THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

ELECTROSPHERICS AND MAGNETOSPHERICS

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INTRODUCTION

A considerable body of electrical literature is concerned with the behavior of charged particles, and the influence of electric fields on charged particles. This paper presents some new observations in which spherical bodies, usually conducting, themselves cause electrification by motion over the surface of a dielectric; and which, if of proper size range, display interesting static and dynamic effects.

The paper continues with a number of new phenomena in which spheres of magnetic material of appropriate size range, when influenced by an alternating magnetic field, do strange, unexpected, and often very fascinating things, depending on whether or not they are magnetized; and sometimes depending on the presence of electrification.

Demonstration of these new behaviors can be arranged for by simple means and at low cost, in terms of equipment described herein. The demonstrations invariably captivate the onlooker, whether innocent of scientific training, or highly sophisticated. Some may remain without application, interesting only in their own right. Others may serve as analogs for various other goings-on, such as Brownian movement, thermal movement of molecules, crystal formation, bacterial chaining, and so on.

In any case, electrospherics and magnetospherics will prove that electrical engineering can be a lot of fun.

All experiments using an alternating magnetic field were done at 60 cycles per second, unless specifically noted otherwise.

ELECTROSPHERICS

Definition

When spheres of appropriate size and mass are shaken, moved, or rolled across an appropriate dielectric surface, thereby becoming charged and giving to the surface an opposite charge, various static and dynamic phenomena can be demonstrated. These phenomena will be called electrospherics.

Discovery

When developing sandbed types of fluid mappers some years ago, the writer acquired some nickel shot, much of which is very smooth and quite round. These little balls, about 18 mils (0.018 inches) in diameter, are shown in Figure 1. On pouring them into a polyethylene container, it was noted that they became electrified. Shaking them across the bottom further electrified them. Many workers in different fields have been shown these electrospheric phenomena, with a high degree of fascination ensuing in each case. Only one or two had seen such things before, and they were people who had noted that polystyrene beads distribute themselves with a spacing-apart tendency over the inner surface of a glass bottle, when the bottle is tilted or shaken.

Distribution by Repulsion

In Figure 1, the mass of balls was shaken in a hard plastic bowl, to produce electrification. It was then tilted quickly to about 45°, bringing the far side up toward the observer. The spheres rolled down and most of them massed together; but many sprang back up again, to distribute themselves at random over much of the bottom surface. Each

Figure 1. Electrified Balls Spaced Out Over Sloping Bottom of a Bowl. Streaming is Displayed by the Balls Showing Movement.

sphere is held to the hard plastic bowl's surface by the attraction of opposite charges. But each is repelled by its neighbors by repulsion between like charges. Here then, is a simple way to cause numerous particles to distribute themselves, spaced apart at random and more or less uniformly. When the spheres have come to rest, they are in static equilibrium.

Dynamic: Movement of Spheres about Their Locations

If weak charges occur, shaking a polyethylene container will cause all or nearly all of the distributed shot to flow around to new locations. But with enough shaking to give strong electrification, each sphere becomes "tied" to its home on the dielectric surface. Thereupon, mild shaking or vibration of the container will cause all of the spheres to oscillate in various ways, each in the little region it has staked out for itself.

In this dynamic situation, each sphere is, of course, still acting to repel its neighbors. Each sphere affects the movement of nearby spheres. This is not necessarily a true analog for the thermal movement of molecules in a solid, but it is effective as a visual demonstration of the ideas involved.

Fronds, Branches, Chains

These formations are best observed in a polyethylene container with a reasonably flat bottom. Such vessels are available for storing foods in the refrigerator. After repeated shaking of the spheres across the bottom to get strong electrification, the vessel is tilted a little. Various effects show up, if this is repeated time and again, and closely watched. Fronds, branches, and chains of spheres will form at the upper edge of the mass of spherical shot, as distributed spheres pour down to the mass in the tilted container. Or, with small enough tilting, patches of monolayers will form on the bottom, and their edges are prone to show these formations.

If these phenomena are viewed in terms of possibly analogous phenomena, some light may, for example, be shed on crystal growth.

Streaming

Streaming, shown in Figure 1, is a striking dynamic phenomenon in electrospherics. As described above, the bowl had already been tilted. Next, the cup was rotated a little, by drawing the thumb back and moving the finger forward. The mass then had to readjust.

Normally, the upper spheres at the left would tend to roll downhill along the upper edge of the mass, to the right. But the presence of charge does not permit that. These spheres take off, leave the edge, stream upward away from the edge, flow across and among the distributed spheres, and come to rest somewhere to the right. This must be seen to be appreciated. It is best seen in a flat-bottom polyethylene container.

The picture was taken at 1/50th second exposure, which was too long to stop the motion. Looking closely, one can see many of the nickel shot showing streaks of movement.

Here, in a little bowl, one gets at least a rough simulation of what goes on when electrons are thrown out of a hot cathode, but if there is no potential gradient to make them leave home, they must return again. Other simulations of somewhat analogous phenomena may occur to workers in various fields.

Size of Spheres

Spheres only a few mils smaller than those described above will electrify, but will refuse to display dynamic effects. Their mass is too small, as compared to the electric forces, and they simply stick tight to their chance locations on the dielectric surface.

Going the other way, metallic spheres a few mils larger begin to be so heavy as compared with the electric forces acting, that electrification by shaking by hand can hardly be made strong enough to get the several effects described. (Later in the paper, larger spheres will be found to respond, but it will take more movement than can be induced by hand.)

Thus, it was a stroke of luck that the writer's observation of electrospherics happened to be made with nickel shot of somewhere around the optimum size.

The source of the nickel shot is not given, for these came from an experimental batch, and may be unobtainable. Later, suitable shot will be described that is available.

Other Electrospheric Effects

These will be taken up later, where they appear along with magnetospheric phenomena.

MAGNETOSPHERICS

Definition

When spheres of magnetic material are acted upon by an alternating magnetic field, various static and dynamic phenomena can be demonstrated, depending on whether or not the spheres are magnetized, and depending in some cases on the presence of electrospherics. These phenomena will be called magnetospherics.

Discovery

Again, luck entered in; and again, in connection with fluid mappers. Back in 1943, some hard cast iron shot had been acquired from an Adrian, Michigan firm, and the writer had copperplated it to stop rusting. The size was about the same as that of the nickel shot.

In March 1958, the writer wanted to delineate an alternating magnetic field with iron filings. No filings being at hand, the cast iron shot were tried. They worked remarkably well, but: some of them danced. They moved rapidly in and out among their quiescent comrades. This was unexpected, confusing, and stimulating.

The suspicion dawned that these dancers might somehow have become magnetized. This was readily proved. A single little dancing ball was heated, whereupon it refused to dance. Remagnetized, it danced again. There was no hint on that day, that all spare time for some months to come would be totally occupied with experimenting, theorizing, research, and the utterly entrancing business of seeing the birth of one new phenomenon after another.

