High Centrifugal Fields

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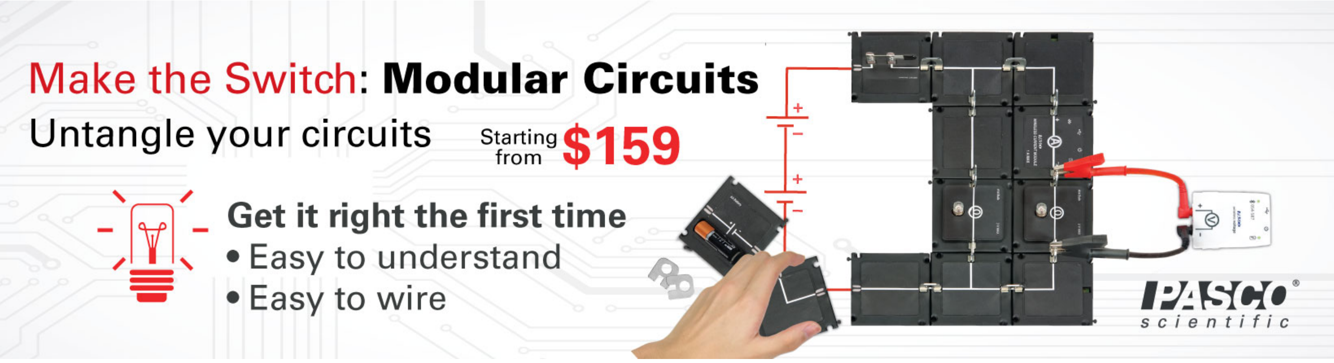

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High Centrifugal Fields

J. W. Beams, University of Virginia

By use of appropriately designed centrifuges, it is possible to produce acceleration a billion times that of a falling body. The design of such apparatus and its use in a variety of types of research are described. Such centrifuges can be used for molecular sedimentations and separation. From measurements on these processes, molecular weights can be determined. By magnetic suspension, friction has been reduced so that a rotor may "coast" without drive for years with the loss of one revolution per second per day when the initial speed is 800 revolutions per second.

Centripetal forces are so universally present that there is no doubt that ancient man was qualitatively familiar with their action. However, it was not until after Sir Isaac Newton (1642-1727) formulated his three basic laws of motion, that a quantitative relation was derived for the value of the centripetal force. By means of these generalizations of Newton, the centripetal force, F, was shown to be given by the relation

$$F = \frac{Mv^2}{R} = M\,\omega^2 R,$$

where M is the mass of the body, v its velocity, R the radius of its circular path, $\omega = v/R = 2\,\pi\,N$ is the angular velocity, and N is the number of revolutions per second. The nature of the force is illustrated by Fig. 1, which is a diagram of a man rapidly whirling a stone on the end of a string. It will be observed that a tension in the string is required to make the stone travel in the horizontal circular path. The centripetal force, F, is inward along the string and equal in magnitude to the tension in the string. The centrifugal force is the reaction to the centripetal force necessary to hold the stone at a fixed point in a frame of reference with its origin at the man and rotating with an angular velocity, ω. Therefore, it is equal in magnitude and opposite in direction to the centripetal force. The centripetal force acts on the stone and the centrifugal force on the constraints, i.e., the string and the hands of the man holding it.

It will be observed that although the speed or absolute magnitude of the velocity, v, may not necessarily be changing, the direction of the velocity is changing continuously. Consequently, a rate of change of the velocity occurs since the velocity has both magnitude and direction. This is called the centripetal acceleration, which is often more convenient to determine than the centripetal force. For velocities considered in this article which are small in comparison to the velocity of light, the centripetal acceleration of a mass is substantially proportional to the centripetal force and vice versa. According to the Einstein general relativity theory and recent experimental results, a centrifugal field is equivalent to that of a gravitational field. In view of this equivalence, we usually express centrifugal acceleration in terms of the standard acceleration produced by gravity, g, at the surface of the earth since this is one of our most familiar concepts. The acceleration produced by gravity, g, varies slightly from point to point on the earth's surface but is about 981 cm/sec^2 or 32.2 ft/sec^2. This acceleration is equal to the centrifugal acceleration pictured in Fig. 1 if the

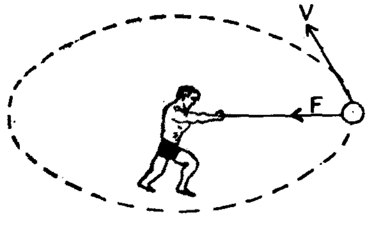

Fig. 1. Man whirling a stone on the end of a string.

