The Production of High Rotational Speeds

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The Production of High Rotational Speeds

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Methods of spinning rotors to very high speeds by means of compressed air are discussed. A detailed description is given of the construction of apparatus to spin rotors both in gases at various pressures and in vacuum. Some uses of the apparatus and its operating characteristics are outlined.

In many problems in physics as well as in the other sciences it is essential to utilize high mechanical speeds of rotation. Frequently it is necessary that the rotating member even be mounted in vacuum or at reduced gas pressure and maintained at a constant known temperature. The purpose of this paper is to describe simple inexpensive methods of fulfilling these needs.

A very useful and convenient apparatus for producing high rotational speed when the rotor need not be in vacuum is shown schematically in Fig. 1 and in the picture Fig. 2. The method of spinning the rotor is a modification of one first used by Henriot and Huguenard[1] and, in principle, is essentially the same as we have previously described.[2] However, certain helpful variations in the design have been added, so that the apparatus will be described again somewhat in detail.

Air under pressure, admitted to the stator cup through flexible rubber pressure tubing, passes through the straight holes along $L'L$ (Fig. 1a) and impinges upon the flutings of the rotor. These air jets both lift the cone shaped rotor off the stator and start it spinning. The rotor does not fly out of the cone shaped stator because of the Bernoulli forces, but rides upon a thin cushion of air just above the stator surface. Air from the atmosphere entering the vertex of the stator cone (labeled "stabilizing air flow" in Fig. 1b) greatly improves stability and assists in adjusting automatically the air cushion for different air pressures, speeds and weights of rotors. In fact, the rotor spins in such stable equilibrium on the resulting air film that the air pressure can be changed abruptly from say 10 to 150 lbs./in.^{2} (the range we use) or *vice versa* without disturbing the stability. Also the weight of the rotor may be increased suddenly (e.g., by pouring liquid into a hollow rotor while it is spinning) without disturbing its equilibrium. The diameter of the hole through the vertex of the stator is not critical and is usually bored with from a No. 50 to a 3/8-in. twist drill for the apparatus shown in Fig. 1. Fig. 3 shows a few of the different types of rotors that we have spun successfully and serves to illustrate the wide range of sizes, weights, and shapes the rotors may have.

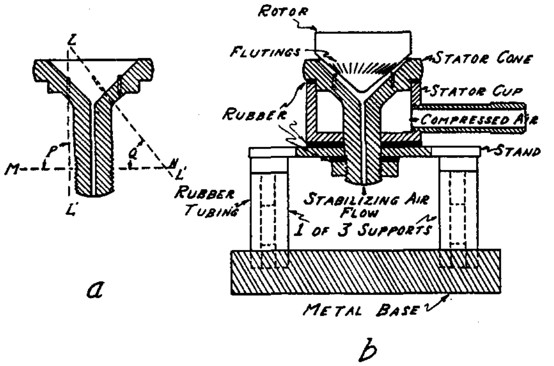

FIG. 1a. Cross-sectional drawing of stator cone. 1b. Cross-sectional drawing of stator and supports with rotor in place.

Fortunately the rotor does not have to be dynamically balanced with extreme care, because the automatic adjustment of the supporting air cushion allows the rotor to seek its own axis of rotation within certain limits. Rotors have been purposely unbalanced by boring small holes near their peripheries and are found still to spin smoothly on the air cushion. This freedom which the rotor possesses of seeking its own axis of rotation adds greatly to the utility of the method since it makes feasible the mounting of apparatus

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[1] Henriot and Huguenard, Comptes rendus **180**, 1389 (1925); J. de phys. et rad. **8**, 443 (1927).

[2] Beams, Rev. Sci. Inst. **1**, 667 (1930); Beams and Weed, Science **74**, 44 (1931); Beams, Weed and Pickels, Science **78**, 338 (1933).

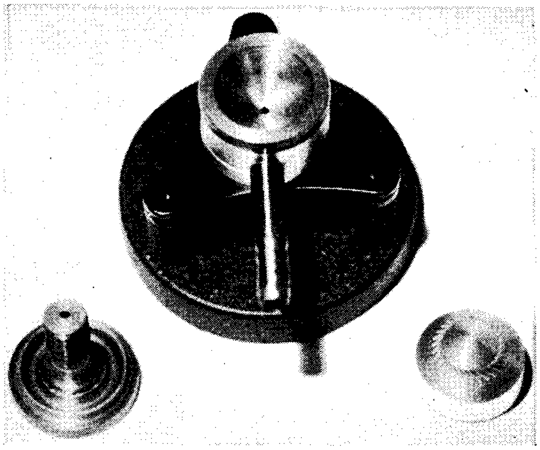

FIG. 2. Photograph of stator, rotor and stator cone.