Spheres as Synchronous Motor Rotors

The early experiments were done with a vertical air-core solenoid carrying alternating current, with a horizontal glass plate mounted on top. The dancing shot were allowed to cavort inside of a ring on the plate, or in a bowl resting on it. In addition to the vertical component, this field had, away from the axis, a strong radial (horizontal) component. It was not then known that the horizontal component is undesirable. However, there was a dance.

After it was recognized that a ball might be rolling along as a synchronous motor rotor, the stroboscope gave good verification. On the straighter parts of a path, the ball rolled approximately one revolution in one cycle. Complete verification came later, on the racetrack.

The Ball Ballet

Soon, hundreds or even several thousands of tiny magnetized cast iron shot were put into action, even though a good a-c field conformation to induce the action was yet to be worked out. Seeing a great number of balls weaving in and out among each other of course led to the designation, the ball ballet.

Accounting for the Ball Ballet

Several factors making this display possible are now discussed.

Self-starting: if the magnetized ball is small enough, it is able to produce enough torque to begin turning, and through friction with the floor, start rolling and spinning at synchronous speed.

Irregularities: cast iron shot are not true spheres, and irregularities may account for some of the more complex gyrations. However, highly accurate steel balls do much the same things.

Gyroscopic effects: if a rolling ball is acted upon by deflecting influences such as by crossing a field of changing density, or suffering a change of friction with the floor, or in starting to climb the slope of the bowl at the edge of the floor, forces between itself and the floor will induce gyroscopic action. Precession of the axis will lay larger or smaller contact circles into floor contact, linear speed will change, and direction of motion will change. Such behaviors are constantly demonstrated in lesser degree at the billiard table.

Path: the path of a single ball is constantly changing through longer and shorter arcs and whirls. A near-circle may change to elliptical form or to any other simple configuration.

Collisions: there are many collisions when plenty of balls are used. Some of these can result in balls magnetically sticking together, at lower field strengths. Magnetic repulsion tends to reduce collisions.

Magnetic repulsion: unmagnetized balls, placed close together on a horizontal plane, will repel each other when a vertical alternating field is turned on. The repulsion force again is there, even if they are magnetized. Thus, in the ballet, magnetic repulsion plays a prominent part in enabling the balls to avoid collisions. (Electrostatic repulsion may also be present, but this is taken up later.)

The Coil Arrangement

It was gradually learned through much experimentation, that the magnetized shot would put on their best dance in a plastic bowl, if subjected to an alternating field which, first, is vertical or nearly so, and second, whose density decreases somewhat from the center outward.

Both requirements were met by the use of two coils, arranged as shown in Figures 2 and 3. Plaster posts, Figure 3, support a glass plate somewhat above the lower coil, and the bowl is set on the plate. Other plaster posts placed on the glass support the upper coil. Spacings are given in Figure 2.

This two-coil arrangement is reminiscent of the Helmholtz coil design, which might work equally well here. The fact is, these coils are a fortunate compromise. Two unlike coils like these were needed for a development described further on. After making them, it was found that they also serve the present purpose very well.

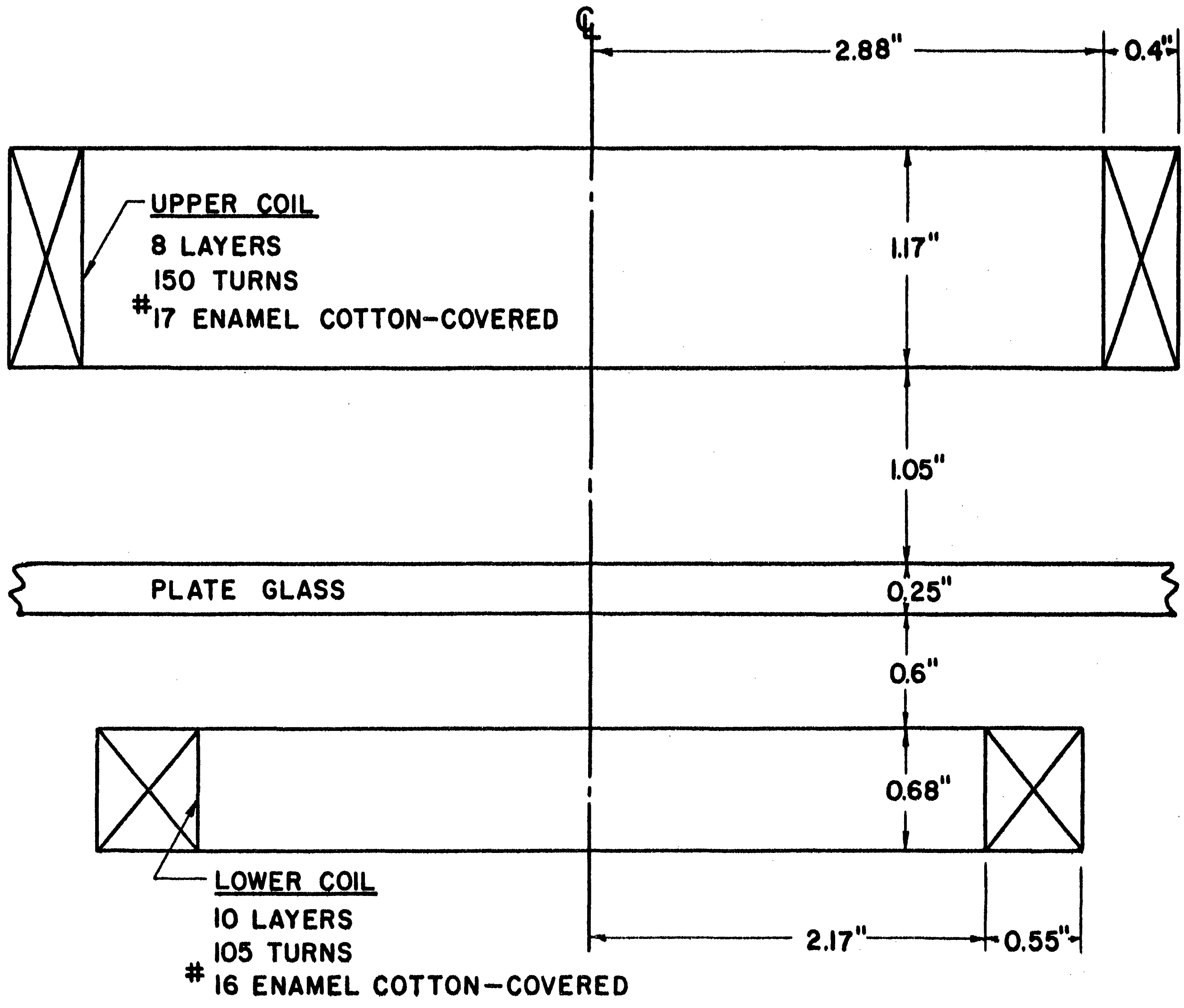

Figure 2. Data On Coils, and Vertical Spacings Used for the Ball Ballet and Related Demonstrations.

