ORO-210

Report UVA/ ORL-2400-58
~~PR No. 1~~

MASTER

Progress Report
on
Contract AT-(40-1)-2400

THE DEVELOPMENT OF SHORT BOWL ULTRACENTRIFUGES

BY

Gernet Zippe
J. W. Beams
A. R. Kuhlthau

Submitted to:

Physics Branch
Division of Research
U.S. Atomic Engergy Commission

December 1, 1958

Research Laboratories for the Engineering Sciences

University of Virginia

Charlottesville

DISCLAIMER

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(Including a Proposal for Extension)

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I. INTRODUCTION

During World War II, Professor Beams and his co-workers at the University of Virginia demonstrated that a gas centrifuge in the form of a long tube rotated about its axis could be used successfully for the separation of uranium isotopes (1). It has recently been announced that Professor Groth and his colleagues in Germany, who have been working on this problem since 1941, are developing gas centrifuges which they expect to be suitable for the large scale separation of these isotopes (2).

In principle one can separate with such a device any gas mixture having components of different molecular weights, but it is especially suitable for the separation of heavy gases because the separating effect depends upon the absolute difference in mass of the two components, ΔM., rather than the relative difference $\frac{\Delta M}{M}$ which is the case for most other methods. (See Appendix A for elementary considerations of design parameters). Cohen (3) has presented a theory of the gas centrifuge which permits the calculation of the optimum performance for three types of operation: evaporative method, con-current or "flow-through" operation, and counter-current operation.

In the report of Beams etal (4) at Geneva it was shown that good agreement between theory and experiment exists for all three cases. However, the gas centrifuges described in the present report utilize oounter-current flow in which the gas flows in one direction along the axis and in the opposite direction near the wall. Because it permits a larger separation factor this method has been shown to be superior for isotope separation.

The great promise of the gas ultracentrifuge as a separating device for uranium isotopes as related to the future energy supply of the world was reported by Kistemaker and his co-workers at the 1958 Geneva Conference (5).

During the period from 1946-1954 a group of German Scientists under the direction of Professor Max Steenbeck*

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* Now Director of the Institute for Magnetics, Jena

worked on the development of a gas ultracentrifuge in the Soviet Union. This group was composed of approximately 60-65 workers (both German and Russian). Professor Steenbeck directed the theoretical work, Dipl. Eng. Scheffel** the experimental electrical part, and the author led the experimental group for mechanical development and separation tests.

In the period 1946-53 work was done by this group on a long tube approach using short elements of tubes connected by sylphons so as to give an overall length of 3 meters and a l/D of 50. This was considered suitable for the final enrichment stages of a uranium hexaflouride gaseous diffusion plant. When the group was informed that this application was no longer required, they devoted their efforts to the development of a device suitable as the basis for a complete plant starting with natural uranium. As a result of their experience with the long tube program, a very simple short tube gas ultracentrifuge with exceptional performance characteristics was built. Because of the inexpensive construction made possible by its simple design, the very low electric power consumption, and a novel method for handling the process gas this device is believed to be superior for large scale separation of uranium isotopes to gaseous diffusion or other known types of gas centrifuges.

The present research program has as its principal objectives, the reproduction of this device, a careful study of its mechanical characteristics and a thorough demonstration of its separating ability as applied to the uranium problem.