on rotors that would be almost impossible to balance accurately around a previously determined axis of rotation. However, it should be emphasized that the rotor always should be as symmetrically made and as accurately balanced as the method of construction will permit. It should be noted that the Bernoulli forces can be made so strong that the rotor will run smoothly with the apparatus inverted or tilted. In order to increase the torque exerted on the rotor by the impinging air jets, flutings are made on the rotor in the positions shown in Figs. 1, 2 and 3. An investigation has been made in this laboratory by Garman[3] of the proper shapes and kinds of flutings to use in order to obtain greatest efficiency, and his paper should be consulted for complete details. However, with the present design a large variety of flutings will work satisfactorily (see Fig. 3). A simple type of straight fluting, cut preferably at an angle to an element of the cone (as shown in Figs. 1 and 2), by an end-mill, is efficient enough for most purposes. The flutings, of course, can also be made by hand, lathe tools or profiling machines. The number of flutings range from 20 to 35 for the rotors in Fig. 3, and their depth depends upon the size of the rotor. For the larger rotors which run slower and require greater torques, the flutings are made deeper. In general neither the depth nor number of flutings is critical. Fig. 1a shows the stator cone and the attached stem which holds it in the stator cup. Figs. 1b and 2 show the stator assembled and mounted on three legs. The direction of the stator holes LL^1 can be varied over limited ranges, but if maximum speed is to be obtained, care should be taken to get them in the correct position.[3] On the other hand, the size and number of holes can be varied over wide ranges, the proper magnitudes being determined by pressure and quantity of air available. The following work quite satisfactorily: $P=90°$; $Q=45°$ to $46°$; number of holes from 3 to 18; LL^1 bored with twist drill sizes 50 to 70; angle of stator cone 91° to 92°; and angle of rotor cone 102° to 103°. The upper openings of the holes LL^1 lie in a circular section of the stator cone approximately midway between its vertex and base. The stator cone can be built to fit any size of rotor by simply changing all dimensions proportionately. The holes in the stator cone are perhaps most easily bored in the direction from L to L^1, the bit being held in position by a "jig" which fits into the cone. If trouble is experienced in boring the holes the "split cone" construction shown in Fig. 4 can be used. At the right is seen a complete stator and at the left the parts before they are assembled (the two stators are not exactly alike but near enough for illustration). The parts of the stator include an outside and a central piece shown at the top left and the nut and lead or rubber washer at the bottom of the picture. The outside part, made of

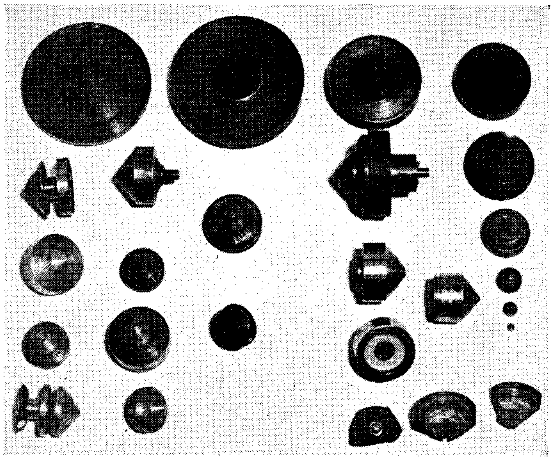

FIG. 3. Photograph of miscellaneous collection of rotors. In center column are the rotors used for curves A, B and C of Fig. 6. At bottom right are some pieces of exploded rotors.

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[3] Garman, Rev. Sci. Inst. 4, 450 (1933).

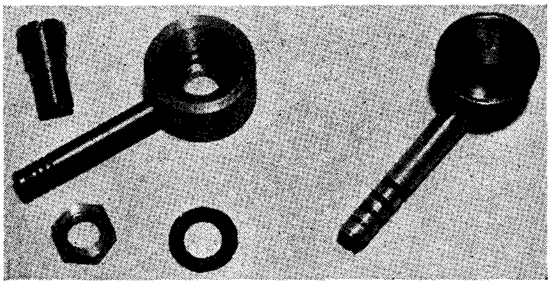

FIG. 4. Photograph of "split cone" stator. On left are the various parts and on right is the assembled stator.

one piece of metal except for stem, has the cone shaped surface as shown and an annular space hollowed out which connects with the stem and serves to distribute the air. The inside or central part, also made of one piece of metal, contains the vertex of the cone and is threaded at the bottom. It is shaped to fit snugly into the outer piece along a cylindrical section. In this cylindrical section is a series of grooves as shown in the picture, cut either by hand, on a lathe, or with a miller. These grooves, when the stator is assembled, provide the holes through which the directed air jets emerge. This latter construction is especially convenient when the stator is very small. For example, we have constructed stators small enough to accommodate 4 mm rotors by this method. It will be noted that the stators shown in Figs. 1, 2 and 4 can easily be taken apart and cleaned. Often one or two of the holes may become clogged and give rise to tilting of the rotor or other undesired effects.

Although the stator can be fastened rigidly[2] and still function satisfactorily, it is highly desirable to mount it in flexible supports when this is possible.[4, 2] The air jets impinging on the flutings of the rotor together with the asymmetries in the rotor set up vibrations in the air which are communicated to the stator and its mounting. At certain frequencies these may produce resonance unless the stator mounting is so constructed as to damp them out. Of course, if the rotor is accelerated very rapidly it will pass through these critical frequencies too quickly for them to cause much trouble, but it is better to keep the vibrations damped in the mounting when possible. One of the most effective damping agents is the human hand, although cork or rubber serves almost as well. The damping arrangements shown in Figs. 1b and 2 consist of rubber cushions, rubber washers and the three legs set in flexible rubber tubing. Where the stator must remain fixed in position it is necessary to eliminate the slight twisting or movements, caused by the changing air pressure in the rubber tubing connected to the "inlet" stem on the stator cup. Fig. 5 shows an arrangement which avoids this difficulty and is most satisfactory for rotating mirror experiments where the position of the axis of rotation must remain fixed. Air enters the stator through 3 brass tube supports which, in turn, are supported by short sections of rubber tubing. With some rotors vibrations may develop but are easily damped by rubber or cork supports (not shown in the picture) under each arm, near the stator and at one or two other points along its length.

