nu$ (Diffusivity Density/Viscosity) = 1.33. See Hougen and Watson, "Chemical Process Principles", John Wiley and Sons, for example.

where P_s is pump-suction pressure, T is absolute temperature, L is weight flow rate, M is molecular weight, subscript 1 applies to UF_6 , n_1 equals 28,200 rpm, and n_2 equals 35,000 rpm. The higher shaft speed was used for the other gases, since speeds of this order are foreseen in improved centrifuge designs.

The bowl peripheral pressures were calculated with the following relationship for the pressure ratio:

$$\ln \frac{P_2}{P_1} = \frac{1}{g_c} \frac{M V^2}{2 R T} \quad (1.3)$$

Where R is the gas constant, g_c is the gravitational constant, P_2 is the pressure at the bowl periphery, P_1 is the centrifuge axial pressure, and V is the bowl peripheral velocity. Although the centrifuge axial pressure should be used in equation (1.3) for P_1 , the pump-suction pressure may be used as an approximation that estimates the bowl peripheral pressure about 10 per cent low.

The pressure at the bowl periphery should be less than the vapor pressure at the temperature of the gas. Where possible, 75°C was used for the gas temperature, since this was the working temperature for UF_6 . For the compounds of molybdenum and zinc the vapor pressures at this temperature were sufficiently in excess of the bowl peripheral pressures to insure satisfactory operation. In the case of SnI_4 , the boiling point was quite low (-52°C), and the working temperature could be reduced below 75°C. Calculations made at a working temperature of 18°C, or about room temperature, indicate that the vapor pressure at this temperature is considerably in excess of the peripheral pressure, and, therefore, operating conditions would be satisfactory. However, for $Pb(CH_3)_4$ and CrO_2Cl_2 , it was necessary to go to higher working temperatures due to the relatively high boiling points of these compounds: 110°C and 117.6°C, respectively.

It should be noted that for the same operating temperature a reduction in the shaft speed from 35,000 rpm to 28,200 increases the pump-suction pressure by a factor of 1.24, but decreases the bowl pressure-ratio by a factor of 0.648. The net effect is a reduction in the bowl peripheral pressure by a factor of 0.805, and, therefore, an increase in the difference between the vapor pressure and the bowl peripheral pressure.

Chapter 2

CENTRIFUGE DESIGN

Studies on the process and mechanical features of the centrifuge itself, as opposed to cascade performance, are given in this chapter. The relationship between pressure and flow rate, the performance of seals, and the effects of heat transfer in the end-caps are examined for various gases. Mechanical considerations of vibration and balancing, bearings, drives and other features are then discussed. Methods of bringing the centrifuge through its critical speeds are analyzed in an appendix to this chapter.

Pressures and Flows

Figure 2.1 is a schematic diagram that indicates the flow pattern through a centrifuge in a cascade. The forward stream enters the lower shaft through an orifice, flows into the centrifuge through an end-cap, passes up the centrifuge bowl in an annular stream, discharges through an end-cap into the upper shaft, and passes through another orifice before being pumped to the next bank of centrifuges. The backward stream follows a similar path down through the centrifuge. (The orifices are a simple means of assuring uniform flows through machines in parallel, but they involve higher axial pressures, which increase plant inventories and which may limit the speed of rotation if the process gas is condensible.)

Weight flow rates that are desired for good separation performance tend to be about the same, through a given centrifuge, regardless of the gas being processed, as pointed out above. Likewise, the volumetric rate of flow into the pump remains about constant. Consequently, the axial pressure in the centrifuge, which is roughly proportional to the pump section pressure, is inversely proportional to the molecular weight of the gas being processed. Minor variations due to differences in gas viscosities, etc. can be corrected by adjusting the inventory in the machine, so that the desired flow rate can always be obtained by increasing or decreasing the pressure in the system. The following paragraphs develop these points for uranium hexafluoride, xenon, and hydrogen, which more than cover the range of conditions anticipated.

Table 2.1 gives pressure analyses for the three gases at particular values for the flows through the machine (5). The axial pressures are inversely proportional to molecular weight, within a factor of 2.

Figure 2.2 shows the relationship between flow rate and axial pressure for UF_6 and for Xe. The variation is essentially linear for UF_6 because of streamline flow in the passages and acoustic flow through the orifice on the pump inlet. However, for xenon the relationship is not linear, because the flow through both orifices is non-acoustical at the desired flow rate ($m = 4$). Flow in the shaft passages would be streamline regardless of the gas being processed.

Figure 2.1
Flow Pattern for a Centrifuge
In a Cascade

7F-53S

Figure 2.2

Weight Flow Rate Vs. Axial Pressure
For Xenon & For UF_6

Table 2.1

Pressure Drop Analysis for Various Gases⁽¹⁾

Gas	<u>CF₆</u>	<u>Xe</u>	<u>H₂</u>	<u>Pressure Point</u> ⁽²⁾	<u>Remarks</u>
Flow rate, mg/sec	55.0	73.5	27.0		
Axial Pressure (gas out) ⁽¹⁾	8.70	41.6	836	P _a	
Pressure Loss in Shaft	0.21	0.2	-		Area 0.109 in ² , length 20 in
Orifice Fore-pressure	8.49	41.4	836	P ₁	
Pressure Drop across Orifice	3.22	9.4	3.26		Area 0.0084 in ²
Pump-suction pressure	5.07	32.0	832.74	P ₂	
Pump Compression Ratio	2.80	1.45	1.0059		
Pump Discharge Pressure	14.00	46.3	837.65	P ₃	
Pressure Loss in Lines and Manifold	0.50	0.6	-		Equivalent to 68.5 ft 1/2-inch pipe
Orifice Fore-pressure	13.50	45.7	837.65	P ₄	
Pressure Drop across Orifice	4.57	3.8	1.65		Area 0.0093 in ²
Shaft Inlet Pressure	8.93	41.9	836	P ₅	
Pressure Drop in Shaft	0.23	0.3	-		Area 0.109 in ² , length 21.6 in
Axial Pressure (gas in)	8.70	41.6	836	P ₆	

(1) All pressures and pressure drops in mm Hg
Centrifuge speed is 28,200 RPM; temperature 75°C.

(2) See Figure 2.1 for location of points in system.

Thus it is seen that valves are not required in the manifolding system to give the necessary pressure drops for each gas. The desired flow rate can be obtained by running the system at the proper pressure level. Flexibility of operation is assured since flow rate is proportional to pressure level.