** Now at DEGUSSA, Frankfort/Main

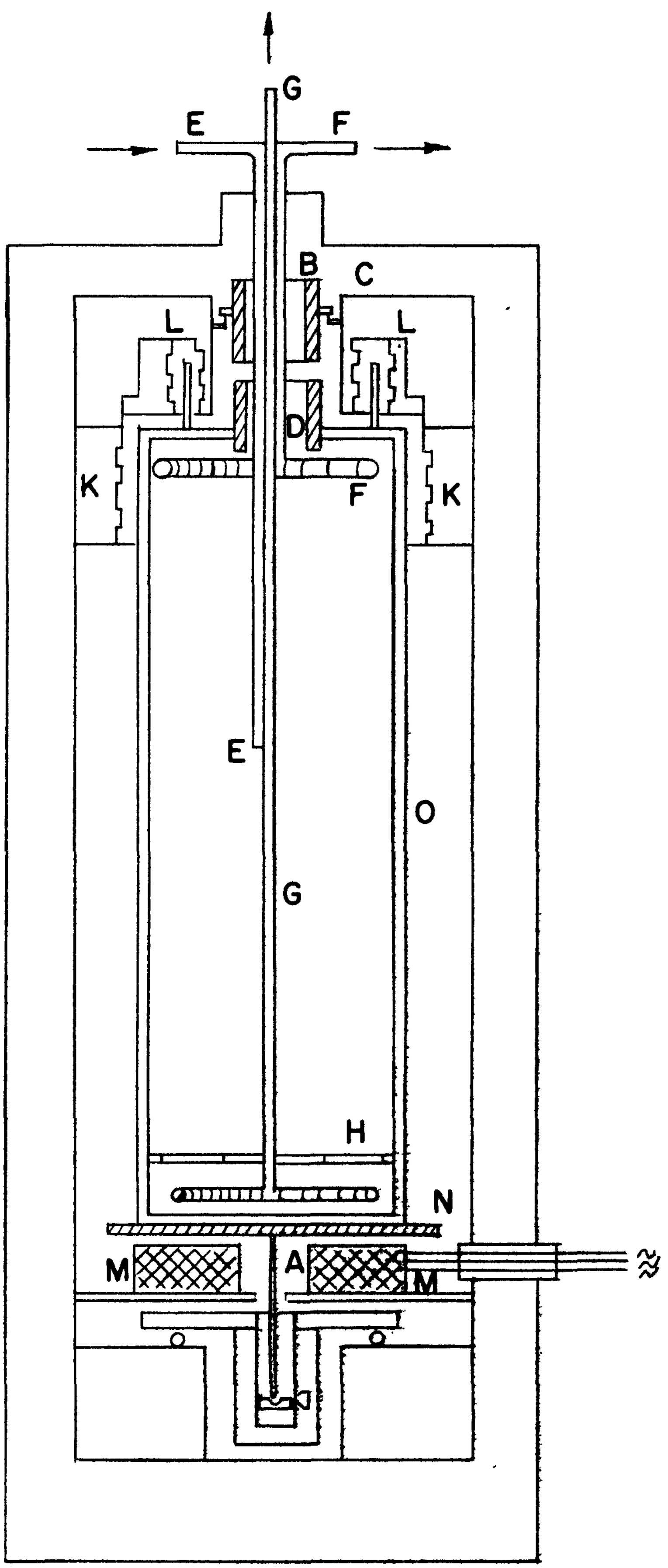
II. GENERAL DESCRIPTION OF METHOD

The type of centrifuge developed in Russia is a self-stabilizing system as shown in Fig. 1. The centrifuge rotor, O, spins about its inertial axis on a thin, flexible steel needle, A. The needle itself is centered in a depression of a hard metallic plate, J, which in turn is centered elastically and whose lateral motion is damped by oil friction. The upper bearing, B, consists of a hollow cylindrical permanent magnet mounted in a damped Cardanic suspension, C, which attracts a steel tube, D, mounted rigidly on the rotor. There is no mechanical contact between these parts.

Three tubes for the insertion and extraction of process gas pass through this opening. The feed tube, E, ends in the middle of the rotor, while the other two tubes, F, and G, terminate at opposite ends of the rotor and have their extremeties bent into a hook-shaped curve in a plane perpendicular to the axis of rotation. These end sections, known as scoops, make use of the high impact pressure in the vicinity of the periphery for transport of the heavy and light gas fractions. Simultaneously, one of the tubes, F, by means of the reduction of the angular velocity of the gas induces the desired counter-current flow, while the other, G, is shielded by a plate, H, so as not to disturb the flow of the gas.

Screw type grooves in the wall of the vacuum cylinder, K, in combination with the rotating tube act as a molecular pump to maintain a vacuum around the rotor. A similar pump is located on the end of the rotor, L, which serves to direct the output of the first pump into the interior of the rotor. These pumps suffice to keep the pressure in the space outside the rotor to a very low value which reduces the gas friction to a negligible value.

The rotor is driven by an electric motor, M, the armature of which is a flat hardened steel plate, N, attached rigidly to the bottom of the rotor. The field winding, M, is located in the vacuum and is fed by an alternator at a frequency synchronous with the speed of the rotor.



SHORT BOWL CENTRIFUGE
FIGURE 1

A prototype model of this device which was completed in the Soviet Union in 1954 had the following characteristics.

(a) Length of rotor - 0.5 meter
(b) Diameter of rotor - 0.1 meter (l/D ratio is selected to insure full speed operation below the first critical of the tube).
(c) Peripheral speed of rotor - 350 meters/sec or 1100 rps
(d) Total power requirement for operation with process gas - 14 watts as measured by rate of slowing down of rotor with no power input.
(e) Electrical power requirement of motor - 40 wats corresponding to a motor efficiency of 40%
(f) Separation coefficient, α, - 1.14 (the ratio of the concentrations of the extracted to the feed gas for uranium hexaflouride)
(g) Efficiency of separation process - 30% of the maximum theoretical value without consideration of back diffusion. Losses due to this cause were about 55%.

On the basis of the experimental results obtained with this prototype machine the group calculated the characteristics of a "unit plant" designed to produce, in an ideal cascade arrangement, one kilogram of uranium metal enriched to 96% U_{235} per day. The concentration of U_{235} in the waste stream was assumed to be 0.5 percent.

For a peripheral speed of 350 meters/sec. a length of 20,000 meters of rotor which corresponds to an energy requirement of 3 megawatts (including a reserve for unforeseen control and pumping units) is required. Improvements in the energy consumption (eg. the efficiency of the drive motor was assumed to be only 40%) as well as a reduction in the total length of the tubing (an efficienty of only 30% with respect to the optimum theoretical separating power was assumed) appear to be certainly obtainable even if an increase in the peripheral speed of the rotor is not possible. As pointed out in Appendix A, such a speed increase would contribute heavily to improved performance.

The cost was estimated by Soviet engineers to be 1000 rubles per unit. The basis for this figure is not known.

However, it is believed that this device could certainly be produced in large quantities in the United States for less than $1,000.00 per unit (excluding the external gas handling system and power supply).

III. REPORT ON PROGRESS TO DATE

The work of reproducing the original effort is divided into three parts.

Part I - Construction and lifetime testing of mechanical prototypes.

