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HIGH SPEED ROTATING DEVICES

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ABSTRACT

Physical problems which require the use of high speed rotating devices are reviewed, and the technical development of small rotors is surveyed. Applications to the purification of materials in solution and to the separation of isotopes are discussed.

I, indeed, am highly honoured and much pleased by the invitation to present a paper at this conference which honours Philip Moon. The title of this conference is most fitting since Moon has made many fundamental and pioneering contributions to this field. In reviewing the subject matter for this talk I re-read a review article entitled "Some Scientific Applications of High Speed Rotation" by Moon published over 20 years ago (Moon 1953). This excellent article is still remarkedly modern and covers the fundamental principles which are employed for producing high speed rotation. In this paper I will not attempt to match his article but will only endeavour to supplement it by re-reviewing the field with a somewhat different emphasis on the subject matter. Actually time does not permit a complete review of the field, so I will limit this paper to a discussion of those developments with which I am most familiar. Although the primary motives for the development of high speed rotating devices, which will be discussed in this paper, was the need for their scientific applications, I will not attempt to do more than indicate a few of their uses and then only as illustrations of their performance.

In general, problems which require the use of high speed rotating devices fall into four categories. (1) Those which require high angular velocities ω directly. (2) Those which employ high peripheral velocities $v=\omega r$ directly where r is the radius of the rotor. (3) Those which require large centrifugal potentials or a large $\omega^2 r^2$ and (4) Those which require large centrifugal fields or a large $\omega^2 r$. Typical examples of the above categories are, respectively, (1) Experiments in magnetism, superconductivity, and certain types of rotating mirrors, (2) Doppler effect and molecular accelerating and velocity selection rotors used by Moon and his students and by F. R. Metzger, (3) The equilibrium ultracentrifuge, the gas centrifuge, strength of materials measurements, etc., (4) The rate of sedimentation ultracentrifuge, studies of adhesion, etc. As will be shown later, with modern techniques the mechanical strength of the rotor sets the upper limit in all of the above categories. For a given rotor material and shape the maximum stress produced in the rotor is proportional to $\omega^2 r^2$ or to the peripheral velocity squared. Consequently, the rotor must be carefully designed in order to reduce stress concentrations to a minimum. If the rotor carries no load or a comparatively light load, the rotor material should have as large strength to density ratio as possible. If the rotor load is comparatively large then the rotor should be specially designed to carry the required load at the maximum $\omega^2 r^2$. Usually tough materials are preferable to brittle ones if the strengths and densities are equivalent.

Although with the present techniques the maximum rotor speed is limited by the rotor strength, in most cases several other problems must be solved. As a rotor is accelerated it passes through critical vibration modes which, unless they are damped, may destroy the rotor and its bearings. These critical vibrations usually occur when the rotor speed $\omega=2\pi n$ passes through the various natural resonances of the rotor and or its mountings and the natural vibration frequencies of the rotor itself. For example, if the centre of mass of a 1 kg rotor spinning at 1000 rps is 0.1 cm off of the axis of rotation the radial force on the shaft is approximately 4×10^4 newtons. As pointed out by W. J. M. Rankine (1869), this driving force may become destructive when the natural frequency of the rotor system is approached. For example, in figure 1 suppose the disk of mass M is rotating about a vertical axis with an angular velocity ω. Let the centre of mass of M be a distance ε from the axis of rotation ($\omega \rightarrow 0$). The resulting centrifugal force will then be balanced by the deflection r of the shaft and $kr = (r+\varepsilon)M\omega^2$ where k is the restoring constant of the shaft and bearings. The critical frequency $\omega_o = (k/M)^{\frac{1}{2}}$ and $r = \varepsilon\omega^2/(\omega_o^2 - \omega^2)$ which becomes infinite when $\omega = \omega_o$. However, C. G. P. de Laval (1883, see Stadola 1927) found that by mounting his steam turbine rotor on a flexible shaft, he not only was able to spin his rotor through the critical frequency but found that it spun stably above ω_o. The detailed theory of the transition through ω_o has been worked out by several different investigators (Stadola 1927, Kapitza 1939). The factors involved in this transition can best be followed by referring to figure 2. The axis of rotation coincides with the Z-axis, the vector deflection of the shaft is $\mathbf{r}$, the centre of mass is displaced by $\boldsymbol{\varepsilon}$ and a is the phase angle between the vectors $\mathbf{r}$ and $\boldsymbol{\varepsilon}$. Introducing a damping term into the equation and with some simplifying assumptions, it can be shown that

$$\frac{|\mathbf{r}|}{|\boldsymbol{\varepsilon}|} = \frac{q^2}{\sqrt{(1-q^2)^2 + b^2q^2}}$$
$$\cos a = \frac{1-q^2}{\sqrt{(1-q^2)^2 + b^2q^2}} \qquad (1)$$

where $q = \dfrac{\omega}{\omega_o}$, $b = \dfrac{H}{M\omega_o}$ and H is the damping coefficient.

It will be observed that when the damping is zero $|\mathbf{r}|/|\boldsymbol{\varepsilon}|$ will become infinite so that some damping is essential to negotiate the critical frequency ω_o. Also as the angular velocity increases from zero, the phase angle a also increases and when $\omega = \omega_o$ the vectors $\mathbf{r}$ and $\boldsymbol{\varepsilon}$ are at right angles. With further increase of ω the centre of mass of M continues to turn around O′ in the direction of the rotary motion until a approaches 180° and the centre of mass of M approaches $\mathbf{r}$ at a point nearer the axis than O′. It will be noted that when $\omega = \omega_o$, $|\mathbf{r}| = \varepsilon/b$ = maximum deflection of the shaft. Also, that for a smooth transition through the critical point $H^2 \geq 2M^2\omega^2_o$ and the vibrations become aperiodic when $H^2 \geq 4M^2\omega^2_o$. While the above theory can give an outline of the operation of a single disk type rotor, its detailed motion is influenced by gyroscopic phenomena, vibration of the rotor itself, friction in the bearing, rotor balance, air friction on the rotor, flexibility of the shafts, internal friction of the shaft, etc. In most cases, the principal damping action takes place in the bearings due to the action of the oil film and the bearing mountings.

The de Laval turbine (Stadola 1927) may be considered to be the first of the high speed rotating devices. It was a single disk type rotor mounted on a flexible shaft and the higher critical modes were either absent or small. It is a general law of mechanics that any rotating body tends to seek its own axis of rotation. Consequently, if the shaft is flexible enough to bend into the proper shape to allow this to happen, the rotor spins smoothly. However, regardless of the flexibility of the mounting and shaft, in practice, it is desirable to balance the rotor as accurately as possible; i.e., reduce ε in the above relations to as small values as possible. In order to increase its efficiency the de Laval steam turbine is often operated with an ω 6 or 7 times ω_o. In some of the steam turbines a rotor speed of 433 rps was obtained and a peripheral speed of 3.9×10^4 cm s^{-1} (Stadola 1927). This flexible shaft design has been used in its various modifications in many types of commercial centrifugal devices which are familiar to everyone.

Another method of spinning small rotors to high speed in air is to mount the rotor on a whirling cushion of air. This method has been known for a long time and is a common demonstration in science museums, lecture demonstrations, etc. However, it was not until 1925 that Henriot and Huguenard succeeded in spinning small cone shaped rotors to high speeds (1.17 cm dia. to 11000 rps) that the method has been used in research. The cone shaped surfaces of the rotor and stator are designed so that the Bernoulli forces constrain the rotor to spin on a thin gas or air cushion. The original method has been modified and improved by a number of different workers until at the present time the air cushion is very stable and allows the rotor to seek its own axis of rotation (Beams 1930, 1937; McBain 1939). This method has

been used primarily for spinning small mirrors, for doppler effect studies, and for the study of the sedimentation inside of living biological cells (Beams 1930, 1937; Beams and King 1934, 1935; Harvey 1938; Metzger 1956).