Elimination of orifices would permit operation at the lowest pressure level for fixed shaft-passages, pump-design, etc. The flow rate would still be proportional to pressure level. Elimination of orifices may be desirable in cases where it is necessary to minimize gas inventory. With no orifices it may be necessary to have a more rigid selection of shaft passages, pumps, etc. within given tolerances to assure essentially equal flows in all machines.

A higher speed for the centrifuge results in a higher compression ratio for the pump. The desired flow rate is unchanged. With an acoustical orifice before the pump, the downstream pressure of the orifice (i.e., the pump suction pressure) would decrease and the system would balance out. This means the axial pressure does not change but the centrifuge peripheral pressure increases. A higher operating temperature may be required to prevent condensation of the process gas at the periphery. If this orifice were not acoustical, the axial pressure would decrease with an increase in speed until a speed were reached where this orifice became acoustical.

Limiting Pump Flow: The pump capacity at the point where the compression ratio begins to decrease is of importance since it will show what performance may be expected from the centrifuge pump. Using the impeller dimensions given for the wartime machine and a shaft speed of 28,200 rpm, an analysis of the impeller-eye conditions was made following the procedure described in Zucrow (6). The results indicate the impeller eye will have a maximum capacity of about 17 cfm and the compression ratio will fall off sharply at higher suction volumes. For all of the gases considered for isotope separation in the centrifuge the operating conditions will give suction volumes of the order of 1 to 2 cfm. Thus it can be concluded that the characteristic curve for the centrifuge pump will be fairly constant over the range of weight flow rates of interest, i.e., the compression ratio will be essentially constant.

Seals

Figure 2.3 is a schematic diagram of the type of seal used on the wartime centrifuge for use with UF₆. A buffer gas, nitrogen in this case, separates the process gas from the lube oil. In general, such a design is satisfactory for other gases, although in certain cases simplifications are possible, as described below (7).

Buffer gas is required for cases where the process gas can react with the lube oil. For other cases, the buffer gas can be eliminated; the outleaking process gas mixes with lube oil, is recovered from the oil by a liquid-gas separator and is returned to the centrifuges. In these cases, vacuum pumps must pump the process gas back to the centrifuges.

Figure 2.3

Schematic Arrangement of Upper Seals and Pump

For cases where the process gas and oil react and the process gas is easily condensed, a system similar to the UF_6 case is satisfactory. The process gas outleakage is condensed from the buffer gas in a cold trap and the buffer gas is pumped to the atmosphere. The condensed process gas is vaporized back into the centrifuges. If the process gas is not easily condensed, then the buffer gas should be.

Table 2.2 gives a comparison of seal performance with uranium hexafluoride, xenon, and hydrogen, presuming a buffer gas is needed in the latter cases (see below). The buffer-gas requirement is greater for the lower-molecular-weight process gases. The vacuum-pump capacity to pump the buffer gas out of the system as designed for UF_6 is adequate for the other cases. Process gas leakage is higher for the lower-molecular-weight gases but is still a small fraction of the flow in the centrifuge. Because of the increased leakages of process gas and buffer gas for lighter gases, it may be necessary to increase the capacity of the cold traps. Loss of process gas by back diffusion is negligible in all cases.

Actually in the case of Xe and H_2 a buffer gas is not needed and a cold trap system is not required. Process-gas leakage would be separated from oil in a drum and pumped back to the centrifuge by the vacuum pump. This pumping requirement is less than that shown for nitrogen in Table 2.2. To operate on H_2 or Xe, the only changes in the UF_6 design are the elimination of buffer gas and the cold traps, and minor changes in valving and piping in the recovery system.

Thus it appears that the seal-gas system as designed for operation of the centrifuge with UF_6 is adequate, with possibly minor changes, for operation with any other gas.

End-Cap Heat Transfer

There is a considerable difference between the pressure ratio produced by isothermal compression of a gas and that produced by isentropic compression. In the centrifuge bowl, the pressure distribution tends to be that obtained by isothermal compression. Unless the compression in the end-caps (see Fig. 2.1) through which the streams enter and leave the centrifugebowl is isothermal, pressure differentials are set up which cause radial flow and a loss in separation efficiency. The radial flow increases with increasing molecular weight and ratio of specific heats of the gas, and with increasing speed of rotation of the centrifuge (8).

Table 2.3 shows that isentropic compression in the end-caps would lead to practically complete loss of separating effect. Note that, in general, the ratio of radial flow to axial flow increases with molecular weight, but that radial flow with xenon is especially bad. This is due to the high ratio of specific heats for this monatomic gas.

Table 2.2

Seal Performance with Various Gases (1)

<u>Gas</u>	<u>UF₆</u>	<u>Xe</u>	<u>H₂</u>
Pressures, mm Hg			
Centrifuge Axis	8.7	41.6	836
Inlet to Process Gas Seal	13.75	46.0	838
Pressure Drop Across Seals, mm Hg			
Process Gas Seal	2.5	2.5	2.5
Buffer Gas Seal	3.75	3.75	3.75

Process Gas Leakage			
SCFD	0.24	0.605	34.5
% of Axial Flow	2.1	1.5	3.5
Process Gas Back Diffusion			
Through Buffer Seal, gm/day	10 ^{-5.1}	10 ^{-12.6}	10 ^{-92.2}
Buffer Gas (N ₂) Requirement, SCFD	1.5	5.2	96
Vacuum Pump Capacity, (2) Approx.CFD	157	117	-

(1) Seal clearance 0.002 inch; centrifuge speed 28,200 RPM

(2) Assuming 2.5 mm Hg pressure loss between seals and vacuum pump.

Table 2.3

Effect of Isentropic Compression in End-Caps

(1)

<u>Gas</u>	<u>Molecular Weight</u>	<u>Normal Axial Flow, mg/sec.</u>	<u>Radial Flow, mg/sec.</u>	<u>Ratio: $\frac{\text{Radial Flow}}{\text{Axial Flow}}$</u>
UF ₆	352	54.4	100	1.8
Xe	131.3	73.5	273	3.7
Pb(CH ₃) ₄	267.4	37.8	18.3	0.5
MoF ₆	210	45.8	42.0	0.9
CrO ₂ Cl ₂	155	68.5	60.0	0.9
SnH ₄	123	56.2	65.5	1.2
Zn(CH ₃) ₂	95.5	33.4	12.7	0.4

(1) Centrifuge speed 28,200 RPM (peripheral speed 2.7×10^4 cm/sec)

The radial flow for isentropic compression may be estimated from the following equation, which is derived from the results presented in reference (1):

$$\gamma_{ad} = \frac{\left(\frac{k-1}{k}\right) \left[\frac{M (\omega r_2)^2}{2 g R T} \right]}{\frac{1}{\pi} \left[\frac{0.0451 (\omega r_2)^2}{g J T K_0} + \frac{0.245}{\mu} \right]} \quad (2.1)$$

where γ_{ad} = radial flow rate of gas per unit length of centrifuge (positive is flow inward) due to adiabatic compression in end-cap.

k = ratio of specific heats
 M = molecular weight
 ω = angular speed
 r_2 = outer radius of centrifuge
 g = gravitational constant
 R = gas constant
 T = absolute temperature
 J = mechanical equivalent of heat
 K_0 = thermal conductivity
 μ = viscosity

The first term in the denominator is usually negligible in comparison with the second, and therefore:

$$\gamma_{ad} \sim (k-1) \frac{M V^2}{T}, \quad (2.2)$$

using V for peripheral velocity.