Part II - Study of the dynamic properties of the scoop system using an inert gas. Particular emphasis will be placed upon power requirements and pressure.

Part III - Application of such a rotor to the actual separation of uranium isotopes.

At the present time work is underway on Parts I and II of the above program as outlined below.

A. General Preparatory Work

The start of the program was delayed somewhat by the fact that it was impossible for the author to arrive in this country before mid July. Because of the rather long delay between the original discussion pertaining to this program and its actual inception, it was necessary to change the plans for housing the work somewhat. An unexpectedly large graduate student enrollment at the University of Virginia in Physics restricted somewhat the space that would be available in the physics building. At the same time a separate building located near the physics shop was made available to the Ordnance Research Laboratory for on-campus projects. Consequently it was decided that the best interests of this project could, in the long run, be met by using this newly acquired building. Very little renovation was necessary, and the installation of services and facilities for the work did not cause much delay. The space available under the new arrangement was much larger than could have been secured in the physics building, and the privacy and independence afforded is a valuable asset in carrying out the work according to ones own schedule.

Under the present arrangement, large machine work is done in the physics shops by Mr. August Deutch who accompanied the author from Europe as instrument maker for the project. The Ordnance Laboratory has provided a small shop in the new building which is adequate for more than 70% of the machine work. An electronic technician, Mr. Wilbur May, is employed full time by the project, and the services of various members of the staff of the Ordnance Research Laboratory have been made available to assist in selecting materials, equipment etc., since U.S. products and procedures are unfamiliar to the author. Although this mode of operation has undoubtedly caused some delays, the liason has been good and it is believed that the work is progressing with all due dispatch.

B. Mechanical Construction and Tests

The first project was to build test stands for the rotors as well as to build the rotors themselves, and to wind the drive motors.

The first stand constructed was one to be used for experiments in air (Fig. 2) such as testing unbalance of rotors, observing damping in upper and lower bearing assemblies, performance of various motor designs, etc. The power supply for this stand is a 400 cycle, 3-phase generator developing 100 watts.

The second stand was a vacuum stand for the more general testing of rotors and bearings. It will accommodate rotors up to 4" O.D. and up to 25 inches long and is shown in Fig. 3. This stand is powered by a 1.5Kw, 3-phase generator variable

