THE CONSTRUCTION AND SOME APPLICATIONS OF AN ELECTRICALLY DRIVEN ULTRACENTRIFUGE

A Thesis Submitted to the Faculty
of Graduate Studies and Research
of McGill University, in partial
fulfilment of the Requirements for
the Degree of Doctor of Philosophy

by

Avrahm B. Rotenberg, B.A., M.Sc.

The Macdonald Physics Laboratory,
McGill University.

September, 1941.

ACKNOWLEDGEMENT

Sincere thanks are due to Professor J. S. Foster for the encouragement and support he has given this work. His ready interest and numerous suggestions were of great assistance. I also wish to express my appreciation to Dr. A. N. Shaw, Director of this Department, for his support of this project.

Much valuable advice was obtained from Professor J. W. Beams, Dr. C. Skarstrom, and Mr. E. C. Hutter of the Rouss Physical Laboratory, University of Virginia. Dr. D. Shugar supplied details of his experiences in working with the rotors. Professor H. Hibbert, Dr. L. M. Cooke, and Mr. R. F. Patterson of the Pulp and Paper Research Institute, cooperated in the study of the lignin samples. In the biological work the assistance of Dr. D. Siminovitch was invaluable.

Grateful acknowledgement must be made to Messrs. Tweeddale, Pye and Taylor of the Laboratory staff, who constructed most of the apparatus. Mr. S. Amesse supplied helpful technical assistance.

SUMMARY

The construction and operation of a vacuum ultracentrifuge are described. The duralumin rotor carries up to 96 cc of material for centrifugation. It is driven by a two phase induction motor supplied by a 1 kw audiofrequency generator, also described. The rotor is suspended from the armature, in vacuo, by a flexible stainless steel shaft. The whole rotating system is supported by an electromagnet.

With this drive the rotor has been accelerated to 30,000 RPM in 13 minutes, with 1 kw power input. With 400 watts input and no attention from the operator, the speed remained within 3.1% of this figure for nine hours. By reversing the current, the system was brought to rest in 8 minutes, with only 300 watts applied.

The centrifuge has been used for a preliminary study of the molecular weight of lignin dissolved in ethanol. The effects of high centrifugal fields on living cells are also described.

TABLE OF CONTENTS

I. INTRODUCTION

(a) Historical.

Centrifugal force is familiar to everyone; the physical principles underlying it have been understood since the time of Newton. An early mention of an application of the centrifuge is by Knight (1) in 1806. He arranged a water wheel in such a way that plants could be attached in various positions at its periphery and rotated rapidly about a vertical axis. In this manner he found that plants respond in a characteristic way to centrifugal force. The most widely known application, the centrifugal cream separator, has been in use since at least 1877. Today many diverse applications are found both in industry and in the biological, chemical and medical sciences. However, it is only during the past ten years that the importance and usefulness of very high rotational speeds have become apparent. The man most responsible for this development is Professor The Svedberg, of Upsala, Sweden, who has been working in this field since 1923. His comprehensive monograph "The Ultracentrifuge" (2), is the standard work in this field. It contains a bibliography covering every aspect of this subject, complete until June, 1939.

Svedberg suggests that the term ultracentrifuge be reserved for an instrument by means of which sedimentation in a centrifugal field is measured quantitatively, and that an ordinary laboratory centrifuge of high speed be called supercentrifuge. However, this distinction loses its validity in the case of machines which may be used in both ways, as the one here. For this reason, as well as for brevity, the term centrifuge, unprefixed, will be employed throughout.

The classical experiments of Perrin (3) for determining particle weight by measuring the sedimentation velocity of particles suspended in a fluid and under the influence of gravity, are well known. In a similar fashion, particle mass has been determined by measurements of particle distribution in small volumes in which equilibrium has been attained between sedimentation and diffusion, in a gravitational field. However, the weakness of the earth's field puts a definite limit to the application of these methods, as only relatively large particles of high density can be studied in this way. For the investigation of colloids and high molecular weight substances the field must be increased many thousandfold. This can be accomplished by rotating the solution and so exposing it to a centrifugal field.

The first attempt in this direction was made in 1913 by Dumanski (4), but was unsuccessful due to deviations from ideal sedimentation caused mainly by convection currents. Nothing further appears to have been done until Svedberg, Rinde and Nichols (5) became interested in the subject in 1923. They built a small optical centrifuge with which sedimentation could be followed visually and photographically. They found the following conditions for convection-free sedimentation: the sample must be sector-shaped, completely enclosed, and of not too large dimensions; the friction of the surrounding medium must be reduced; the heat from the bearings must be removed.

During the following years the work of Svedberg and his co-workers proceeded along two different lines. In the first place, their original mechanically driven centrifuge was improved so as to make it more trustworthy and semi-automatic. With it a usable speed of 18,000 RPM was reached in 1933, corresponding to a centrifugal field of 19,000 times gravity. Secondly, they built machines capable of creating fields of the order of 100,000 times gravity, such as are necessary for sedimentation velocity measurements on substances like proteins. The importance of the latter lies in the fact that a detailed analysis of the different molecular species present in a solution is possible only by means of sedimentation velocity measurements. The basic features of these first extremely high speed centrifuges are a steel alloy rotor mounted on a horizontal axis and driven by oil-turbines in an atmosphere of hydrogen at reduced pressure. With one of these a speed of 77,000 RPM, corresponding to 400,000 times gravity, was reached in 1933. This is the limit imposed by the mechanical strength of the rotor material. However, further experiments were carried out with smaller rotors, by which higher fields were obtained at the sacrifice of height of column of solution and homogeneity of the centrifugal field. Thus a speed of 154,000 RPM, corresponding to 900,000 times gravity, was reached in 1934: unfortunately these rotors exploded after a few runs. In 1935 the size was further reduced and useful fields of 750,000 times gravity were obtained at 148,000 RPM.

Svedberg has compared measurements made in very intense fields using a low column of solution and a small mean radius, with similar measurements made in less intense fields using a higher sample situated farther from the center of rotation. He found the accuracy much greater in the latter case, at least as far as sedimentation velocity measurements are concerned. Hence he has concluded that a larger rotor is preferable for standard equipment. This is important since with most types of driving mechanism the opening for the optical path is fixed in advance, and rotors used with it must conform. Svedberg found the mean radius of 6.5 cm to be the optimum. Rotors carrying transparent cells and intended for photography of sedimentation velocity or equilibrium are usually called "Svedberg" rotors. Those with larger openings for carrying comparatively large quantities of material for centrifugation are known as "quantity" rotors.

The Svedberg high speed centrifuge is a model of machine design and precision workmanship. Unfortunately, it is very elaborate and costly both to build and to maintain. However, a somewhat more recent development along considerably different lines has led to the building of cheap and relatively easily made centrifuges which compare favorably with Svedberg's in every respect.

The fact that a ball can be freely supported by a jet of air or water is common knowledge. However, it was only in 1925 that Henriot and Huguenard (6) applied the principles involved in that experiment, and succeeded in spinning small cone shaped rotors to high speeds in air at atmospheric pressure. This work was taken up first by Beams (7), and later by McBain and O'Sullivan (8). Its essential features were retained; changes were introduced to improve the stability of the rotor and make it a useful research tool. Its chief disadvantages are due primarily to air friction: these are the difficulty of maintaining temperature equilibrium, and the large amounts of power necessary to drive rotors of more than an inch or so in radius. To overcome them, Pickels and Beams (9) used a small air-driven and air-supported rotor (turbine) to drive a much larger rotor inside a vacuum chamber by means of a driveshaft passing through an oil gland. Later (10) two air lines were used to separate the functions of driving and supporting the rotating system.

This centrifuge has been developed considerably and in a variety of forms, by Professor Beams and his collaborators, until it possesses few of the disadvantages of previous machines. Its advantages are as follows: If sufficient air pressure is available, the speed of the centrifuge is limited only by the explosion speed of the rotor. Since the rotor is run in a vacuum, and at its working speed vibrations are absent, convection-free sedimentation is assured. The centrifuge is self-balancing, so avoiding extreme precision in dynamically balancing the rotor, which is one of the drawbacks of Svedberg's machine. However, it requires either the constant attention of an operator or special controlling equipment to ensure a reasonably constant speed below the probable explosion speed. This difficulty was overcome by Beams and Snoddy (11) by using an electric motor to drive the system, in place of the air turbine, while retaining the air support. Later Beams and Black (12) improved the machine by using an electromagnetic support for the rotating system. Finally Skarstrom and Beams (13) improved the drive by adding an automatic controlling circuit through which a high degree of constancy of speed was attained.

The optical systems used with almost all of these centrifuges have been modelled after that of Svedberg (2), (14). Especially interesting is the development of cells for carrying the samples which can withstand the enormous fields imposed on them and still retain their shape; these are fully described in the references just cited.

(b) Previous Work at McGill.

Early in 1937, Professor J. S. Foster and Dr. D. Shugar began the construction of a high speed vacuum centrifuge in this laboratory. A stout vacuum tank and a vacuum system for it were built. Two rotors, resembling those described by Bauer and Pickels in (14) and (15), were made in the shop here. Compressed air drive and support were used; several types were tried, similar to those described in (15) and by Pickels in (16). With the latter, rotational speeds of 18,000 RPM with the quantity rotor and 30,000 RPM with the Svedberg rotor were reached early in 1940. These compare with probable safe maxima of 30,000 and 60,000 RPM respectively. The reason only relatively low speeds were attained was the limited capacity of the air compressor. This could have been remedied by installing a larger compressor; instead it was decided to build an entirely new drive, of the electrical type described by Beams and Black (12). This was only partially complete when a letter from Dr. C. Skarstrom was received, giving the details of a much more satisfactory electric drive, later published by him and Beams (13). This used most of the parts already on hand.

Furthermore, it appeared to be so much more powerful, reliable and efficient than the earlier one, that it was decided to scrap the unfinished electric drive and build the new one. Most of the additional equipment required for the new drive was obtained, and shortly thereafter the writer was given the work of building the new driving system.

In the course of the early trials with this drive, a great deal of trouble was experienced in damping precessional vibrations. Due to inadequate damping the driveshaft became fatigued and broke when the system was rotating at about 10,000 RPM. This made the Svedberg rotor unfit for further experimentation, and the alloy necessary for a new one could no longer be obtained. Hence this work will be concerned entirely with the heavier and slower quantity rotor.

II. THE CONSTRUCTION AND ASSEMBLY OF THE CENTRIFUGE.

A scale drawing of the mechanical arrangement of the centrifuge, in section, is included in this thesis. Throughout the following detailed description, the letters used refer to the drawing. The setup is fairly similar to that of Skarstrom and Beams (13), but differs in numerous details.

(a) The Rotating System.

This consists mainly of the armature A, the support core T, and the rotor R, all mounted coaxially on the shafts S_1 and S_2. These parts comprise two separate assemblies: the upper is the armature assembly, and forms a rigid unit; the lower is the rotor assembly, which will usually be called simply the rotor. They will be described from the top downwards.