If the flow through the end-cap is nearly isothermal, the radial flow can be estimated by the following equation:

$$\gamma \approx \frac{2\pi \left(\frac{\Delta T}{T}\right)}{\frac{M(\omega r_2)^2}{2 g R T} \left[\frac{0.0451 (\omega r_2)^2}{g J T K_c} + \frac{0.245}{A h} \right]} \quad (2.3)$$

where γ = radial flow rate per unit length of centrifuge
(positive is flow inward) for nearly isothermal
compression)

ΔT = temperature difference between gas and end-cap

The temperature difference is greatest at the outer radius of the end-cap and may be obtained from the equation:

$$\Delta T = \frac{L \omega^2 r_2 \ell}{J g h A} \quad (2.4)$$

where L = upflow or downflow rate, weight/time

ℓ = length of flow-slot in end-cap

A = heat transfer area of flow-slot in end-cap

h = heat transfer coefficient

Table 2.4 gives the temperatures calculated for end-caps similar to those of the wartime design for UF_6 and for xenon. Table 2.5 gives the radial flows induced by these temperature differences.

Table 2.5 indicates that the inefficiency, if assumed to be proportional to the ratio of radial flow to axial flow, is about twice as great for Xe as for UF_6 . Thus if the efficiency with UF_6 is 85 per cent, it can be expected that it will be about 70 per cent with Xe. The heat transfer area provided in the wartime machine for operation on UF_6 is barely acceptable for Xe. If one wishes to maintain the same efficiency for Xe as for UF_6 , it is necessary to increase the transfer area by about 87 per cent.

Table 2.4

Temperatures in End-Caps ⁽¹⁾

Gas	<u>UF₆</u>	<u>Xe</u>
Flow Rate, mg/sec	54.4	73.5
Temperature Difference at Outer Radius for:		
Inner Channels	3.7	7.2
Middle Channels	3.4	6.6
Outer Channels	2.7	5.3

- (1) Centrifuge speed = 28,200 RPM; gas feed temperature is 75°C. The end-cap flow passages consist of three groups of radial channels through which the gas flows in series: an inner group of 86 channels each 3/4 inch long, a middle group of 172 channels each 0.812 inch long, and an outer group of 344 channels each 0.71 inch long. Each channel has an equivalent diameter of 0.0288 inch, a flow area of 0.00165 in², and a heat transfer periphery of 0.226 in.

Table 2.5

Radial Flow in End-Cap ⁽¹⁾

Gas	<u>UF₆</u>	<u>Xe</u>
Axial Flow, mg/sec	54.4	73.5
Radial Flow, mg/sec	4.8	12.3
% of axial flow	8.9	16.7

- (1) See Table 2.4 for basis of estimates

Mechanical Design

If a centrifuge with a long, narrow bowl could be developed, important economies and improved efficiencies might be realized. At a given radius, longer bowls mean fewer machines, which would reduce the investment in drives and auxiliary equipment and which might reduce the relative importance of separation inefficiencies due to end-cap mixing. For machines of a given length, narrower bowls mean increasing the number of machines inversely as the bowl radius, but the holdup of process gas in the plant decreases in proportion to the bowl radius (neglecting the effect of holdup in interconnecting piping, which is a small fraction of the total holdup). Narrower bowls require higher-speed drives and, because of increased flexibility, introduce difficult problems that stem from vibration in the manufacture and operation of the centrifuges.

Many interesting and useful ideas about the mechanical design of high-speed, flexible-bowl centrifuges were suggested and discussed during meetings with manufacturers (9, 10)*. These are presented in the following paragraphs. Vibration is one of the most important problems. An analysis of methods of bringing the centrifuge through its critical speeds is given in the appendix to this chapter. Table 2.6 gives mechanical specifications for the centrifuges.

Vibration and Balancing: Vibration at critical speeds is the major problem in the design of the centrifuge. In the wartime design, dampers were used to remove the vibrational energy and little or no balancing was done during manufacture. Current manufacturing methods emphasize balancing as the most important method of reducing excessive vibration in high-speed rotating equipment.

Balancing techniques and devices have been advanced markedly in the last ten years. Multiplane balancing, in which flexible shafts are balanced in many planes transverse to the rotor axis, is practiced by manufacturers of turbines for the power industry. Some of these machines are occasionally operated at a critical speed, on a routine basis. Other machines that operate above the third critical speed are manufactured on a production basis. Balancing can be accomplished by sensing the vibration amplitude at speeds just below a critical speed, without touching the rotor, estimating the vibration at the next critical speed with the aid of digital computers, and then removing material from the rotor at appropriate locations.

The centrifuge would be manufactured by balancing for each critical speed in turn, the lowest speed first. The goal would be to balance the machine well enough so that the bearings would supply any damping that might be required. Dampers would be added merely as a safety measure.

Bearings: Gas bearings were suggested as a means of improving the design. Such might be spaced at intervals along the bowl and might be used either continuously or only when passing through a critical speed. If these bearings could be developed, balancing would be less crucial and the machines might cost less.

Each gas bearing would consist of a stationary ring with a number of gas-pockets on its inner side, next to the rotating bowl. Gas would be supplied to each ring from an external source, through an orifice. If the bowl were to approach a gas-pocket, the gas pressure would increase and force the bowl back into position. The main power requirement for such bearings is not for friction but for compressing the gas to the pressure in the bearing.

Several questions about this suggestion are evident. If the bearings remain in place, would axial temperature variations that would affect separation on performance occur inside the bowl? What would the power requirement be? Fewer bearings might be needed on the shaft, which would tend to offset any power increases due to bearings on the bowl. If the bowl-bearings are used intermittently, high power would be needed only while the

*See Foreword.

Table 2.6

Mechanical Specifications for Centrifuge1. Pump

Impeller Diameter	3.5 in.
Impeller Passages	12 equally spaced radial holes, each hole 3/16 inch diameter.