Dr. Jesse W. Beams is the Frank Smith Professor of Physics at the University of Virginia, Charlottesville, Virginia. He was born near Belle Plaine, Kansas, December 25, 1898. He obtained his A. B. Degree (1921) at Fairmount College (now University of Wichita); M. A. (1922) Degree, University of Wisconsin and Ph.D. Degree (1925), University of Virginia. He was an Instructor of Physics and Mathematics 1922-23 at Alabama Polytechnic Institute and at Yale 1927-28. From 1925 to 1927 he was a National Research Fellow at Virginia and at Yale. Dr. Beams was President of the American Physical Society 1958-59 and is a member of a number of organizations including the American Association of Physics Teachers; The National Academy of Sciences; The American Philosophical Society; The American Academy of Arts and Sciences and the American Optical Society.

Dr. Beams has carried out research on the nature of light and the interaction of radiation with matter, the Kerr cell light shutter, linear accelerators for charged ions and electrons, electrical breakdown and discharge in gases, development of ultracentrifuges and their application to molecular weight measurement and to the purification of materials, separation of isotopes by centrifuging, ram jets, strength of materials, magnetic suspensions, measurement of partial specific volumes, phenomena which occur in very short times.

radius is 1 meter and whirling at only 0.5 rev/sec. Consequently, it is possible to produce centrifugal accelerations many times that of gravity *g*, actually well over a billion times. Astronomers have found that the gravitational fields on the surface of astronomical bodies vary over wide ranges. For example, the gravitational acceleration on the moon is about one-sixth *g*, that on the sun 28 *g*, and that on the star van Maanen 80,000 *g*; i.e., a man weighing 180 lbs. on the earth would weigh about 30 lbs. on the moon if spring balances were used as scales.

The ever present centrifugal effect which occurs when the direction of motion of a body changes naturally has led man to develop a multitude of uses for it in his numerous activities. For many purposes it has the great advantage of being a "body force" like that of gravity. Also, it can be made extremely constant for long periods of time. Furthermore, unlike gravity which cannot be changed easily centrifugal forces may be varied from zero to very large values in a continuous manner. Also, enormous centrifugal field gradients can easily be produced. Another important factor is that no one has been successful in shielding a macroscopic mass from the effects of an applied centrifugal field. Because of the above properties, centrifugal fields not only find wide use in industry and in everyday life, but also in research. In this paper, an attempt will be made to describe briefly some modern methods of producing very high centrifugal fields and a few of their uses in research in science.

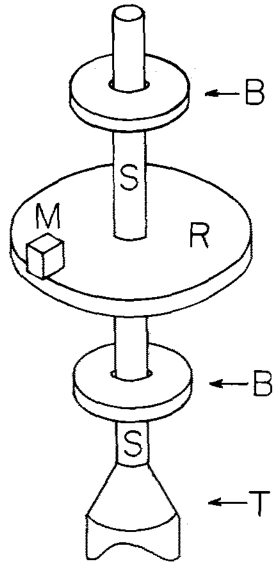

Fig. 2. Rotor on a stiff shaft, supported in fixed bearings.