The power required to spin high speed rotors in air at atmospheric pressure becomes very large as the peripheral velocity and radius of the rotor increases (Beams 1930, 1937). For example, in order to spin a cylinder 30 cm long and 15 cm radius at 400 rps ($\omega r \sim 4 \times 10^4$ cm s^{-1}) in air at atmospheric pressure it requires about 30 horsepower (Theodorsen and Regier 1944). Also if such a rotating cylinder is surrounded by a closed chamber the rotor gets very hot and an aluminium alloy rotor, for example, may lose its high strength due to the heat and explode. Furthermore, if the rotor is enclosed the gaseous friction introduces rotor whirl and instabilities which are difficult to damp out (Kapitza 1939). One way to reduce both the gaseous rotor friction and the resulting climb in rotor temperature is to reduce the pressure surrounding the rotor or substitute hydrogen or helium for the air. Svedberg developed an oil driven ultracentrifuge which spins in flowing hydrogen at about 20 Torr. Hydrogen at this pressure has a large ratio of heat conductivity to rotor friction and thus helps to keep the temperature constant throughout the rotor. The difference in temperature between rotor and wall was about 1.5K at 15 Torr. The rotor cell which contains the material to be centrifuged is provided with crystal quartz windows for observing molecular sedimentation. Svedberg and his associates have used this ultracentrifuge in their pioneering studies of protein molecules and other biologically important substances. Reference should be made to T. Svedberg and K. O. Pedersen (1940) for a description of this convection free centrifuge (ultracentrifuge) and its applications.

In order to obtain convection free sedimentation in a liquid or solution, it is necessary to avoid rotor temperature gradients in a direction which decreases the density toward the periphery. The principal factor which generates convection in a centrifuge is roughly proportional to the radial density gradient multiplied by the centrifugal acceleration. Since the latter usually is comparatively large (10^3 to $10^8 \times g$) the density gradient (and hence temperature gradients) must be very small. It should be noted that centrifugal acceleration and the gravitation acceleration are considered to be equivalent so that the former is usually measured in terms of the earth's acceleration of gravity $g = 980$ cm s^{-2}. Fortunately, the density of liquids and gases increases toward the rotor periphery due to pressure and in the case of solutions the sedimentating material also increases the density in the same direction. For a pure liquid or gas the maximum stable or adiabatic radial temperature gradient $\mathrm{d}T/\mathrm{d}p = (T/c_p)\ (\partial v/\partial T)$, where p is the pressure, T the Kelvin temperature, v the volume and c_p the specific heat at constant pressure. In a centrifugal field of $10^5\,g$ for air at 20°C, $\mathrm{d}T/\mathrm{d}r \lessapprox 10°$C/cm and in water $\mathrm{d}T/\mathrm{d}r \lessapprox 0.18°$C/cm while for a field of 1000 g the values are 0.1°C/cm and 0.0018°C/cm, respectively; i.e., the larger the centrifugal field, the more stable the sedimentation column becomes. Clearly the ideal centrifuge would be one in which the rotor spins in a high vacuum. This not only would greatly reduce the power required to drive the centrifuge but would insure that the rotor temperature could be held constant at a known value and completely free of temperature gradients. Starting in 1934, E. G. Pickels and I developed a method of spinning rotors in a high vacuum (Pickels and Beams 1935; Beams and Pickels 1936). This vacuum type ultracentrifuge consisted of a large centrifuge rotor which spins around a vertical axis inside a vacuum tight chamber, a small air-driven air-supported turbine located above the chamber and a thin flexible shaft which joins them together and which is coaxial with their common axis of rotation. Figure 3 shows a schematic diagram of an early air driven vacuum type convection free centrifuge (Beams 1937, 1938a, b, 1942, 1947). The centrifuge rotor C inside the vacuum chamber V is connected to the air-supported air-driven turbine T by the vertical (0.1″ o.d.) flexible steel shaft A. G_1 and G_2 are vacuum tight oil glands mounted in O-rings. The rotating parts are supported on an air-thrust bearing between B and T and are spun by air jets impinging on T. Reverse jets are provided for decelerating the rotor. Usually G_1 and V are held at a constant temperature by circulating oil. The small diameter flexible shaft A not only has a very small friction in G_1 and G_2 but also permits the large rotor C to seek its own axis of rotation and spin stably. It also permits G to seal the vacuum chamber without an appreciable amount of the low vapour pressure (10^{-7} Torr) oil leaking into V. Since T is much smaller than C the maximum rotational speed is limited only by the mechanical strength of the rotor C. The combination of high centrifugal field, large or small size rotors, lack of thermal gradients, lack of need for accurate dynamical balance, low power requirements, etc. make this centrifuge almost ideal for the purification of biological and other large molecular compounds as well as determining their molecular weights. The rotor C in figure 3 is used for the purification of the above materials. To analyze them and to measure their molecular weights, the rotor C is replaced by a so-called analytical rotor which carries a sector-shaped cell with crystal quartz windows through which the sedimentation can be observed by various optical methods (Svedberg and Pedersen 1940; Beams 1937, 1938a, b, 1942, 1947). Because air turbines are noisy and require special devices for controlling their speed, the turbine was soon replaced by an electrical motor, and the air thrust bearing was replaced by a partial magnetic support (Beams and Snoddy 1937, Skarstrom and Beams 1940). Figure 4 shows a section of an early type of electrically driven magnetically supported vacuum type ultracentrifuge. The rotating system consists of the steel motor armature D, the steel magnetic support core R and the rotor C. F is the field coils and L the lifting solenoid. The drive essentially was a two phase a.c. induction motor supplied with up to 1 kW at 1188 cycles per sec. The power input to the motor was automatically controlled to keep the rotor speed constant to at least $\frac{1}{2}$ rps at 1000 rps. Here again the limiting factor which sets the maximum rotor speed is the strength of the rotor. The weight of the rotating system was practically all carried by the lifting action of an iron core shielded solenoid. The small remaining weight was carried by a small thrust bearing. Since the magnetic field of the solenoid is axial and symmetrical it produces no electromagnetic drag and, hence, no friction on the rotating system; i.e., it essentially is a frictionless thrust bearing. In many cases a permanent magnet replaces the lifting solenoid. It turns out that the centrifuge of figure 4 is usually more convenient to operate than that of figure 3. E. G. Pickels especially has developed an electrically driven vacuum type ultracentrifuge which is almost automatic. It has now been commercially available for many years and is widely used in research.

It should be noted that the lifting magnet or solenoid above the rotor makes it possible to put the driving turbine or motor below the vacuum chamber. In this way, the lifting magnet is usually mounted in dampers and serves both as a support and as a damper of horizontal disturbances of the rotor. Although the magnetic bearing of figure 4 itself is essentially friction free, there is still some drag due to the stabilizing oil thrust bearing. Also the small amount of low vapour pressure oil which leaks into the vacuum chamber is sometimes not desirable. P. B. Moon and his colleagues (Moon 1951, 1953; Marshall *et al.* 1948) eliminated the oil from the vacuum chamber by sealing the rotor in a glass vacuum chamber as shown by figure 5. The rotor is a steel rod doubly tapered in such a way that it will reach a maximum peripheral velocity. It has in its base a small hardened steel ball which runs on a glass plate and supports about 10% of the weight of the rotor. The remaining 90% is taken by an electromagnet mounted in dampers as shown in figure 5. The rotor is driven by a magnetic field rotating at 2700 Hz produced by two sets of coils in quadrature. With this arrangement they obtained peripheral speeds of over 10^5 cm s^{-1}. The rotor speed is measured by allowing the rotor tips to interrupt a beam of light which falls upon a photocell. They have used this device for the study of the resonant nuclear scattering of gamma rays, for the activation of fast reactions, time-of-flight of atomic beams, etc. You will no doubt hear more about the extension of these and other experiments later in this conference.