2. Seals

Clearances	2 mils maximum
------------	----------------

3. Shaft Passages

Two passages in each shaft; one for gas flow in, the other for gas flow out. Flow area for each, 0.10 sq in. minimum.

4. End Cap Heat Transfer Requirements

4" Diameter Passage (inner stream)	9 sq in. of heat transfer surface between a radius of 1.625" and a radius of 2.0".
7.2" Diameter Passage (outer stream)	Heat transfer surface 16 sq in. between $r = 1-1/8"$ and $r = 2"$ 32 " " " $r = 2"$ and $r = 2-7/8"$ 55 " " " $r = 2-7/8"$ and $r = 3.6"$

5. Bowl Speed and Dimensions

Inside Peripheral Speed (Min.) 3.0×10^4 cm/sec
 Inside Diameter (Max.) 7.2"; Target 6"
 Length (Min.) 126" (Inside)

bearings are functioning. Would flutter of gas bearings occur?

Drive: The drive for the centrifuge is a minor problem. Turbines or electric motors could be used, with the latter being generally preferred.

Induction motors of high efficiency with outputs from a few horsepower to 400 Hp that operate at speeds up to 120,000 RPM are now available. The motor could be cantilevered on the shaft, and therefore would not require additional bearings.

Steam turbine drives have an advantage of high power output for startup and shutdown. Speed control for the turbines could be obtained by a conventional scheme in which an electromagnet on the shaft generates a current which goes to a tuned circuit. The tuned circuit resonates at the speed desired for control and presents a power drag that the turbine bucks and thereby maintains speed.

Shaft, Seals, and End-Cap: The flow rate through a centrifuge is proportional to bowl diameter, and therefore smaller diameter shafts could be used if smaller bowls were to be obtained. However, for a given pressure loss in the shaft, halving the bowl diameter only reduces the shaft diameter by 16 per cent, since in streamline flow the diameter is proportional to the fourth root of the flow rate. The shaft passages could be concentric tubes, rather than D-shaped passages as in the wartime model.

A new seal design should be considered. Adaptations of the seals on the centrifugal pumps at the K-25 plant in Oak Ridge might be a fruitful avenue for development.

The end-cap on the wartime machine was actually a plug that was set inside the end of the bowl. A cap that overlapped the bowl might be better from a strength point of view. German work on centrifuges has evolved some useful ideas on the construction of end-caps (11).

Appendix to Chapter 2

BRINGING THE CYLINDRICAL BOWL THROUGH ITS CRITICAL SPEEDS.*

The question of rotor balancing for the prevention of excessive amplitudes which could cause the destruction of the rotor bowl is closely tied to the process of bringing the rotor through its critical speeds. Large deflections occur at the critical rotor speeds, so that if it were possible to avoid the critical speeds or to pass through them rapidly it would not be necessary to have an accurately balanced rotor, and possibly, it would not be necessary to balance the rotor at all. This is an important consideration since the balancing of a flexible rotor is difficult and may turn out to be a significant obstacle in the construction of a satisfactory machine. Some methods of bringing the rotor bowl through its criticals are discussed here.

The kinetic energy contained in an element of rotor length dx is

$$dE = 1/2 \rho I \omega^2 dx \quad (1)$$

where ρ is the mass density, I the polar moment of inertia and ω the angular speed. A rotor with clamped-clamped end fixity will assume a shape approximating

$$y = y_0 \sin^2 \pi \frac{x}{L} \quad (2)$$

when going through its first critical. The polar moment of inertia of a thin hollow rotor is given as

$$I = 2\pi R^3 t + 2\pi R t y^2 \quad (3)$$

where R is the mean rotor radius and t the wall thickness.

Setting (2) in (3), and (3) in (1) and integrating gives the kinetic energy contained in the rotor as

$$KE = \left[1 + \frac{3(y_0)^2}{8(-R)} \right] \pi \rho R^3 L t \omega^2 \quad (4)$$

where L is the rotor length. The energy in the undeflected rotor is

$$KE_c = \pi \rho R^3 L t \omega^2 \quad (5)$$

An observation that may be made at this point is that the rotor thickness is a factor in determining the amount of energy that must be expended in bringing the rotor up to speed, but more important, it is a factor that determines the amount of reserve energy that must be available to bring the rotor through its critical speeds. The other quantities in expression (5) are determined from process and strength considerations.

* see reference (12)

The thickness affects neither the bowl strength nor does it influence the natural frequencies of vibration. Other things being equal, advantage can be gained from making the bowl as thin as manufacturing requirements will permit.

The deflection of the bowl at a given speed depends upon the irregularities in the rotor. The center of mass of the rotor is assumed to be displaced an amount e from the geometrical center of the rotor. The resonance curve then has the form

$$\frac{y_0}{e} = \frac{\left(\frac{\omega}{\omega_n}\right)^2}{\left\{ \left[1 - \left(\frac{\omega}{\omega_n}\right)^2 \right]^2 + d^2 \left(\frac{\omega}{\omega_n}\right)^2 \right\}^{1/2}} \quad (6)$$

where d is a damping constant. The damping is to a large extent due to windage, which is a viscous type of damping resulting from the drag of the air on the rotor bowl. In this connection it is important to consider the atmosphere in which the rotor bowl is balanced. When a rotor is balanced in air at atmospheric pressure, it may not be in balance when rotating in an atmosphere of low pressure hydrogen. In low pressure hydrogen the amplitude of vibration is bound to increase and there will be some change in the resonant frequency or rotational speed at which the amplitude will be a maximum.

In equation (6), assume the damping constant $d = 1/\sqrt{40}$ and that the mass eccentricity $e = \frac{R}{4}$. Then setting Expression (6) into (4)

$$KE = \left[1 + \frac{.0234 \left(\frac{\omega}{\omega_n}\right)^4}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2 \right]^2 + \frac{1}{16} \left(\frac{\omega}{\omega_n}\right)^2} \right] \pi \rho R^3 L t \omega_n^2 \left(\frac{\omega}{\omega_n}\right)^2 \quad (7)$$

Consider for example, an aluminum bowl 132 inches long with a mean bowl radius of 3.85 inches and a wall thickness of 1/2 inch. If the bowl has clamped-clamped end conditions, its first critical mode will be attained at approximately 6560 RPM. The energy, neglecting friction and damping forces, required to bring the undeflected bowl up to speed is

$$KE_0 = \pi \rho R^3 L t \omega^2$$

and

$$KE_{on} = \pi \rho R^3 L t \omega_n^2 = 43.9 \text{ HP-minutes} \quad (8)$$

Equations (6), (7) and (8), which give the rotor deflections and energy input for the deflected and undeflected rotor, in terms of the rotational speed, are plotted in Fig. 2A. As the energy input into the rotor is increased, the speed and deflection will increase. With an energy input of 75 HP-min. shown as point C in Fig. 2A, the speed will be at 95% of the first critical speed, and the amplitude at 82% of the resonance amplitude.