Figure 2 shows schematically a simple method of producing centrifugal fields. The rotor, *R*, mounted on a stiff staff, *S*, which rotates in the fixed bearings, *B*, is spun by the turbine or motor, *T*. At first sight, one might think that this simple arrangement would produce any desired centrifugal force at the mass *M*. Unfortunately, several factors make the attainment of high centrifugal fields with the arrangement in Fig. 2 difficult. In the first place, if the rotor, *R*, is even slightly unbalanced large forces are exerted on the bearings and eventually causes them to fail. For example, if the wheel, *R*, has a mass, *M*, which weighs one ounce attached to a point on its rim and if the centrifugal acceleration at *M* is 10^6 *g* then the unbalanced forces on the bearings, *B*, are about 63,000 lbs. or over 30 tons. In the second place, if the shaft is stiff, the wheel-shaft combination vibrates like a reed or a violin string at certain speeds. The amplitudes of these natural critical vibrations are usually so large that unless they are damped the shaft or bearings are destroyed. It is not difficult to show that unless the rotor in Fig. 2 is perfectly balanced and the shaft perfectly straight neither of which can be done in practice, the rotor speed must be kept comparatively low to avoid critical vibrations. A major step forward was made by the Swedish engineer De Laval in 1883 when he substituted a long flexible shaft for the stiff shaft, *S*, in Fig. 2. This allowed the rotor to spin about its "own axis of rotation" and made it possible to spin the rotor to speeds above its critical frequency. The theory of the complete motion of an unbalanced rotor is very complex and reference must be made to books on higher mechanics for an exact treatment. However, a little physical consideration will show that if the shaft is flexible enough the rotor, even though unbalanced, will spin about a line approximately through the center of mass of the rotor. The higher the rotor speed above the critical vibration frequency and the more flexible the shaft the closer the axis of spin passes through the center of mass. This axis of spin is often referred to as the body's "own axis of rotation." In view of this property of rotating bodies, it should be possible to spin any rotor up to its bursting speed if it could be made free enough to rotate around its own axis of rotation. De Laval incorporated this idea into his famous single stage steam turbine and succeeded in greatly improving its efficiency since the efficiency of a steam or gas turbine increases until the peripheral speed of the turbine reaches about half the speed of the steam jet. He actually obtained a rotor speed of 433 revolutions per second and a peripheral speed of 1300 ft/sec.

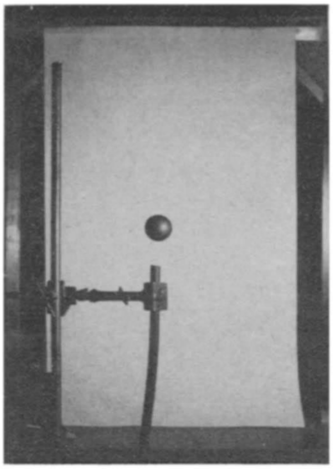

Fig. 3. Photograph of light ball spinning on jet of air issuing from clamped rubber tube.

In addition to the flexible shaft scheme of De Laval, there are other methods of spinning rotors to very high speeds. One such method is to spin the rotor on a whirling jet of air. This method is illustrated by a very old experiment shown in Fig. 3, in which a ball is supported and spun on a whirling jet of air. This experiment can easily be performed by anyone if an air pressure supply from a small tank or pump such as found in a garage or in certain types of vacuum cleaners, a small length of rubber tubing and say a ping pong ball are available. In 1925 two Belgian scientists, Henroit and Huguenard, employed this principle to spin small cone-shaped rotors to high speeds. Figure 4 shows a diagram of an adap-

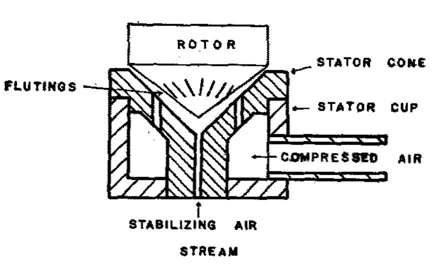

Fig. 4. Schematic diagram of method of spinning cone shaped rotors on a whirling cushion of air.

tation of the Henroit and Huguenard method for spinning rotors to high speeds. (*1*) Air under pressure enters the stator air box and is directed as jets onto flutings milled into the cone-shaped under-surface of the rotor. This both lifts the rotor off the stator and starts it spinning. The rotor does not fly out of the stator due to a principle discovered by Bernouilli (1700-1782). In effect, he found that if the speed of a horizontal air stream is increased its pressure decreases. Consequently, the rotor seeks a position just high enough above the stator so that the air pressure in the stream is automatically balanced by the atmosphere and the weight of the rotor. With this simple device, it is easy to spin small rotors an inch in diameter or less to several thousand revolutions per second and produce centrifugal fields up to the order of a million times *g*. (*1*)

Although the above air driven "top" is useful for many experiments, it has the great disadvantage that it spins in air or a gas at approximately atmospheric pressure. If the rotor speed is high the air or gas friction becomes so large that the rotors will not attain high speeds except when they are small or unless a very large amount of power is used for the drive. In both cases, the air friction heats the rotor and the expanding jets cool it. This is especially troublesome because the surface speed increases from zero at the axis to a maximum at the periphery which produces unavoidable non-uniform heating. For example, this renders the method almost useless for many sedimentation problems because of the convection generated by the thermal gradients. The recognition of the necessity for eliminating thermal gradients in a centrifuge in which sedimentation takes place by the Swedish chemist, Svedberg in 1924, enabled him to carry out his epoch-making experiments on the characterization of proteins by means of his ultracentrifuge. Ultracentrifuge is the name usually given to a convection free high speed centrifuge.