Figure 3. Coils Set Up for the Ball Ballet, the Ball Crystal, and Related Phenomena.

Coil Data

Dimensions of the actual windings (not including the coil forms) are given in Figure 2.

The upper coil has 8 layers, 150 turns, of No. 17 copper, enamel cotton-covered. Resistance, 1.22 ohms; reactance at 60 cycles, 1.95; impedance, 2.30. The lower coil has 10 layers, 105 turns, No. 16 copper, enamel cotton-covered. Resistance, 0.54 ohms; reactance, 0.80; impedance, 0.96. Both coils were wound by hand, regularly (not haphazard), and with the layers heavily treated with Glyptal (registered trade mark) varnish as they were put on.

The change of wire size was made for an excellent reason. The writer ran out of No. 17 wire in winding the upper coil.

Connected in series, the two coils have a resistance of 1.76 ohms. When arranged as in Figures 2 and 3, and additive, reactance and impedance are 3.02 and 3.50 ohms. When arranged as they will be later as in Figure 11, resting one on the other except for the glass plate between, reactance and impedance when coils are opposed, are 1.92 and 2.61.

The forms were easily made, each being a three-piece job. Each cheek is an annulus, cut from hard, stiff pressboard (salvaged from office filing separators). The third piece was a long strip of appropriate width, cut from a manila folder (salvaged from the same "stockroom"). Scissor-cuts were made inward for half an inch from each side, to make ears that would bend over to be cemented to the cheeks with Duco (registered trade mark) cement.

These coils will carry about 4 amperes continuously. Much higher currents are carried for short times. If overheating threatens, a fan can be set up for forced cooling.

Data on the Field

With the coils arranged as in Figure 2, connected in series with fields additive, a search coil of 20 turns and diameter of 4.25 inches was laid coaxially on the glass plate. Using 10 amperes direct current and a fluxmeter, the flux through the search coil was found to be 13,200 lines.

As a check, computation found that the upper coil would put 7400 lines through this area; and the lower coil, 5700 lines; the sum being 13,100 lines.

The average flux density at 10 amperes was thus found to be 930 lines per square inch, or 93 lines per square inch per ampere.

Density variation over the area was investigated by a small search coil. Density at the center turned out to be about 10% higher than the density 1.75 inches away from the center.

The Plastic Bowls

The hard yellow plastic bowls seen in Figure 3 were purchased at the experimenters' paradise (5-and-10 cent store) at a nickel apiece. The rim diameter is 3.75 inches. Different types or sizes of balls can be assigned, one kind to a bowl, and thus kept separated and identified. Each bowl can be labelled by means of adhesive marking tape.

One of these bowls, selected for smoothness and flatness of the bottom, is reserved for use when the balls are made to dance. Naturally, it is called the Ballroom.

Cast Iron Shot

Many people who have been shown these phenomena have asked why cast iron shot is made. It is cheap stuff, made by the ton. Impelled by air blast, it is used for cleaning castings, and for shot-peening surfaces. Quite a range of sizes is available. As it comes, a large fraction of the shot will be fairly round and fairly smooth; but there will be any number of defectives.

The defectives must be largely eliminated, for our purposes. A two-step process was worked out. First, a small batch of raw shot is placed on a large sheet of drawing paper. The paper is picked up by opposite edges, stretched, and shaken slowly, to let the rounds roll down a gentle slope, off the edge, and into a large tray. Many defectives are left behind. This process is repeated several times. The defectives that pass the first step are caught in the second, by visual inspection. A few shot at a time are scattered onto a piece of white paper. Defectives spotted by eye are picked out with a magnetic picker. The picker is a small iron wire, wrapped around the end of a small Alnico bar magnet, and extending from the end by an inch or so.

This is hard cast iron shot we are now considering, which is magnetically retentive. Malleabilized cast iron shot can also be had, but its retentive quality is much too low for the ball ballet.

Thus, the cast iron shot industry is a cheap source of supply for one who needs small retentive "spheres" by the thousands.

Two Samples of Shot, Different Performance

The original dancing-shot discovery was made with the old 1943 sample. A new supply was needed. Industrial Metal Abrasives of Jackson, Michigan kindly supplied a number of generous samples with which to develop magnetospherics. The Jackson shot put on a good ball ballet, even before selecting out the defectives. But there was a difference.

The Adrian shot, occasionally, would demonstrate swirls; and very rarely, complete circulation around the ballroom floor. The Jackson shot stubbornly refused to do this. This was a baffling situation. Repeated efforts to make the Adrian shot perform this way, and do it at the will of the operator, met with no success. Either it happened, or it didn't happen. The conclusion seemed to be this: if shot is made in Adrian, it will unpredictably swirl, but if made in Jackson, swirling is out of order. This not being a satisfactory state of affairs, quite a series of experiments was engaged in.

Electrospherics Again

These experiments were down the dark alley of no-understanding, and fruitless. Nothing worked, until it was recalled that the Adrian shot had been copper-plated. In a mood to try anything, some Jackson shot were copper-plated. There was improvement, but not much. Along about then was when the idea came, very dimly, that electric charge effects might be needed if the dance were to turn into a swirling or streaming effect.

With that in mind, the next thing was tried: burnishing the rough copper-plating, to smooth the ball surface. The results were spectacular.

Without electrospherics, we can have the ballet; but without electric charge effects, the balls are too prone to collide. Also, at least momentarily, some tend to stick together magnetically. With electrospherics, mutual electrostatic repulsion greatly helps to prevent collisions, each ball then being often able to find a path among its fellows. Streaming can develop. A strongly electrified situation apparently depends on the balls having a smooth surface.

Copper-Plated Shot

The routines for shot preparation as finally worked out are very simple. The selected shot are dumped into a flexible rubber bowl, emery paper is pressed down on the batch and moved around, and the shot are thus cleaned and somewhat smoothed. An acid bath is used to clean them further, and remove oxide. After a rinse, a little water is poured onto the batch, and some powdered copper sulfate is stirred in. The copper at once begins to displace the iron. In a moment or so there is a heavy, but dull copper plating on the shot.

The shot are now dried on a paper towel, and put back into the rubber bowl. The thumb is used to press into the mass of shot and rub the shot against each other. Before wearing out the thumb, the shot will have burnished each other to a bright, shiny finish.