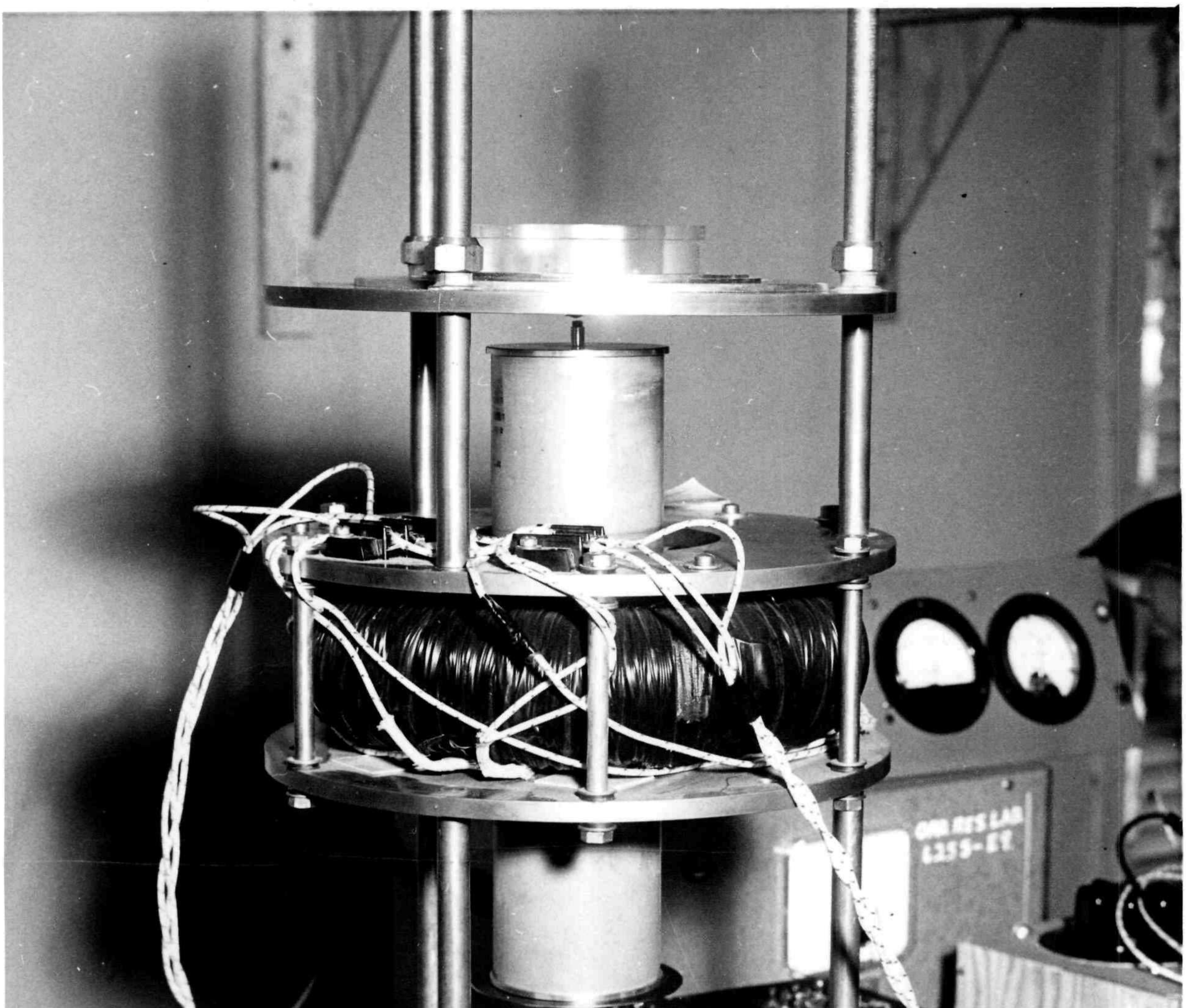


FIG. 2

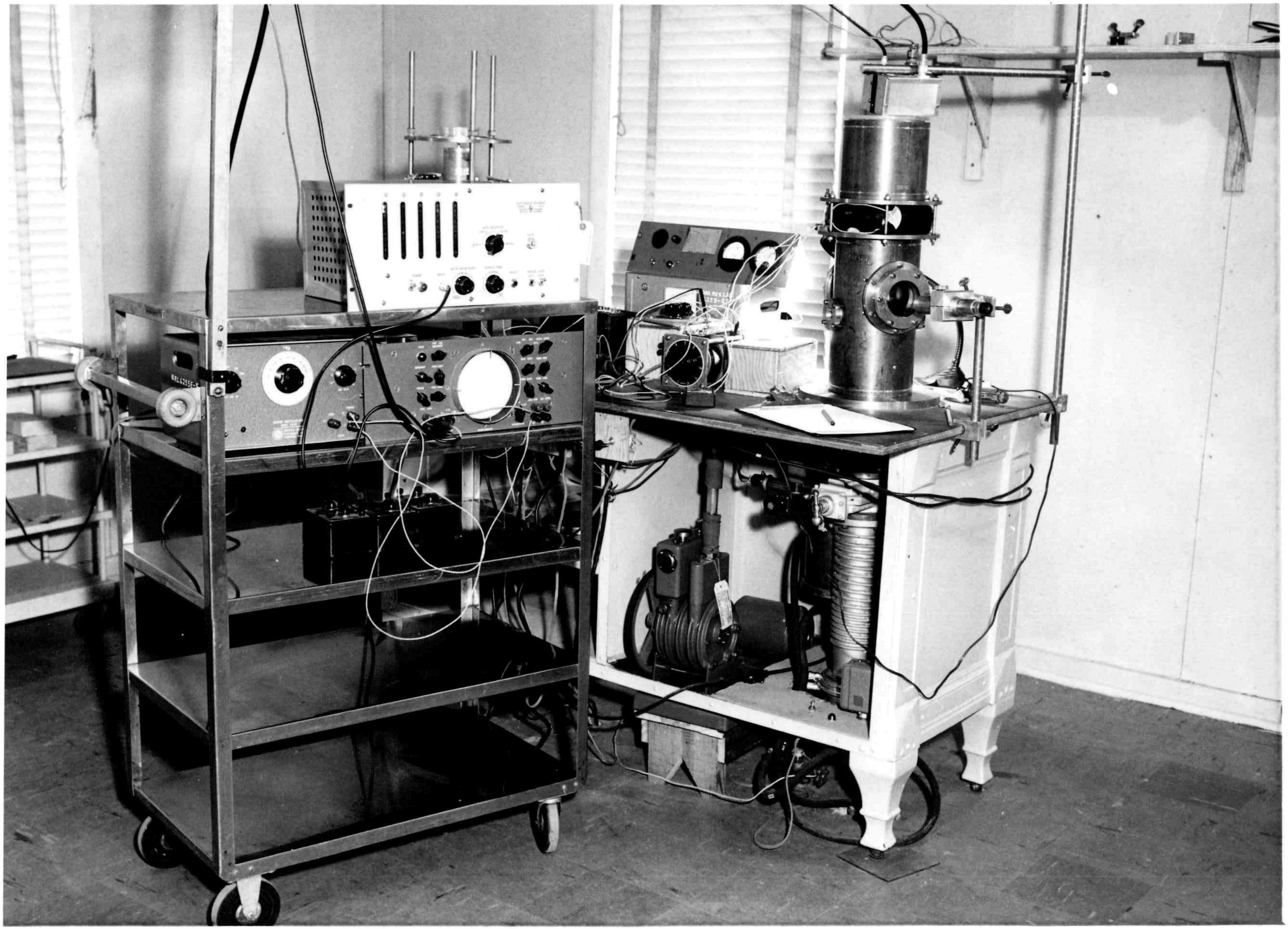


FIG. 3

in frequency from 750 to 3600 cps. The vacuum system is of a usual type containing a mechanical pump and an oil diffusion pump and they are connected together to provide maximum versatility in operation as well as in opening the system for access to the rotor.

A third test stand has recently been completed for the special lifetime experiments called for in the project. This consists of 2 heavy walled metal vacuum cylinders connected to a common pumping system (Fig. 4). At present it is planned to use only a mechanical pump on this system and it should be possible to operate two rotors continuously without constant observation and without danger. These cylinders will accommodate rotors 11 inches long by 2.75" O.D. in the initial lifetime experiments. This test stand is driven by the same power supply as stand No. 2.