Because of the many undesirable effects produced by air or other gases at appreciable pressures on high speed rotors, a method was developed at the University of Virginia beginning in 1934 for spinning rotors to very high speeds in a high vacuum. (*1*) This so called vacuum-type centrifuge consisted of a large centrifuge rotor which was spun in a vacuum-tight chamber by a small air-supported air-driven turbine situated above or below the chamber. The turbine and rotor were connected by a long thin flexible shaft which passed through a vacuum-tight oil gland; i.e., the centrifuge rotor was made free to rotate about its own axis of rotation in a vacuum by combining the whirling jet air turbine technique with the De Laval shaft and adding a practical vacuum-tight oil gland. With this arrangement, the only limiting factor on the rotor speed is the strength of the rotor material. Many modifications and improvements in this design have been made in various commercial and other designs of ultracentrifuges. These have been the principal "work horses" of molecular sedimentation experiments in this country over the last 25 years.

An ideal method of producing high centrifugal fields would be one in which the rotor is free to spin about "its own axis" and thus need not be accurately balanced or limited in size or weight. It should spin in a vacuum, in air or other fluids as desired. It should require no separate turbine or motor drive or shaft, it should spin on a friction free bearing and attain rotor speeds which are limited only by the strength of the rotor. This ideal, of course, cannot be completely attained in practice; but starting in 1937, workers at the University of Virginia have been developing a magnetically suspended electromagnetically driven rotor device which closely approaches the ideal described above. (*2*)

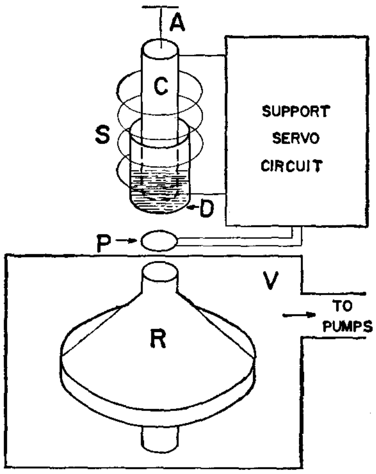

Fig. 5. Schematic diagram of a method of magnetically suspending a rotor.

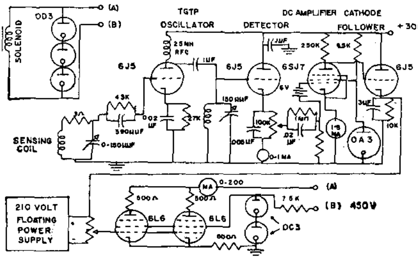

Fig. 6. Diagram of servo circuit used for magnetically suspending ferromagnetic rotors and other ferromagnetic bodies.

Figure 5 is a schematic diagram of a method of magnetically supporting a rotor, *R*, in the vacuum chamber *V*. The rotor, *R*, or its central core is made of steel or other ferromagnetic material. Consequently, it is attracted by the electromagnet, which is composed of the solenoid, *S*, and the iron core, *C*. Since the rotor is attracted upward with a force $F = M\ \partial H/\partial Z$ where M is the magnetic moment of rotor and $\partial H/\partial Z$ is the vertical gradient of the magnetic field H, it will fly up to the electromagnet unless the current through *S* is propertly regulated. As the rotor, *R*, rises the impedance of the pick-up coil, *P*, is changed in such a way that the current through the solenoid, *S*, is reduced. When the rotor falls the current through *S* is increased. Derivatives of the signal in the circuit prevent oscillations. This type of pick-up and circuit is known as a servo circuit and will hold the rotor very precisely at the desired vertical position. Figure 6 is a schematic diagram of a circuit which is very stable, but many types of servo circuits may be used successfully. Also instead of the pick-up or sensing coil, *P*, a photoelectric pick-up may be employed; i.e., the intensity of a light beam which falls upon a photoelectron-multiplier cell control, is determined by the height of the rotor. Since the axial field of the electromagnet is diverging downward and the highest field is on the axis, the rotor automatically will seek a position of equilibrium on the axis. If the rotor receives a horizontal disturbance the lower end of the core, *C*, which hangs as a pendulum from the wire support, *A*, is dragged along with it. Consequently, any horizontal oscillations of the rotor are damped by the motion of *C* through the dash pot of oil, *D*.