One more note about this process must be entered here. Soon after success was first achieved in this way, and the ball ballet had admirably turned itself into streaming effects, the streaming stopped. Acute frustritis ensued. (Frustritis: disease caused by frustration). Then it was noted that the ballroom floor had acquired a metallic, coppery sheen. This was acid-removed, and at once, the show was on again. Thus, freshly coppered shot may put a conductive coating on the floor, and kill the electrospherics.

Cast Iron Shot Sizes Investigated

The Jackson shot samples came in three sizes: Nos. 110 (smallest), 230, and 390. Each sample exhibits a considerable range in diameter. After selecting, plating, and burnishing, shot from each sample were screened, to separate each into a smaller and a larger group. Visual inspection was then resorted to, to pick out those much smaller or much larger than average group size. Six groups were thus secured. Since there is still some size variation within a group, it is perhaps best not to identify these groups with any standard gage system. Therefore, the word "size" is adopted. Size 25, for example, means the average number of balls per inch is 25: a scale was pushed against some of the shot on a flat surface, and those resting against the scale and touching each other, were counted over a known length.

The smallest are Size 50, having an average diameter of 20 mils. Other sizes, in order, are 44, 32, 27, 22, and 20.

All of these do the ball ballet, and all can be made to circulate.

A Cycle of Events

One who opens his own ballroom will soon learn the habits and dancing abilities of his little performers if he repeats several times, the cycle now to be described. We begin by pouring about one gram of Size 50 balls (about 2500 hardboiled troupers) into the ballroom.

Magnetizing: two U-shaped Alnico magnets are seen in Figure 3, right foreground. The ballroom is picked up, and a magnet is brought up under it to touch the bottom. Tapping the poles to the bottom two or three times will magnetically mass the balls as in Figure 4, and magnetize them. The ballroom is put in place, Figure 3, and the field current is about to be increased from zero.

Minor activity: at 2 amperes, a few dozen balls are dancing, but most of the mass is still intact.

Major activity: at 3 amperes, nearly all have gone into action. Only a small mass remains.

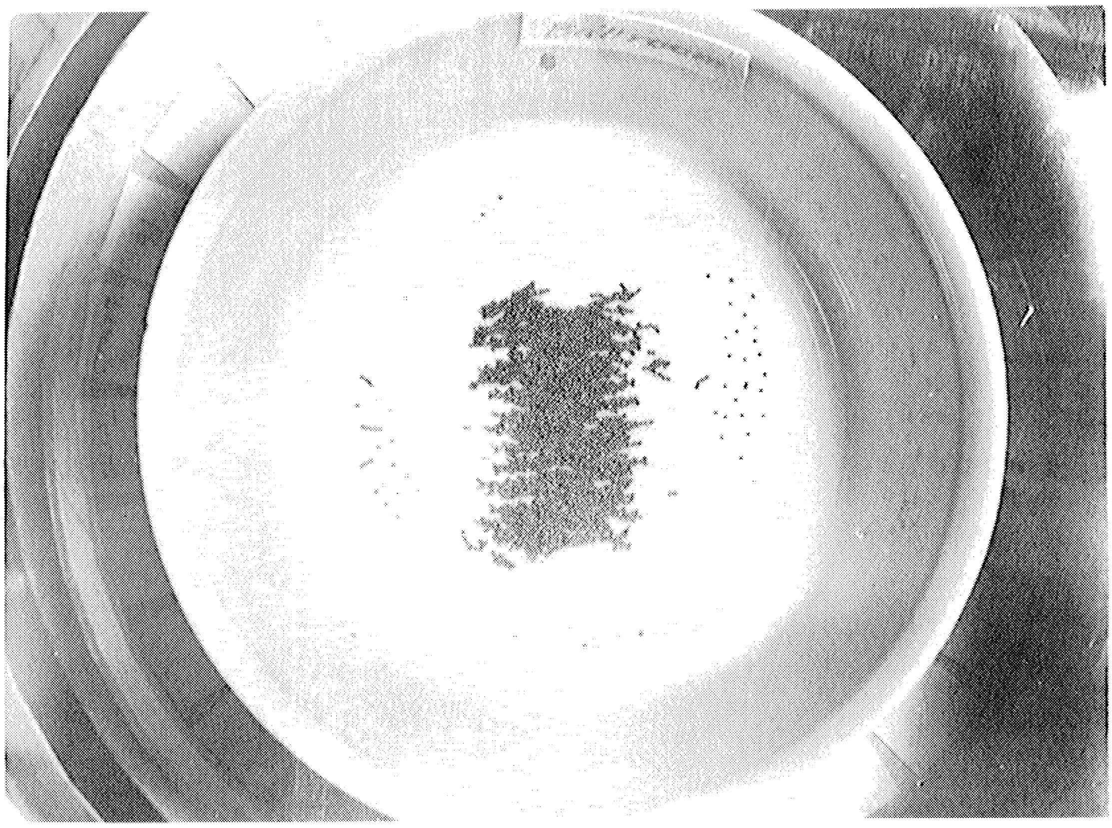

Figure 4. A Mass of Size 50 Balls (Hard Cast Iron Shot) Being Magnetized. The Magnet is Below the Bowl.

The ball ballet: at 4 amperes the ballet is in full swing, and audibly so. There is a constant shuffling sound. The activity will be somewhat as the camera has caught in Figure 5.

Start of trees: at 6 amperes (watch for coil overheating from here on) a few trees have barely started to grow. Nearly all of the balls are still in action, but with reduced path lengths.

Trees: at 9 to 12 amperes, the forest appears, Figure 6. Balls are stacked up in peaked groups, or trees. Many singles are sitting around vibrating (fanning themselves?) but going nowhere. The ballet is over.

Demagnetization: already done. The strong alternating field acting on stationary balls has largely demagnetized most of them.

Magnetizing: starting the cycle over again, as above. The cycle can be repeated endlessly.

Streaming

The Cycle of Events did not include the streaming phenomenon, for there were hardly enough balls of Size 50 present to induce it. We put in more balls, to bring the total to 1.5 or 2 grams. Going up to 4 amperes, we have the ball ballet. If some streaming does not start soon, we back down to about 3 amperes, or just to where a few balls threaten to stop and mass together.

Local streaming, whirls, vortices: streaming starts locally, in terms of distinct local whirls or vortices, each being geared to adjacent vortices. These look so much like their counterparts in a liquid, that the illusion is strong.

Figure 5. The Ball Ballet, in Circulation.