In our laboratory, F. T. Holmes (1937) was able to construct a magnetic suspension which supported a small steel rod freely. With this suspension Holmes and I succeeded in spinning a small steel cylindrical rotor up to 1000 rps in a vacuum and observed that it was remarkedly free of friction (Holmes and Beams 1937). Subsequently, L. E. MacHattie spun a small steel sphere up to its bursting point (MacHattie 1941). Incidentally, small rotors were also freely supported in our laboratory by electrical forces but at the time the magnetic suspension seemed to be best suited for our purposes. After World War II we were able to greatly improve and stabilize the free magnetic support for rotors and figure 6 shows a schematic diagram of the method (Beams *et al.* 1946). The ferromagnetic rotor is freely suspended inside of the glass vacuum chamber by the axial magnetic field of the solenoid. It is held at the desired vertical position by the automatic regulation of the current in the solenoid and on the axis by the geometry of the axial (diverging symmetrically downward) field of the solenoid; i.e., the rotor will seek the strongest part of the field which is on the vertical axis of the solenoid. The upward force on the rotor is $M(\partial H/\partial z)$, where M is the magnetic moment of the rotor and $\partial H/\partial z$ is the vertical gradient of the magnetic field. In general, this upward force is a function of the current in the solenoid. If the rotor moves vertically it changes the impedance of a small sensing coil in a servo-control circuit in such a way that the current in the circuit increases when the rotor moves down and decreases when it rises, consequently, since the control circuit contains derivatives and damping the rotor is very accurately maintained at the desired height (Beams *et al.* 1946). Interferometer measurements show that the vertical motion of the rotor is less than 0.1 the wavelength of light (Beams 1963). This absence of observable vertical motion can be intuitively understood in the following way. With a good control circuit, at any time the upward magnetic force balances the weight of the rotor to about one part in 10^6. Consequently, the maximum vertical acceleration of the rotor is $10^{-6}\,g$ so the vertical distance travelled Δz in the time Δt required for the circuit to correct the current is $\Delta z \sim (10^{-6}g/2)\,(\Delta t)^2$. If $\Delta t \sim 10^{-3}$ s $\Delta z \sim 10^{-9}$ cm. A more exact calculation gives a larger value but it is still extremely small. If the rotor encounters a horizontal disturbance it will oscillate and means must be provided to damp this approximately horizontal pendulum motion. In figure 6 this is accomplished by hanging the iron core of the solenoid by a fine wire in a "dash pot" of oil. For comparatively small rotors a steel damping needle surrounded by oil is mounted in a way similar to a reed below the vacuum chamber (Beams *et al.* 1946). The rotor is spun by a rotating magnetic field produced by the drive coils. If the rotor temperature need not be constant an induction type of drive can be used to accelerate the rotor. If the rotor temperature must remain constant during the acceleration then a variable frequency synchronous or other types of drive must be used. A low power synchronous drive is preferable when the rotor spins at the desired operating speed. Actually, in most cases, the friction is so small that no drive is necessary to keep the rotor speed constant enough for the experiment. Many types of servo-controlled circuits have been used successfully. Since these circuits are discussed at length in the textbooks on electrical engineering, they need not be described here except to note that in many cases a light beam-photodiode or other type of rotor height sensor may be preferable to the sensing coil of figure 6. The rotor speed is measured by reflecting or scattering a beam of light off of the rotor into a photomultiplier cell or photodiode in such a way that it gives a signal with a frequency equal to the rotor speed or a multiple of it. This frequency is usually multiplied and compared with a known frequency or, in some cases, is made to automatically control the rotor drive frequency. The accuracy of the speed measurement is determined by that of a standard known frequency. In fact, the inertia of the almost friction free rotor has a smoothing effect on the standard drive frequency. Rotors which vary in weight from 10^5 g to 10^{-6} g have been supported and spun stably but experience indicates that this range can be extended from ferromagnetic particles just large enough to give an observable signal by light scattering to rotors so massive that they overload the lifting magnet. Incidentally, for the heavier rotors a large permanent magnet or solenoid is often placed (usually above the solenoid which carries the servo-current) to support most of the weight of the rotor; i.e., the servo-current functions only as a stabilizer.

The type of magnetic suspension shown in figure 6 has been used to test the mechanical strength of rotors of different shapes and of different materials (Beams 1949, 1953). A series of spherical rotors of different sizes were first tested. They were selected steel balls (from ball bearings) and ranged in size from 0.397 cm to 0.0398 cm diameter. They all exploded at the same peripheral speed (10^5 cm s^{-1}) within a few percent which gave a calculated maximum stress at the centre of the ball, assuming elastic theory, of about 3.8×10^4 kg cm^{-2} (454,000 lbs in^{-2}). This method of determining maximum tensile strengths of material is free of stress concentrations due to clamps, etc. If the rotor is very slowly accelerated, as the yield point of the rotor material is approached the rotor expands, the moment of inertia increases slightly and the rotor speed decreases due to the conservation of angular momentum. As a result, a rotor explosion can often be avoided. Measurements of the strengths of very small single crystals or iron (iron whiskers) confirms the high values found by other methods. They show a marked increase in strength at the smallest diameters (Piotrowski *et al.* 1966). This centrifugal method also has been used for determining the tensile strengths of thin films of materials which also show increased strengths at very small thickness as well as at low temperatures (Beams *et al.* 1955). The method is especially useful for determining the absolute value of the adhesion of one material to another (Beams 1956, 1959). In the latter experiments cylindrical rotors are used where their diameter to length ratio was always greater than 2 to $\sqrt{3}$ in order to insure dynamic stability. If the length to diameter ratio is too large the rotor reaches its fundamental flecture vibration before it explodes and if the driving force is large enough and the damping small it will bend into a V shape (Beams 1949). Since the rotor strength is determined by $\omega^2 r^2$ and the centrifugal field by $\omega^2 r$ with small rotors, both ω and $\omega^2 r$ can be made very large; i.e., rotor speeds of over 10^6 rps and centrifugal fields of 10^9 g have been obtained with small rotors ($\leqslant 0.03$ cm diam) (Beams 1959). The method is also useful for producing high speed rotating mirrors (Beams *et al.* 1952). Due to the very small frictional drag, it can be made free of troublesome "hunting" which is very important for precise measurements. A mirror with six faces each 4.25 mm dia was spun at 20,000 rps and used for several experiments. Its speed was as constant as the driving oscillator which was good to one part in 10^6. Higher precision could have been obtained by increasing the accuracy of the drive oscillator. When the composition of the residual gas is known the above method can be used to measure the absolute pressure of the gas (Beams *et al.* 1962; Spitzer 1962). The method consists in determining the frictional drag produced by the gas or vapour on a spinning rotor. It turns out that in a properly magnetically suspended symmetrical spinning rotor the friction due to all other causes is negligible in comparison to the gaseous friction down to pressures of at least 10^{-8} Torr. Consequently, it is only necessary to spin the rotor to the operating speed and then determine its deceleration in order to measure the absolute pressure p. For example, when the molecular mean free path is larger than the rotor radius in the case of a spherical rotor of radius r, it can be shown that

$$p=\frac{rd}{5C(t-t_0)}\left(\frac{2\pi RT}{M}\right)^{\frac{1}{2}}\ln\left(\frac{N}{N_0}\right) \qquad (2)$$