Several test rotors of 2014 aluminum alloy have been built to date. They are all 11 inches long by 2.75 inches O.D. Two of these rotors have been given extended life tests at 1500 rps in a vacuum. The bearing assemblies used in these tests, although similar in principle to the ones previously described, are slightly different in detail and these are discussed more fully in the next section.

One rotor successfully ran for 300 hours before failure. The failure occurred at the end cap. The top cap was designed so that it slipped over the tube on the outside with a press fit. After 300 hours of operation this fit loosened and the end cap came off. The reason for this is not clear, but could have been caused by differential creep between the end cap and rotor. The second rotor made the same way with the same materials is now under test to see if this failure repeats. It has been in operation for 100 hours at the time of this writing.

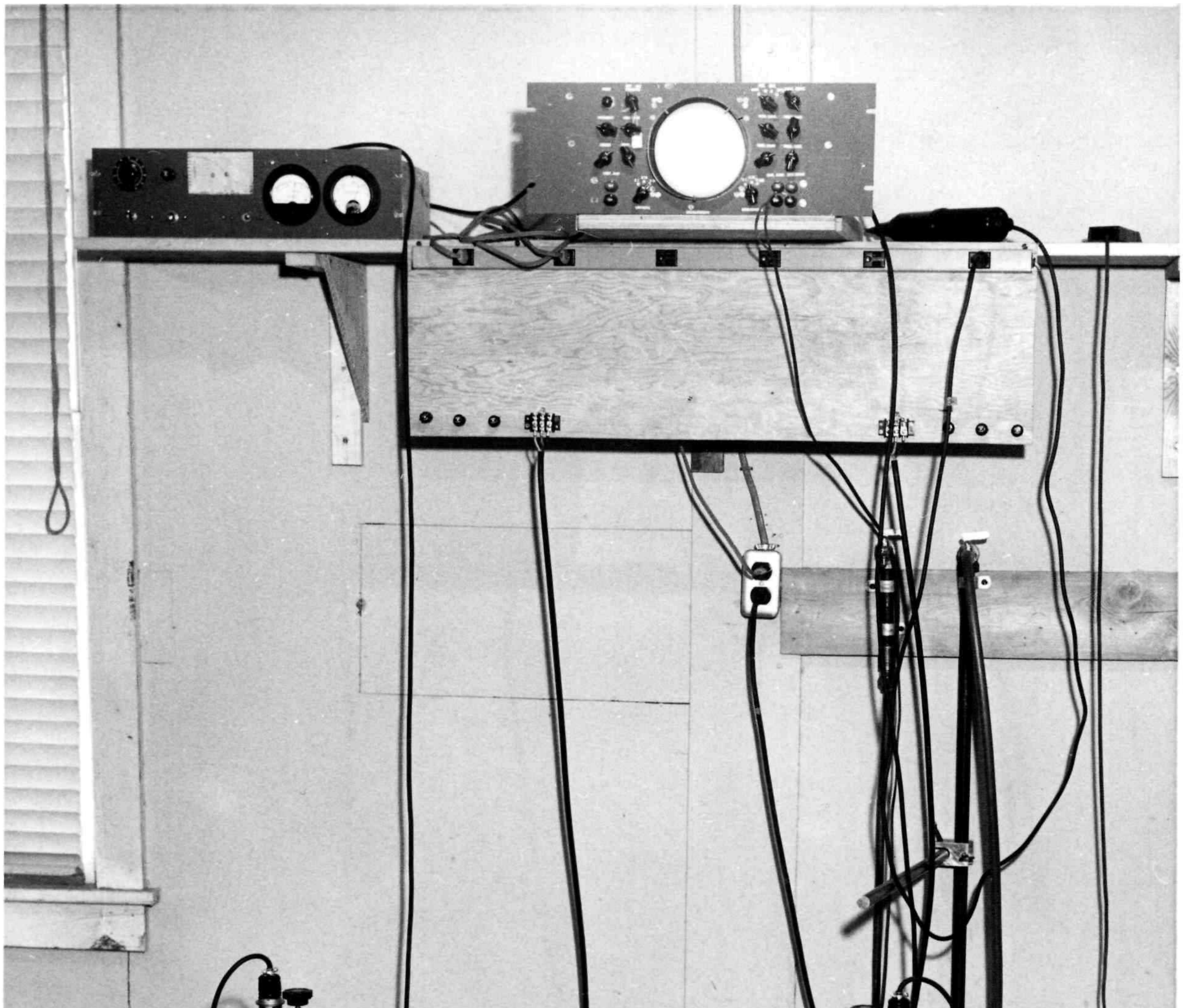


FIG. 4

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C. Description of Principal Mechanical Components.

1. Electric Motor

The electric motor drive is basically very simple. As explained previously, the armature is a flat steel plate attached rigidly to the bottom of the rotor and of course located in the vacuum. The stator consists of a flat winding on a laminated core mounted in these mechanical tests outside of the vacuum jacket at the bottom. A photograph of a typical stator winding is shown in Fig. 5.

2. Upper Bearing Assembly

The upper bearing assembly can be seen schematically in Fig. 6. This is the type bearing being used on the mechanical tests and is different from that which will be used when separating gases. It is a magnetic bearing without mechanical contact.