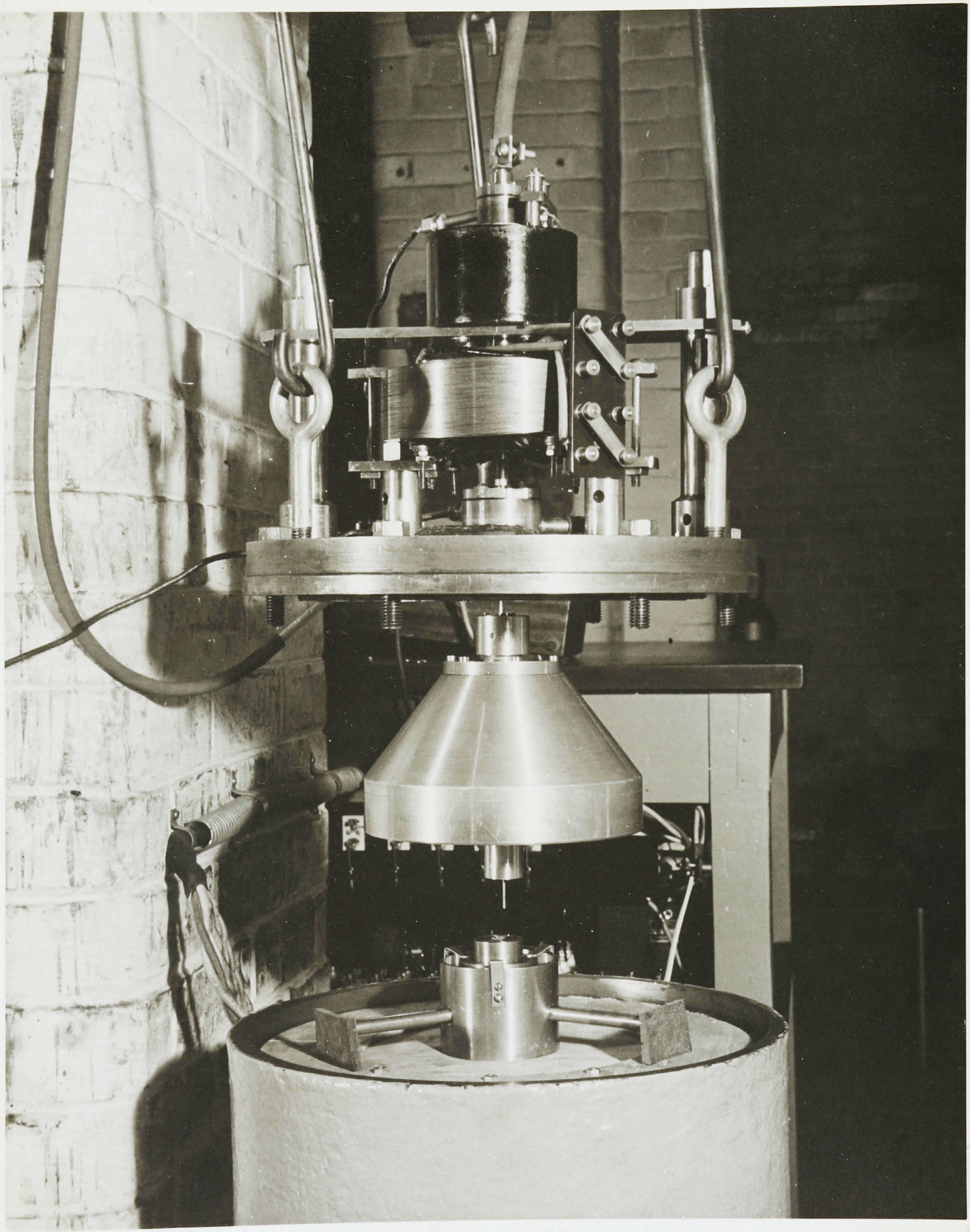
The driveshafts are of seamless tubular stainless steel, #18-8, temper 3, obtained from the Superior Tube Company, Norristown, Pennsylvania. Its outer diameter is 1/8", and wall thickness 0.040". The exposed part of the upper shaft S_2 is 1-9/16" long. It is fitted tightly into the steel plug Q, and serves merely to center the upper end of the rotating system. The hole at the top of this shaft forms the inlet for the water cooling.

The steel plug Q is 1/4" in outer diameter and 13/16" long. Its length was adjusted to give the required total length of the rotating system. It is screwed firmly into T.

The core T and the armature A were made of a single piece of cold rolled steel. T is 13/16" in diameter and 1-7/8" long, while A is 1-9/16" in diameter and 2-3/16" long. A 1/4"

Figure 1

Photograph of the Assembled Centrifuge



diameter hole was drilled centrally through them, to act as a passage for the coolant. The magnet, when energized, pulls T vertically upwards, supporting the whole rotating system.

The steel piece D serves several purposes. Its upper portion is 1-1/8" in diameter and 1/4" thick; it fits snugly into a recess in the base of A, and is held by three screws. A tight fit is necessary in order to prevent leakage of water. The inner surfaces and the screws are greased to counteract rusting. The main body of D is 3/8" in diameter and 13/16" long. At present a piece of black paper is pasted over the whole of its surface except for a narrow vertical strip; the latter serves as a mirror by means of which the speed of the rotating system is measured. This part of D could act as the armature of a coil in which alternating currents corresponding to both motor frequency and centrifuge speed would be induced; these could be used both to measure and to control the speed of the centrifuge. The lowest part of D is 1/4" in length and diameter. Its function is similar to that of Q.

The driveshaft proper, S_2, is exposed for 4-5/16" of a total length of about 5". It was fitted tightly into D, a rivet driven through, and the central portion drilled out to leave an unobstructed hole in the driveshaft. Rivetting was necessary to ensure support of the weight carried by this shaft. A #56 drill hole in the wall of the shaft, 7/8" below the bottom of D, acts as the water outlet. It should be noted that the action of centrifugal force at this hole is such as to require that it be the water outlet rather than the inlet. The lower end of the shaft is plugged. The use of a flexible shaft allows the centrifuge to seek its own axis of rotation, which for a reasonably well balanced rotor is so close to the vertical that no appreciable fatigue results in the drive-shaft. Hence dynamic balancing of the rotor to a high degree of precision is unnecessary, and stable operation is easily obtained.

The rotor consists of four main parts: R is the rotor proper, N its head or cap, C the chuck, and Z the spindle. Rotor, cap and chuck are similar to those described by Bauer and Pickels (15). R was machined from a solid block of forged duralumin alloy 17 S-T, x-rayed to ensure absence of flaws. This material combines relatively high tensile strength with low density; Biscoe, Pickels and Wyckoff (17) have found that, of the aluminum alloys, only 14 S-T is superior to it. The chief advantage of aluminum alloys over special steel alloys, as used by Svedberg, is that the stock supplied by the manufacturers, although already heat-treated to bring out its maximum tensile strength, is relatively soft and easily machined. Thus the rotor can be finished completely without subjecting it to the additional heat treatment and subsequent grinding process that are necessary with steel alloys. It is also sufficiently malleable to allow a slight flow under tension, a property which minimizes the danger of generating localized stresses and strains that are apt to initiate a rupture at high speed. Moreover, having only about one-third the density of steel, and being very much softer than a heat-treated steel alloy, a duralumin rotor exploding at excessive speed is not nearly so dangerous as a steel one.

The maximum diameter of the rotor proper is 7", for a height of 1-3/8", and then it tapers off to a diameter of 3" at the top. A 1" diameter stem projects 1-3/16" beyond the bottom of the rotor. This was convenient when machining the rotor, and now carries the spindle Z. As shown in the drawing, some metal was removed from the central portion of the bottom of the rotor, around the stem, in order to reduce the weight. A cavity was cut to a depth of 1-17/32", at the top of the rotor. Sixteen equally spaced holes were drilled around the lower edge of this cavity. Each is 1/2" in diameter, 2-1/2" long, and inclined at 45° to the vertical. The considerations governing the optimum inclination of these holes are as follows: According to Wyckoff and Lagsdin (18), the separation efficiency of a quantity rotor increases with decreased angle of inclination. However, the weight of a 20° rotor, say, is so much greater than that of a 25° one that the increased time and driving energy required to start and stop the former combat its greater efficiency while running at speed. Then too, centrifuge tubes will collapse more readily the more erectly they are placed. Hence they compromise by using 25° rotors. On the other hand, Masket (19), who is apparently unconcerned by increased rotor weight, uses quantity rotors of greatly increased efficiency due to an angle of inclination of only 10°, and prevents collapse of the centrifuge tubes by neat duralumin plugs inserted at their mouths.

The material to be centrifuged is carried by these holes, either directly or in celluloid containers which fit snugly in them. The effects of high rotational speed on these tubes in the 45° rotor will be detailed in a later part of this thesis. The outer wall of the rotor was made comparatively thick towards the top, where the holes are close to each other and additional strength is needed. At the bottom the holes come within about 3/32" of the outside; however, a minimum wall thickness of 1/4" would be preferable for safety. Each hole can carry 6 cc of liquid, so that a total of 96 cc can be centrifuged during one run. A working speed of 30,000 RPM is certainly safe for this rotor (15). At that speed, the fields at the end and center of the cell holes are 85,000 and 65,000 times gravity, respectively.

The rotor head, N, was machined from a separate piece of duralumin, and made to fit snugly into the upper part of the rotor. Its lower portion consists of a 3/8" diameter stem which fits into a hole in the center of the rotor, and so helps to center the head properly. A flat rubber washer 3/8" in width, placed in the step joint between the head and the rotor proper, forms a vacuum-tight seal between the contents of the rotor and the outside. The head is fastened to the rotor by means of six equally spaced steel screws. The top of the rotor head was machined and threaded to fit the chuck.

The chuck C is necessary to fasten the whole rotor assembly firmly to the driveshaft. In construction it is exactly as described in (15), except that for greater strength the overall diameter was increased from 1-1/4" to 1-3/8", with corresponding increase in wall thickness. The main body of the chuck is of duralumin, while the central portion, which is forced tightly around the driveshaft, is of steel. Two small holes were drilled into the wall of the chuck, opposite each other. A small, specially made spanner wrench fits into them and is used to tighten the chuck. Since the thread is righthanded, the centrifuge is always run in the clockwise direction, viewed from above. This is a precaution which ensures that the spinning of the rotor tends to tighten the chuck, rather than loosen it (except when the rotor is decelerating).

The spindle Z is a steel rod about 1/16" in diameter and 7/8" long. It is fitted tightly into the center of the stem at the bottom of the rotor. Its function is to help damp vibrations, as will be described presently. With the spindle, the overall height of rotor and chuck is 7-1/2", and the total mass is 4131 g. The total mass of the rotating system is 4.8 kg or 10.6 lbs.

(b) <u>The Bearings and the Lubrication System</u>.

There are three bearings, B_1, B_2 and B_3, as shown. They are similar in design to those used by Professor Beams for several years; (20) is the first paper in which they appear. All are made of brass, lined with babbitt metal. They are of different dimensions, but all were made in similar fashion, as follows. A brass rod was machined to the shape and size indicated, and a 1/4" hole was bored along its axis. A certain length of this hole, depending on the length of the bearing, was threaded, from each end. Babbitt plugs were then threaded into the holes as far as they would go. Since the rotation of the centrifuge is always in a clockwise direction, viewed from above, the upper and lower bearing threads were made in the righthanded and lefthanded directions, respectively. Thus the only possible action of the rotating driveshaft would be to tighten the plugs. The babbitt was then drilled out axially to a size slightly smaller than that of the shaft, and reamed to fit it as closely as possible without forcing. The upper and lower faces of the brass portion of the bearing must be accurately perpendicular to the hole through it. Finally a small hole was drilled in the side of the bearing to act as an oil inlet. When properly finished, these bearings create very little friction.

The bearings are set in flat neoprene rings about 1/8" thick. Neoprene is used because of its oil-resistant quality. Rings of appropriate sizes were cut from a flat sheet on a lathe. The length of the brass portion of the bearing had to be such that when the whole is assembled it is under a suitable degree of compression. This had to be determined by trial. A semiflexible mounting is used so that the bearings can "float" to a certain extent; they touch no metal apart from the drive-shaft.

The bearing B_1 rests in the center of the magnet core P, and is held in place by the brass piece E. B_3 rests in a hole in the center of the vacuum chamber lid, held in place by the brass block H. B_2 rests in the upper part of H, and it is held by the brass plate G. This will be described in greater detail under Assembly.

The function of bearings B_1 and B_3 is primarily that of fixing the axis of rotation of the system. The lower babbitt surface of B_1 acts as the stop against which the plug Q presses when the rotating system is completely lifted by the magnet. However, the centrifuge is usually run so that the upper babbitt surface of B_2 carries a small fraction of the weight of the rotating system, transmitted to it by the lower surface of D. It is lubricated by leakage of oil from the bearing proper. B_2 is really only necessary to provide for the water outlet O, and could be dispensed with if oil were used for cooling as well as for lubrication. The lower part of B_3 constitutes the vacuum seal between the driving mechanism and the vacuum chamber containing the rotor.

The bearings are lubricated by Hyvac pump oil 93050, under pressure obtained from the local compressed air system. This oil is used because of its low vapor pressure. There are two oil inlets, as shown, I supplying B_1 and J supplying B_2 and B_3. If the babbitt plugs are to be lubricated continuously, some oil leakage past them is necessary. Hence there is always some oil leaking out through the bottom of B_1, which is a nuisance; through the top of B_2, which is a help; through all three bearings into the water, which does not matter; and through B_3 into the vacuum chamber. The latter oil leakage could easily be collected by a shallow dish surrounding the driveshaft, above the rotor, but this was not considered necessary for work with the quantity rotor. However, if the bearings are properly made, and run in carefully with a straight driveshaft, the leakage of oil through them is small.