where N_0 is the number of rev/sec at the time t_0 and N is the number at t, d is the density of the rotor material, T is the absolute temperature, M is the molecular weight of the gas and C is a constant which usually turns out to be the order of unity for a polycrystalline rotor surface. When the mean free path is less than r a different relation must be used (Kuhlthau 1949). It was found that spherical steel rotors with diameters between 0.318 cm and 0.04 cm when spun at speeds well below the yield point of the material were most convenient for the measurements. The vacuum system containing the rotor was carefully cleaned and baked and was attached to a calibrated Alpert ionization gauge. The measurements of the two gauges were in reasonably good agreement down to about 10^{-8} Torr where the ionization gauge was believed to become unrealiable. However, by sealing off the vacuum system and freezing out the residual gas by reducing the temperature to that of liquid helium there still remained a small residual drag which clearly was not due to the gaseous friction. This residual drag is probably due to a number of causes: If the axis of spin and the axis of the symmetrical magnetic field and the direction of gravity are the same, an axial rotation does not change the flux through the rotor and no eddy currents and resultant drag are produced. However, apparently this ideal arrangement has never been completely realized in practice. For example, it is a difficult and tedious procedure to bring the axis of permeability and the mechanical axis of the rotor into sufficient coincidence to avoid induced currents in the surrounding media. Also, the rotor is a gyroscope and its axis of spin tends to remain fixed in space while the earth rotates; this gives rise to rotor drag. Unless great care is taken during the acceleration period, the rotor warms up. Consequently, upon reaching full speed it cools and contracts which reduces the moment of inertia and, hence, increases the speed due to conservation of angular momentum. For example, the speed of a 0.03 cm steel rotor spinning at about 10^6 rps increases about 20 rps if its temperature drops 1K. Mechanical vibrations of the rotor system produce flux variations of such a nature as to change the speed of the rotor. Earth tides due to the moon and sun also may be troublesome. The pressure of light on the rotor has been found to produce acceleration or deceleration unless it falls symmetrically on the rotor. The rotor drag may be introduced by improperly aligned dampers, kind of damping, or variation in height of the rotor. The stretching of the rotor also affects the deceleration. Incidentally, the stretching of the rotor produces a small electrical potential difference between the axis and periphery in addition to the Lorentz potential (Beams 1968). Electrostatic charges on the rotor and vacuum chamber walls also may produce deceleration. The above list is not complete. These effects have been discussed and investigated by almost every worker in the field because of the importance of obtaining, in practice, a rotor support which is as friction free as possible. J. C. Keith (1963), D. J. Kenney (1960) and more recently J. K. Fremerey (1971, 1972, 1973a) especially have carefully investigated the drag of a magnetically suspended rotor and the latter (1973b) has interpreted part of his drag data as probably due to gravitational radiation of the type proposed by Keith (1963). The Keith type of gravitational drag is supposed to occur in spherical as well as non-spherical rotors and in all cases is many orders of magnitude larger than that predicted by the Einstein-Eddington-Weber relation (Weber 1961). It is probably observable if it exists. Consequently, it is to be hoped that the above rotor drag work can be extended and improved until this uncertainty can be clearly resolved. In addition to the use of magnetically suspended rotors for measuring absolute gas pressure, they have been effectively used as bakeable molecular pumps for producing ultrahigh vacuum (Williams and Beams 1962). The low friction magnetic suspension has made possible the development of a high precision analytical equilibrium ultracentrifuge for measuring the molecular weights over the range from 10^2 to 10^8 daltons (Beams 1959; Beams *et al.* 1961, 1962). In general, there are two principal methods of measuring the molecular weights of substances in solution with an ultracentrifuge. The first or rate of sedimentation method requires a high centrifugal field. Consequently, the sedimenting column is stable and the rate of sedimentation is measured in a comparatively short time. From this rate of sedimentation the molecular weight can be calculated essentially on the basis of Stoke's law. In the equilibrium method the material is centrifuged for a long time until the sedimentation is balanced by back diffusion. Since no material can be allowed to settle out on the periphery of the centrifuge cell which contains the solution, the centrifugal fields (rotor speeds) must be comparatively low. As a result in order for the sedimentating column to be free of convection the temperature must be held constant (to ≈ 0.002 K in practice) and rotor speed fluctuations (hunting) must be absent. The steel rotor in use is 19 cm diam., 14 cm high, weighs 14 kg and carries a sector shaped cell near its periphery which contains the material under investigation. The cell has crystal quartz windows and is divided into two sector shaped compartments side by side, one of which contains the solution and the other the solvent. In this way the strains in the windows can be balanced out and the refractive index (and hence the density of the solution) can be accurately determined as a function of the radius of the cell by light interferometer methods. The rotor spins in a thick brass carefully thermostated cylindrical vacuum chamber, where the gas pressure is less than 10^{-7} Torr. The molecular weight measurements are made by accelerating the rotor to the desired speed without raising its temperature and allowing it to coast freely. The rotor deceleration is usually so small ($\approx 10^{-1}$ rps/day) that the sedimentation approaches quasi-equilibrium (≈ 1 day). The molecular weight can then be determined to about one part in 10^3. This equilibrium method is based on thermodynamic theory which is more reliable than Stoke's law. In some cases it is desirable to hold the speed constant for long periods of time so a synchronous drive is used. The molecular weight is, of course, one of the most important factors in characterizing a substance in solution. Finally, it should be pointed out that all of the above methods used for spinning rotors in a high vacuum have been simply modified for spinning the rotors at liquid helium temperatures ≈ 2 K to high rotational speeds.

Perhaps the two most important potential practical uses of high speed rotation are in the purification of materials (biological, etc.) which are in solution and in the separation of isotopes for use in nuclear fission power reactors. In the former case the separation usually takes place in solutions while in the latter the separation occurs in gases (UF_6). In both cases it is advantageous to use long (tubular) rotors which are operated at as high peripheral speed as possible with as little drive power as possible. This dictates that the rotors should spin in a vacuum. In both cases where it is desired to separate large quantities, the material is flowed through the centrifuge continuously although batch methods have been found useful in purifying solutions of biological material in litre quantities and less. Because of the theoretical advantage of the tubular centrifuge for large scale separation processes, work was started in our laboratory on a method of spinning tubular rotors in a vacuum soon after the vacuum type ultracentrifuge was developed (Beams 1937, 1938a, b, 1942, 1947). In general, the spinning of long tubes is more difficult than that of disc type rotors for two principal reasons. First, for a long tube spinning about its length L the moment of inertia about the spin axis is usually considerably less than that about its diameter D, so that the motion is only quasi-stable; i.e., if allowed to spin without constraints it will turn over and spin about a diameter through its centre. Consequently, it must have some type of bearings that constrains the axis of the tube at least roughly to that of the spin axis. Second, in addition to the critical vibration frequencies produced by the rotor-shaft-bearing combination discussed previously (equation (1)), the tubular rotor itself encounters severe critical flecture vibrations at rotor speeds a few percent above the natural flecture vibration frequencies. This frequency shift is caused by the "stiffening" of the tube produced by the gyroscopic forces. These frequencies consist of the fundamental and the harmonics. In the disc type rotor the harmonics are usually too small to be of consequence so that efficient tuned dampers can be used. On the other hand, both the fundamental and the harmonics are often almost equally severe in long tubular rotors and dampers tuned for one are in general not tuned to the others. Furthermore, a tubular rotor balanced for one frequency may be unbalanced for the next unless special balancing experiments are carried out. Although in the early 1940's (Beams 1937, 1938a, b, 1942, 1947) our aluminium tubular gas centrifuge rotor (345.5 cm long, 20.4 cm O.D., 18.88 cm I.D.) was spun very stably for long periods above its second critical flecture vibration frequency and was used for uranium isotope separation, most of the published work since that time has been carried out with tubular rotors with an L/D ratio small enough so that the rotor operates below its first flecture critical.

Especially important work has been carried out by Norman Anderson and his colleagues at the Oak Ridge National Laboratory on the purification of substances of importance in biology and medicine using the subcritical tubular vacuum type ultracentrifuge (Anderson 1966). They use density gradient centrifugation where a radial density gradient is established (usually with non-reactive substances) in which the density varies from values greater to values less than that of the substance to be purified. Consequently, the purified substance collects in a thin tube-like column with a constant radius (zonal centrifuge). They have devised ingenious ways of getting the material into and out of the centrifuge. Their procedure is presently being used to prepare certain vaccines on a commercial scale. For example, flu vaccine prepared in this way is so pure that the harmful effects due to impurities are absent and larger more effective doses can be administered without discomfort.

The possibility of separating isotopes by centrifugation was first suggested by Lindemann and Aston (1919). Also, they worked out the equilibrium theory for the centrifugal separation in an ideal gas and in an ideal incompressible liquid. This theory was critically discussed by R. S. Mulliken (1922, 1923), S. Chapman (1919) and W. D. Harkins (1922) and several unsuccessful experimental attempts were made to obtain isotope separation in specially constructed centrifuges (Mulliken 1922, 1923; Harkins 1922; Joly and Pool 1920; Pool 1921). However, after the development of the vacuum type ultracentrifuge the method was undertaken again and the separation found to be approximately that predicted by theory (Beams 1937, 1938a, b, 1942, 1947). In the first successful experiments the vacuum type ultracentrifuge was used to concentrate the Cl^{37} and Cl^{35} isotopes in CCl_4 (Beams 1937, 1938a, b, 1942, 1947, 1959). However, soon after the discovery of nuclear fission, the work was switched to the separation of U^{235} and U^{238} in UF_6. During World War II independent efforts to separate the uranium isotopes by high speed centrifuging were carried out at least in the U.S.A. (Cohen 1951) and Germany (Beams *et al.* 1958). The centrifuge method of heavy isotope separation such as U^{235} and U^{238} is theoretically attractive because it depends upon the differences in the isotopic masses rather than their absolute values and the elementary separation process *per se* is a quasi-reversible process; i.e., most of the energy consumed in the separation process goes into bearing friction and flowing the gas through the individual centrifuges and their cascades, not the separation process itself. The concept of separative work U done in an isotope separation process may be used as a standard to evaluate the effectiveness of the various separation processes. In the centrifuge process K. Cohen (1951) following previous work of P. A. M. Dirac derived a value for the maximum separative power $\delta U_{\max}$ of a single centrifuge under ideal flow conditions in a gas containing two isotopes