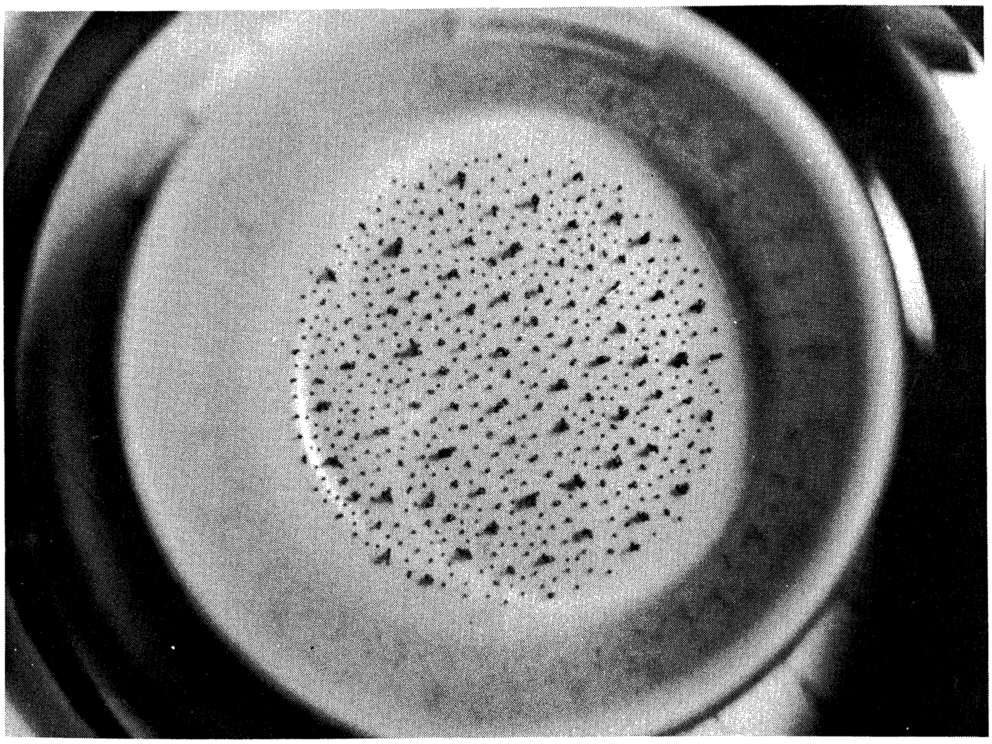

Figure 6. The Forest. Balls Are Stacked Up in Pine Tree Formation, By Stronger Field.

Circling: in anywhere from a few seconds to a much longer time, one of the eddies seems to predominate, and all-the-way-around circling may ensue, as in Figure 5. This can be reversed at will, just by grasping the top of the bowl and sharply twisting it the other way. A complete reversal at once takes place.

Interference: if a thin strip of plastic, perhaps an inch wide, is placed with its end on the ballroom floor to block some of the circular flow, eddies will form in front of it and behind it, and other eddies will appear. Again, one has the illusion that he is playing around with a liquid.

Electrospherics: streaming depends on strong electrification, which holds the balls to the floor, but causes strong mutual repulsion. If, with streaming going on, we breathe into the bowl, the dampness dissipates the charges. All streaming stops, even though the ball ballet continues. It will not resume again until surfaces get dry, and friction again builds up the charges. High humidity will inhibit streaming. When this happens, the bowl can be warmed and dried by holding it close to a light bulb.

Other Shot Sizes: The Ballet and Streaming

It is very interesting to find that irrespective of shot size in the whole range from Size 20 to Size 50, the phenomena in the Cycle of Events are duplicated at much the same field currents. Likewise, streaming and circling occur at much the same currents, or field strengths.

However, this is true: the larger the balls, the less the total weight of balls to get successful circulation. Thus, while four or five thousand of Size 50 are needed to circle the ballroom floor, only about 50 or so will do it in Size 20.

The larger the ball, the more reluctant it is to be self-starting; for with increase in diameter, the moment of inertia rises faster than the torque on the ball. The larger balls may need some help to get started - to break up the magnetized mass. Banging the ballroom bowl on the plate usually suffices.

Circling: Momentum Constant?

The largest shot used, Size 20, when circling, circle so fast that most of them tend to race around the edge of the ballroom. It is therefore excluded from the following suggestion, which pertains to circling as shown in Figure 5, with the balls active pretty uniformly over the whole area. Sizes 22, 27, 32, 44 and 50, are included. For them, very roughly, weight of balls to do a good job of circling seems to vary inversely with ball diameter.

Now, the average speed of a ball should vary directly with the diameter, if it is rolling in a 60-cycle field as a synchronous motor rotor. The total momentum, then, of the circling balls, could be represented by total mass times velocity. If, among different sizes, total mass and velocity vary inversely and directly, respectively, with diameter, it follows that total momentum is constant.

The data at hand are much too rough to serve as proof for this idea; and probably, the untrue cast iron shot would never yield data trustworthy enough to be taken as proof. This research would require true spheres (adequate quantities of ball bearing balls). But the idea is there, and it might turn out to be true and if so, interesting. Any new phenomenon, such as this business of circling, may be found by someone to be a useful analog for something else; and the constant-momentum concept might become a key factor in the relationship.

Chain Reaction

One or two balls may trigger off the whole assembly. This is done with larger balls, such as Size 27. After magnetizing the balls, enough current is used to break up the mass and get all balls into action. The current is then cut off. Many balls are left scattered; some have magnetically chained up with others. The current is then suddenly raised to perhaps 3 amperes. These larger balls are reluctant to start. But one will begin a path; another, influenced by its approach, starts out; the effect builds up, and very soon, all have gone into action. Here again, interesting and possibly useful analogs may be developed.

Very Small Balls

There is apparently no lower limit to ball diameter, for the ball ballet. Industrial Tectonics Inc. of Ann Arbor, kindly contributed a dozen steel balls, accurately ground and highly polished, of 1/64 inch diameter. Their path behavior is, to their scale of size, like that of larger balls.

Drawing Lines

Those three lines of shot seen in Figure 7 came from another accidental discovery. The writer was using the magnetic picker described above, happened to draw it along the floor among the shot, and was astonished to see a line form! Many others to whom this thing has been demonstrated, have been equally intrigued. Since the picker is a magnetized iron wire, the first guess was that this was a new magnetospheric phenomenon. Not so. Non-magnetic wires were tried, and they drew the lines, too.

One way to get good line effects is to carry the ballroom through the Cycle of Events, ending with the forest, and demagnetization. The balls

Figure 7. Electrified Lines, Formed By Drawing a Metal Wire Along the Bottom, Through the Electrified Balls.

have now built up electric charges. When the current is cut off, they will stand around as in Figure 7, mutually repelling each other. Draw a metal wire along the bottom, with light pressure, and the balls form on the line. The lines are extremely durable. Start the cycle over again, start the ball ballet, and erase the lines. Shut off the current, and the lines are still there: the balls reform on the lines. Set the bowl aside until tomorrow, and again, the lines may still be there.