(c) <u>The Supporting System</u>.

Almost the whole of the weight of the rotating system is carried by the lifting action of the magnet M upon the core T. The magnetic circuit is arranged so that the field is symmetrical over the circular end of T. Hence there is practically no drag due to eddy currents in it. The magnet consists of a copper winding on a brass form, sheathed in cold rolled steel. The diameter of the outer casing was limited by the necessity of clearing the optical path for the Svedberg rotor, and hence was made 3-3/4". The overall height of the main body of the magnet is 2-1/4". The thickness of the steel of the side wall is about 3/16", and of the end plates 1/4". A 1-1/4" hole in the top plate is threaded for the adjustable core P. The lower plate has a central hole 29/32" in diameter, through which T fits.

The wire is wound on a brass form which fills most of the casing, as shown. The form is 3-5/16" in outside diameter, has a central hole 1-5/16" in diameter, and is 1-5/8" high, giving a winding space 15/16" by 1-1/2" in cross section. In determining the best wire to use in winding the coil, the following considerations were noted:

It was thought desirable to operate the magnet from storage batteries, for reliability and convenience. Twelve volts should be the maximum required. Furthermore, nearly 2000 ampere-turns were needed; the winding-space was fixed; a maximum of 30 watts heat could be allowed - since no water cooling was being provided; and the coil had to be waterproof. Considering only the voltage limit and fixed winding-space, it was found that both the ampere-turns obtainable and the power consumption increased with the diameter of the wire used. However, the former was found to be independent of the proportion of copper and insulation in the winding space, while the power decreased with increasing copper for any given size of wire. Finally, the efficiency or number of ampere-turns per watt decreased with increasing wire diameter. Thus it was concluded that for greatest efficiency the smallest wire should be used, limited by the number of ampere-turns necessary. Also, enamel wire should be used, if possible, for the greatest ratio of copper to insulation. It was found that the choice of wire sizes was rather limited, and the form was wound with #20 double cotton covered wire. Enamel wire could not be used because the waterproofing coating of beeswax would have attacked it. The form held 22 layers, each containing about 34 turns, for a total of roughly 750 turns. The total resistance was found to be 4.75 ohms, so that with 12 volts the current is 2.5 amperes, the power 30 watts, and the number of ampere-turns 1900 — all of which is satisfactory. The leads to the coil are brought out through the top of the casing, and connected to terminals mounted on the magnet but insulated from it.

The core of the magnet, P, was made of cold rolled steel, 2-1/4" long, and threaded to fit the upper hole in the magnet casing. The lower edge was tapered ("shaded"), as shown, since that was believed to increase the field. The inner diameter of the lower portion is 29/32", the same as the hole in the lower plate. The ledge has a central hole 7/16" in diameter, and it extends for 3/8". The upper central portion of P is 7/8" in diameter, and holds the bearing B_1. The oil inlet tube I was soldered into the side of P near the top. The brass piece E is fastened to the top of P by means of five small screws, with a leather washer between the surfaces. The hose from the water supply is clamped to the top of E.

The gap of the magnet had to be adjusted for maximum pull by varying the position of P. This was not found to be very critical, the optimum gap being about 11/16". P was fixed in this position by a large hex nut which fitted flat against the magnet top plate, as shown in the diagram. Only when P was fixed was it possible to fix the length of the plug Q, which was made such that if the magnet pulls the rotating system upwards it can only move through about 1/16" before the top of Q strikes the lower babbitt surface of B_1.

With the magnet described, it was found that it began to raise the rotating system with a current of 1.9 amperes, corresponding to 17 watts and 1400 ampere-turns. Thus there is ample reserve for use with heavier rotors when necessary.

The magnet rests upon the brass plate F, 1/4" thick, which rests in turn upon ledges cut in the steel rods K_1 and K_2. These rods were screwed tightly into the lid of the vacuum system. The magnet is held in place by four heavy screws inserted from the lower side of F. The holes in F were drilled slightly large, to allow proper centering of the magnet. To increase the stability of the mounting, brass collars were attached to F, and fitted around K_1 and K_2 as shown. Setscrews are located in either end of F to keep the assembly more firmly in place.

(d) The Two Phase Induction Motor.

The stator lamination was obtained from the Rouss Physical Laboratory, and is identical with that used by Skarstrom and Beams (13). It consists of a stack of about 200 similarly punched silicon steel sheets. These are 0.0075" thick, made of

"American Transformer #72 Electrical Sheet". Their outer diameter is 6", the central hole is 1-3/4" in diameter, and further metal was punched out to leave four salient poles each 1" wide. A small hole had to be punched in one side to clear the light path for the Svedberg rotor. This was a portion of a circle 1.8 cm in diameter, with its center 5.8 cm from the center of the lamination. The thickness of the assembled lamination is about 1-3/4".

Each pole was covered with two layers of Empire cloth insulation, and wound with 105 turns of #18 single cotton covered enamelled copper wire. The windings were impregnated with shellac. The DC resistance of each winding was found to be about 0.37 ohm. The method of connecting to the windings will be given subsequently.

The motor stator rests on three heavy brass rods, which are screwed firmly into the lid of the vacuum system. They are located at points midway between the poles, the fourth space being required for the optical path. The stator is clamped firmly to these rods by means of short, heavy brass bars and steel bolts. This proved to be a rigid mounting from which the motor could easily be removed, for access to the lower bearings. When so mounted the center of the motor is 3-3/8" above the top of the lid. The mounting was omitted from the scale diagram for simplicity.

With the parts as described, the clearance between the armature and the pole faces is 3/32". This is slightly less than that used by Skarstrom and Beams, but nevertheless in operation it has proved eminently satisfactory. Furthermore, there has never been any tendency for the motor to pull the armature towards one of the poles, which must be avoided when small flexibly mounted shafts are used.

(e) The Vacuum System.

In order to obtain convection-free sedimentation it is necessary to avoid temperature gradients. This can be brought about by running the rotor either in a high vacuum or in an atmosphere of hydrogen at a pressure of about 2 cm Hg. In this installation only a vacuum system has been used. This consists merely of a Cenco Megavac pump run at about 330 RPM, and a McLeod gauge. Without any particular precautions, the pump brings the vacuum system to a pressure of 0.002 cm Hg in about ten minutes. For accurate work with a Svedberg rotor a pressure below one micron would be necessary.

The vacuum chamber V also serves the important function of protecting the operator in case the rotor explodes or a driveshaft breaks. The sides and bottom of the chamber are a single piece of heat-treated vanadium steel, as is the lid L. The outer diameter of the chamber is 35 cm, with a wall thickness of 6 cm, leaving a space 23 cm or roughly 9" in diameter. This thickness of steel should be proof against deformation by the explosion of any duralumin rotor. There is ample room for rotors up to 8" in diameter, which is about as large as they are ever made. The bottom of the chamber and the lid are each 1-1/2" thick. Rectangular holes 3 by 6.5 cm were cut in them, opposite each other, for the optical system and for visual observation when no optical system is being used. For the latter purpose these holes were covered with plate glass windows

8 mm thick, with plasticine as the cementing and vacuum sealing medium. As shown in the diagram, there is a ledge in the lid of the vacuum chamber which supports a flat rubber gasket 3/8" wide. This forms a vacuum seal when the lid is bolted to the chamber. The hole in the center of the lid is in three steps: first a portion 2" in diameter and 1/8" deep, to which the brass piece H is screwed, with a leather washer in between; then a further 7/16" step, 1-1/4" in diameter, for the bearing B_3; and the balance is 3/4" in diameter.

The vacuum chamber rests on three short, stout, steel legs cast integrally with it. These rest in turn on three short posts imbedded in a block of concrete poured so as to be a part of the floor of the room. For photographic work it might prove necessary to use some rubber or cork as vibration insulation between the chamber and the concrete.

The outlet U to the vacuum system is as indicated. Near it is the rubber connection which provides the necessary flexibility between the vacuum system and the centrifuge.

(f) Vibration Damping.

During the early trials of the driving system considerable trouble was experienced with various kinds of vibrations. As already noted, the Svedberg rotor was smashed when a drive-shaft became fatigued and broke, due to inadequate damping of precessional vibrations. Dr. Shugar had succeeded in running the quantity rotor to 18,000 RPM with the air turbine drive, without any damping device whatsoever; hence this rotor was first tried without any damping. However, with the more flexible shaft used with the electric drive, a vibration having a period corresponding to a simple pendulum developed almost immediately. Its amplitude soon became such that the run had to be discontinued for fear of breaking the driveshaft. Finally the damping device shown in the drawing was found satisfactory. It is an adaptation of one first described by Beams, Linke and Sommer (21) and used also by Skarstrom in yet another form.

The main parts of the device are the brass piece W and the brass base Y. The lower part of W is 2" in diameter and 1/4" high; the upper is 1/2" high and 1-1/4" in diameter, leaving a ledge 3/8" wide. At the top of W there is a funnel-shaped hole 3/8" across and with a 1/4" vertical height; the stem below it is #42 drill, 1/8" long. This funnel is essential for getting the spindle Z into the center of W. The lower part of the central portion of W is a threaded hole 7/16" in diameter. A leather washer about 1/8" thick fits up into this, and has a 1/16" hole through its center. It is held in place by a brass insert screwed tightly against it; the insert is about 1/4" thick and has a #42 drill hole through it also. As shown in the diagram, the spindle Z fits into the hole in the leather washer. Thus any vibrational motion of the rotating system is imparted to W, whose weight alone has a considerable damping effect. Further damping is obtained from the mounting of W.

The base Y is a solid block of brass 2-1/4" high and 3" in diameter, with three brass rods 3/8" in diameter projecting a distance of 2-7/8" from it. The upper part of Y is turned down to a height of 2", leaving a rim 1/8" wide around the circumference. In the center of the upper surface there is a hole 3/8" in diameter and 1/8" deep; this leaves room for the end of the spindle in case the rotor is mounted lower than usual on the shaft. Three flat brass springs are fastened to the side of Y and arranged to press heavily on the ledge around W, as shown. Y rests on the floor of the vacuum chamber, with 1/8" space between the projecting rods and the side wall. It is centered by sponge rubber pads, normally 1/4" thick, placed between the rods and the wall. Thus Y has very little freedom of motion, and imposes considerable restraint upon any motion of W.

In operation a film of oil is kept between W and Y, so that W cannot accidentally stick in one spot with probable damage to the rotating system. The hole in W is filled with oil to keep friction between the spindle and the leather to a minimum. The arrangement has been found to work remarkably well, as at no time has any vibration of the quantity rotor been seen, and the friction has apparently been negligible.

(g) The Measurement of Speed.

Numerous methods for determining the speeds of centrifuges have been devised. There are direct methods such as the stroboscope or the frequency bridge; comparison methods such as the standard audio oscillator and the cathode ray oscillograph, or tuning forks and audible beats; and the very convenient indirect method of Skarstrom and Beams, using synchronous clocks.

A simple stroboscope is used here. This is a thin aluminum disc, 14" in diameter, with twenty 1" holes punched near its circumference. The disc is driven by a rubber pulley which can be moved by a screw across the face of a brass plate. The plate, in turn, is driven by a constant speed DC motor. The disc can be run at any desired speed up to about 2000 RPM: this is measured by means of a tachometer attached to the shaft of the disc drive, and a stopwatch.

The black paper on the central portion of D has already been noted. To find the speed of the centrifuge, D is illuminated by a DC lamp and viewed through the holes in the stroboscope disc. When the speed and the frequency of interruption of vision by the holes are the same, the bright part of D will appear stationary, although blurred. Stationary patterns can also be obtained when one speed is one and one-half, two or even three times the other, but after a little practice it is easy to discriminate against them. The disc described is suitable for the range of speeds used with the quantity rotor. One with 50 or even 60 holes or slots would be better for higher speeds. In any case, if the correct coincidence is observed, the speed of the centrifuge is the product of the speed of the disc and the number of holes in it.

(h) <u>The Assembly of the Complete Mechanism</u>.

The assembly of the centrifuge mechanism will be described in considerable detail, since smooth running depends as much upon this being performed properly as on the care with which the parts were made. Before commencing assembly, the vacuum chamber lid carries only the steel rods K_1 and K_2, the three brass rods of the motor support, the upper window, and the three hooks by which the lid is raised.