A magnet, 1, mounted in the upper end cap of the rotor, 6, is attracted by another magnet, 2, which is held against a third magnet, 3, by means of the steel ball, 4. This permits universal motion of 2. Damping is accomplished in this assembly by means of the plastic filaments, 5, which damp by means of their internal friction. The fixed magnet, 3, increases the magnetic attraction in the unit.

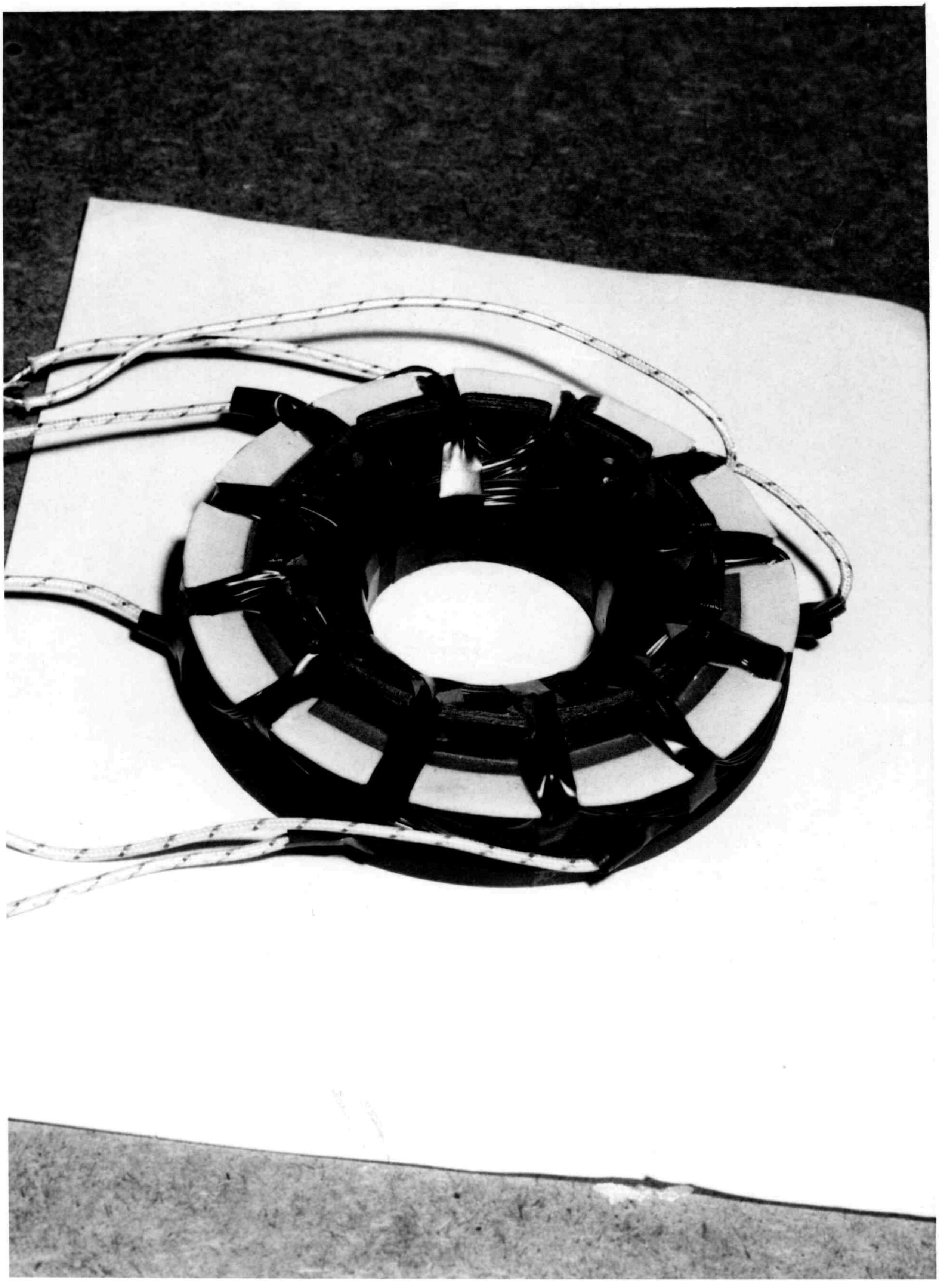
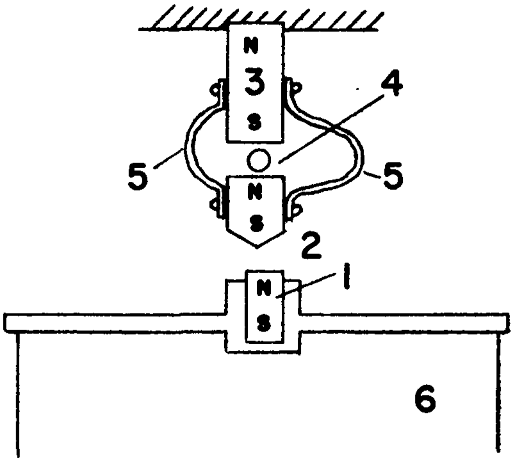