$$(\delta U_{\max})=\frac{Dp}{RT}\left[\frac{(M_2-M_1)(\omega r_2)^2}{2RT}\right]^2\frac{\pi Z}{2}\ \text{(moles/sec)} \quad (3)$$

where p is the pressure of the gas, D the diffusion constant, M_1 and M_2 the molecular weights of the light and heavy isotopes, respectively, T the Kelvin temperature, R the gas constant, ω the angular velocity, r_2 the inside peripheral radius and Z the length of the centrifuge tube. Although (3) above must be modified (reduced) by a factor less than one depending upon the type of flow pattern used, etc. inside the centrifuge, it does show that the separative power increases rapidly with increase in peripheral speed and length of centrifuge but is independent of the tube diameter. Since the maximum peripheral speed which can be obtained in a gas centrifuge is roughly proportional to the strength/density ratio of the tube material, special efforts have been made to design tubular rotors which maximize this ratio. Peripheral speeds of 500 m s^{-1} are reported by the press to be in use. Various types of gas flow patterns inside the centrifuge have been tested, but the so-called counter current type is generally believed to be the most efficient. In a spinning tube the ratio of the peripheral pressure p to the axial pressure p_o is

$$\frac{p}{p_o}=\exp\frac{M\omega^2r_2{}^2}{2RT} \quad (4)$$

This ratio becomes very large and p_0 may become small; i.e., for UF_6 gas and peripheral speed of 500 m s^{-1}, $p/p_o \sim 5\times10^7$. If we take the vapour pressure on the rotor periphery as 150 Torr, then the pressure on the axis is about 3×10^{-6} Torr. Consequently, some means must be provided for extracting the light and heavy fractions from the spinning tube. One way of doing this is to mount stationary (non-rotating) scoops near the bottom and near the top of the spinning tube, respectively. These scoops convert the kinetic energy of the gas at a given radius into pressure energy which not only is large enough to extract the gas but when desirable can force it through a cascade of centrifuges. The gas is usually fed into the centrifuge by a stationary inlet on the axis of the tube. It will be observed that the angular momentum of any small mass dm of the gas varies from zero on the axis to ωr^2dm at the radius r, and its pressure varies from a small value on the axis to the peripheral pressure p. If now we suppose that the small mass of gas, say near the periphery, moves inward along the radius its angular velocity increases since its angular momentum is conserved; this increases the centrifugal force and it moves back outward along the radius. Also, the volume of dm expands as it moves inward and cools. This increases its density which also tends to force it back to its original radial diatance. Consequently, the gas will not flow in the radial direction unless sufficient heat and angular momentum transfer is provided. On the other hand, the gas can flow freely in the axial direction except, of course, for viscous forces. It has been found both experimentally and theoretically that counter current flow in the centrifuge, when carried out properly, produces the largest separative work per unit length of the centrifuge tube for long spinning tubes (Cohen 1951; Beams *et al.* 1958; Groth *et al.* 1957, 1958; Zippi 1960; Kistemaker *et al.* 1957, 1958; Groth 1973; Avery and Davies 1973). Figure 7 shows a schematic diagram of a three stream internally driven counter current flow method. The small feed tube F F′ is stationary and the centrifuge CT is spinning in a vacuum. The flow of the gas is represented very schematically by the dotted lines. The feed gas flows from F to F′ where it enters the centrifuge and mixes with the gas streams (spinning with the centrifuge). At AA′ angular momentum is added to the gas by the end cap and by some mechanism such as a baffle and or a radial temperature gradient in such a way that the gas moves radially from A to A′. These mechanisms induce an axial flow from A′ to B′. The flow is in axial concentric cylindrical streams down along the periphery, one of which is shown by the dotted line A′B′. Angular momentum is extracted and or heat is added along B′B and the gas flows in concentric streams from B to A. The centrifugal separation takes place between BA and A′B′ and the light fraction collects at AA′ where it is continually extracted as product at P. The heavier isotope collects at B′B and is continually extracted at W. It will be observed that the overall separation factor may be many times the single elementary separation factor; and also, that it will depend upon the amount of feed F, the product P and waste W and the ratio of the latter, etc. It is not possible to discuss this process properly in the time available and reference should be made to the literature. Furthermore, according to press reports due to the urgent need for nuclear power, a number of national governments are at present sponsoring research and development of the gas centrifuge isotope separation process so that any separation data now available in the literature is probably obsolete. The gas centrifuge seems to have promise of providing an economical method both in cost and energy for separating the uranium isotopes.

In closing this review it might be of interest to mention very briefly how the same techniques for producing high speed rotation discussed above can be used for producing very constant speed rotation as well as constant angular acceleration.

There is an increasing need for extremely constant speed rotating devices not only for equilibrium ultracentrifugal experiments as previously discussed but also in the accurate measurement of time, in the investigation of many phenomena which occur in short times, in the compensation of certain cyclic changes in the horizontal component of the gravitational field of the earth etc. At first sight one might expect that a properly designed rotor driven by a synchronous motor would have a speed as constant as the driving frequency f which in the case of an atomic clock or properly made maser or laser could be $\Delta f/f \approx 10^{-13}$. However, this will be so only if "hunting" is absent. Fortunately, if necessary, the use of low friction rotor supports described previously apparently can eliminate this hunting. Also by employing a double magnetic suspension (Beams 1963, 1965) for the rotating parts it should be theoretically possible to increase the constancy of the rotor speed well beyond that of the motor drive frequency; i.e. in the double magnetic suspension one rotor may surround the other so that gaseous friction is eliminated. Also since with a magnetically supported rotor coasting in a vacuum $\Delta f/f \approx 10^{-8}$ such a supported rotor may have a constancy of many orders of magnitude greater than the synchronous drive. Constant angular acceleration devices can be used for measuring very small torques ($\approx 10^{-11}$ dyne cm.) as for example is encountered in measuring the absolute value of the gravitational constant G. You will recall that one of the most reliable early (1891–94) measurements of G was made by J. H. Poynting here at the University of Birmingham. In the constant angular acceleration method of measuring G two large tungsten spheres (large mass system) are mounted on a table that can be rotated (Beams 1963, 1965). Also a gas tight chamber which contains a horizontal cylinder (small mass system) is mounted on the same rotary table. The horizontal cylinder is supported by a twist-free tungsten fibre attached to the top of the chamber and on the axis of rotation of the table. The gravitational interaction between the two mass systems tends to deflect the horizontal axis of the suspended small mass system into a line connecting the centres of the two large spheres (large mass system). However, a light beam-photodetector-servo system which actuates a motor attached to the rotary table produces an angular acceleration of the table of just the right amount to maintain the angle between the axes of the large and small mass systems constant. As a result the gravitational torque and, hence, G can be accurately determined by measuring the acceleration of the rotary table. The method has three inherent advantages. First, the acceleration of the table can be accurately measured because it involves frequency determinations which may be extended over a long time. Second, the horizontal axes of the mass systems rotate about a vertical axis many times during a measurement which cancels out all but the high order effects of the troublesome gravitational fields, and field gradients introduced by extraneous masses, and, third, the distances between all parts of the small and large mass systems stay constant during a measurement. At the present time, the measurement of G by the above method is being carried out at the National Bureau of Standards by R. Deslattes and G. Luthur of the Bureau and W. Towler and R. Lowry of the University of Virginia. There is good reason to believe that the accuracy of the measurement of G will soon be increased substantially. In addition to the need for measuring the absolute value of G, it is very important to search for a small predicted change in G with time because of its cosmological significance (Rose *et al.* 1969; Dirac 1937, 1938; Van Flandern 1974). By combining the modern techniques for producing constant angular speeds with that of producing temperatures below 1K there seems to be a reasonable chance that the predicted value of $\Delta G/G$ of 10^{-10} to 10^{-11} per year might be observed in the laboratory.