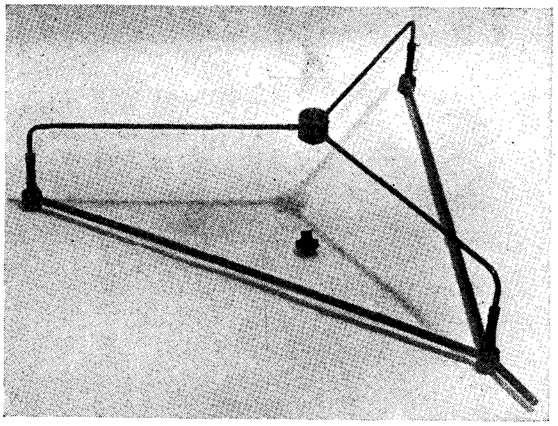

FIG. 5. Photograph of stator designed to eliminate movements caused by changing air pressure. Small mirror mounted on rotor shown below the stator.

The stator may be made of almost any easily machined metal such as brass, bronze, duralumin or soft steel. On the other hand, the rotor should be made of the strongest possible material since in general the maximum rotational speed is set only by the breaking strength of the rotor, provided sufficient pressure and quantity of air are available. Of course for solid rotors it is not the absolute strength that sets the limit but rather the breaking strength divided by the density of the material. Some rough experiments

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[4] Lawrence, Beams and Garman, Phys. Rev. **31**, A1112 (1928).

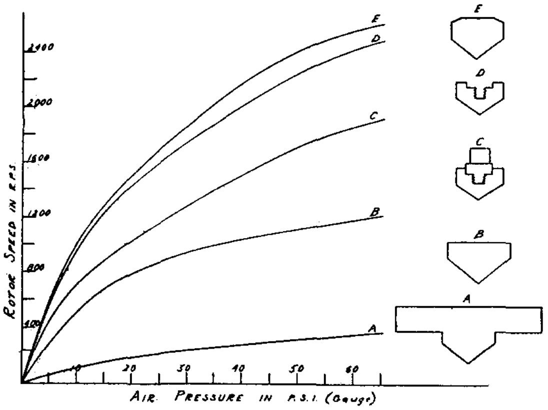

FIG. 6. Curves of the relation of air pressure to rotor speed for the case where air surrounding rotor is at atmospheric pressure. At right are sketches of rotors to scale with which the curves were secured. Diameter of *D* was 1-1/8 in.

on the bursting strength of rotors will be described later.

As the size of the rotor is decreased the rotational speed will of course increase if the same stator and air pressure are used. Fig. 6 shows a series of curves *A*, *B*, *C* and *D* taken with the same stator (8 holes bored with No. 66 twist drill. A picture is shown in Fig. 5). The rotor *D* upon which the mirror in *C* is mounted is $1\frac{1}{8}$-in. in diameter and the others are drawn to the same scale. The rotors *A*, *B* and *C* are shown in the center column of Fig. 3. Curve *E* was taken with the stator of Fig. 2 which contained 8 holes bored with drill No. 61. These curves are seen to illustrate the well-known fact that the air resistance increases very rapidly with the speed of the moving surface. Also they show the desirability of keeping the rotor size small when this is possible and of reducing its air resistance to a minimum. Curve *E* illustrates the effect of increasing the diameter of the driving jets as the rotor speed of *E* is always above *D* even though *E* is the larger rotor. The resistance experienced by a rotor spinning in a gas of course depends upon the nature of the gas and can be made considerably smaller by surrounding the rotor with hydrogen instead of air. Moreover, if hydrogen instead of air is used to drive the rotor, as well as to surround it, much higher rotational speeds can be attained. For example, we have obtained rotational speeds in excess of 20,000 r. p. s. with a 9-mm rotor driven by hydrogen at 160 lbs./in.^{2}. The centripetal acceleration at the periphery of the rotor was thus more than 7 million times the acceleration of gravity.

The types of air-driven rotors described above have been utilized already in quite a number of different experiments. It seems to be the best method known for spinning small mirrors at very high speeds.[1, 2, 5] Also it proves to be of considerable value as a centrifuge in biological experiments as is evidenced by the work of Harvey,[6] H. W. Beams[7] and others. Optical schemes[6, 8] have been devised for viewing the biological material while it is being centrifuged. A few successful experiments upon the sedimentation of small particles and molecules from solution have been carried out.[2, 9, 8, 10]

It has been our experience that the great difficulty in the use of the air-driven rotor as a centrifuge is to keep the centrifuge "bowl" at uniform temperature throughout. Since convection currents are essentially a buoyancy phenomenon, it is easy to see that inequalities in density arising from nonuniformity of temperature will produce increased "stirring" or remixing when the centrifugal force on the fluid is increased. As can be seen from the curves in Fig. 6 considerable energy is dissipated in air friction at the surface of the centrifuge. This gives rise to a heating effect. On the other hand, the rapid expansion of the air in the air jets impinging on the cone-shaped under side of the rotor tends to cool the rotor so that temperature gradients are set up. Complicated means have been devised for equalizing the temperature[9] in the centrifuge bowl to a very high degree of approximation. However, in many experiments for obtaining the rate of molecular sedimentation, the air-driven rotor, surrounded by air at atmospheric pressure, is less satisfactory than the very beautiful but more expensive method of Svedberg.[11] Also for many other types of experiments it is desirable to have the main rotor

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[5] Beams, Phys. Rev. **35**, 24 (1930); **36**, 997 (1930); **44**, 803 (1933); J. O. S. A. **25**, 48 (1935).