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1. J. W. Beams, Jour. Appl. Phys. **8**, 795 (1937); Rev. Mod. Phys. **10**, 245 (1938). (See for other references)

2. J. W. Beams, Science **120**, 619 (1954); Physics Today **12**, 20 (1959). (See for other references)

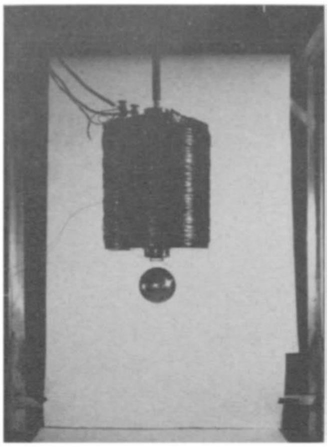

Fig. 7. Photograph of magnetically suspended steel sphere.

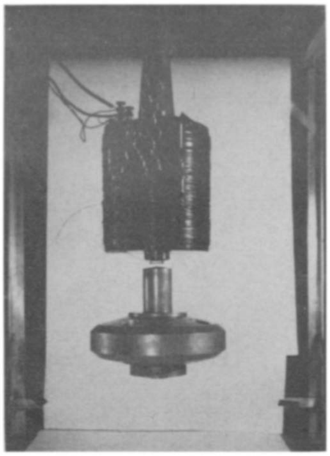

Fig. 8. Photograph of magnetically suspended equilibrium ultracentrifuge rotor. Vacuum chamber and motor drive are not shown.

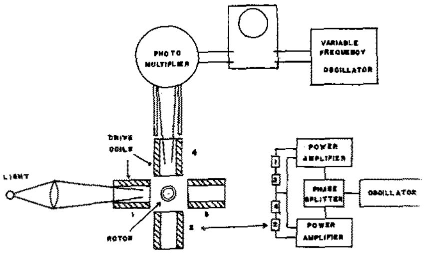

Fig. 9. Schematic diagram of method of measuring rotor speed and method of driving rotors at high rotational speeds.

When the servo circuit is properly adjusted no vertical or horizontal motion of the rotor can be observed even with a microscope focused on the rotor surface. Figure 7 is a photograph of a magnetically suspended 2 in. steel sphere without the surrounding vacuum chamber.

If now the rotor is given a spin around its vertical axis no appreciable change in the magnetic flux through the rotor occurs and consequently there is negligible electromagnetic drag. As a result the only friction on the rotor is that due to the air friction. Fortunately, as shown in Fig. 5, the magnetic suspension system will support the rotor inside of a completely sealed vacuum chamber made of nonferromagnetic material such as glass, copper, or stainless steel just as well as in the air so that the air can be removed from around the rotor. When the wall of the vacuum chamber is a conductor, *P*, of course, must be placed inside the chamber. When the gaseous pressure is reduced to the order of 10^{-7} mm of mercury pressure (about one ten billionth of an atmosphere) which is easy to do with ordinary diffusion pumps the 30 lb ultracentrifuge rotor shown in Fig. 8 will lose about one revolution per second per day when coasting freely (without drive) at a rotational speed of 800 revolutions per second; i.e., it would take over 15 years for this rotor to slow down to one revolution per second. *(3)* For this reason it is always necessary to provide means of decelerating the rotor to rest. Even at this low air pressure of 10^{-7} mm Hg all of the friction on the rotor can be accounted for as due to air friction. This is especially true when the center of permeability of the rotor and the center of mass or gravity lie very closely on a vertical line which is also the axis of the diverging magnetic field of the supporting solenoid. The size of the rotor may be varied over wide ranges depending upon the strength of the electromagnet and the electronic power supply. At the University of Virginia rotors from less than one thousandth of an inch to over a foot in diameter have been supported and spun. Their weights have varied from about one billionth of a pound to over 100 lbs but both smaller and larger rotors could, of course, be used. Rotor speeds well in excess of one million revolutions per second have been used, giving centrifugal accelerations of over one billion times *g*.*(2)*