First the lowest bearing, B_3, with its two neoprene rings is assembled on the lid L; the leather washer which fits around it, on the ledge in L, is also put in position. The block H is fitted over B_3, and the three bolts driven a short distance into the lid, leaving H with some freedom of motion. The plate G, its leather washer, and the bearing B_2 with its neoprene rings are assembled on the driveshaft S_2, and pushed up against D. The latter assembly is then fitted into the former, and the three screws through G put in loosely. Thus the armature assembly is supported at the correct height, but sufficient freedom of motion remains that it can be properly aligned vertically. To do this, the rotor is suspended from the driveshaft in the normal manner, namely, with as much as possible of S_2 inside the chuck. The lid is lowered to rest on the main body of the vacuum chamber, to ensure that it is in its usual horizontal position. Then the magnet assembly, consisting of F, P, and M but minus the upper bearing B_1, is put into place on K_1 and K_2. The top of Q is now visible through the center of the magnet core P. By rotating the armature by hand it is easy to see whether Q moves from side to side in P. If it does not do so, then the driveshaft S_2 is straight, as it should be, and, in view of the freedom of the lower bearing assembly, the shafts S_1 and S_2 are in a vertical line. The position of the magnet on F is adjusted so that Q is centered in P: the eye is sufficiently accurate for this. The screws holding H and with it B_3 in place are now tightened as much as possible, and in such a manner that Q retains its central position in P. Sections of G were removed to make this possible. Finally the screws holding G and with it B_2 in place are tightened similarly. The alignment of the bearings may now be checked by removing the rotating system and feeling how a length of straight shaft pushed through the top bearing meets those below it.

It is useful at this point to blow through the top of S_1 to make sure that the cooling passage is unobstructed. It should be so if the armature assembly itself was known to be clear. The magnet assembly is now removed and the motor stator placed in position, with an equal gap between it and the armature, all the way around. The bolts holding the stator in place are tightened as much as possible, since any motion on its part would wreck the machine. The magnet can then be replaced; it is held firmly by tightening the setscrews and the screws holding the brass collar around K_2, as those around K_1 are left tight permanently. The bearing B_1 and its neoprene rings are inserted in P, and the brass piece E is fastened to P with a leather washer in between. The water supply hose is kept permanently clamped to E. Check to see that the system is relatively free to rotate.

The lid L is now raised and the damping assembly placed at the bottom of the vacuum chamber. The base Y should be approximately centered in the chamber, as should W on top of Y. The rotor can now be loaded, replaced on the driveshaft, and lowered carefully into the vacuum chamber. The latter operation must be performed slowly and smoothly if the spindle Z is to fit into W and remain straight. It is desirable to turn the rotating system by hand while lowering it, in order to make the fit easier. To facilitate this operation the side of W is made visible from above by a small mirror placed at the side of the vacuum chamber. Finally the lid is bolted firmly and evenly to the chamber, the two oil lines are attached, and the electrical connections to the motor and to the magnet are made.

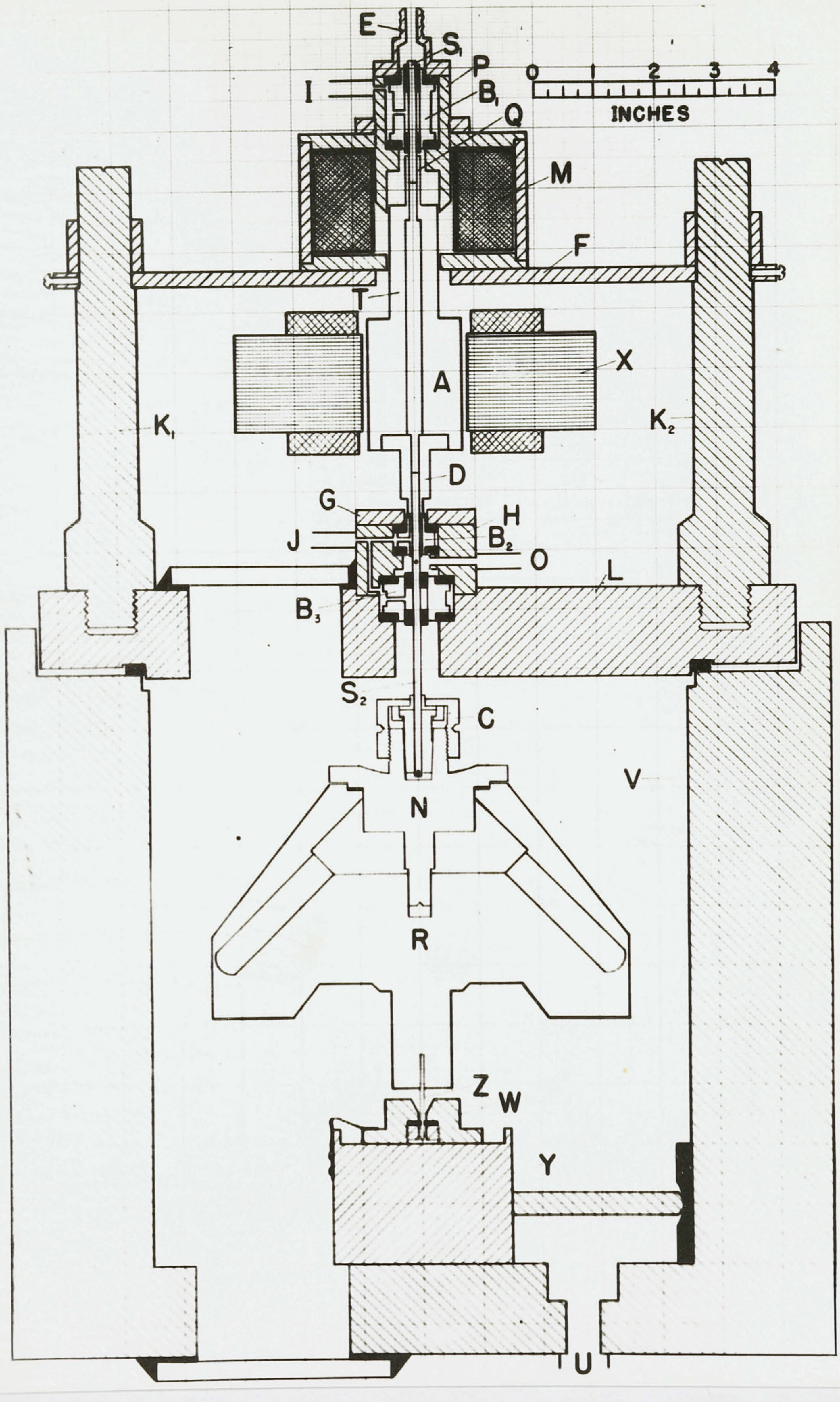
Little needs to be added concerning disassembly, except when it is necessary to avoid jarring the contents of the rotor. In that case the following procedure was found to be least harmful. Air is let into the vacuum chamber, and the bolts holding the lid in place are removed to prevent catching when the lid is raised. The brass piece E is unscrewed from P, and then the whole magnet assembly removed. The lid is raised slowly and as evenly as possible, until the tip of the spindle is completely out of the vacuum chamber. A plywood form made for the purpose is placed on the ledge of the vacuum chamber; it is relatively free to move around on the ledge, and has a 1" hole at its center. The lid is now slowly lowered so that the 1" stem below the rotor fits into the 1" hole, until finally the rotor is resting on the wood form. The magnet has to be removed to allow sufficient vertical motion of the rotating system and thereby avoid any danger of bending the driveshaft during the operation just described. The chuck can now be loosened without jerking the rotor, and the lid lifted to allow free access to it. The armature assembly may then be removed and cleaned, to prevent rusting.

LIST OF PARTS

A	Steel armature	M	Magnet
B_1	Upper bearing	N	Head of rotor
B_2	Middle bearing	O	Water outlet
B_3	Lower bearing	P	Core of magnet
C	Chuck	Q	Steel plug
D	Steel Shaft	R	Rotor proper
E	Brass water inlet	S_1	Upper driveshaft
F	Brass plate	S_2	Main driveshaft
G	Brass plate	T	Support core
H	Brass block	U	Outlet to vacuum system
I	Upper oil inlet	V	Vacuum chamber
J	Lower oil inlet	W	Vibration of damping bearing
K_1	Left steel upright	X	Motor stator
K_2	Right steel upright	Y	Base of damping bearing
L	Lid of vacuum chamber	Z	Spindle

Figure 2

Partial Section of the Centrifuge, to Scale



E
S1
P
I
B1
Q
0 1 2 3 4
INCHES
M
F
T
X
A
K1
K2
D
G
H
J
B2
O
L
B3
S2
C
V
N
R
Z
W
Y
U

III. THE ELECTRIC DRIVE

As already mentioned, the motor is driven by two phase alternating current. This AC is obtained by amplifying the output of an independent audiofrequency oscillator, and converting the single phase power to two phase by condenser phase shifting. The system operates solely from the 60 cycle mains. The circuit diagram is included herein.

Skarstrom and Beams (13) use an additional speed controlling circuit which is automatic in operation. It acts to keep the speed of the motor constant within 0.05%. This is a considerable reduction from the 1% due to line voltage and bearing friction variations, found without the automatic control. In the present installation it was deemed sufficient to reduce line voltage variations by installing a power line separate from other local AC loads. In any case, constancy of speed within 1% is sufficient for the work here.

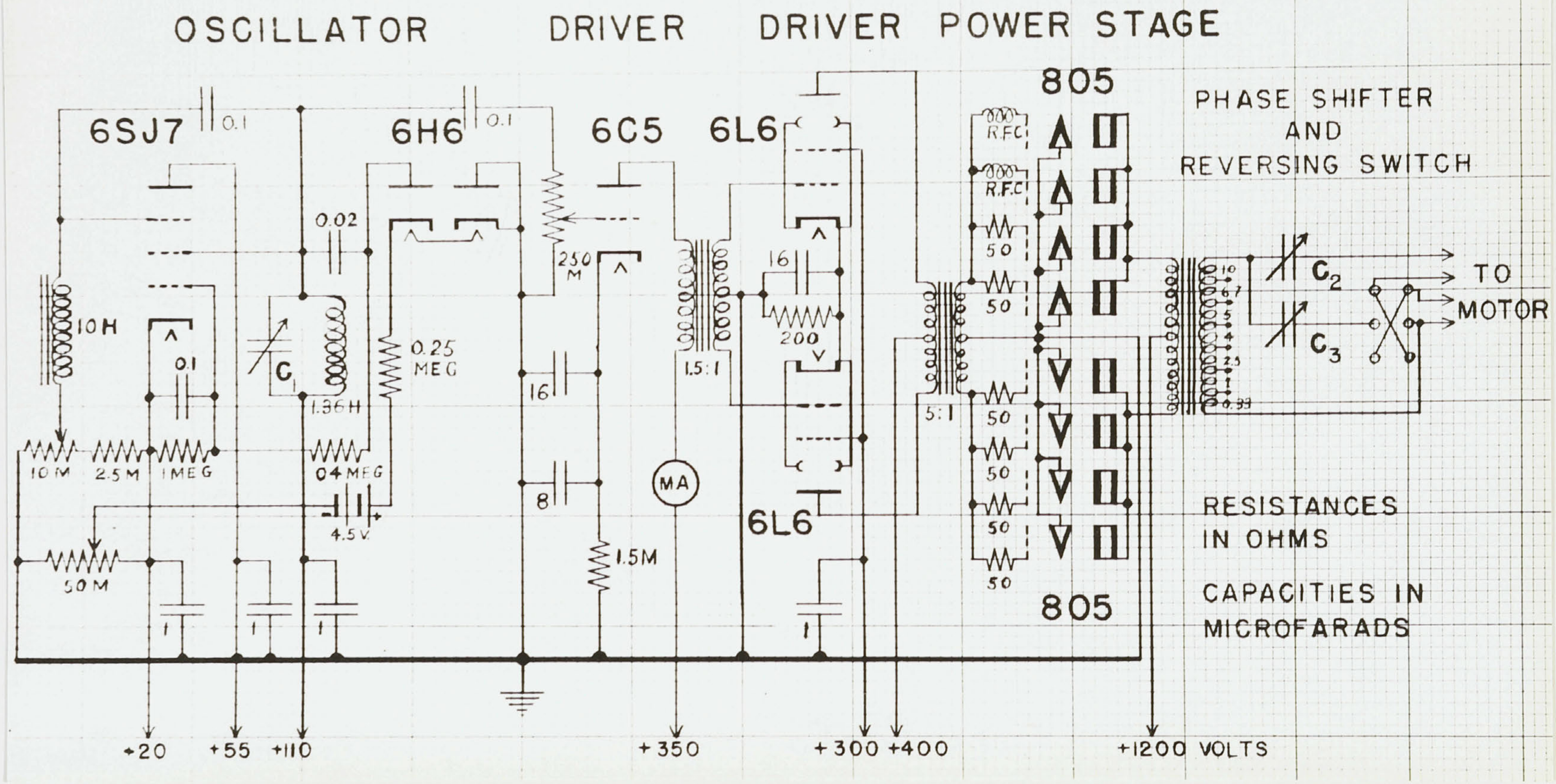
(a) The Audiofrequency Oscillator and Driver Stages.