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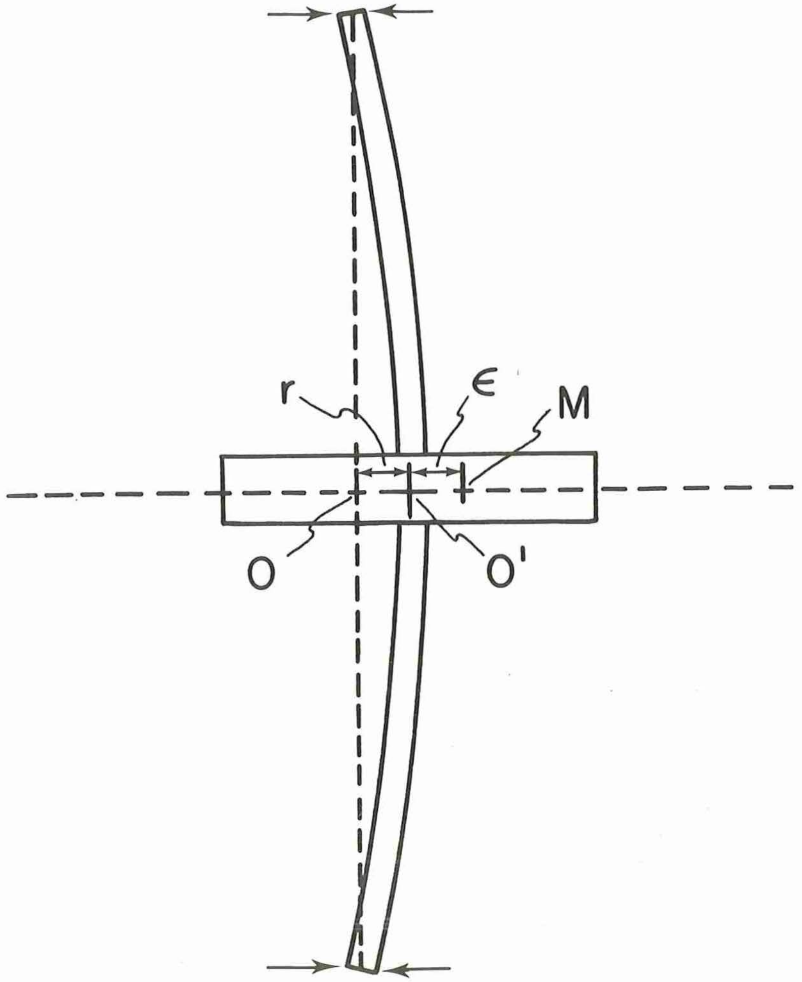
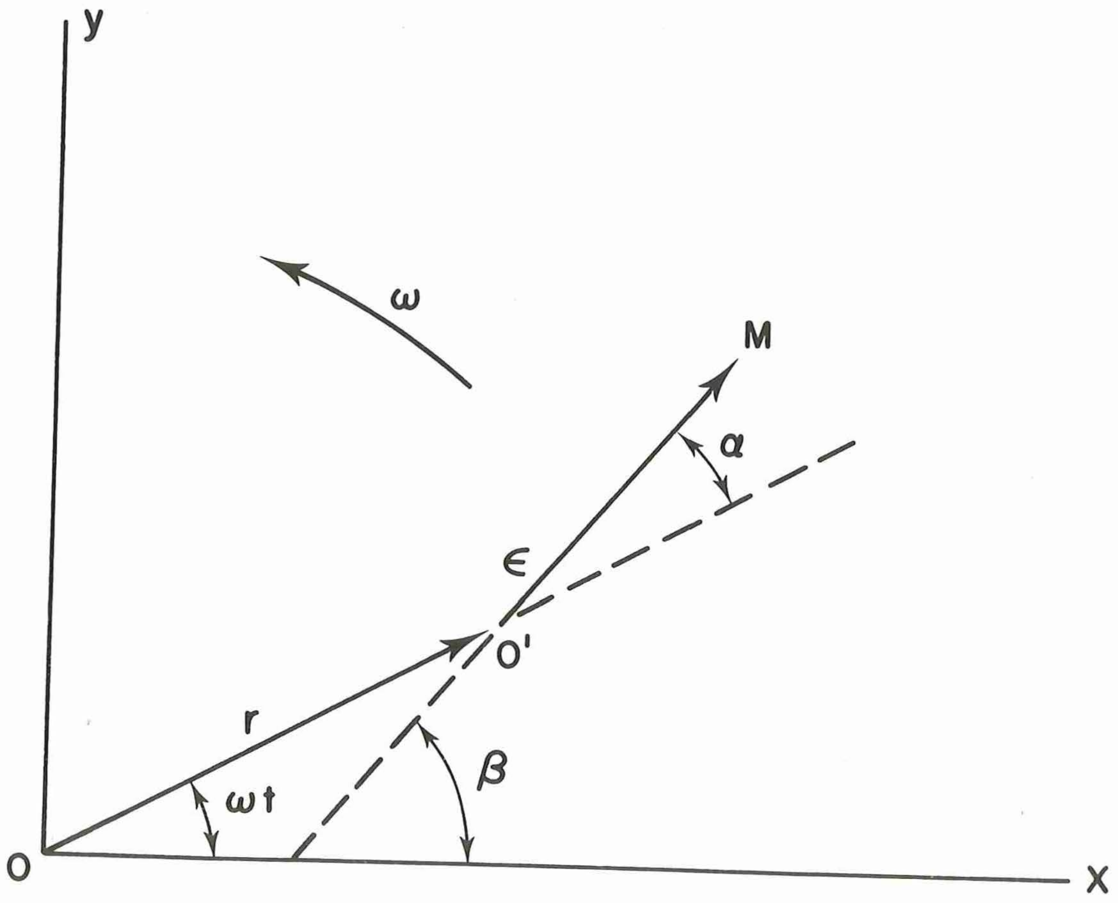
FIGURE 1





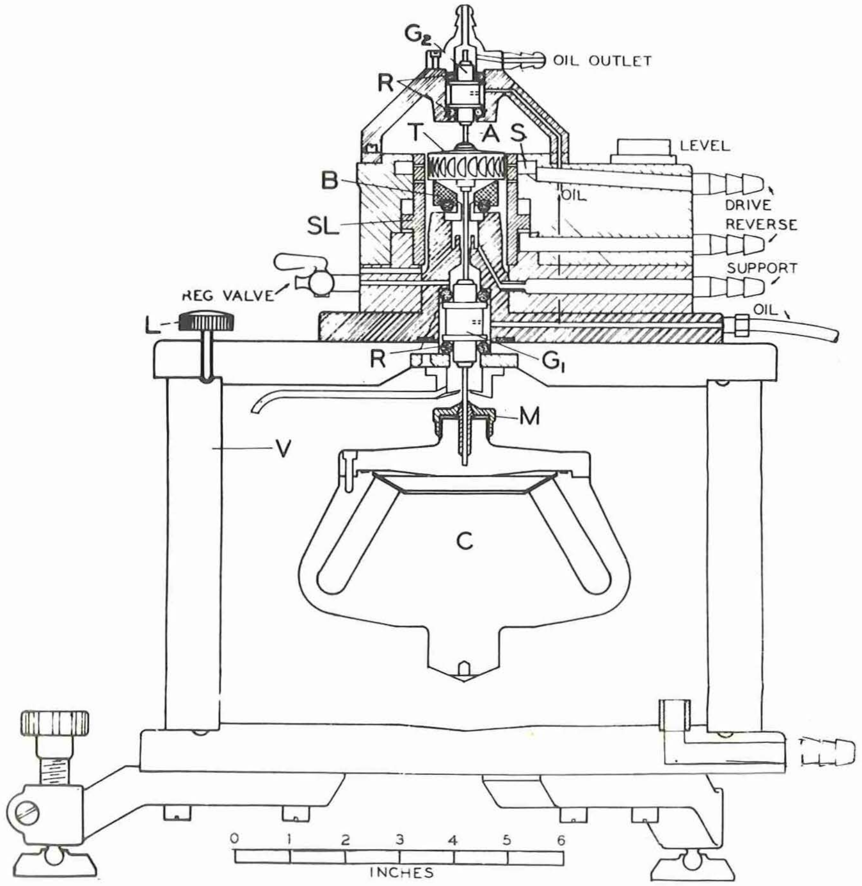


FIGURE 3. Diagram of method of spinning rotors in a vacuum by an air turbine.