Rotors magnetically suspended inside of a high vacuum chamber are usually spun in a manner similar to that of the armature of an induction, reluctance or synchronous motor. The necessary rotating magnetic fields are produced by field coils situated outside of the vacuum chamber. The rotor speeds are determined by reflecting or scattering light off of the rotor into a photoelectron multiplier cell. The repetition rate of the cell's electrical output is equal to the rotor speed. This output of the cell is amplified and applied to one pair of plates of an oscilloscope where it is compared with a known frequency applied to the opposite pair of plates. Figure 9 shows a schematic diagram of the rotor drive and the method of measuring the rotor speed. Other types of drives are used for the ultracentrifuge because of possible rotor heating by the method shown in Fig. 9.

The rotational speed at which a given rotor explodes depends upon the shape of the rotor and upon the mechanical strength divided by the density of the material of which it is made. For example, a series of steel spheres or ball bearing balls were spun to destruction and it was found that they all exploded at the same peripheral speed of about 3300 ft/sec; i.e., rotors of exactly the same shape and made of the same material will explode at the same peripheral velocity. In practice the only limiting factor on the rotor speed which can be obtained is the strength of the rotor material. Because of this limitation it is necessary to use small diameter rotors when very high centrifugal fields are required since the field is given by $\omega^2 r$ while the peripheral velocity is ωr.

The principle of the magnetic support bearing often can be utilized to great advantage with very simple apparatus in some cases where the rotor is very heavy or where it exerts a large force on its thrust bearings. A permanent magnet can be used to support almost all of the weight of the rotor with just enough remaining on the thrust bearing to keep it from flying up to contact with the magnet. Since there is no appreciable drag due to the lifting magnet, the overall friction is greatly reduced.

In addition to the standard bearing, the air-bearing support and the magnetic support discussed above there are other types of supports. Electrostatic supports have been developed for use with comparatively light rotors by a number of different workers. However, electrostatic forces are exerted on the surface of the rotors and in practice are comparatively small so

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3. The drag on the rotor due to air friction is given by the relation $\log_e (N/N_0) =$ constant x $(t_i - t_0)$ where N_0 is the number of rps at time t_0 and N is the number of rps at time t. The constant depends upon the pressure of the air surrounding the rotor, the shape, size, and density of the rotor and the temperature.

that their use at present is restricted. In recent years a number of workers have devised methods of supporting permanent magnet rotors at very low temperatures with properly shaped superconductors. This ingenious method may find valuable use for experiments near temperatures of absolute zero, but as yet its use also has been limited. As mentioned previously the uses of high speed rotation are so universal that almost anyone, after a little consideration, could think of many applications. For this reason in this article the emphasis has been on some recent techniques rather than the uses. However, a few applications in modern research may be of interest.

Perhaps the most valuable application so far of high centrifugal fields has been in the purification and characterization of substances which occur in solutions and mixtures by the process of sedimentation. It is a common observation that if muddy water flows into a large quiet pond the silt settles to the bottom of the pond. The larger heavier particles settle out first followed by the finer ones. The British physicist, Sir George Stokes, in 1847 showed that the velocity of settlings of a small spherical uncharged particle of radius a and density d_p in a liquid or gas of density d_e and coefficient of viscosity η in a gravitational or centrifugal field F is given by the relation

$$v = \frac{2}{9\eta} (d_p - d_e)\, a^2 F,$$

i.e., the rate of settling of a particle in a quiet liquid is approximately doubled if its density is doubled and increased four fold if its radius is doubled, its density remaining constant. It also is doubled if F is doubled. Consequently, the process of settling in the gravitational field or in a comparatively low speed centrifuge is widely used as a means of separating particles of different densities and sizes in many laboratory, mining, and manufacturing processes. On the other hand, when the particles are reduced to molecular dimensions the velocity of settling, v, becomes very small. For example, in the case of sucrose dissolved in water at room temperature it requires over 100 years for a sucrose molecule with radius of about 5×10^{-8} cm to fall a distance of one millimeter in the earth's gravitational field. Consequently, if the sugar solution is unsaturated no sugar will settle out because the above velocity of settling is many orders of magnitude less than the average velocity of a sucrose molecule produced by the natural random motion of the molecules. This random motion was observed by the British biologist, Brown, in 1828 when he noticed that very finely divided inanimate particles suspended in water or air were in rapid random motion. This phenomenon is called Brownian motion and is produced by the numerous impacts on the particle by the molecules which are in rapid motion. It can be shown that this ever present Brownian motion increases as the size of the particle becomes smaller and is relatively large when the particle approaches molecular dimensions. *(4)* Consequently, because of collisions there is a transport or diffusion of small particles or molecules from regions of high concentration to regions of low concentration, As a result, sedimentation is always opposed by this back diffusion and unless the sedimentation rate is the larger of the two, no particles will settle out. For example, in the case of the unsaturated sucrose or sugar solution at room temperature mentioned above it is, of course, a common observation that the sugar molecules will never settle out under the influence of gravity alone. However, in a centrifugal field of say a million times gravity the sugar molecules will sediment at the rate of a millimeter in about 1.5 hours and most of the sugar will settle out of the water solution.