[6] Harvey, J. Frank. Inst. **214**, 1 (1932).

[7] Beams and King, Anat. Record, 1934; Nature **135**, 305 (1935); Beams, Mulryil and Gatenby, Nature **134**, 810 (1934).

[8] Pickels, Phys. Rev. **45**, 748 (1934).

[9] Beams, Pickels and Weed, J. Chem. Phys. **2**, 143 (1934).

[10] McBain, Nature **135**, 831 (1935).

[11] Svedberg, *Colloid Chemistry*, 2nd edition.

in vacuum and to keep it thermally insulated. Accordingly, a small air-driven rotor was made to drive a much larger rotor inside a vacuum chamber by means of a wire passing through an oil gland.[12] Fig. 7 shows a cross section of the apparatus first used. The rotating member consists of three parts: the air-driven, air-supported turbine described above; a much larger rotor that spins in the vacuum chamber; and a steel (piano) wire extending vertically downward along the axis of rotation from the vertex of the turbine above the vacuum chamber to the larger rotor which it supports and drives. The wire enters the vacuum chamber through a small oil-sealed bearing or gland. These glands usually consist of two or three pieces soldered together and have the shape shown in the figure. A hole many times the diameter of the wire is first bored along the axis of the gland to serve as an oil chamber. In the ends of this larger hole are fitted two cylindrical plugs with carefully aligned holes just large enough for the wire to slip through without forcing. These plugs should preferably be made of bronze, though brass will do. The lengths of the small holes through the plugs are not critical. Each should be about 1/4 in. in length while the oil chamber should be about 1 in. long. The figure shows the oil gland screwed to the top of the vacuum chamber. A somewhat preferable design in which this connection is flexible will be described later. "Cenco Hyvac" pump oil or the very low vapor pressure Apiezon oils, if an extremely high vacuum is desired, is forced into the oil inlet under a few pounds pressure and serves both to seal the vacuum chamber and to lubricate the bearing. A small disk fastened on the wire just inside the chamber throws the oil leaking through the bottom bearing into an oil collector which prevents its reaching any windows or apparatus that may be mounted inside the vacuum chamber. If the gland is properly constructed the oil leak through the bottom bearing amounts to only 1 or 2 cc an hour. Below the rotor is a circular block composed of wood, metal and cork. This is free to move about the floor of the chamber over a limited range. A small steel rod (about 1/16 in. in diameter) fastened in the bottom of the rotor fits with a slight clearance into the lubricated cork. This fit must be just loose enough for the friction to be negligible. The purpose of this arrangement is to prevent pronounced precessions from being set up in the rotor. Also it may serve as a brake in stopping. The steel wire which supports and drives the large rotor passes through a closely fitting hole along the axis of the turbine and is fastened at the top to a friction clutch which rides upon the turbine. This prevents sudden accelerations and decelerations from unnecessarily twisting the wire, especially in the stopping and starting. The size of the steel wire can be varied over a considerable range. We have used from 0.2 mm to 0.5 mm in this apparatus. For most purposes the larger size is preferable. It is important to keep the unguided sections of the wire as short as is conveniently possible in order to prevent occurrence of standing waves.

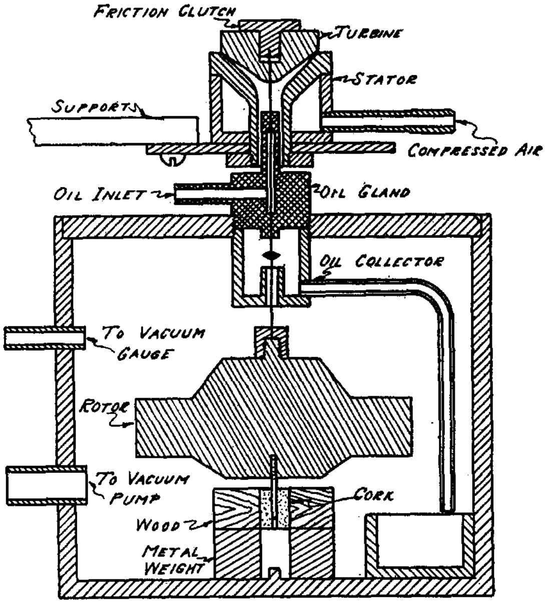

FIG. 7. Cross-sectional drawing of first apparatus used for spinning large rotors in vacuum. The turbine is both driven and supported by the same air jets.