Or again: buy a new plastic bowl, and before it is ever used, draw unseen lines on the floor. Pour in the shot: they show where the lines were drawn. Obviously, then, pressure of the wire has highly electrified the plastic where the wire has touched. Such lines are erasible, simply by using the humid breath from the mouth.

Some things are better "understood" if we do not look too far into them. The trouble here is, that if we repeat this thing often enough, parts of a line, or sometimes the whole line, does just the opposite: it repels shot that are already charged. And as far as the writer's many experiments have gone, this happens both unpredictably, and unaccountably. Someone is needed here, who knows more about plastics and their frictional electricity phenomena, than is known by the writer or any of his laboratory visitors.

Patchy Effects

Sometimes, either in the ball ballet or in the circling demonstration, patchy effects occur. The balls may crowd to an area, or they may avoid an area.

In view of the line-drawing phenomena just described, it can be seen that when balls are poured into the bowl, extra-high electrification of the surface may occur; and unpredictably, it may be of either sign. When bothersome, patchy effects are erased with the moist breath, and we start with a clean slate.

Bacterial Chains, Crystal Growth

Some of the most beautiful and fascinating effects of all these phenomena are indicated by the wiggly loops and chains in Figure 8. Here, we start the ball ballet, then ease off on the field current and see what happens. Differing kinds and degrees of magnetic-attraction chaining up of the balls will occur, depending on how fast the current is reduced. The balls, having like charges, repel each other and tend to stay apart. But as reduced ball activity occurs, balls are rolled to positions where the South pole of a ball may catch onto the North pole of another, and a chain or loop begins to form. The degree of magnetization of the balls also plays a large part in what happens, and in the formations achieved.

Thus we have here a variety of activating causes, one result of which is the formation of some or many chains. It may well be that the viewing of these phenomena as they take place, may, in the minds of experts in various fields, help to demonstrate or even explain, something about viral and bacterial chains, crystal formation, polymerization, and so on.

The most rewarding sight is to view the dynamic situation. After getting the scene into something like that shown in Figure 8, we raise the current just enough to have minor activity. One can see the end of a chain waving back and forth. One can see it lose a ball as a near approach or a collision tears it away. One can see a ball make an approach, tend to link on, and miss. Perhaps next, two balls join the end of the chain. And so on, endlessly, and most fascinating.

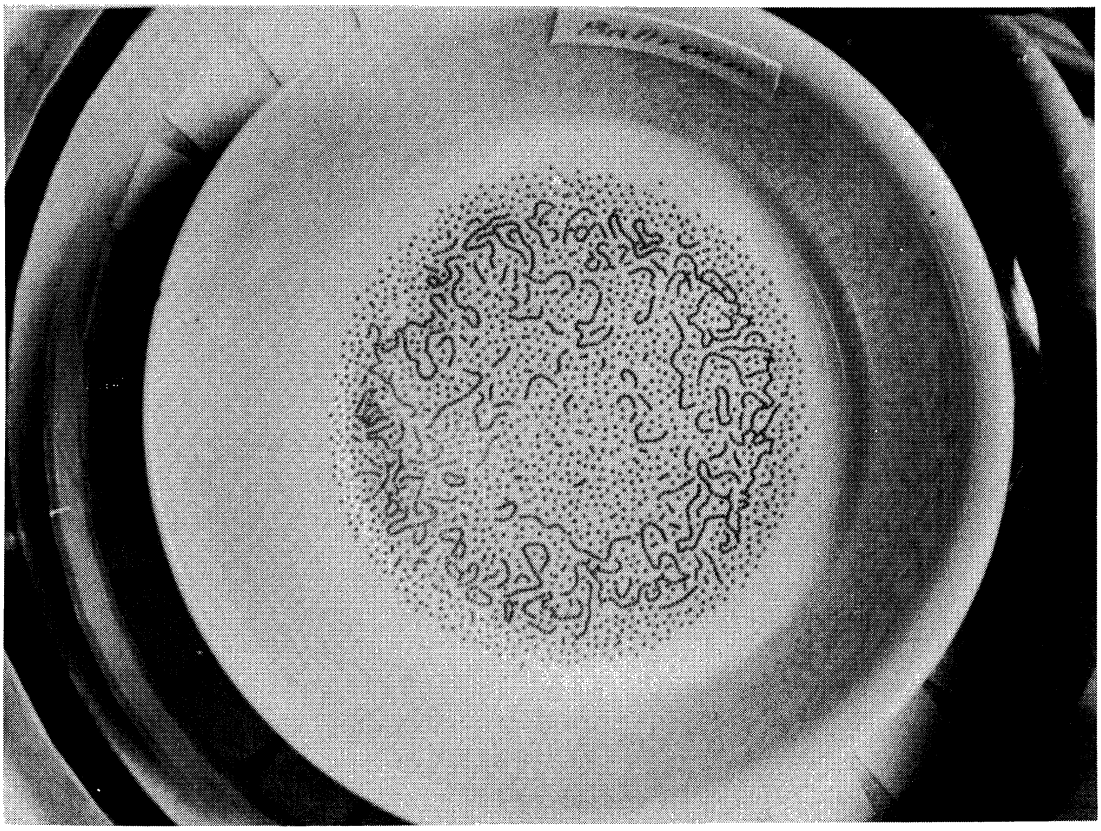

Figure 8. Chaining-Up of Magnetized Balls At Reduced Field Strength.

The Octopus Dance, or Saturday Night at the Beach

This majestic affair is arranged by using a batch of many small balls and adding 25 or 50 much larger balls. At high currents - 10 amperes or more - a dozen or so small balls gather in under a large ball, and hoist it up. The large ball is the head of an octopus, the small balls are the tentacles. Each octopus slowly moves sidewise, as vibration occurs. Anyone in a despondent mood will profit from viewing this comic spectacle.

Brownian Movement

Nearly all of the engineers and scientists who have witnessed the ball ballet have exclaimed, - "Brownian movement!" Actually, since the balls in a particular ballet are all of about the same size and doing about the same things, what they are representing as best they can, is, say, the thermal movement of the molecules in a fluid.

So: we chew up a piece of paper to make pulp, then roll bits of pulp into tiny spitballs, and let the spitballs dry. These can have two or three times the diameter of the balls that will activate them. For easy observation, we use larger balls, such as Size 32, and put only two or three hundred balls into action. The spitballs will be erratically kicked around, and give what is perhaps the simplest visual, large-scale demonstration of the Brownian phenomenon. If the spitballs vary considerably in size (as they no doubt will anyway) the demonstration is all the better for it: the smaller the spitball, the greater the movement displayed.

Underwater Ball Ballet

The ballet performs underwater, but not as actively as in air. The greater resistance offered by water means that fewer balls will go into action. Also, a ball spinning at synchronous speed may be lubricated by the water and slip more on the floor. If so, its linear speed would be less - and this happens. Thus, the paths that smaller balls take, such as Size 50, are much more clearly seen in underwater operation.