The transitron oscillator of Brunetti (22), as adapted to AC operation by Skarstrom and Beams, was used. This proved to be a simple, inexpensive and constant audio source. The wiring was simplified by using a 6SJ7 instead of a 6J7 tube, and the circuit made more flexible by the use of a 6H6 in place of a 6ZY5-G tube. An automatic amplitude control forms part of the circuit. This is a delayed automatic volume control, the net delay voltage being the difference between the EMF of the 4.5 volt C battery and the voltage tapped off the 50,000 ohm potentiometer. The battery is in a 1.4 megohm circuit, and so should last its shelf life.

Figure 3

The Circuit of the Two Phase Audiofrequency Generator, Less Power Supplies

DRIVE CIRCUIT - LESS POWER SUPPLY



The frequency of oscillation is approximately that of the tank circuit, which consists of the capacitance marked C_1 in the diagram, and the inductance in parallel with it. There are twenty separate frequencies available, from 430 to 1890 cycles. These are obtained from the various positions of the decade condenser switch on the front of the oscillator chassis, and from position 5 of the tap change switch on the top of the chassis. Altogether five mica condensers are used: further frequencies could be obtained by connecting suitable condensers to other positions of the tap change switch. The coil was wound on a birch form shaped as nearly as possible to the optimum, so as to obtain the maximum inductance from a given amount of wire. The overall dimensions were limited by the space available. The optimum shape is a square multi-layer coil having the mean diameter of the winding equal three times the winding thickness. Actual dimensions were:-

Outer Diameter	4.02"	Depth of Winding	1.02"
Inner Diameter	1.98"	Height of Winding	0.975"
Mean Winding Diameter	3.00"		

The inner surface of the form was coated with Amphenol "912" liquid, and allowed to dry. The winding space was filled with #28 enamelled copper wire, and then the whole was given a "912" liquid coating. The inductance as measured on a General Radio Impedance Bridge was 1.36 henries at 1,000 cycles, corresponding to a Q of 35.

For optimum operation of the oscillator, the 10,000 ohm potentiometer was set so that oscillations took place at the lowest frequency to be used. Then the 50,000 ohm control was adjusted so that AC line voltage changes caused minimum change in output amplitude. Once set, there is no further need to change these controls, and so they were placed inside the chassis. When so adjusted, and after operation for about an hour, the frequency stability is of the order of 0.005% per line volt change. The output voltage of the oscillator is roughly 3 volts RMS throughout the frequency range available, and the waveform is uniformly excellent.

The 3 volt signal is applied across a 250,000 ohm linear potentiometer, marked "Master Gain" on the chassis. This is the sole control for varying the amount of power applied to the motor. The 6C5 stage is a standard voltage amplifier. Series feed is used, as shown, in preference to parallel feed, as used by Skarstrom, because the former has better waveform at higher signal levels. The transformer used is a Thordarson T-17D01, connected for a turns ratio of 1.5:1, half primary to secondary. An electromagnetic and electrostatic shield was inserted inside the oscillator chassis just ahead of this transformer, to increase the separation between the oscillator proper and the 34-watt stage. Further shielding of the oscillator was placed on the under side of the table top, over the power stage.

The 34 watts required to drive the grids of the 805's are supplied by a pair of 6L6's in push-pull, Class AB_1. The correct audiofrequency voltage, 268 peak volts grid-to-grid, is given by a special Hammond transformer having a 5:1 turns ratio.

All the above components are contained in a small chassis placed so that the controls are easily accessible while keeping the operator well protected from the high voltages of the power stage. The connections to it were arranged so that changes could readily be made if desired, and provision was left for the addition of an automatic speed controlling circuit if necessary.

(b) Low Voltage Power Supply.

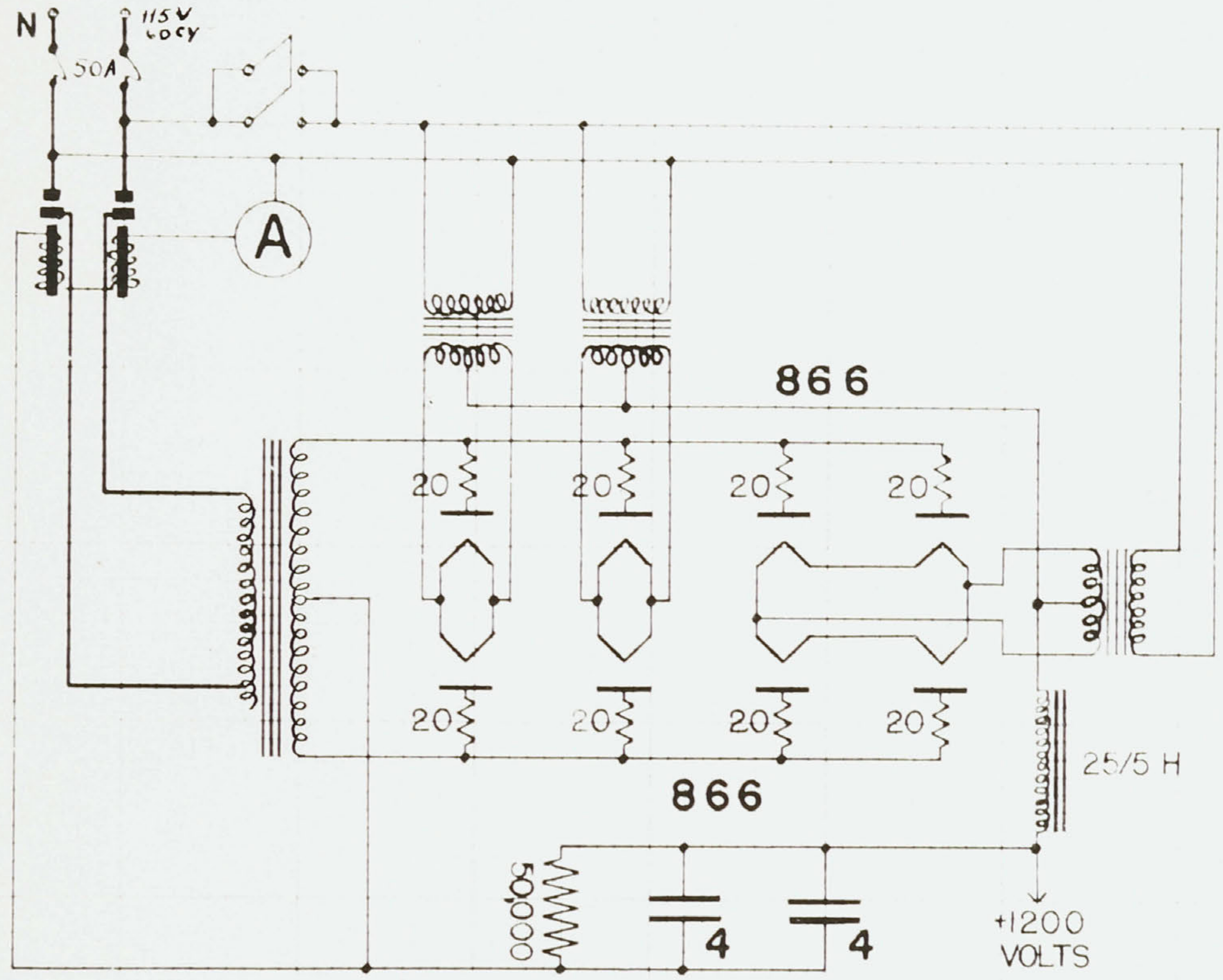
The circuits described above are fed from a single power pack utilizing a 5Z3 tube. As can be seen from the circuit diagram, this is fairly straightforward. For simplicity, the primary of the Hammond 275-X power transformer is fused on the neutral side of the AC supply line only, with the switch on the high side. The ground used throughout the wiring is the neutral side of the power line; this is permanently attached, so that there is no possibility of shock from exposed metal parts.

With a high AC line the no load voltage from the rectifier may rise above 600 volts, which is the working limit of electrolytic condensers. Because of this the input section is made up of two 450-volt 16-μfd condensers in series, each shunted by a 0.5 megohm resistor to balance the voltage. The other condensers are rated at 600 volts. All three filter chokes are made by Hammond, and rated at 30 henries at 100 milliamperes. The voltage for the 6L6 plates is obtained from the end of the first filter section because they constitute the main load on the power pack, and a small ripple has no effect on their operation. Except for this,

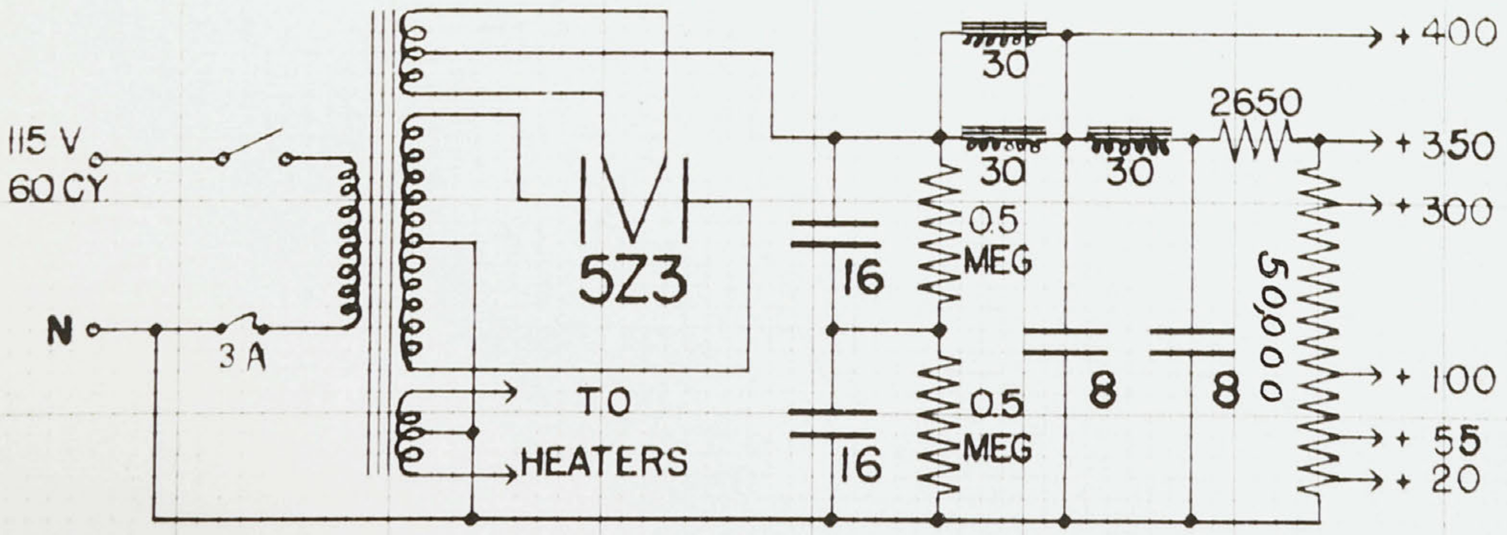
Figure 4

The Power Supply Circuits

HIGH VOLTAGE POWER SUPPLY AND PROTECTIVE RELAY



LOW VOLTAGE POWER SUPPLY



the ripple in the output of this power supply is negligible, and as a result there is no appreciable 120 cycle component in the output of the 6L6's. The regulation is only fair, but this does not matter because a constant output is required only when a fraction of the available output is being used.

(c) The Power Stage and the Motor.