The stator is made as described previously in this article except that care must be taken to make the central hole along its axis large enough to contain the upper part of the oil gland and still leave sufficient clearance for enough air to flow in from the atmosphere to keep the supporting air cushion stabilized. The stator can be

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[12] Pickels and Beams, Phys. Rev. **47**, 336 (1935); Science **81**, 342 (1935).

supported in a number of ways as long as its position is adjustable. In the apparatus shown in Fig. 7 it was supported by three arms of light stiff channel brass about 6 in. in length. Each arm was flexibly supported by rubber at its outer end and by a cork near the stator to assist in damping vibrations sometimes developed (particularly at the higher speeds). Adjustments for accurately centering, raising and lowering the stator were provided. The vacuum chamber is cylindrical and usually made of 1/4 in. brass. The top wall of the brass chamber is carefully machined so that the top itself can be made vacuum tight with wax or other sealing compounds. The vacuum obtainable is limited only by the vapor pressure of the oil and wax used and can of course be made extremely low. The size of the main rotor inside the chamber may be made many times larger than the driving turbine outside. For example, an air turbine weighing less than 50 grams will drive an 800-gram rotor in vacuum at a speed but slightly less than that of the turbine alone. The maximum rotational speed is limited only by the strength of the large rotor. A duralumin rotor 9 cm in diameter and shaped as shown in Fig. 6 was exploded at 2200 r.p.s. The air turbine was 3 cm in diameter and had 30 flutings. The stator contained 8 holes bored with a No. 60 drill and was supplied with approximately 12 cu. ft. of air per minute (as measured at atmospheric pressure, room temperature) at a gauge pressure of 70 lbs./in.^{2}. This rotor and vacuum chamber after the explosion are shown in the center of Fig. 8.

As in the case of the air turbine itself, extremely high precision in machining and balancing the main rotor is not absolutely essential because the flexibility of the wire allows it to seek its own axis of rotation within limits. A rotor purposely unbalanced by boring a 1/4-in. hole near its periphery spun smoothly. Again this lack of necessity for complete dynamical balance greatly extends the utility of the rotor. The discussion of the advantages and disadvantages of this particular apparatus will be continued after another type of driving apparatus has been described.

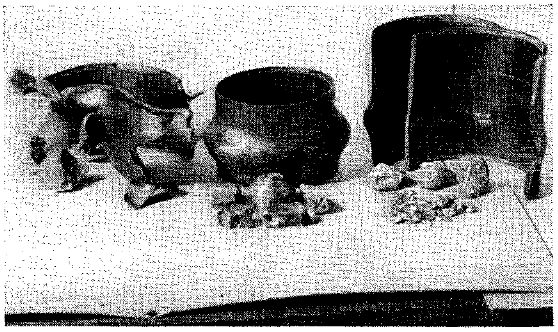

FIG. 8. Photograph of solid metal rotors and vacuum chambers after explosion by centrifugal force.

In the apparatus just described the rotating members are not only driven but also supported by air jets. As a result the rotors spin very smoothly as long as the air pressure is great enough to support them but in stopping care must be taken to prevent twisting the wire or damaging the rotor. When stopping, the air pressure is usually reduced to a value just sufficient to support the rotors and then the stator is lowered so that the rotor is brought to rest by rubbing on the lower cork guide. However, this may unduly heat the rotor. In order to overcome this trouble an apparatus has been designed in which the rotating members are supported by an air cushion. The pressure of the air in this cushion can be regulated independently of that in the driving air jets. Hence in stopping it is only necessary to turn off the driving jets completely and let the rotor "coast" smoothly on the supporting air cushion to a standstill. If more rapid deceleration is desired reverse jets can be provided.

At first we introduced a separate supply of air into the bottom of the stator (Fig. 7) which acted as an independent air bearing so that the rotors could be slowly stopped by abruptly turning off the air jets and letting the rotors lose their speed. Fig. 9 shows a cross section of a more recent design in which the drive and support are completely independent. Fig. 10 shows a photograph of the same apparatus. The rotating parts consist of a large rotor *R* inside the vacuum chamber, the wire *T*, the oil disk *Z*, and the air driven turbine *C*. In this type, 1/25 in. (piano) and 1/16 in. (spring steel) wires have been employed but other sizes could be used as the size of the wire does not seem to be very critical. *C* is a cylindrical turbine wheel about 13/16 in. in diameter and 3/8 in. thick (not including stems). Around the periphery are 15 flutings cut with a 3/8 in. miller in the following manner. The axis of the miller is set perpendicular to the axis of the turbine wheel, the distance between the axes being about 1/4 in. The adjustment should be such that the flutings are centered with respect to the two flat surfaces of the turbine. To cut a single fluting the turbine wheel is moved in a direction parallel to the axis of the miller. The depth of the cut is such as to bring successive flutings into tangency. The finished turbines are shown in Fig. 11.