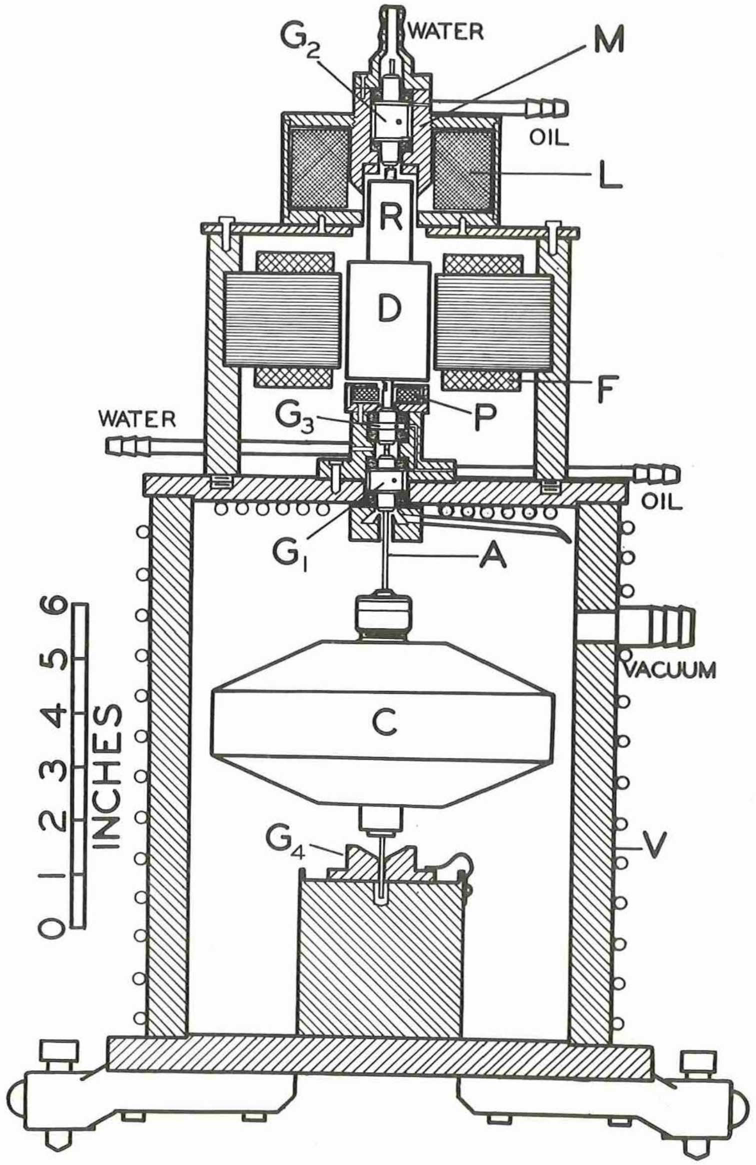


Figure 4. Diagram of method of electrically spinning rotors in a vacuum.

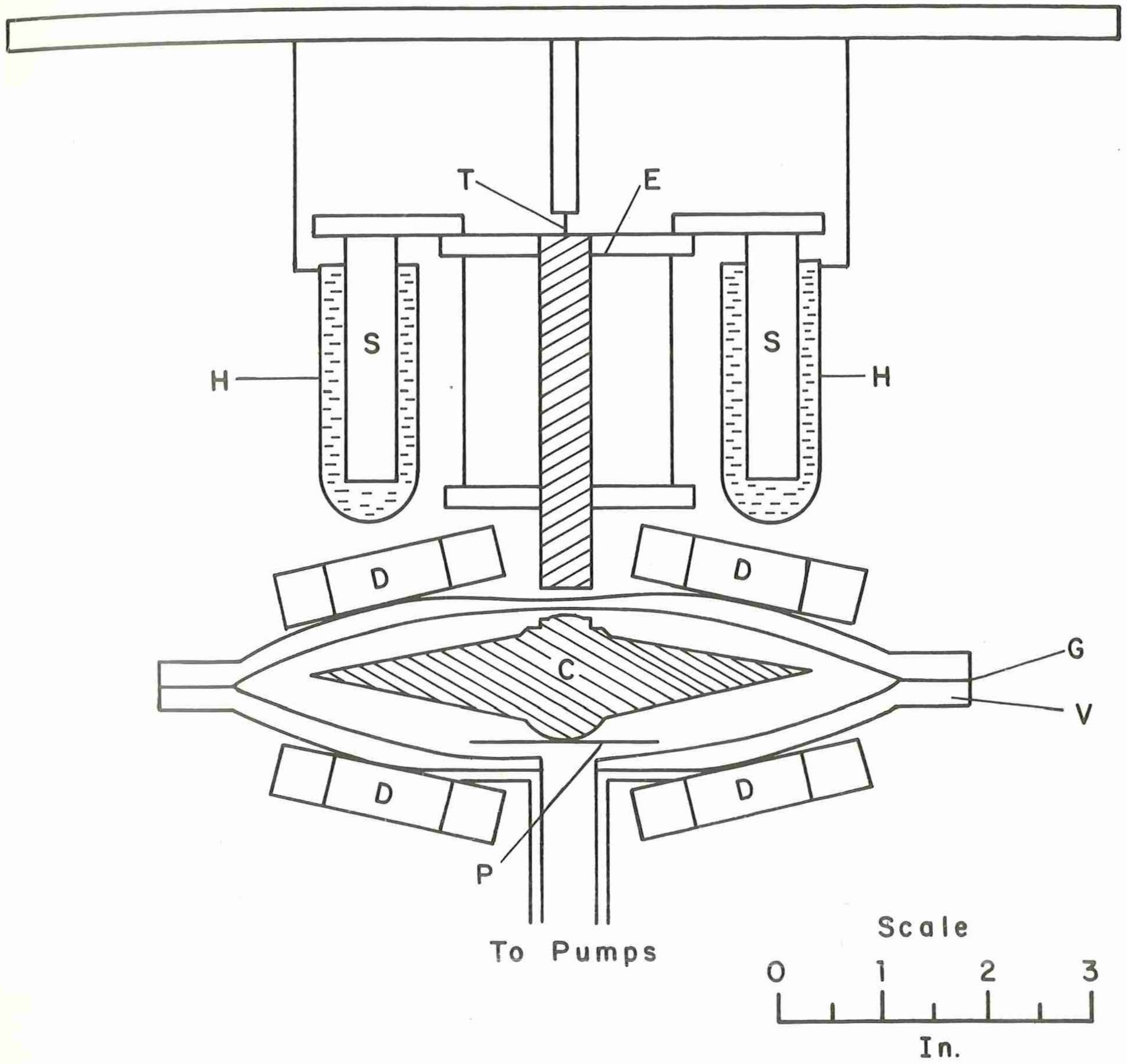


Figure 5. Diagram of rotor drive method used by P. B. Moon: V, glass vacuum chamber; G, ground glass joints; D, driving coils; E, electromagnet; T, thread; H, dash pots; S, damping rods; C, rotor.