In practice, as can be gathered from the above discussion, it requires comparatively large centrifugal fields to produce molecular sedimentation. Fortunately, the techniques described above may be used to generate centrifugal fields which are large enough to produce sedimentation in all known substances either in the gaseous phase or in liquid solution. As a result, it is now possible to purify almost any known substance that can be dissolved in a liquid or which can exist in the gaseous phase from liquid helium temperature to well above room temperature by high speed centrifuging. Actually, it was shown at Virginia in 1937 and later in Germany and elsewhere that the isotopes of the elements could be purified by centrifuging. This, of course, is well known to be one of the most difficult separation processes. The centrifuge is especially useful for the purification of compounds of interest in biology and medicine. Many of these substances occur naturally in dilute solutions and in complex mixtures. Furthermore, they are easily deactivated or destroyed by large temperature changes, or by the ordinary chemical methods of purification. Fortunately, these substances are not effected by a high centrifugal field so that the development by many people of the high speed convection free centrifuge has furnished the research workers in medicine, biology, and chemistry with a most valuable tool. In addition to the actual purification of materials the centrifuge may be used as a means of measuring the molecular weights of substances which are difficult or impossible to determine by the standard chemical methods. As pointed out above, the heavier the molecule the faster it will settle out. Consequently, from the rate of sedimentation of a substance in the centrifuge the molecular weight can be computed. The molecular weights also can be determined by centrifuging for a time sufficiently long to allow back diffusion to just balance sedimentation. When this occurs the density gradient across the centrifuge cell containing the solution together with the rotor speed and temperature give the molecular weight. The use of the centrifuge for molecular weight measurements was pioneered by Svedberg and his students about 35 years ago and now is in general use all over the world. Present magnetically suspended equilibrium ultracentrifuges are capable of determining molecular weights to a precision of much better than one per cent over the molecular weight range from about fifty to at least a hundred million molecular weight units. *(5)*

In addition to many kinds of sedimentation experiments mentioned above, the high speed rotor techniques have been applied to the study of the strength of materials both in bulk and in very thin films and to the measurement of adhesion of one substance to

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4. It was shown by Einstein that the average distance $\bar{X}$ which a particle moves in a time t because of Brownian motion is given by the relation

$$\bar{X} = (2Dt)^{1/2} \left(\frac{RT}{N} \frac{t}{3\pi\eta a} \right)^{1/2}$$

where D is the diffusion constant, R the gas constant, N the Avogadro number, η the coefficient of viscosity, and a the radius of the particle. (See E. F. Burton, *Physical Properties of Colloid Solutions*, Longmans Green and Company, New York, 1938.)

5. J. W. Beams, R. D. Boyle, and P. E. Hexner, Rev. Sci. Instr. **32**, 645 (1961); Jour. Polymer. Sci. **57**, 161 (1962).

temperature of 65° to 75°F. Sufficient heat is supplied in the canister by dissipation of electrical energy from the solar cells to maintain this temperature. The container is well insulated to keep its temperature relatively stable, and it has shutters that open automatically if it begins to get overheated (*see Figure 4*). The operating characteristics of the solar cells on Telstar's surface also had to be considered; they work better at rather cool temperatures. So we decided to keep the satellite's skin at an average temperature of about 0°F, although temperatures actually will range quite a bit above and below the average as the satellite moves from sun to shadow.