Motor torque of the order of 500 gm-cm is necessary if the starting time of the usual 7 to 10 lb. rotor is to be under half an hour. About 700 gm-cm can be obtained from the motor described with a power input of 1000 watts. This power is easily obtained from four pairs of 805 triodes operating in parallel push-pull, class B, with zero bias. These have a rated maximum audio output of 1200 watts with 1250 volts on the plates. The 805 is convenient in that it is a zero bias tube; but it would be simpler to use only one pair of a more powerful triode, such as the Taylor 822. The first circuit tried had 50 ohm resistors in series with each grid and 25 ohm resistors with each plate, to suppress parasitic oscillations and divide the grid driving power uniformly. However, the heating of the grid resistors when no signal was being applied indicated the presence of radiofrequency oscillations of considerable amplitude. These took place between two or more of the four Taylor 805's, depending on their relative physical positions and not on whether they were in parallel or in push-pull. At no time did the four RCA 805's show any signs of oscillation. A position was found in which only two of the four Taylor tubes oscillated, and with small amplitude; these oscillations were then prevented by substituting 2.5 millihenry RF chokes for the resistors, as shown in the diagram. These have a DC resistance of 43 ohms, which is sufficiently close to 50 ohms so that the amount of audio driving power supplied to the grids remains about the same. The plate resistors were removed as the tubes continued to function satisfactorily without them, leaving the circuit as shown.

The output transformer was specially made by Hammond. It has a total primary impedance of 1900 ohms, and secondary impedances of 10, 6.7, 5, 4, 2.5, 1, and 0.33 ohms available, as marked in the diagram. Since it is inconvenient to change output taps while the centrifuge is running, the table of Optimum Operating Conditions was made up so that as far as possible such changes are avoided. The best output impedance for any particular frequency was that which gave maximum audio power output, within the rated maximum total 805 plate current of 1.6 amperes. It can also be calculated roughly from the values of the phase shifting condensers at that frequency.

The single phase audiofrequency current is converted to two phase by the phase shifting condensers C_2 and C_3, as indicated. Altogether some 50 µfds in 1, 2 and 4 µfd units, and 1.2 µfds in 0.1 µfd units are available. All are of the oil-filled type and are rated at 1,000 volts or higher. These were connected in suitable groups to switches, and the whole arranged so that any desired combination of capacities can be obtained. The actual values of the capacities attached to the various switches, as found on a General Radio Impedance Bridge at 1,000 cycles, along with the nominal values, are as follows:

Table 1: Capacities for Phase Shifting.

Switch Number	Nominal μfd	Actual μfd
1	3	3.00
2	2	2.05
3	1	1.03
4	0.3	0.300
5	0.2	0.198
6	0.1	0.106
7	0.1	0.107
8	0.2	0.211
9	0.3	0.300
10	1	1.00
11	3	3.00
12	7	6.7
I	1	1.02
II	2	1.64
III	4	3.35
IV	7	6.5
V	19	19.0

Of these numbers 1 to 12 are single pole, double throw switches, while numbers I to V are single pole, single throw. Thus the larger capacity value can be obtained only on one side of the phase shifting network; in practice this is always C_3. Since the torque produced by the motor depends directly on the accuracy of the phase shifting, it is essential that the same condensers be used each time for the indicated values of C_2 and C_3. The following convention was adopted in order to assure this: First C_2 is obtained from the first of switches 1 to 12, in that order. Then C_3 is obtained from the first of those switches remaining, and then from I to V, in that order.

The two pairs of poles of the motor constitute essentially two crossed solenoids. A rotating magnetic field was obtained by series tuning one pair of poles above resonance (using C_2, say) and the other below resonance (using C_3). When the image in an oscillograph connected to the poles showed an approximately circular pattern, it indicated that the voltages and currents were 90° apart. When this is the case, maximum torque is developed by the motor, and the power tubes can be operated at their maximum ratings into practically a resistive load. The departure from a pure resistance is due to hysteresis; this also explains why the patterns actually obtainable in the oscillograph resemble squares with rounded corners rather than circles.

Opposite motor poles can be connected either in series or in parallel; a terminal panel was arranged so that this can be done easily and quickly by means of shorting bars. The mode of connection is determined by the necessity of matching the motor impedance to one of a limited number of transformer output impedances; the impedance of the series-connected motor is four times that when parallel-connected. The values of C_2 and C_3, and the mode of connection of the motor, for the various frequencies, are given in the following Table. This Table is valid only for the armature at present in use in the centrifuge.

Table 2: Optimum Operating Conditions

Frequency c.p.s.	Position of Switches	Motor Connection	Output Impedance			Nominal C_2 µfd.	Nominal C_3 µfd.
			Value	Transformer Terminals			
				Join	Connect To		
430	5 and 10	Series	10	3 and 4	1 and 6	7.1	14.3
440	5 and 9	Series	10	3 and 4	1 and 6	6.5	12.5
452	5 and 8	Series	10	3 and 4	1 and 6	6.2	12.0
465	5 and 7	Series	10	3 and 4	1 and 6	6.0	11.3
487	5 and 6	Series	10	3 and 4	1 and 6	5.5	10.5
498	5 and 5	Series	10	3 and 4	1 and 6	5.3	10.3
523	5 and 4	Series	10	3 and 4	1 and 6	4.7	9.5
540	5 and 3	Parallel	2.5	1 and 4 3 and 6	1 and 6	17.8	33
568	5 and 2	Parallel	2.5	1 and 4 3 and 6	1 and 6	16.5	33
593	5 and 1	Parallel	4	3 and 4	2 and 5	14.9	29
600	10	Parallel	4	3 and 4	2 and 5	14.9	29
630	9	Parallel	4	3 and 4	2 and 5	13.8	26
665	8	Parallel	4	3 and 4	2 and 5	12.6	25
720	7	Parallel	4	3 and 4	2 and 5	10.6	23
800	6	Parallel	5	3 and 5	1 and 6	8.9	20
847	5	Parallel	5	3 and 5	1 and 6	8.0	17.2
987	4	Parallel	5	3 and 5	1 and 6	6.2	14.0
1120	3	Parallel	6.7	3 and 4	1 and 5	5.1	11.6
1400	2	Parallel	6.7	3 and 4	1 and 5	3.4	7.8
1890	1	Parallel	10	3 and 4	1 and 6	2.0	4.6

The frequency of rotation of the magnetic field produced by the motor is the same as that of the AC fed to it. Hence the centrifuge is inherently limited to a speed somewhat less than that corresponding to the drive frequency, as there is always some slip due to friction. This is an advantage over the air- and oil-turbine drives, which can "run away with themselves" if too high a driving pressure is used for too long. Also, there is no limit to the speed attainable by this type of motor other than that determined by the bursting speed of the rotating system, provided sufficient power is at hand. A further independent safety speed control is provided by the type of phase shifting used, since it gives maximum motor torque only for the drive frequency for which it was adjusted. Thus an accidental change in the drive frequency would unbalance the system and reduce the motor torque.

A heavy duty reversing switch was inserted in the wiring to one pair of motor poles. This is necessary in order to be able to bring the rotating system to a stop within a reasonable time; and it is convenient in getting the centrifuge rotating in the proper direction.

(d) High Voltage Power Supply and Protective Relay.

As already stated, a maximum of 1.6 amperes at 1250 volts is required for the plates of the 805's in order to obtain their maximum power output. The power transformer available, made by Benjamin Hughes, has two secondaries each conservatively rated at 2750 volts AC, 0.5 ampere. These are connected in parallel, giving a 1.0 ampere rating, and the transformer immersed in Voltesso transformer oil for protection in view of the considerable overload. The supply line is connected to the 105 volt terminals on the transformer in order to obtain as high a voltage as possible. With a 115 volt AC line the voltage actually obtainable is about 1200 with a plate current of 1.5 amperes, giving a power output of 1 kilowatt at 430 cycles.

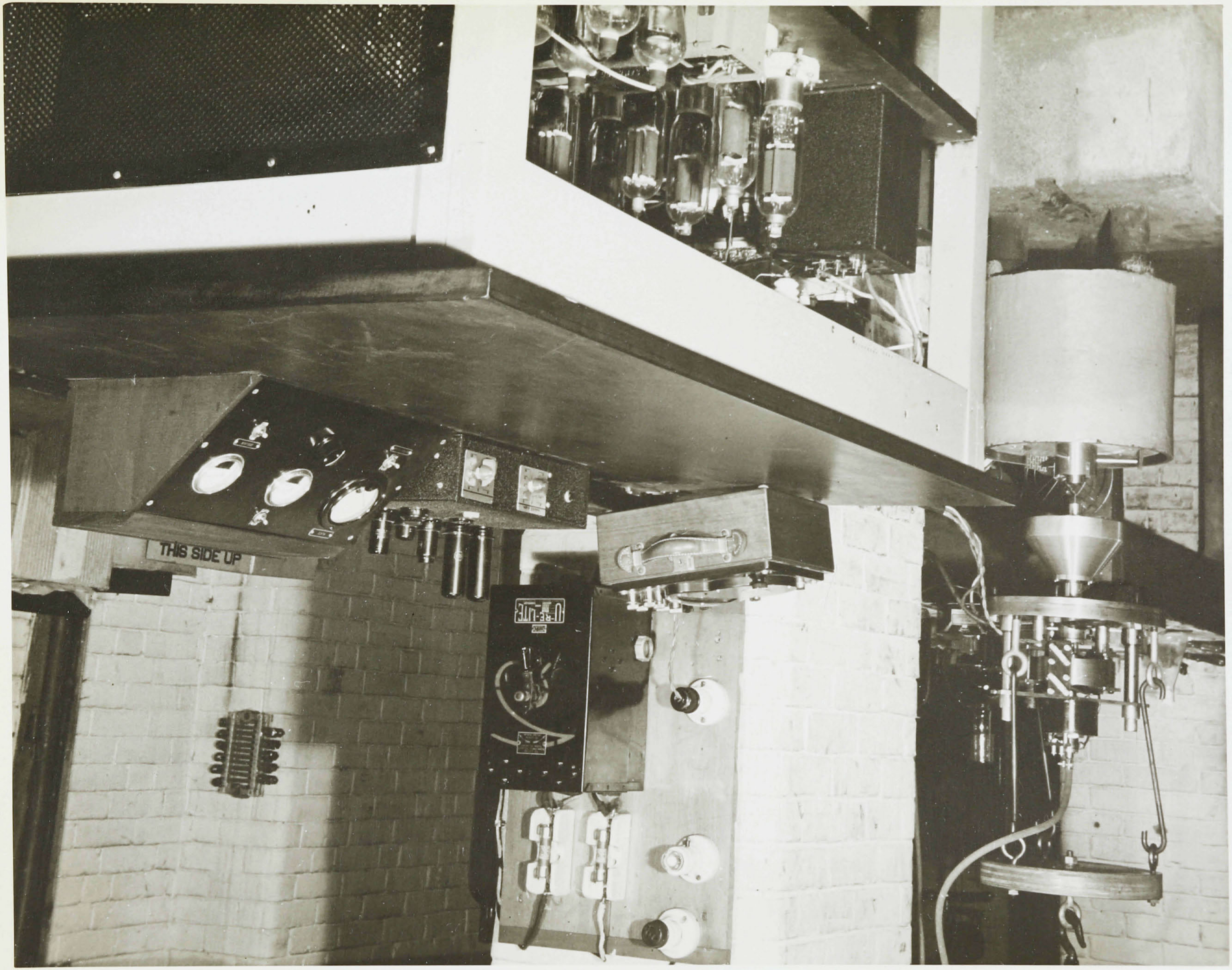
As shown in the diagram, the switch for the transformer primary has an overload relay attached to it. The magnet coils were rewound and the gap set so that they trip, breaking the primary current, when the current through them reaches two amperes. This is thought to be a reasonable figure in view of the rated 1.6 amperes maximum of the 805's.

Type 866 half-wave mercury vapor rectifiers are used, as indicated. Two of the filament transformers are Hammond 1166's, while the third is a U.T.C. S-59. The latter has a 5 volt secondary, so that pairs of 866's have to be connected in series across it, as shown. When this has to be done, it is best to have filaments with nearly equal resistance, in series. It was interesting to find that the four RCA 866's had to be used for this, though the Taylor 866's appear to be superior structurally. The twenty ohm resistors in series with the plates tend to divide the load more evenly among the tubes.

The filter is of the standard choke input type. The specially made Hammond swinging choke has an inductance of 5 henries at 1.5 amperes. The oil-filled paper condensers are rated at 2000 volts, and the bleeder resistor at 80 watts. The ripple remaining from the filter is calculated at 2-1/2% —

Figure 5

General View of the Audiofrequency Generator and Controls, with the Centrifuge in the Background


THIS SIDE UP

a satisfactory figure. The regulation of this power supply is about 10%: though not very good, it does not matter in this application, as already stated.