Figure 2A
Energy and Deflection of Unbalanced Rotor

If the energy input were increased to 84 HP-min., the peak amplitude would be attained. Any further input of energy into the rotor would cause a sudden increase (about 30% above critical) in the rotor speed, and a decrease in amplitude. The energy-velocity position would be on the deflected rotor curve somewhere above F, and the corresponding deflection on the curve in Fig. 2A, somewhere to the right of B.

It appears to be possible to bring the rotor from point C to E and from position A to position B without going through the peak amplitude. Points A and B correspond to the same rotor energy, point A representing a higher amplitude and lower speed, and point B representing a lower amplitude and higher speed. Assume the rotor is at the energy-velocity position C. If the rotor amplitude were suddenly decreased to zero (for example, by whacking it with a broomstick handle at its center), the rotor would momentarily find itself at point F. Since this is not an equilibrium position for the given mass eccentricity, it would adjust itself to point E in the energy equilibrium curve and to point B on the amplitude curve.

The above method of going through the critical speed without excessive amplitude is used by some experimenters*. From this particular example, in which the operation is performed when the amplitude is already 82% of the peak amplitude, it might appear that no great advantage is gained. However, if the damping constant were smaller (as it may well be) there would be much higher peak resonances and large amplitudes could be avoided.

The critical frequencies of the rotor depend, among other things, upon the end-fixity of the bowl and its length. This suggests that if either the end-fixity, or the distance between bearings were altered it might serve as a means of bringing the rotor suddenly through its critical speeds. The first critical speed for the clamped-clamped rotor is 6560 RPM whereas the first critical speed for a similar hinged-hinged rotor is 2890 RPM. If the bearings were held rigidly to simulate the clamped end condition and the speed brought up to say 4000 RPM and then the bearings suddenly released so that they would be free to rotate (about an axis perpendicular to the rotor axis), the rotor would find itself past its first hinged-hinged critical. It could then be brought past its clamped-clamped critical of 6560 without going through a resonance region. The procedure of alternately clamping and releasing the bearings could be used to bring the rotor through all of its criticals. Mechanically, it may be possible to accomplish this by setting the bearing into the ball section of a ball and socket joint.

Another method of avoiding the rotor critical speeds would be to change the effective length between rotor bearing supports. When the bearings are 11 feet apart the first critical speed is at 6560 RPM. Let the rotor be brought up to about 5000 RPM, and each of the bearings suddenly displaced 18 inches outward to give an effective rotor length of 14 feet. The critical speed of a 14 feet clamped-clamped rotor is 4050 RPM. So that at 5000 RPM the rotor would find itself past its first

*At the University of Virginia

critical. The speed could then be increased and the procedure repeated to bring the rotor through the subsequent critical speeds.

Other methods such as applying compressive or tensile forces to the rotor to alter its critical speeds were considered, but the practical problems involved appeared to be too difficult.

Although specific numbers are mentioned in the above discussion, they should be looked upon only in a qualitative light. The detailed picture is more complex. The rotating element between bearings, for example, consists of rotor and shaft of different flexibilities. Also, the representation of the unbalance in the rotor was greatly simplified. Whether the proposed methods of bringing the rotor bowl through its critical speeds could be applied successfully can be determined only through experiment.

Chapter 3

CASCADE PERFORMANCE

Studies of cascade performance were undertaken to determine whether a plant designed for one separation could be readily adapted to another, either for a different amount and concentration of an isotope of the same element or for an isotope of a different element. Granting compatibility of the process gases with materials of construction, it appears that a centrifuge plant would be completely versatile. The key reason for this versatility is that the process piping is small and is therefore easily rearranged to accommodate different shapes for the cascade.

This chapter presents the results of calculations on the separation performance of cascades of three different sizes, 10, 25 and 100 machines, when producing two different isotopes, uranium-235 and chlorine-37. The process gas for uranium is uranium hexafluoride; that for chlorine is monochlorotrifluoromethane, which is sold under the trade name "Freon-13" and which is recommended as a test gas for pilot plant studies of centrifuge operation (see Chapter IV). All of these cascades are rectifiers. The 10-machine plant is a square cascade with the ten machines in series (13). The other plants are "squared-off" cascades, one with 10 stages and the other with 25 stages. Table 3.1 gives the centrifuge characteristics that were used as the basis for the cascade calculations.

10-Machine Plant

Table 3.2 gives the separation performances for the square cascade of 10 machines in series, operated as a rectifier. It is interesting to note that uranium-235 enrichments that are more than adequate for use in light-water-moderated reactors are obtainable with such a plant. However, with only ten machines, the product rate is so small that of the order of 50 years would be required to accumulate a critical mass of material for a light-water-moderated reactor.

The square cascade is not especially suited for either separation, as evidenced by the cascade efficiencies, but the uranium separation has a somewhat higher efficiency than the chlorine separation. The series arrangement of machines gives the greatest change in concentration, and therefore is useful in obtaining accuracy in pilot-scale work.

25-Machine Plant

Table 3.3 gives the separation performances for a plant with 23 machines, arranged in 10 stages and operated as a rectifier. The product concentrations are the same as those in the 10-machine plant, but the product rates are more than tripled, even though the number of machines is only slightly more than doubled. The increased cascade efficiencies are a result of "squaring-off" the cascade so that it approaches the ideal shape. Note the similarity in cascade shapes, despite the apparent difference in the character of the separations.

Table 3.1

Centrifuge Characteristics (1)
with UF_6 and with $CClF_3$

Desired Isotope	Uranium-235	Chlorine-37
Other Isotope	U-238	Cl-35
Process Gas	UF_6	$CClF_3$
Molecular Weight	352	104.3
Temperature, $^{\circ}F$	167	70
Mol Fraction Desired Isotope in Feed	0.00715	0.246
Machine Characteristics (2)		
r_1/r_2	0.534	0.534
$m = L \sqrt{2 \ln(r_2/r_1)} / 2\pi r_2 (Dp/RT)$	4	4
$B = (MV^2/2g RT) [1 - (r_1/r_2)^2]$	0.0269	0.0215
$n = [Z/r_2 \sqrt{2 \ln(r_2/r_1)}] [2m/(1+m^2)]$, ideal corrected (3)	14.7 11.7	14.7 11.7
nB Ideal	0.396	0.316
Corrected (3)	0.315	0.252
$\rho_2/\rho_0 = \exp(MV^2/2g RT)$	83.9	4.77
$\bar{\rho}/\rho_0 = [(\rho_2/\rho_0) - 1] / \ln(\rho_2/\rho_0)$	18.7	2.41
$L =$ Upflow or downflow, gm-mols/hr	0.561	1.462 (4)
$W^1 \text{ max} = nB^2 L/4$, gm-mols/day, machine, ideal corrected (3)	0.0358 0.0286	0.0597 0.0477

(1) At 28,200 RPM. Bowl material is aluminum alloy St-14.