FIG. 5



UPPER BEARING ASSEMBLY
FIGURE 6

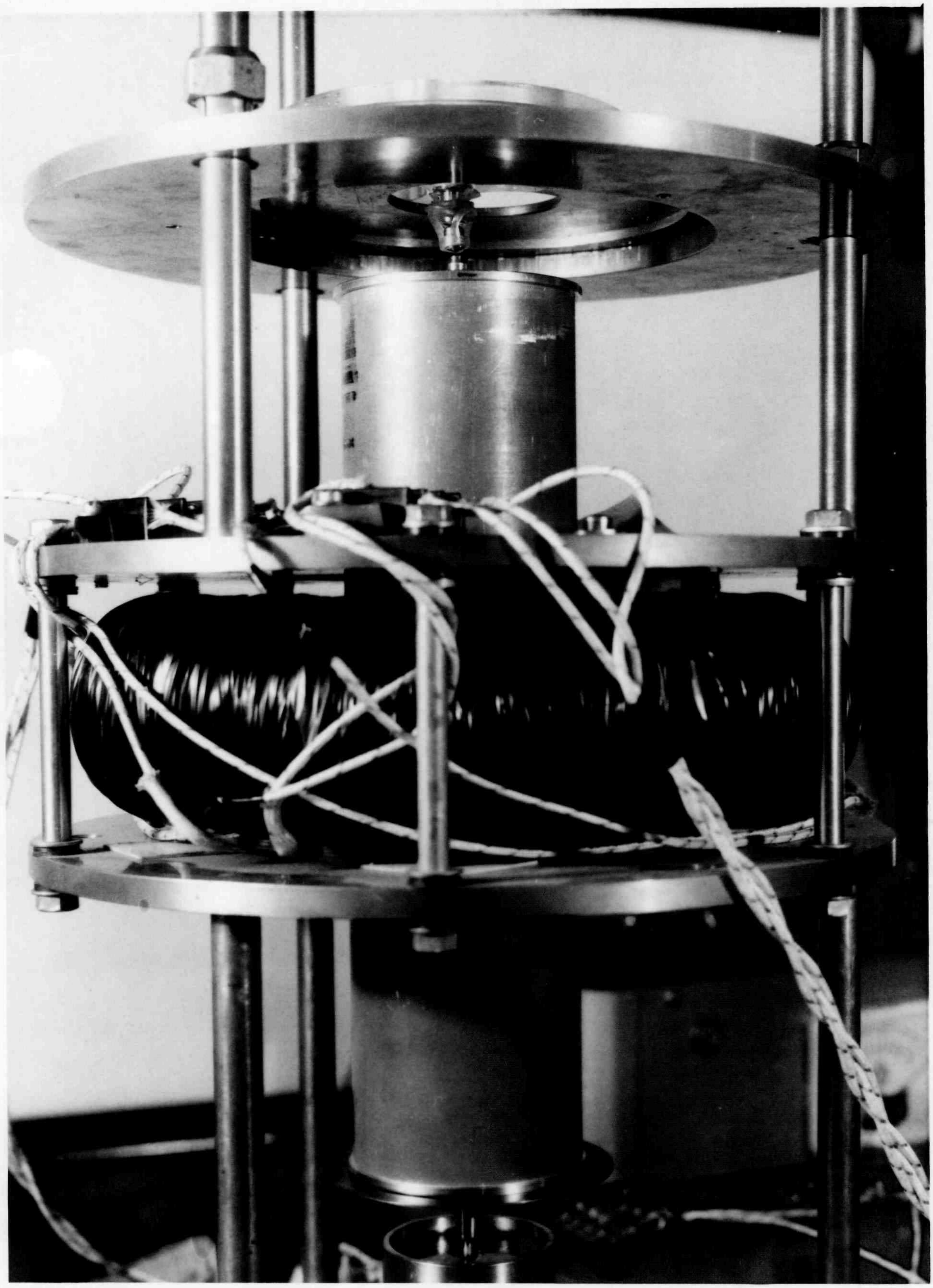


FIG. 7

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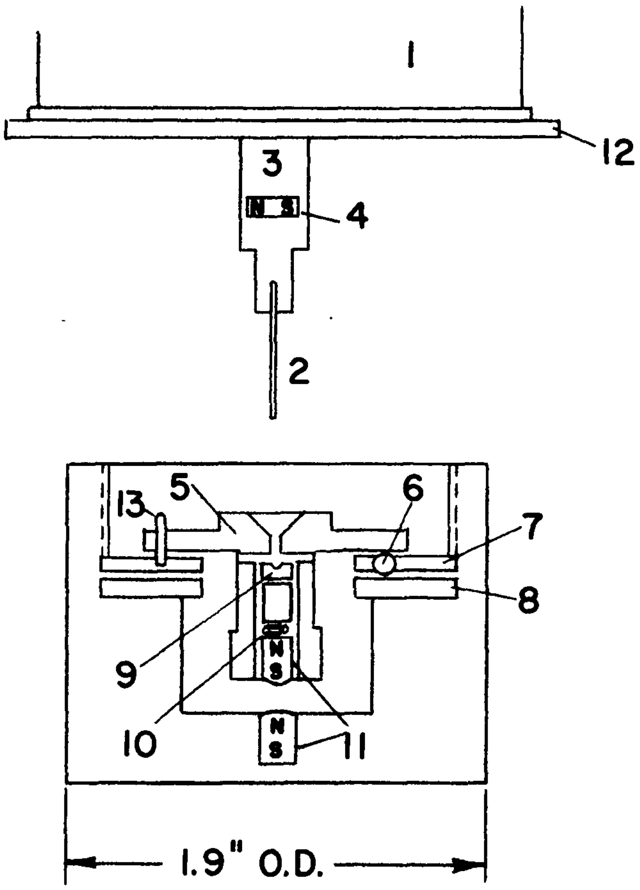