(e) The Control Panels.

The main control panel is on top of the table, to the right of the oscillator chassis. It is easily subdivided into three sections. To the left are the plate current meter and the switch, marked "Filament Voltage", controlling the power to the filaments of the 805's and 866's. This switch should be turned on at least a minute or two before the high voltage is applied. In fact, it would be desirable to have another relay which would prevent the application of the high voltage until these filaments had been heating for at least 15 seconds, and also prevent removal of the filament voltage while the high voltage was on. In the center of the panel are the supporting magnet controls: a toggle switch, an ammeter, and a 6 ohm, 25 watt rheostat. And at the right are the 6C5 plate ammeter, indicated in the circuit diagram, and the low voltage power supply switch, marked "Oscillator".

The switch for the high voltage transformer, and its associated relay, are on another panel, on the brick post to the left of the table. In addition, this panel carries a neon glow lamp, which indicates when the master AC switch is on; and also AC and DC line outlets, the latter for the stroboscope used to measure the speed of the centrifuge.

IV. THE OPERATION OF THE CENTRIFUGE

(a) Starting and Stopping the Centrifuge.

Before commencing a run, the machine is assembled as already detailed, and the electric drive set for the frequency decided upon. The best starting procedure has been found to be as follows:

1. Load the rotor and attach it to the driveshaft.
2. Lower the mechanism onto the vacuum chamber: check to see that the spindle rotates freely.
3. Turn on the vacuum pump.
4. Switch on the oscillator: set Master Gain Control to zero.
5. Tighten vacuum chamber bolts.
6. Connect the motor, the magnet, and the oil lines.
7. Apply about 7 lb./sq. in. oil pressure.
8. Switch on the 805 and 866 filament voltage.
9. Check the 6C5 plate milliammeter, and the direction of the reversing switch.
10. Switch on the fans; adjust for best coverage of the motor.
11. Turn on the water: a flow of about 300 cc/min. is required.
12. Switch on the high voltage.
13. Switch on the magnet current: check the ammeter.
14. Apply 1000 watts to the motor, checking the direction of rotation.
15. Adjust the magnet current.

and when the motor has reached the desired speed,

16. Reduce the power to the amount required.
17. Reduce the water pressure.
18. Reduce the oil pressure to 3 or 4 lb./sq. in.

19. If run longer than 3 hours, arrange a fan to cool the 805 and 866 filament transformers.

While the centrifuge is running, the various meters and gauges should be checked periodically, and the magnet rheostat adjusted to keep the current constant as the battery voltage falls. The Master Gain control needs occasional adjustment to compensate for line voltage changes.

The above list has been made up so as to allow for the time delays necessary between certain of the items. Thus the pump is turned on as soon as possible, in order to have a good vacuum when the run actually commences. Likewise the oscillator will have warmed up by the time constancy of frequency is required. Oil pressure must be applied early to allow time for the escape of the air in the narrow bore lead tubing and around the bearings.

The magnet is usually adjusted to a current just less than that required to raise the rotating system. This is about 0.1 ampere greater than the current which will allow the rotating system to lower itself once it has been raised. The system can of course be run in the raised position, if it is so desired. It was found that the upper babbitt surface of bearing B_2 wore rather rapidly even when the weight carried by it was small. At times this would lower T so much that the magnet would no longer be able to lift the rotating system. To remedy this a steel bushing 3/64" thick is inserted just below D. It is wide enough to rest on the brass shoulder of the bearing as well as on the babbitt, by now level with it. Its operation has proven eminently satisfactory.

Rather high pressure is necessary to force water through the cooling system at the rate of 300 cc/min. As a result, a mixture of oil and water tends to leak out of the bottom of the upper bearing, B_1. Hence no higher water pressure should be used than that necessary to keep the outflowing water well below the boiling point, as indicated above. Only from 3 to 4 lb./sq. in. oil pressure is required to lubricate the lower bearings once they have been run in; the higher pressure tends to balance the increased water pressure during the starting period.

The motor stator becomes rather warm after only a few minutes' running with a power input of 1 kilowatt. Hence two eight inch fans are used to provide some cooling, as a precautionary measure. Due to this heating it is advisable never to exceed a power input of 1000 watts for any length of time.

There is little to add concerning the action necessary to bring the rotor to rest. The power is reduced to zero, the reversing switch is thrown, and power again applied. Since now friction will be adding to torque, rather than opposing it, not more than 500 watts should be applied to decelerate the rotor, in order to avoid excessive strain on the driveshaft. Actually the rotor can be brought to rest in a reasonably short time with only 250 to 300 watts of decelerating power. This must of course be shut off just before the rotor stops or it will be rotated in the opposite direction. In shutting off the power to the audiofrequency generator the high voltage must be switched off before the filament voltage, otherwise damage will result to the power tubes and the rectifiers. When the rotor has come to rest, disassembly can proceed as already indicated.

(b) The Performance of the Machine.

Skarstrom and Beams (13) found that for drive frequencies between 800 and 1500 cps the average total starting torque of their motor was roughly inversely proportional to the drive frequency, for the same motor input power. This was also true of this motor, for the lower frequencies used with the quantity rotor; it is probably partly due to the fact that hysteresis losses increase with the frequency. On two successive runs, with the bearings in about the same condition, it took about 9 minutes to accelerate the rotating system to 19,600 RPM at a drive frequency of 498 cycles, but only about 7 minutes at 430 cycles, with 1 kw input in each case. Hence the usual procedure was to start the rotor on the lowest available drive frequency, 430 cycles, and after 7 or 8 minutes to switch to a higher frequency.

The highest speed recorded with the quantity rotor has been 30,500 RPM or 508 RPS. At the start of that run, a speed of 29,800 RPM was reached after a total of 13 minutes acceleration, 8 of which were at 430 cycles and the remainder at 568 cycles, with 1 kw input throughout. This run lasted for over 9 hours, and the data obtained during that time are typical of the operation of the machine.

After the acceleration period the power input was reduced to 400 watts and the Master Gain control was not touched for nine hours. The power input fluctuated between 380 and 420 watts, or within 5% of the value set, due mainly to line voltage variations. The speed also fluctuated, principally because of this, but also because of changes in friction and perhaps slight variations in drive frequency. However, it could not vary rapidly in view of the large inertia of the rotating system.

Table 3: Speed Chronology

Time h: m	Speed rps	Time h: m	Speed rps
0: 0	496	3:35	508
0:05	495	4:15	483
0:15	495	5:30	482
0:40	499	5:55	497
1:00	501	6:40	499
1:35	488	7:00	502
2:10	506	7:45	499
2:35	504	8:20	499
3:00	506	8:55	504

The average speed, weighted approximately in accordance with the time intervals, was 497 RPS or 29,850 RPM during the nine hour period. The maximum deviation is 3.1%, which is less than the fluctuation of the power input, as might be expected. This could have been reduced by occasional adjustment of the Master Gain control; the value of Skarstrom and Beams' automatic control is evident. On another run, over a period of two hours, the speed variation was easily kept within 1% by manually reducing the power input fluctuation to a maximum of 1%. The latter, however, was with a power input of 600 watts, and it is probable that variations in friction had less effect then than during the longer run with only 400 watts input.

The reproducibility of speed is of importance when it is desired to subject various substances to the same centrifugal field, at different times. This is easily obtained with this drive, as illustrated by the following: The steady speed with a power input of 600 watts at 498 cycles was found to be 27,600 RPM during one run, and a week later it was 27,400 RPM, under the same conditions.

Rapid deceleration is often necessary so that there will be little time for further changes in the centrifuged material. The highest decelerating power continuously applied was 300 watts, at 430 cycles: this brought the rotating system from 30,000 RPM to rest in 8 minutes. If the full 500 watts deemed permissible were applied, this figure would perhaps be halved. A further 8 to 9 minutes are required to disassemble the mechanism, as described, and remove the head from the rotor.

When running at constant speed with constant power input, all the power must appear as heat, since the electromagnetic radiation is negligible. The portion which heats the coolant flowing through the armature is easily calculated:

With 400 watts input at 568 cycles:

50 cc/min water raised from 19° to 44°C., corresponding to 90 watts.

With 600 watts input at 498 cycles:

83 cc/min water raised from 19.5° to 44°C., corresponding to 148 watts.

The balance heats the stator and the metal parts around the bearings. The stator lamination was heated to 66°C. during the acceleration period of the 9 hour run, and remained at about that temperature despite the forced air cooling and the lowered power input. It would be advisable to have the vacuum chamber and especially the brass block H water-jacketed, to prevent conduction of heat through the shaft to the rotor.

The vacuum obtainable was not very good, as already noted. During the nine hour run it varied from 2.6 to 0.4×10^{-3} cm Hg. This proved to be enough air to cause appreciable heating. Actually the temperature of the rotor at the end of the run rose from 21.5° to 41.5°C.; this was probably due to conduction as well as to air friction.

During most of this run a magnet current of 2.3 amperes kept the rotating system in the raised position, as the centrifuge seemed to run a little more quietly that way. In general, the operation of the mechanism was very smooth and free from vibrations at speeds above 10,000 RPM. Below that there are several speeds at which vibrations could be heard; they could never be seen due to the effectiveness of the damping device. These vibrations are not usually very noticeable when the machine is accelerating, because of the rapidity with which this takes place. They are usually more pronounced when decelerating, and it seems likely that this would be reduced with a higher power input than the 300 watts tried thus far. However, at all times the system passed through such vibration periods without ill effects.

(c) Power Supply Performance.

The following Table is illustrative of the values of representative voltages and currents for various values of the power output of the audiofrequency generator. The values were obtained when the centrifuge was rotating at about 25,000 RPM, and the drive frequency was 498 cycles.

Table 4: Power Supply Performance

Watts Motor Input	AC Line Voltage	805 Plate Voltage	805 Plate Amperes	6C5 Plate Milliamps.	6L6 Plate Voltage	"+110" Bleeder Voltage
0	113.5	1240	0.50	8.5	415	118
100	113.0	1210	0.60	8.4	418	112
200	110.5	1180	0.70	8.4	400	113
300	113.0	1200	0.85	8.4	417	114
400	110.5	1165	0.88	8.3	410	111
500	113.0	1190	0.95	8.5	419	111
600	111.8	1165	1.00	8.4	410	109
700	113.0	1165	1.10	8.5	418	109
800	108.5	1100	1.22	8.0	398	100
900	110.5	1120	1.25	8.0	400	102
1000	111.0	1100	1.40	8.0	402	100

Unfortunately, this particular run took place at a time when the supply line voltage was somewhat low and its variations unusually frequent. Thus the effect of the regulation of the DC power supplies is masked to some extent by these line variations.

The maximum power output noted on the wattmeter was 1220 watts, with an AC line voltage of 113.0 volts, a total 805 plate current of 1.61 amperes, and at a frequency of 430 cycles. These figures compare closely with the maximum ratings of the power tubes, already given; and they show that correct impedance matching of the various amplifier stages was achieved. Since this maximum output was obtained only with the full driver voltage available, there is never any danger of exceeding the total 805 rating as long as the conditions of Table 2 on page 36 are adhered to.

The only trouble experienced with the audiofrequency generator since it first operated successfully, has been with a blown condenser in the phase shifting network. With this exception, it has performed with remarkable stability, so that no attention need be given it.

V. THEORY OF SEDIMENTATION

Svedberg and Pedersen (2) include in their book an exhaustive treatment of the theory by means of which molecular weights and other quantities are obtained from observations with the centrifuge. Beams (23) and Loofbourow (24) have short but adequate summaries. Hence only the chief results are stated here.

The simplest case is the equilibrium state, in which sedimentation and diffusion balance each other, and which is reached if the solution is centrifuged for a sufficiently long time. Then, for uncharged particles, the molecular weight is given by

$$M = \frac{2\,R\,T\,\ln(c_1/c_2)}{(1-\rho V)\omega^2(r_1^2 - r_2\ )} \quad ,$$

where R = gas constant = 8.313 joules/degree/mol,

T = absolute temperature,

c_i = concentration at r_i,

r_i = distance from the axis of rotation,

ρ = density of solution,

V = partial specific volume of the substance,

and ω = angular velocity of the centrifuge.