See Tables 1 and 2.6 for other specifications.

(2) Symbols are defined in the Nomenclature at the end of this report.

(3) Based on wartime tests with UF_6 . See reference (2) (NNES X-1, Chapter 2).

(4) Assuming $(D/\mu) = 1.4$

Table 3.2

Separation Performance
of
Ten-Machine Plant (1)

Desired Isotope	<u>Uranium-235</u>	<u>Chlorine-37</u>
Mol Fraction Desired Isotope		
In Feed	0.00715	0.246
At top at total reflux	0.144	0.802
In Product at optimum product rate	0.0336	0.536
Optimum Product Rate (2)		
Gram-mols/day	0.0800	0.290
Grams desired isotope/day	0.631	5.75
Cascade Efficiency, FV_p/MW^*	0.616	0.538

(1) Square rectifier with 10 machines in series. See Table 3.1 for other bases.

(2) Product Rate that maximizes separative work of the cascade.

Table 3.3

Separation Performance
of
25-Machine Plant (1)

Desired Isotope	<u>Uranium-235</u>	<u>Chlorine-37</u>		
Mol Fraction Desired Isotope				
In Feed	0.00715	0.246		
In Product	0.0336	0.536		
Product Rate				
Gram-mols/day	0.246	1.00		
Grams desired isotope/day	1.94	19.83		
Cascade Efficiency, PV_P/MW^1	0.824	0.806		

<u>Enriching Stage Number</u>	<u>Machines</u>	<u>Avg. Conc.</u> (2)	<u>Machines</u>	<u>Avg. Conc.</u> (2)
1	5	0.774	4	25.8
2	4	0.904	4	28.25
3	3	1.058	3	30.85
4	3	1.235	3	33.6
5	2	1.444	2	36.45
6	2	1.690	2	39.4
7	1	1.970	2	42.45
8	1	2.30	1	45.55
9	1	2.69	1	48.7
10	1	3.13	1	51.95
Total	23	1.34	23	34.45

(1) Ten-stage rectifier with 23 machines. See Table 3.1 for other bases.

(2) Average concentration in mol per cent desired isotope.

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This 23-machine plant could produce 10 kilograms of U-235, at a concentration of 3.36 mol per cent in uranium, in a little over 14 years.

100-Machine Plant

Table 3.4 gives the separation performances of plants with about 100 centrifuges, arranged in twenty-five stages and operated as a rectifier. Again, the cascades are quite similar, although the chlorine-plant tapers more gradually and is more efficient.

The Geneva Reactor is a swimming-pool type, using uranium enriched to 20 mol per cent U-235, whose fuel loading is 5 kilograms of U-235. The 100-machine plant would produce 5 kilograms of U-235, at an enrichment of 27 mol per cent, in about 3 years. Some of the smaller nations might be interested in such a plant.

Table 3.4

Separation Performance
of
100-Machine Plant (1)

Desired Isotope	<u>Uranium-235</u>		<u>Chlorine-37</u>	
Mol Fraction Desired Isotope				
In Feed	0.00715		0.246	
In Product	0.271		0.884	
Product Rate,				
Gram-mols/day	0.0724		1.00	
Grams desired isotope/day	4.61		32.7	
Cascade Efficiency, FV_P/MW^1	0.865		0.883	

<u>Enriching Stage Number</u>	<u>Machines</u>	<u>Avg. Conc.</u> ⁽²⁾	<u>Machines</u>	<u>Avg. Conc.</u> ⁽²⁾
1	14	0.774	9	25.8
2	12	0.904	8	28.25
3	10	1.058	8	30.85
4	9	1.235	7	33.6
5	8	1.444	6	36.45
6	7	1.690	6	39.4
7	6	1.970	5	42.45
8	5	2.30	5	45.55
9	4	2.69	5	48.7
10	4	3.13	4	51.95
11	3	3.64	4	55.05
12	3	4.245	4	58.05
13	2	4.945	4	61.1
14	2	5.745	3	64.05
15	2	6.66	3	66.95
16	2	7.70	3	69.7
17	1	8.90	3	72.25
18	1	10.27	2	74.65
19	1	11.80	2	77.0
20	1	13.56	2	79.25
21	1	15.54	2	81.2
22	1	17.70	1	83.0
23	1	20.1	1	84.7
24	1	22.8	1	86.25
25	1	25.65	1	87.7
Total	102	3.27	99	48.2

(1) Rectifier with 25 stages. See Table 3.1 for other bases.

(2) Average concentration in mol per cent desired isotope.

Chapter 4

PILOT PLANT

A detailed design and cost estimate for a pilot plant using ten long-bowl gas-centrifuges, based on uranium hexafluoride as a test gas, has been given in the most recent report of this series (13). That pilot plant was estimated to cost about \$1,300,000, with the ten centrifuges accounting for \$750,000. Delivery of the first machine would take 18 months and the nine remaining machines would be delivered in an additional 6 months. The plant would be an independent facility, housed in a one-story building with a floor area of 10,000 square feet.

There were some undesirable aspects to that pilot plant. First, uranium hexafluoride, although its properties are well known and techniques for handling it have been established, is not the most attractive material to use as a test gas because of its corrosiveness and toxicity. Second, no manufacturer is set up to produce long-bowl centrifuges, and development of the teams and tools and techniques for their manufacture would result in high-cost machines and might involve longer delivery times than those quoted in the preceding paragraph.

To overcome these difficulties, a search for a better test-gas was initiated and plans were laid for obtaining stiff-rotor centrifuges of a type being manufactured by a German firm, Sartorius-Werke. Tests using these machines would speed the overall program by allowing American manufacturers to devote their efforts to development of an inexpensive, reliable long-bowl machine while operating know-how and basic separation data were being obtained with the stiff-rotor centrifuges.

This chapter describes the test gas, discusses the purpose and the types of tests to be carried out in a pilot plant using stiff-rotor centrifuges, and presents a summary design and cost estimate for the plant, which is assumed to be housed in an existing facility.