Metallic spheres do not like to be wetted. The nuisance is, that when we want them to sink, many prefer to ride around on top of the water. Therefore, the writer typically used a wetting agent in the water, to avoid floaters, and make sure that dry shot that did sink would not carry bubbles down with them. At this point, one more happy accident has to be mentioned. Once, in preparing to demonstrate the underwater ballet, the wetting agent was forgotten.

The nuisance appeared: a monolayer raft of shot floated around on the water. The current was raised, things happened, and another line of discovery was opened up.

MAGNETOSPHERICS AFLOAT

Floating Ball Techniques

The trick for building a shot raft of any size, is to hold the Size 50 balls in a plastic teaspoon. With half an inch or so of water in the ballroom bowl, and a field current of 3 amperes, the spoon is lowered slopingly to near the water surface. The balls are now active. They hop off and float individually, then move to join the others. A raft is thus formed.

The raft rides in its own depression, held up by surface tension.

A major nuisance now develops. Floaters tend to wander to the meniscus at the water's edge where the water bends down due to the unwettability of the plastic, and stay there. The cure is to use a paper collar, cut to form a bowl liner. The water wets the paper, bends upward at the edge, and makes the floaters stay out on the surface where they belong.

Sinking the Raft

A raft of any size will float when there is no field. But when the raft is large (say, half an inch across) the alternating field will sink it, and the process is most interesting. With gradual increase of field current, the raft bulges downward more and more, forming a dry pocket or cavity. Finally, the pocket suddenly pulls down so far that the raft edges meet, a bubble of air is entrapped, and the folded-up raft goes to the bottom, still grasping its bubble.

The Many-Rayed Star

Using unmagnetized or largely demagnetized shot, we make a raft about 0.2 inches across, of something like 150 balls. Since the raft is in a plane normal to the field, the field will cause magnetic repulsion.

As the field is increased, a many-rayed star grows. At lower currents, the center is still solid. At higher and higher currents, the separation increases, until there is a field of individual balls, spaced several diameters apart. Lower the current, and the balls again collect. Here is an expanding and contracting universe that can be put through its beautiful performance any number of times.

Standing Waves

When the star is in a stronger field due to 6 amperes or more, the outer balls especially will display some movement due to vibration. A weak display of standing waves can be observed.

With balls magnetized, there is a far stronger display of standing waves. Using from one to several balls, different patterns of waves can be set up. This phenomenon may deserve consideration as a demonstration of standing wave propagation.

Passive Floater Formations

Using unmagnetized balls, or those very weakly magnetized after demagnetizing at the end of the Cycle of Events, floaters will show some interesting stable formations. On the one hand, a few balls tend to get together, all resting in the same depression of the water surface. On the other, a vertical magnetic field makes them hold each other apart by magnetic repulsion.

Stable formations of the passive type that have been repeatedly observed are shown in Figure 9, (a) to (f). There is the pair (a); the trio (b) has the equilateral triangle formation. For the foursome (c) the square is unstable, and we invariably get the diamond. Five balls (d) might be expected to have four in a square, with the fifth centered, but the balls will have none of it: they take the 2:3 formation shown. With six or seven balls, (e) and (f), symmetry returns: the pentagon or hexagon, with ball at center. This is not the end of it, of course. With balls selected for size equality, one could certainly get a regular hex-formation of the 1:6:12 combination: a center ball, and two shells. And so on.

Active Floater Formations

Here, we get some truly fantastic behavior, and those with plenty to do had better stay away from this show. It is done with magnetized balls. There are limits: with balls too strongly or too weakly magnetized, best results are not achieved.

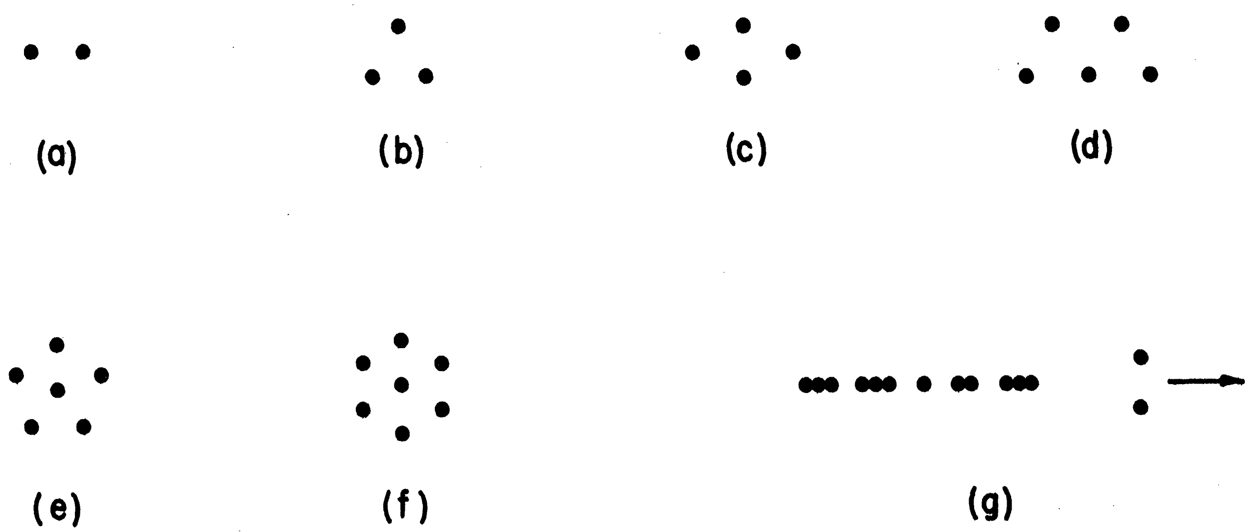

Figure 9. Floating Ball Formations. (a..f), Unmagnetized Balls in Passive Stable Formations. (g), Magnetized Balls, Active Formation Moving to the Right.

First, we recognize that there will be chaining. Two or more balls will tend to chain up, the North pole of one held to the South pole of the next. Second, such balls are vibrating, but not spinning. If they spun as synchronous motor rotors, they would become wet and sink. But with magnetic axes horizontal, the vertical alternating field is bound to make them vibrate, or oscillate. Thus, strong standing waves are set up, and there will be interaction between the balls and the fluid.

There is endless variety to the dynamic performance, and it is very difficult to describe it in detail. For example, half a dozen balls may aggregate, and rapidly whirl (rotate) in a fixed position. Chains near each other may remain stationary for some time, and then begin gyrating, or moving away together, or lining up with gaps between. When chains and singles get into rapid action, with ever-changing patterns and formations, it is difficult not to believe that here are living things, cavorting on the surface.