With this method, concentrations are measured at various distances from the axis when the equilibrium state has been reached. This can be done photographically with a Svedberg rotor while it is rotating, and is the more accurate method. However, it is often inapplicable to biological materials. In that case the analytical method must be used, and here the quantity rotor is especially useful. Samples are removed from different levels after the rotor has been brought to rest; remixing can be prevented in various ways (23). Hughes, Pickels and Horsfall (25) give a useful method for extracting samples at known levels.

Svedberg and Pedersen give the following formula for the time necessary to secure complete equilibrium:

$$t_{max} = \frac{(r_p - r_m)^2}{1800\, D \ln (c_p/c_m)} \quad \text{hours,}$$

where p, m denote the periphery and the meniscus of the solution, respectively, and D = diffusion constant of the substance. The theory of Archibald (26) elaborates on this.

Often an inconveniently long time is required for the equilibrium state to be approached closely enough for that method to be employed. This is especially true for substances of large molecular weight. Also, many substances decompose or otherwise change before sedimentation equilibrium is established. In such cases the molecular weight can be obtained by measuring the velocity of sedimentation; the formula is

$$M = \frac{R\,T\,s}{D(1 - \rho V)}$$

in which the "sedimentation constant"

$$s = \frac{dr/dt}{\omega^2 r} ,$$

and the other symbols are as already defined. This is strictly applicable only to an infinite column of liquid, or, one long enough so that no reflection of particles takes place from the ends. In practice, however, the error is small, and this method has found wide application. The sedimentation constant s can be measured either optically or analytically, as with the sedimentation equilibrium method. Several beautiful optical methods have been devised for observing the concentration of the material as a function of the radius; these are fully described in the references cited.

VI. APPLICATIONS OF THE ULTRACENTRIFUGE

(a) Experiments with Lignin.

Lignin is one of the important basic chemical constituents of wood. Its structure would be more thoroughly understood if an accurate determination of its molecular weight were to be made. A Svedberg rotor is almost a necessity if this is to be done by one of the ultracentrifugal methods. However, some preliminary work with the quantity rotor was performed, and a very rough value of the molecular weight obtained.

Two lignin samples were supplied by the Pulp and Paper Research Institute here; one was made from spruce and the other from maple. They were extracted from the wood with ethanol containing 2% hydrochloric acid, and thoroughly purified by reprecipitation from organic solvents. The samples each consisted of 0.250 g lignin dissolved in absolute ethanol, and the solutions made up to 25 cc. These were called 1% solutions, and the concentrations used are given on this basis. Lignin solutions are highly colored; the degree of coloring depends on the source of the substance as well as on its concentration.

Since the sedimentation velocity method is not practicable with the quantity rotor, the sedimentation equilibrium method offered the only possibility of a result. The time required for equilibrium to be attained can be found from the formula on page 49. Unfortunately, the values for the diffusion constants of spruce and maple lignin dissolved in ethanol were not available, and hence this calculation could not be made. Thus the runs had to be performed without any prior knowledge of when the equilibrium state might have been established.

Since any changes in the centrifuged solution could be studied only after the rotor had been brought to rest, the effect of remixing had to be investigated. It was found that when, say, 5 cc of a 0.1% lignin solution, in a test-tube, had 5 cc of absolute ethanol poured over it, several days were required for the solution to reach a uniform color, if left undisturbed. Hence it seemed likely that the only remixing which had to be allowed for was that due to the change in the "stratification" of the solution from strictly vertical to approximately horizontal as the rotor came to rest. Because of this only relatively large samples, of the order of 0.5 cc, were taken from the centrifuged liquid for concentration analysis.

The first run with lignin samples was for two hours at an average speed of 27,650 RPM. Two samples of each kind of lignin were used; one of each of these was placed in a celluloid tube and the other directly in the rotor cavity. All were of the original 1% concentration. At the end of the run it was found that one of the celluloid tubes had collapsed around the top, sealing the liquid, while the other collapsed to such an extent that it was found doubled up at the bottom of the cell. This was explained by subsequent investigation, which showed that ethanol softened the tubes. It was also found that lignin seemed to stain the tubes; because of this no other attempt was made to carry the lignin samples in tubes. By means of fine pipettes samples were drawn off from the top, central and bottom portions, in that order, of each of the other two samples. However, examination failed to reveal significant differences of concentration among them.

The next run with lignin was at an average speed of 28,500 RPM for 45 minutes; biological samples were run at the same time. Lignin samples diluted to 0.01% with absolute ethanol were used, in order to see whether sedimentation might not be more easily obtainable with much more dilute solutions. At the end of the run it was found that only about one-half of each original sample remained. The reason for this is obscure; it was decided to attempt to seal the rotor cavities containing these dilute solutions, in subsequent runs.

The final run was the nine hour one already detailed. The average speed of 29,850 RPM corresponded to a field of 86,000 times gravity at the bottom of the rotor cavities. Four samples were used: two were the original 1% spruce and maple lignin solutions, while the others were 0.01% solutions. The openings of the cavities containing the latter pair were plugged with cork stoppers. Rubber stoppers were not used because of the possibility that the sulphur in them might affect the solutions. As previously, the 1% solutions failed to reveal any signs of sedimentation. The 0.01% spruce lignin solution was spoiled because the cork had been forced downwards into the solution by the high centrifugal field. Unfortunately, owing to the speed with which samples of the dilute maple lignin had to be removed, in order to prevent changes through exposure to the air, difficulties with two of the pipettes resulted in the loss of the two upper 0.5 cc samples. The bottom sample was successfully removed, however. Its concentration was determined spectrographically in the following manner:

The absorption spectrum in the visible and ultra-violet was photographed by means of a Hilger E2 quartz spectrograph. The source was an incandescent tungsten quartz lamp having a flat strip filament, run on 6.0 volts AC. The sample was contained in a small tubular quartz cell, which acted as a cylindrical lens, and was focussed on the slit. A quartz cylindrical condensing lens was found satisfactory; it focussed the filament on the slit before the cell was inserted. On the same plate with the centrifuged sample, there were also photographed samples containing concentrations of 0.01, 0.015, 0.02, 0.03, and 0.05% maple lignin. These were placed successively in the same cell and were photographed under exactly the same conditions, namely, with an exposure of 2 minutes at slit 95. From the plate it was estimated that the concentration of the centrifuged sample was 0.035%.

In order to apply the formula, the concentration at the top of the solution was also needed: this was estimated at 0.004%. The corresponding distances from the axis of rotation were 8.3 and 5.5 cm, respectively: these are the estimated positions of the centers of a volume of about 0.5 cc at the bottom and top of the solution in the cell hole. The temperature at which sedimentation equilibrium was assumed to have been reached was the final temperature, 41.5°C. or 314.5°K. The density of absolute ethanol at this temperature was found to be 0.771 g/cc, from the formula in the International Critical

Tables; negligible error would be made in assuming that this was also the density of the solution. Preliminary experiments at the Pulp and Paper Research Institute indicate that the partial specific volume of maple lignin, of about this concentration in ethanol, is in the neighborhood of 0.95. Substituting these values in the formula on page 48 yields a value for the molecular weight of maple lignin

$$M = 1100.$$

According to Loughborough and Stamm (27), values for the molecular weight of various lignins have been found all the way from 200 to 20,000. They are of the opinion that 4000 represents the best average value. Dr. Cooke and Mr. Patterson of the Pulp and Paper Research Institute think that the molecular weight of the samples used in this work is of the order of 3000. It is gratifying that the value estimated above is of the same order of magnitude as these figures. So many assumptions were made, both as to the nature of the processes occurring and in arriving at certain of the figures, that no claim can be made for the validity of this result. In any case, the result of a single determination can never be regarded as definitive. However, this work illustrated how a rough approximation to the molecular weight of a substance can be made even with a quantity rotor of this type.

(b) Experiments on Plant Cells.

As an illustration of the usefulness of the centrifuge in the study of the effects of high gravitational fields on living forms, typical samples were centrifuged during two of the runs. The first was at an average speed of 21,800 RPM for 40 minutes, and the second at 28,500 RPM for 45 minutes. These correspond to fields of 45,700 and 78,300 times gravity at the bottom of the cell holes.

The substances centrifuged were Allium cepa and Cornus canadensis. Two pieces of the former, each about 3 x 4 x 10 mm in size, were placed side by side at the bottom of each of two celluloid test-tubes. The tubes were then filled with tap water to about 5 mm from the top, and placed in the rotor in a pair of opposing holes. It was not found necessary to balance either the tubes or their contents by weighing; however, tubes of appreciably different length were not used together. Two pieces of Cornus were also run in each of two tubes, in water; these were cut to a length of 5.5 cm, almost the full length of the tubes.

Similar changes were observed in the structure of the two types of cells after they had been centrifuged. Examination in the microscope revealed that normal cell structure remained, but that both the nucleus and the cytoplasm had been displaced centrifugally, i.e. to the "bottom" of the cell; the vacuole was found in the upper portion. Cytoplasmic streaming was observed, and both neutral red staining and plasmolysis were found. This was conclusive proof that the cells were still alive, and showed the remarkable strength of the cell structure. There was no significant difference in the appearance of the cells run at the two speeds; nor was there any along the length of the Cornus, for which the field varied from 78,300 maximum to 25,000 times gravity, minimum. Apparently very much higher fields are necessary in order to break down the cell structure and, presumably, to kill the plant.

These results are similar to those obtained with various plants by H. W. Beams and King (28), and many others. It is believed that this was the first study made of the effect of high centrifugal fields on these particular tissues.

Contrary to expectations, it was found that the unsupported tops of the celluloid tubes did not collapse even at 28,500 RPM. Nevertheless, one of the four did develop a small leak, during each run. This is contrary to the experience of Bauer and Pickels (15), who found that when a speed of 27,000 RPM was exceeded, the top portion folded over the liquid, sealing the tube, but that leaks did not develop. These differences are probably due to slight differences in the composition of the tubes.

Further experimentation with living cells would be fruitful if much higher centrifugal fields were available here. These could easily be obtained with smaller rotors driven at much higher speeds, since the field increases as the square of the angular velocity while decreasing only linearly with the radius. Since duralumin is not obtainable at the present time, it might prove worthwhile to investigate the possibility of using plastic rotors. These would be light, easily machined, comparatively inexpensive, and could do little damage if they exploded. In this way, the extremely high speeds of which the drive is capable might be better utilized.

BIBLIOGRAPHY

(1) Knight, Phil. Trans. Roy. Soc. Lond. 96, 99, 1806.

(2) Svedberg and Pedersen, "The Ultracentrifuge", Oxford University Press, 1940.

(3) Perrin, C. R. 146, 967, 1908.

(4) Dumanski, Kolloid-Z. 12, 6, 1913.

(5) Svedberg and Rinde, J. A. C. S. 45, 943, 1923.

Svedberg and Nichols, J. A. C. S. 45, 2910, 1923.

(6) Henriot and Huguenard, C. R. 180, 1389, 1925.

(7) Beams, R. S. I. 1, 667, 1930.

(8) McBain and O'Sullivan, J. A. C. S. 57, 780 and 2631, 1935.

(9) Pickels and Beams, Phys. Rev. 47, 336, 1935.

(10) Beams and Pickels, R. S. I. 6, 299, 1935.

(11) Beams and Snoddy, Science 85, 185, 1937.

(12) Beams and Black, R. S. I. 10, 59, 1939.

(13) Skarstrom and Beams, R. S. I. 11, 398, 1940.

(14) Bauer and Pickels, J. Exp. Med. 65, 565, 1937.

(15) Bauer and Pickels, J. Exp. Med. 64, 503, 1936.

(16) Pickels, R. S. I. 9, 358, 1938.

(17) Biscoe, Pickels and Wyckoff, R. S. I. 7, 299, 1936.

(18) Wyckoff and Lagsdin, R. S. I. 8, 427, 1937.

(19) Masket, R. S. I. 12, 277, 1941.

(20) Beams and Linke, R. S. I. 8, 160, 1937.

(21) Beams, Linke and Sommer, R. S. I. 9, 248, 1938.

(22) Brunetti, R. S. I. 10, 85, 1939.

(23) Beams, Rev. Mod. Phys. 10, 245, 1938.

(24) Loofbourow, Rev. Mod. Phys. 12, 324, 1940.

(25) Hughes, Pickels and Horsfall, J. Exp. Med. 67, 941, 1938.

(26) Archibald, Phys. Rev. 53, 746, 1938; 54, 371, 1938.

(27) Loughborough and Stamm, J. Phys. Chem. 40, 1113, 1936.

(28) H. W. Beams and King, Bot. Rev. 5, 132, 1939.