Test Gas

"Freon 13", CClF_3 , is recommended as the test gas because it is essentially a mixture of $\text{CCl}^{35}\text{F}_3$ and $\text{CCl}^{37}\text{F}_3$ (fluorine has only one stable isotope and carbon is 99 per cent C^{12} , 1 per cent C^{13}) and because it has a high vapor pressure, reasonably high molecular weight (104.47), good thermal stability, low mutual solubility with water and with oil, and because it is inert, non-toxic, non-flammable and commercially available in high purity and sufficient quantity at a moderate price (14).

Table 4.1 gives properties of "Freon 13".

Table 4.1
Properties of "Freon 13" (1)

Trade Name	"Freon 13"
Chemical Name	Monochlorotrifluoromethane
Chemical Formula	CClF_3
Molecular Weight	104.47
Boiling Point, $^{\circ}\text{F}$	-114.6
Freezing Point, $^{\circ}\text{F}$	-294
Critical Temperature, $^{\circ}\text{F}$	83.9
Critical Pressure, psia	561
Critical Volume, ft^3/lb	0.0277
Specific Heat, C_p , 1 atm and -22°F , Btu/lb $^{\circ}\text{F}$	0.138
Ratio of Specific Heats, C_p/C_v , 1 atm and -22°F	1.172
Relative Dielectric Strength, 1 atm and 23°C , ($N_2=1$)	1.4
Dielectric Constant, vapor at 0.5 atm and 29°C	1.0013
Solubility in Water, 1 atm and 25°C , w/o	0.009
Flammability	Non-flammable
Toxicity	Probably Group 6 (2)

<u>Temperature $^{\circ}\text{F}$</u>	<u>Vapor Pressure, psia</u>	<u>Viscosity, Centipoises</u>	<u>Thermal Conductivity Btu/hr ft^2 ($^{\circ}\text{F}/\text{ft}$)</u>
-100	22.5	0.0112	0.00445
0	176	0.0133	0.00528
83.9	561	0.0150	0.00595
200	-	0.0170	0.00675

(1) From "Kinetic" Technical Bulletin B-2, "Kinetic" Chemicals Division of the DuPont Co. "Freon" is DuPont's registered trade name for its fluorinated hydrocarbons.

(2) Underwriter's Laboratories Classification. Group 6 produces no apparent injury in concentrations up to 20 volume per cent for exposures of at least 2 hours.

"Freon 13" is supplied in cylinders holding 5, 9, 23 and 80 lbs of gas. The cylinders are equipped with 3/4" pipe connections. "Freon 13" costs 6.50 \$/lb in 5 and 9 lb cylinders, 6.25 \$/lb in 23 lb cylinders, and 6.00 \$/lb in 80 lb cylinders, plus a refundable deposit on the cylinders.

The DuPont Company has other "Freons" under development which could be useful in a pilot plant program. "Freon 115", $\text{CClF}_2\text{-CF}_3$, is about 50 per cent heavier than "Freon 13", and could be used to study the effect of molecular weight on centrifuge performance. "Freon 13 B1", CBrF_3 , could be used to separate the two bromine isotopes, which are almost equally abundant, and would yield information on the effect of molecular weight.

German Centrifuges

The German centrifuges, which are of the stiff-rotor type, are similar to those described in an article by K. Beyerle et al (11) in 1950, but are somewhat more developed. The principal differences are that the standard bowl lengths are now 0.75 and 1.2 meters instead of 0.71 meters and that years of operation with frequent stopping and starting has demonstrated the reliability of the machines. Table 4.2 gives the specifications of the German centrifuges described by Beyerle, which were developed from descriptions by Beams (15) and which were used in estimating the pilot plant performance and operating conditions given below. Table 4.3 gives the characteristics of these machines when operating with "Freon 13".

The German centrifuges incorporate several good features. A strong steel case that fits snugly around the bowl protects personnel from flying fragments in case of an accident. The design is compact and leads to convenient layouts. The drive motor runs in the process gas atmosphere and the single thrust-bearing is located at the top of the machine. This permits the introduction of process gas into the ends of the shafts and thereby eliminates a set of seals at both the top and the bottom of the machine.

Purpose and Types of Tests

Up to the present time, test data have been obtained from only one centrifuge at a time, which leads to considerable uncertainty in the results. Tests on a number of machines run simultaneously in various cascade configurations would yield, with the aid of statistical analyses, more accurate knowledge of not only the behavior of single machines but also the performance and interactions of groups of machines.

An additional purpose would be the creation of an industrial team with experience in all phases of design, development and operation of industrial gas-centrifuges and the auxiliary equipment necessary for their operation.

The types of tests that would be carried out are outlined in the following paragraphs.

Table 4.2

Specifications of German Centrifuges (1)

Bowl

Material (2)	"Bondur", an aluminum alloy
Inner Radius, cm	6.7
Outer Radius, cm	7.5
Length, meters	0.71 (3)
Radial Clearance to Protective Case (4), cm	0.5

Shaft

Inside Radius, cm	0.3
Gas Seal Clearances, cm	0.005-0.0075

Speed (5)

RPM	46,000
Inner Peripheral Velocity (5), cm/sec	3.22×10^4

- (1) As described by Beyerle (11). These are stiff-rotor machines.
- (2) Steel bowls, which permit higher speeds, are available.
- (3) Newer models manufactured by Sartorius-Werke, under the supervision of Dr. Beyerle of the Institute for Instrumentenkunde, are available in lengths of 0.75 meters. The latest models are 1.2 meters long.
- (4) The bowl spins inside a water-cooled, thick-walled steel cylinder which is strong enough to contain the fragments of the bowl in the event of an accident. The protective case is designed to rotate slightly when absorbing the impact of the fragments. This feature of the design leads to a compact, convenient layout for pilot plant work, since bulky barriers are not needed for protection of operating personnel.
- (5) With an aluminum insert 1 mm thick loading the inner surface of the bowl. With the insert removed, the speed could be increased to 49,000 RPM. The drive motors are capable of 60,000 RPM.