Now, using this average temperature of 0°F (converted to 460°R) as T in our formula, we can solve for α/ε. We find that this gives us a ratio of approximately 0.7 for the satellite's surface. However, this presents a problem. Almost 40 per cent of Telstar's surface is taken up by its power plant of 3600 sapphire-covered solar cells. These cells, unfortunately, have a relatively high α/ε ratio—their α is 0.8 and their ε is 0.54, for an α/ε of 1.5. This means that the portion of the surface not used by either solar cells or antenna openings must, in order to give us an over-all average of about 0.7, have a very low α/ε ratio—less than 0.3.

To get this sort of ratio, we had to select carefully the material for the outer surface of the Telstar satellite. There were many kinds of surfaces that might have been used; they could have been metal or nonmetal, rough or smooth, shiny or dull. And they could have been any color from black to white. However, to get a 0.3 ratio we needed something with a relatively high emissivity for the low-frequency electromagnetic radiation that the satellite emits and a rather low absorptivity for the high-frequency radiation coming from the sun. High emissivity meant that we should use a nonmetal surface rather than polished metal, since the emissivity of nonmetals is quite high at the temperatures in which we were interested, while that of polished metals is relatively low. And, to get low absorptivity, we decided that the color of these surface areas should be very close to a pure white.

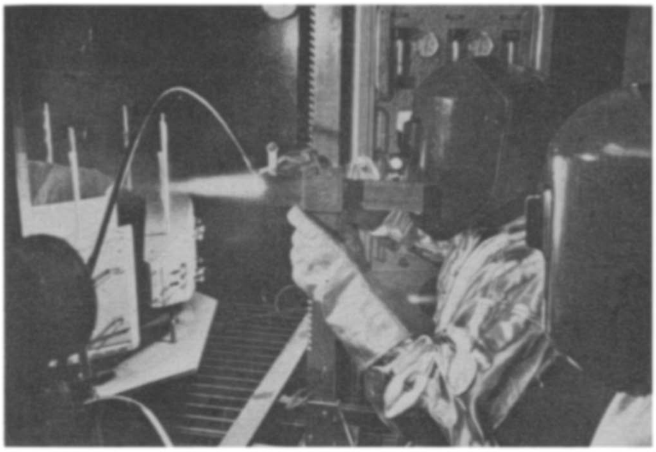

Figure 5. Partially molten aluminum oxide particles being sprayed onto aluminum outer surface panels.

There were several substances that met our requirements. After testing a number of them, we decided to use aluminum panels coated with a thin layer of aluminum oxide (Al_2O_3). This coating is very pure, hard, and stable, and we left it rough to minimize changes due to meteroid abrasion. Its α/ε ratio is 0.24. The aluminum oxide coating can be applied by means of the plasma jet process—particles of aluminum oxide are heated to a partially molten state, mixed with gases, and then sprayed onto the cleaned, precoated aluminum panels (*see Figure 5*).

Using this carefully selected outer surface has helped solve the temperature-control problem. Since Telstar has been in orbit its internal and skin temperatures have kept well within the ranges we wanted them to. Thus you can see how some basic formulas from classical physics helped us choose the right material for the satellite's surface—and even what color it should be. The blue-and-white checkered appearance that Telstar I finally took on was no accident—it was the result of carefully combining various colors and materials in just the right amounts to obtain the temperature balance we needed.

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another. The method possesses the virtue that the results are not affected by clamping devices which produce stress concentrations. Also very constant high speed mirrors have been developed with which phenomena that occur in less than a billionth of a second can be studied. Since the peripheral speed of the high speed rotors is about twice the average molecular velocity they have been used as molecular pumps, for producing homogeneous velocity streams of molecules, neutrons, etc. The fact that magnetically suspended rotors are free of "hunting" and that the suspension has such low friction raises the hope that the rotor can serve as an extremely accurate clock, especially for very short times; i.e., the order of 10^{-6} sec. If so, they should be of considerable value in many important "time-of-flight" measurements, etc.

In closing, it might be of interest to point out that although in this article the technique of high speed rotation has been stressed, this technique was in every case developed to carry out some problem in research and not with the view of developing the technique itself. However, it is an excellent illustration of a universal experience in research of how a technique developed for one purpose becomes useful for others.

We Quote . . .

He who knows not and knows
not that he knows not,
He is a fool—shun him;
He who knows not and knows
he knows not,
He is simple—teach him;
He who knows and knows
not he knows,
He is asleep—wake him;
He who knows and knows
he knows,
He is wise; follow him.
Arabian Proverb.