LOWER BEARING ASSEMBLY
FIGURE 8

FIG. 9

IV. GENERAL ADMINISTRATIVE REPORT.

A. Report of Expenditures to December 1, 1958

1.	Direct salaries and labor	$ 8,842.00
2.	Travel	1,000.00
3.	Materials and supplies	2,743.00
4.	Equipment	2,507.00
5.	University charges	3,838.00
	Total expenditures to Dec. 1, 1958	$ 18,930.00

B.	Estimated expenditures 1 Dec. 1958 - 28 Feb. 1959	$ 13,000.00
C.	Estimated funds remaining in Contract 28 February 1959	3,584.00

D. CHANGES BETWEEN ACTUAL AND PROPOSED RATES OF ACTIVITY

There have been some few alterations between the actual rate of progress on the contract and that outlined in the original proposal. The principal difference was in necessity brought about by the fact that it was impossible for Dr. Zippe to arrive in this country until mid-July instead of earlier in the spring as had been originally anticipated. Thus the contract was inactive until his arrival. It was extremely difficult to prepare the original proposal since it had to be based on a single previous meeting with Dr. Zippe in this country. The inevitable large number of questions involving detail which arose during the preparation of the proposal had to be answered by estimation on our part and after Dr. Zippe's arrival it was found that our estimates as to equipment, materials and supplies were a little low.

Also by increasing the level of supporting help somewhat it is felt that an amount of work essentially equivalent to what is contained in the first three items of Title I, Appendix A of the contract could be definitely completed by February 28, 1959. (i.e. in 8 months instead of a longer period as originally estimated).

Hence, by consultation with Dr. Holstad it was decided that we would go ahead and spend what was necessary to maintain a productive research effort, rather than requiring that the original budget hold for a twelve month period. It was possible to do this since the contract would come up for consideration as to extension and refunding within eight months after the actual start of work.

There was also a change in the physical location of the project as mentioned in an earlier section.

E. INCIDENT REPORT

1. Serious incidents - None
2. Fires, explosions, lightning, windstorns, floods and sprinkler leakage - None
3. Other property damage accidents - None
4. Personal injuries - None

F. TECHNICAL REPORTS AND PUBLICATIONS

There were no technical reports or publications issued during the period covered by this report.

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APPENDIX A

ELEMENTARY THEORY OF THE GAS CENTRIFUGE

The maximum "separative power" of a gas centrifuge is proportional to the fourth power of the peripheral speed and is directly proportional to the length as well as the square of the difference of the molecular weights of the substances to be separated*.

$$\delta U_{max} = \frac{\pi \rho D L}{2}\left[\frac{(M_2 - M_1) v_a^2}{2RT}\right]^2$$

The advantage of the centrifuge process for separation of components of high molecular weight is evident from the above equation. The effect is determined by the absolute difference in the masses of the two components $\Delta M = M_2 - M_1$ instead of the relative difference $\Delta M / M$, which is the case for all diffusion processes.

It is also evident that one should make the peripheral speed of the centrifuge and its length as large as possible. The peripheral speed is limited by the bursting strength of the material of the rotor wall. The wall material must be chosen with a ratio of tensile strength to density which is as large as possible as can be seen from the following equation for the maximum peripheral speed

$$v_a^2 = \frac{T_f}{\rho}$$

The hard duraluminum alloys are especially suitable for this purpose. The tubes of this material are light and in consequence of their high elastic modulus have a relatively high "first critical" speed for a given length. Duraluminum rotors 50 centimeters long and 10 centimeters in diameter do not have to pass through their first critical speed to reach a peripheral velocity of 350 meters per second.

Doubling the peripheral speed results in a sixteen fold increase in the separative power and therefore one sixteenth

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* A table of definitions of the symbols used in this Appendix appear at the end of this section.

as many centrifuge units in a plant of given capacity. A doubling of the length corresponds to a doubling of the "separative power" and corresponds to a nineteen percent increase of the peripheral speed.

The elementary radial separating factor for uranium hexafluoride corresponding to peripheral speeds of 300, 350 and 400 meters per second are 1.056, 1.076 and 1.101 (which may be compared to a value of 1.0043 for the diffusion method). This elementary separating is multiplied in the counter current flow centrifuge to a degree which depends on the ratio of the length of the rotor to its diameter. This is evident from the following equation for a counter-current which has been developed by Cohen and Martin and Kuhn.

$$\alpha = e^{\frac{(M_2 - M_1) V_a^2}{2RT} \frac{L}{2Na}}$$

The total number of meters of the running tube required for a given rate of production of material at any enrichment for the ideal cascade (neglecting leakage and mixing losses) is independent of the ratio of length to diameter if all parts operate at under optimal conditions.

DEFINITIONS

U = separative power

ρ = density

D = diffusion constant

M = molecular weight

v_a = peripheral speed

R = gas constant

T = absolute temperature

σ_f = elastic limit of material (tensile yield strength)

L = length of centrifuge rotor

$2r_a$ = diameter of centrifuge rotor

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