Table 4.3

Characteristics of German Machines (1) Operating with "Freon 13"

Test Gas	CClF ₃
Molecular Weight	104.47 ³
Mol Fraction Cl ³⁷ in Feed	0.246
Mol Fraction Cl ³⁵ in Feed	0.754
Temperature, °F	70
Machines (2)	
r_1/r_2	0.534
$m = \frac{L \sqrt{2 \ln r_2/r_1}}{2 \pi r_2 D p / RT}$	4
$B = \frac{\Delta M V^2}{2 g R T} \left[1 - \left(\frac{r_1}{r_2} \right)^2 \right]$	0.03053
$n = \frac{z}{r_2 \sqrt{2 \ln r_2/r_1}} \frac{2 m}{1 + m^2}$	4.45 per machine (3)
$nB =$	0.1359 per machine (3)
$\frac{\rho_2}{\rho_0} = e^{\frac{M V^2}{2 g R T}}$	9.3
$\frac{\bar{P}}{\rho_0} = \frac{(\rho_2/\rho_0)^{-1}}{\ln \rho_2/\rho_0}$	3.72
$L =$ upflow or downflow (4)	1.073 gm mols/hr
$W'_{\max} = \frac{n B^2 L}{4}$	0.02673 $\frac{\text{gm mols}}{\text{day, machine}}$ (3)

- (1) See Table 4.2
 (2) See nomenclature at end of report
 (3) These values are based on a machine length of 0.71 meters and assume 100% efficiency for the centrifuge.
 (4) Assuming $D\rho/\mu = 1.4$

Separation Characteristics: Separation performance would be measured using several arrangements of machines in series, to eliminate effects of connections, variations in machines, etc. The effects of flow rate and product rate on separative work would be determined.

Cascade Arrangements: Different arrangements of two sizes of machines would be used to determine the effects of interstage mixing and losses, the effect of arrangement on separative work, the effects of flow inequalities in parallel machines, and the effect of bypassing around stages.

Thermal Gradients: Thermal gradients simulating the effects of gas bearings on the bowl would be studied to determine the effects on separation performance.

End-Cap Effects: The effect on separation performance of heat transfer efficiency in the end-cap would be determined by varying the mechanical design of the end-caps on one machine and by varying the coolant flow to all machines. A measurement of end-cap mixing losses would be made by comparing separation efficiencies of 0.75 and 1.2 meter bowls.

Control: The effects of speed of rotation, flow rates, pressures and temperatures, and of their variations would be investigated so that a realistic appraisal of the control problem for a large cascade could be made.

Seals: Control of small pressure differentials and the flow of gases through seals would be studied.

Description of Plant

The plant uses 9 centrifuges: 6 with 0.75 meter bowls and 3 with 1.2 meter bowls. Auxiliary equipment is similar to but considerably simpler than that used in the long-bowl pilot plant (13). The plant occupies 3600 square feet of floor area and needs of the order of 14 feet headroom. Utilities requirements are small and the plant could be accommodated easily in an existing building.

Process piping would be copper tubing. Pumps would be used between centrifuges. Auxiliary systems include motor-generator sets for starting, stopping and running the centrifuges; a casing water system for maintaining uniform temperatures and a cooling water system, including a cooling tower; a hydrogen system for supplying a high-conductivity, low-friction medium between the bowl and the protective case; a CO₂-refrigeration system; a lube-oil system; and the necessary instrumentation, including a mass spectrometer.

The process gas temperature is 70°F and the axial pressure in the centrifuges is about 30 mm Hg. Equilibrium time for the plant under these conditions will be under half a day. Concentrations as high as 55 mol per cent chlorine-37 should be obtained. When operated as a

rectifier with all machines in series, the optimum production will correspond to a product rate of about 0.6 gram-mols per day containing chlorine-37 at a mol fraction of about 0.4.

Cost Estimate

Table 4.4 gives a breakdown of investment costs for the pilot plant using stiff-rotor machines of German manufacture. The total cost is \$756,000, which includes \$356,000 for equipment, \$230,000 for design, procurement and installation of the plant, and \$170,000 for operation. The cost of instrumentation is a large fraction of the equipment cost because of the fact that this is a pilot plant and numerous recording controllers are deemed advisable and mass spectrometers are a necessity.

The program would be carried out in a period of 2.5 years and would require about 280 man-months of effort, which corresponds to an average manpower load of 9 to 10 people. Operation with one or two machines could begin in 8 to 10 months, and shakedown of the whole plant would be complete in 18 months.

Table 4.4

Investment Costs for Stiff-Rotor Pilot Plant Program

		<u>Costs in Thousands of Dollars</u>	
	<u>Item</u>	<u>Per Item</u>	<u>Sub-Totals</u>
<u>Equipment</u>			
Centrifuges			
	6 machines with 0.75 meter bowls	107	
	3 machines with 1.2 meter bowls, including testing	77	
	Shipping charges	<u>7</u>	191
Electrical Equipment and Wiring			
	Generators and switch gear, including \$1000 Shipping	28	
	Foundations, Vibration Meters, Insulators, Wiring, Barrier Wall, Miscellaneous	<u>17</u>	45
Process Equipment			
	Freon Test Gas System		
	Piping and Valves	5	
	Blowers, Compressors, & Vacuum Pumps	17	
	Miscellaneous equipment	2	
	Instrumentation		
	Flow elements and recorder-controllers	37	
	Pressure Indicators and recorders	10	
	Temperature indicators and recorders	8	
	Mass spectrometer, isotope ratio	15	
	Leak detectors	<u>5</u>	99
Lube Oil System			
	Equipment	3	
	Piping and Valves	3	
	Instrumentation	<u>7</u>	13
	CO ₂ System	1	
	Hydrogen System	1	
	Casing Water System	3	
	Cooling Water System	<u>2</u>	<u>8</u>
		Total	356
<u>Engineering Design, Procurement and Installation</u>		<u>230</u>	230
<u>Operation</u>		<u>170</u>	<u>170</u>
		Grand Total	756

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NOMENCLATURE

A = surface area for heat transfer
B = separation constant
C_p = specific heat at constant pressure
C_v = specific heat at constant volume
d = damping constant
D = diffusivity
e = displacement of center of mass from geometrical center
E = kinetic energy
g_c = acceleration constant
h = heat transfer coefficient
I = polar moment of inertia
J = mechanical equivalent of heat
k = ratio of specific heats
K_c = thermal conductivity
KE = kinetic energy
l = length of flow-slot in end-cap
L = upflow or downflow rate through centrifuge; length of rotor
m = ratio of flow rate to ideal limiting flow rate
M = molecular weight; number of centrifuges
n = speed of rotation; separation constant
p = pressure
P = product rate
r₂ = radius of outer flow stream; radius of bowl
r₁ = radius of inner flow stream
R = gas constant; mean radius of hollow rotor
t = wall thickness of hollow rotor
T = absolute temperature
ΔT = temperature difference
V_p = value function of product
W₁ = separative work per machine
x = distance along axis of rotor
y = deflection of rotating cylinder
Z = length of centrifuge
Y = radial flow rate
μ = viscosity
ρ = density
ω = speed of rotation, radians per unit time

Subscripts:

ad = adiabatic
n = resonant or critical speed
o = original or axial
s = suction
1,2 = inner and outer or first and second

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