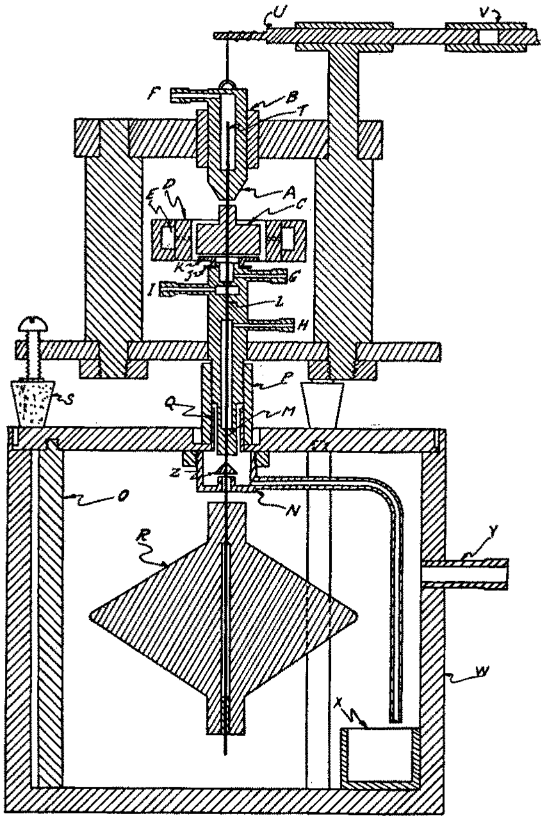

Fig. 9. Cross-sectional drawing of apparatus for spinning rotors in vacuum. The supporting air cushion and driving air jets are independent of each other.

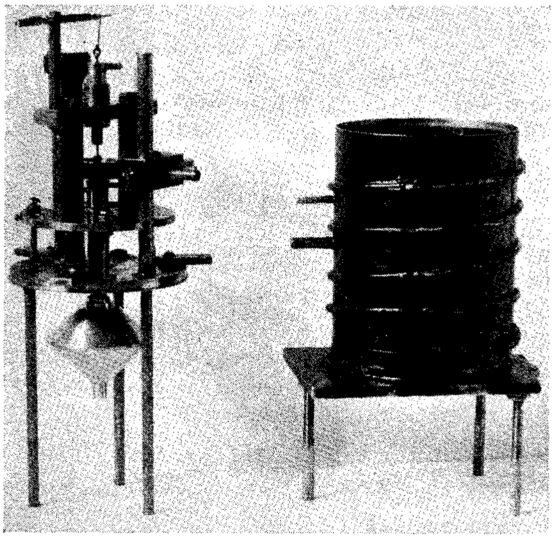

Fig. 10. Photograph of apparatus of Fig. 9. At right is shown the vacuum chamber. At the left can be seen the main rotor, oil bearings and turbine assembled. A large tube with window on top for observing the rotor can be seen in place.

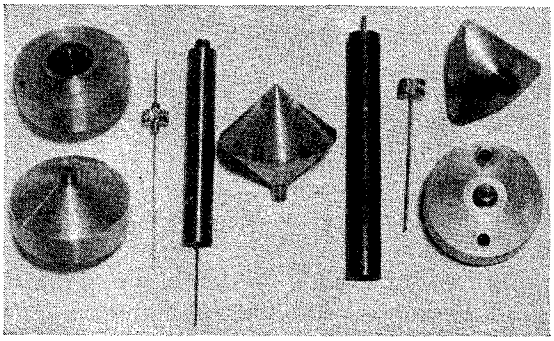

Fig. 11. Photograph of vacuum rotors and driving turbines.

The turbine is driven by 8 air jets whose lines of action are in a plane perpendicular to and about 5/16 in. from the axis of rotation. They strike the turbine wheel at the center of the flutings. The air jets are directed by the holes (dotted in Fig. 9) bored with No. 60 drill in the inner wall of the cylindrical chamber *D*. Compressed air enters the annular space *E*, inside *D*, through a flexible rubber tube connection not shown in the drawing. The clearance between the turbine wheel and the inner wall of *D* is about 1/16 in. or less. The turbine can be made of phosphor bronze or steel but duralumin is much better. The turbine *C* rides upon an air film formed between its lower surface and the upper surface of the Bakelite collar *K*. Compressed air (just enough to support the rotors, e.g., 15 lbs./in.^{2} for arrangement used) enters at *G* and escapes between the flat surfaces of *K* and *C*. *J* is a rubber washer about 0.5 mm thick. The internal radius of *J* and *K* is made as small as conveniently possible so that the net downward force on K is sufficient to hold it tight against J. The depth of the air chamber, i.e., the distance from the bottom surface of C to the top of the bearing L, should be made comparatively small in order to reduce the free length of the wire. In some designs a 1/4 in. brass or bronze stem 7/8 in. in length is fastened (without any play) into the duralumin rotor so the stem protrudes 1/4 in. on either side. The wire is soldered into the stem as shown at the left in Fig. 11. The lower stem extends downward into the air chamber and reduces the free length of wire above L to from 1/8 in. to 1/4 in. The width of the flat ring-shaped top of K should not be larger than necessary (often less than in Fig. 9). Also it should be mentioned that the air cushion has been formed in a number of ways. Air escaping through a small ring-shaped opening 1/128 in. wide surrounding the axis of rotation forms a good cushion between a flat ring and the turbine. Small holes bored in the flat ring also supplied air for the air cushion satisfactorily. In addition to the flat air bearings spherical air bearings have been used successfully.[13] An investigation of the numerous kinds of air bearings is now under way in this laboratory, with the hope that further simplifications can be made.