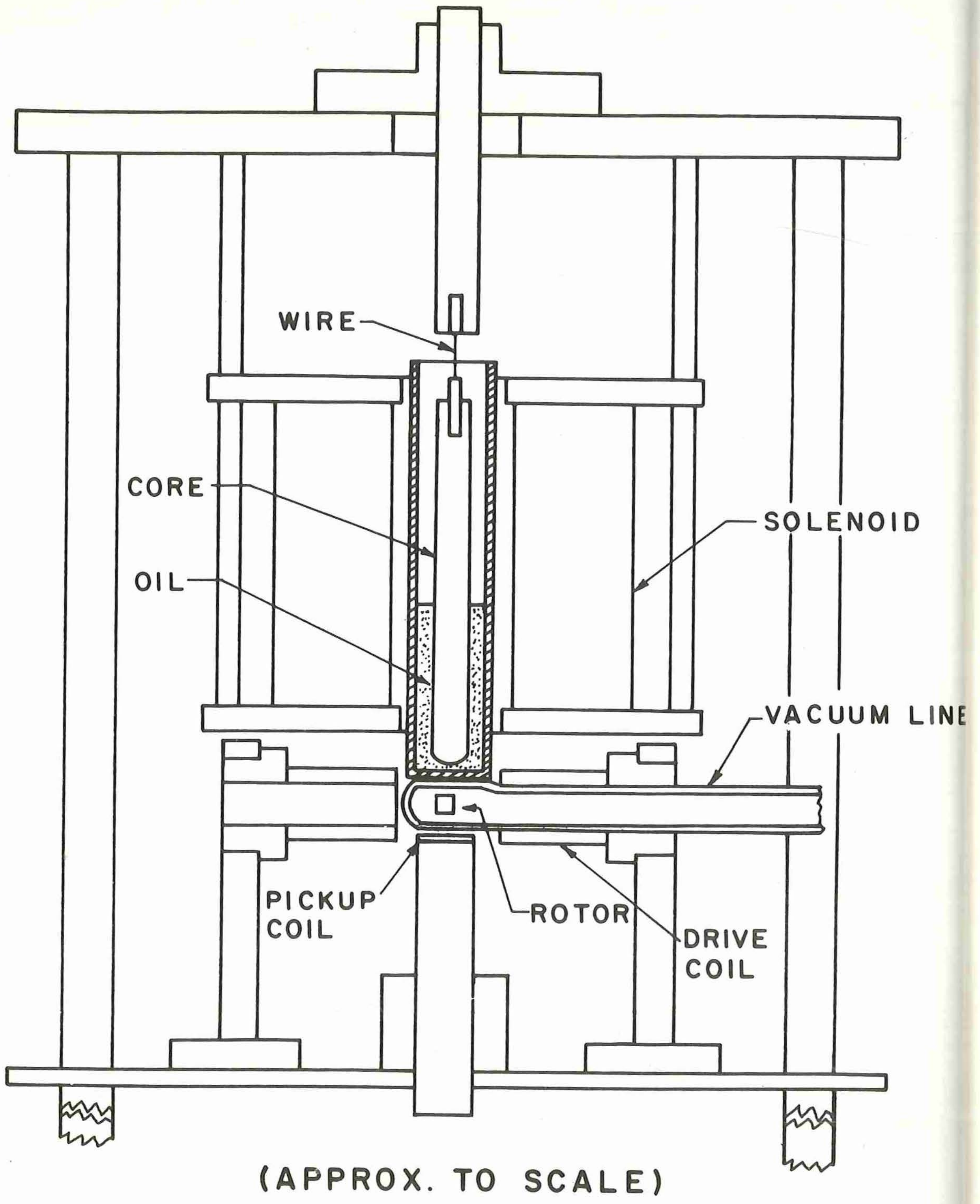


Figure 6. Diagram of method of spinning magnetically suspended rotors in a vacuum.

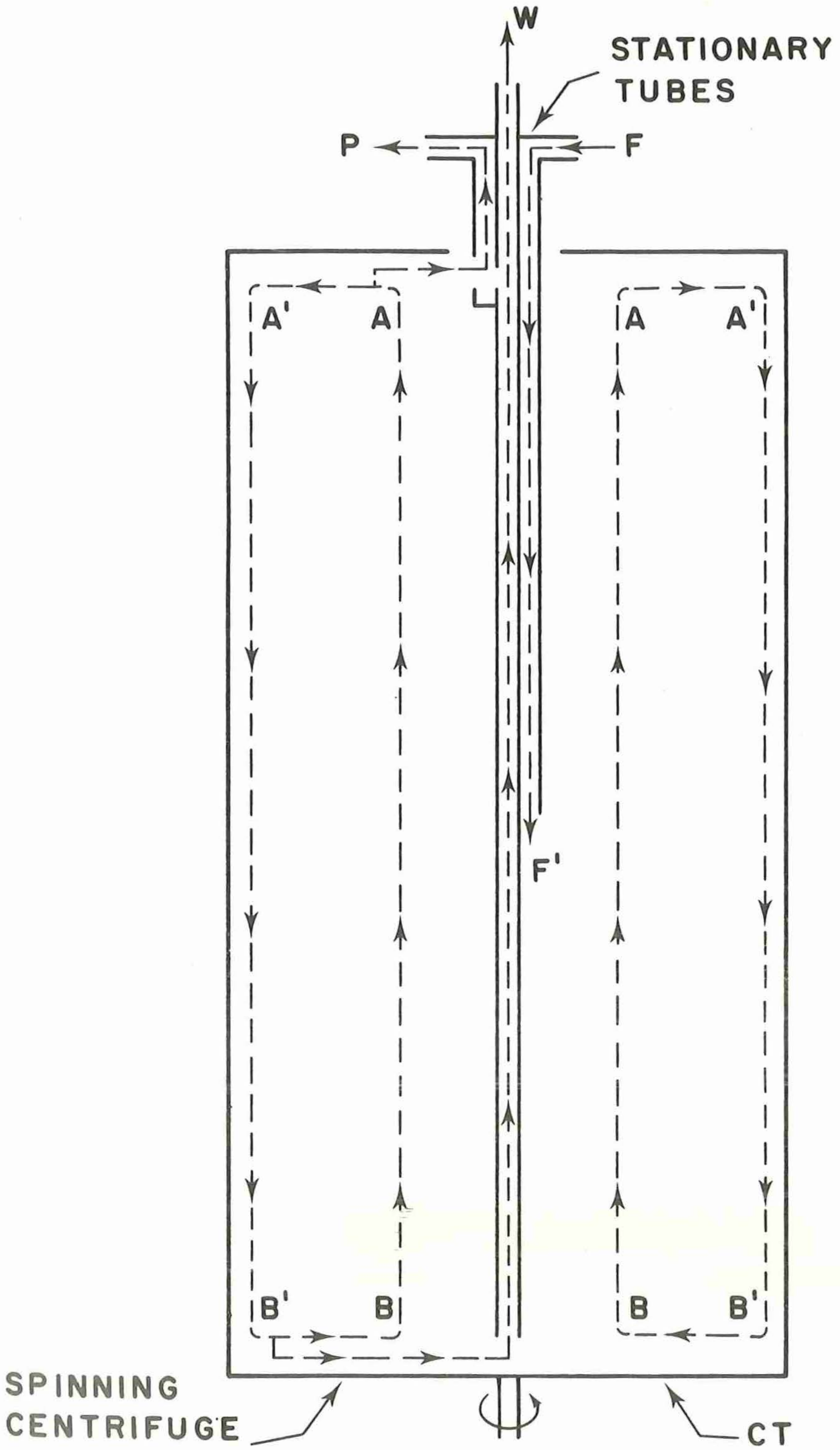


Figure 7. Internally driven gas counterflow in a spinning tube.

P. B. Moon

SCIENTIFIC ASPECTS OF HIGH SPEED ROTATION

A Conference held in the
Department of Physics,
University of Birmingham,
19–20th September 1974,
in honour of Philip Moon

CONFERENCE COMMITTEE

P. J. Black, W. E. Burcham, D. A. O'Connor,
G. R. Isaak, W. F. Vinen

1975

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FOREWORD

On 30th September 1974 Philip Moon retired from the Poynting Chair of Physics in the University of Birmingham. It was the unanimous wish of those who had worked most closely with him over many years that gratitude should be expressed for all that he had done to make the Department of Physics a lively and stimulating place for both staff and students. The Conference on Scientific Aspects of High-Speed Rotation of which this volume is a record was the outcome; it was held in the Department on 19th and 20th September 1974 and was intended both to review the growth and also to predict the future trend of rotor experiments in physics and chemistry. Each of the four invited papers evokes some aspect of Moon's work and we feel that together they provide an excellent coverage of the field and a token of our respect and admiration.

The Conference was recognised by the Institute of Physics and we are grateful to that body for help with advertisement and for permission to reproduce the article High Speed Rotors (p. 47) to record the present trend of rotor development.

We wish to express sincere thanks, on behalf of all who attended the Conference, to Peter Middleton and Hilary Fancote for their care of the organisation of the meeting.

P. J. Black
W. E. Burcham
D. A. O'Connor
G. R. Isaak
W. F. Vinen

February 1975

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Appendix

5. High Speed Rotors, by P. B. Moon, M. P. Ralls, J. B. Saul and J. H. Broadhurst (Reprinted with permission from the Physics Bulletin of the Institute of Physics **25** (1974) 511) — page 47

At a Conference Dinner on 19th September Professor R. L. Mössbauer spoke informally about the original experiments on the effect that now bears his name.