The oil gland is fastened to the chamber with flexible rubber tubing P which fits tightly around the sleeve Q. It is advisable to regulate the length of P and the pressure on the three adjusting screws, resting on the cork or rubber at S, to give the proper flexibility for optimum operating conditions. The gland is constructed as in Fig. 7. The bearings or holes at A, L and M are carefully drilled in bronze slightly smaller than the wire. The wire is then ground and polished with appropriate grades of fine emery paper, while spun in a high speed lathe, until it will just slip through each bearing without forcing. Vacuum pump oil is forced into H and F under the same pressure as that applied to G. The oil leaking through M is collected by N and subsequently X. Between the chamber connected to G and that connected to I is a partition provided with a hole slightly larger than the bearing L. This allows a small portion of the supporting air to escape through the small clearance and carry out through I any oil leaking from L. This oil may be collected and used over again. The upper bearing A is guided by a telescoping sleeve B which fits into a cross bar supported by two metal uprights. These uprights in turn are fastened to a circular metal plate supported by three adjustable screws. Each screw is supported by cork S Fig. 9 or rubber Fig. 10 which rests on the top of the chamber. The distance of A above C is regulated by U and by rubber bands which force it downward. Although operation is generally very smooth with the bearing A set about 1/4 in. above the turbine stem, the adjustment provided sometimes makes possible slight improvements at certain speeds. Oil leaking through A may be collected by a circular collector not shown in Fig. 9. The connections to F, G, I and H are made with rubber tubing or with thin copper tubing which affords the necessary flexibility. The main rotor R is mounted as shown. The bottom guide in Fig. 7 is found to be unnecessary with the type of apparatus which employs larger wires and a flexibly mounted bearing. Incidentally, it was found that a slight precession sometimes found in the apparatus of Fig. 7 was absent. At very low speeds the rotor wobbles a little without the bottom guide but does not bend the wire. If a completely smooth start or stop is desired the bottom guide should be made removable and used only when stopping and starting. Lower bearings constructed similar to A, L and M have been tried with success. They should be flexibly mounted and provided with forced lubrication. This lower bearing is especially useful if long rods (Fig. 11) are to be spun or where the rotor cannot wobble at low speeds. The three rods O are made to support the apparatus when not sealed into the vacuum chamber (Fig. 10). It will be observed that the apparatus can be spun and adjusted outside and then sealed into the chamber. Fig. 10 also shows the vacuum chamber surrounded with cooling coils for regulating temperature. Also it should be noted that even with proper lubrication the bearings heat up appreciably, especially until they have been broken in. In some experiments, particularly those concerned with the centrifuging of molecular particles, they should be water-cooled.

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[13] Beams and Weed, Va. Acad. Sci. Proc., 1935.

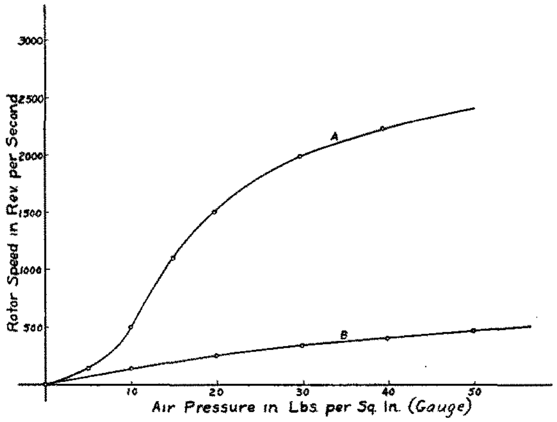

FIG. 12. Relation of driving air pressure to rotor speed for apparatus of Fig. 10. Curve *A*, taken with main rotor in a vacuum. Curve *B*, taken with the main rotor surrounded by air at atmospheric pressure.

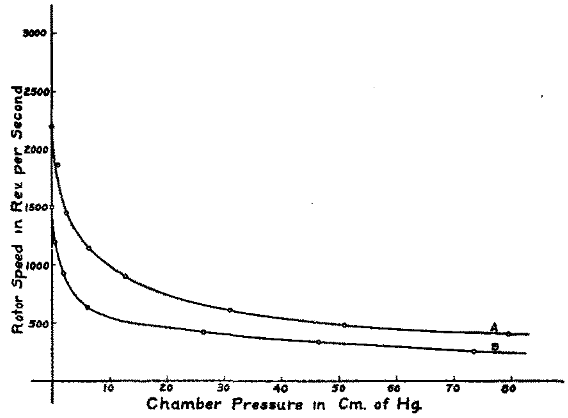

FIG. 13. Relation of rotational speed to chamber pressure for apparatus of Fig. 10. Curve *A* was taken with 40 lbs./in.^{2} gauge pressure on the driving jets. Curve *B* was taken with 20 lbs./in.^{2} on the driving jets.

In order to start the apparatus the oil pressure is first turned on, followed by the air pressure at *G*. The driving jets are next applied for a few seconds in order to set the rotors in motion. If the rotors spin smoothly for some time after the driving jets are turned off the chamber can be sealed and evacuated. The rotor will then spin smoothly up to the speed required to explode it.

To show the effect of air drag on rotors spinning at high speed in air the curves in Figs. 12 and 13 were taken. Fig. 12 shows the relation of the air pressure on the driving jets to the rotor speed in revolutions per second for the apparatus shown in Fig. 10. An enlarged view of the $3\frac{1}{2}$ in. main rotor is shown in the center of Fig. 11. Curve *B* gives the relation when the apparatus is surrounded by air at atmospheric pressure while curve *A* is for the case where the main rotor *R* is surrounded by air at a pressure of less than 0.1 mm of mercury. It will be observed that curve *B* is approximately straight and falls far below curve *A*. The bend in the curve *A* near the origin is possibly due to bearing friction and a slight wobble at low speeds. The curves strikingly illustrate the advantage gained by having the main rotor in a vacuum. For example, at driving pressures of 40 or 50 lbs./in.^{2} the rotors spin about 5 times as fast in vacuum as in air at atmospheric pressure while the centrifugal forces are increased by 25 times. By using the triangular shaped rotor in top right of Fig. 11 instead of the symmetrical rotor shown in the center, the curve for atmospheric pressure fell far below *B* but that for the vacuum fell approximately on top of *A*. Fig. 13 gives the rotor speed as a function of the pressure of the air in the chamber surrounding the main rotor for the same apparatus as used in Fig. 12. Curve *A* is for the case where the driving pressure is 40 lbs./in.^{2} and *B* is for 20 lbs./in.^{2}. Both curves show that starting with atmospheric pressure in the chamber the rotor speed increases gradually as the air is pumped out until the pressure reaches about 10 cm of mercury where it begins to increase very fast. For example, in curve *B* reducing the pressure the last 10 cm of mercury increases the speed about 10 times the increase observed in reducing the pressure from 76 cm clear down to 10 cm. This emphasizes the importance of having a good vacuum if high efficiency is expected. At the same time no heat is developed on the rotor surface which is very essential in many experiments. Some idea of the amount of heat developed with the rotor surrounded by air at atmospheric pressure was obtained in taking the curve *B*, Fig. 12, where the chamber got so warm that water had to be circulated through the coils to keep from melting the vacuum wax. There was, of course, no appreciable heating in taking curve *A*.

As mentioned previously the maximum rotational speed is set only by the strength of the main rotor. Since for solid metal rotors their bursting speeds should depend upon their bursting strength divided by their density, we tried some rotors made of the lighter alloys. These light rotors were found to reach higher speeds than any other material we have tried so far. Fig. 8 shows the pieces of some rotors as well as the vacuum chambers after explosions. The rotors were $3\frac{1}{2}$ in. in diameter and were shaped similarly to the rotor *R* in Fig. 9. On the left the rotor was made of duralumin and the vacuum chamber of brass. It was spinning 2600 r.p.s. when the explosion occurred. The centrifugal force on its periphery was about 1,200,000 times that of gravity. On the right the rotor was of Dow metal[14] and the chamber of 1/4 in. steel. The rotor burst at a rotational speed of 2800 r.p.s., which gives 1,400,000 times the force of gravity on the periphery. It is interesting to note that the steel vacuum chamber split into halves by the exploding rotor while the brass was twisted out of shape. The brass chambers are preferable as they retard the flying rotor pieces better than the steel. The importance of surrounding all rotors described in this article by barricades to protect the operator from rotor explosions cannot be overemphasized. In our work we completely surrounded the apparatus with a wall composed of 4 in. of sand on either side of which is $1\frac{1}{2}$ in. of wood. For larger and heavier rotors the barricades must be made correspondingly thicker.

Some experiments have been carried out with the axis of rotation horizontal instead of vertical. One obvious disadvantage of such an arrangement is the fact that more friction is developed in the oil bearings which must now carry the full weight of the rotors. However, the $3\frac{1}{2}$ in. duralumin rotor was spun 2000 r.p.s. about a horizontal axis. The unguided sections on either side of the rotor were about 1/2 in. in length. The oil bearings were made of bronze or brass as described above and stuck into sections of rubber tubing which in turn were supported by the ends of the vacuum chamber. The general arrangement of the vacuum chamber and driving apparatus was the same as in the type where the axis of spin was vertical. When possible it is advisable to make the rotors spin around a vertical axis not only because of less bearing friction but because of the bending of the wire by the weight of the rotor. This bending apparently causes the wire to fatigue and break after a few hours running unless the rotor is comparatively light or the wire large. However, the rotors spin smoothly and the method can be recommended when the axis of rotation must be horizontal.

No attempt will be made here to make a detailed list of the numerous uses of the apparatus described in this article for obtaining high rotational speed in vacuum. The fact that rotors of a wide range of sizes, shapes and weights can be spun smoothly in a really good vacuum obviously adds greatly to their utility. Also the only parts to wear out are the bearings which may be made replaceable. Actually the same bearings if properly made will last for days of continuous use. Fig. 11 illustrates the variety of rotors that can be spun successfully. At the lower right is a rotor designed to observe the rate of molecular sedimentation in a way similar to that of Svedberg.[11] At the left top and bottom are rotors which have already separated molecules like hemoglobin from their solution, the two fractions being collected.[15] In the center are shown steel rods now being used for experiments on the Barnett effect, etc. In the upper right-hand corner is a triangular rotor used for a velocity selector of gas molecules in some rough preliminary experiments. Stellite mirrors can also be easily spun up to their breaking speed. It may be worth while to note that the rotors may be spun in various gases at different pressures as well as in air. Also that if the chamber is properly constructed, the rotor may be spun in gases at many atmospheres as well as in vacuum.

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[14] Kindly supplied by Dr. J. D. Hanawalt.

[15] This centrifuge work will be described in the near future by E. G. Pickels.