When degree of magnetization and field strength are just right, the most amazing performance will happen: an "organism" will form, and swim around. These "things" commonly have a backbone of several short chains, lined up but with gaps between, and with from one to many outriders - the whole organism busily swimming around here and there at a rapid pace.

The most stable active organism so far observed is shown in Figure 9 (f). Almost straight, it swam around the coils' magnetic axis at roughly an inch radius, in a rough circle, for minutes on end. The arrow shows the direction. This, by the way, was done in a water pool several inches across, where there was plenty of room to maneuver. These things have to be seen to be believed.

Swimming organisms may be more successful if both weaker and stronger balls are used. In magnetizing the shot (Figure 4) the Alnico magnet can be brought gently up to the bottom of the bowl, once or twice, to magnetize the balls weakly; and some of these are now poured onto the water. Then the magnet will strongly magnetize the remaining shot, if brought up several times, and made to tap the bowl. With some of these added, they chain up to form the backbone of the organism, and the weaker ones become the outriders.

Vibration-Induced Movement

These movements of active floaters are not - be it noted again - in any degree due to rotation. Vibration, or oscillation of balls is the only primary motivating principle. The balls affect each other; they interact with the water surface and produce forces; and no doubt, the standing waves react on the balls in some manner.

At any rate, and in ways unexplained at this time, vibration or oscillation leads to propulsion.

MAGNETOSPHERICS AT THE RACETRACK

One-Coil Racetrack

From watching the ball ballet, where balls seemed to be doing their best to run along as synchronous motor rotors, the idea came that if a magnetized ball bearing ball were given a smooth track and a proper driving field, it would perform smoothly. It did.

The first experimental coil was much like the upper coil of Figure 3. It rested on a glass plate, and with a zinc ribbon liner fitted inside of it to give the ball a smooth wall to roll against. A ball was magnetized, put on the track, started with a flip of the finger, and there it went.

But there were troubles. The operating range of alternating current for successful performance was very narrow. At not much increase over minimum current, the ball became erratic, or would even climb the wall somewhat. The climbing tendency was due to the fact that a magnetic body tends to move to where the field is stronger; and next to the wall, the field of the single coil is stronger at its center plane than further down. Also, it seemed that for best operation, the field through the ball should be inclined at 45 degrees. All this experience called for a re-design.

Two-Coil Track

The two-coil design adopted is that already described, and shown throughout this paper. It was originated for racetrack purposes; and then, nicely enough, it was found to be completely adapted to producing a good field for the ball ballet and related phenomena. For the ball ballet, the coils are spaced widely apart, and are additive. For the racetrack, they are brought together closely as in Figure 10, and made to buck each other along the common axis.

The racetrack coils are, however, additive where the ball is, and an exploration showed that the field direction there is at about 45 degrees to horizontal. Also, the wall-climbing tendency is eliminated.

The Wall

Good performance calls for a smooth wall. This problem was finally solved by making a double-band collar of zinc ribbon (also called

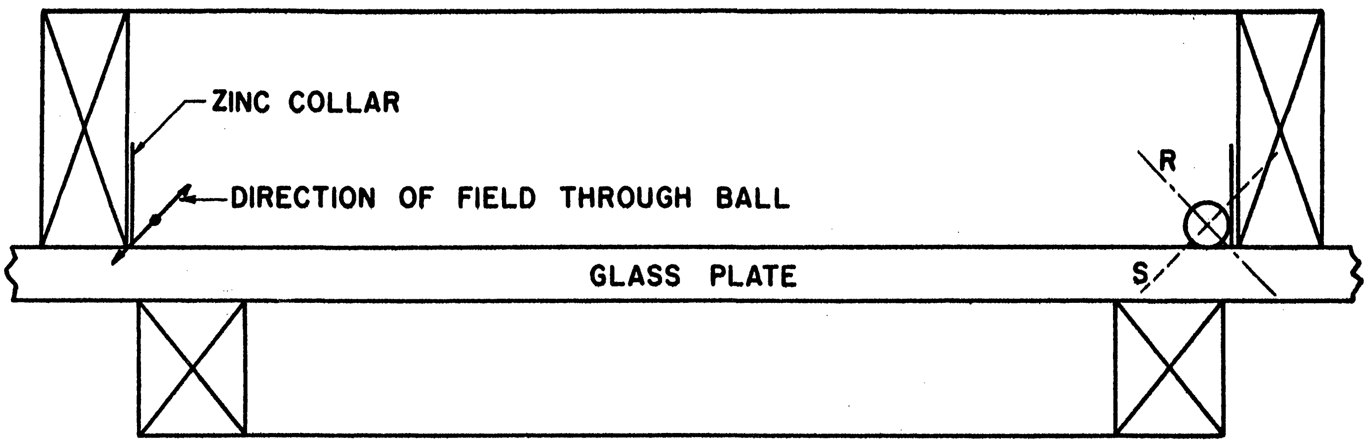

Figure 10. The Racetrack.

zinc tape). This material is half an inch wide, and 0.016 inches thick. The bands have butt joints, with the joints coming at opposite ends of a diameter. There is a strip of paper between, this first being painted with Glyptal varnish to make the bands stick together. The outer band's joint is covered with adhesive tape. The collar is shown inside the upper coil, Figure 11.

Eddy currents induced in this metallic collar appear to have no appreciable effect on racetrack performance.

Copper ribbon can be used, but it is more difficult to make it truly circular, without bumps at the joints.

Balls, and Ball Magnetization

The first balls to enjoy a spin around the track were 1/8 inch ball bearing balls with no pedigrees, bought at a bicycle shop.

These were replaced by steel balls, Commercial A grade, 1/8 inch, kindly supplied by the Hoover Ball & Bearing Co., Ann Arbor. They were magnetized by using the two Alnico magnets shown at the right in Figure 11. One magnet was held in a vise, with the other clinging to it. To magnetize a ball, the upper magnet was tilted to open a gap, a ball was placed in the gap, and the magnet was allowed to close on the ball. Stronger alternating fields of the racetrack sometimes weaken these steel balls' magnetization, and then they must be remagnetized.

Why a Ball Operates

Imagine a perfect ball in a vacuum, placed on a horizontal plane. The ball is magnetized. Its field is much like the earth's field, as is easily determined by use of iron filings. It has a magnetic axis. The axis is now randomly oriented in any direction with respect to the plane.

Figure 11. The Racetrack, with Four Balls Placed on the Track.

Next, let a uniform vertical sine-wave alternating magnetic field be set up, reaching to infinity in all directions. If the magnetic axis has any direction except vertical, there will be a varying torque produced, which has a net value greater than zero. The ball will start to accelerate, rolling on the intersection of a vertical plane with the horizontal plane. This vertical plane contains the line of the magnetic axis. If losses are negligible, it would continue to accelerate until it is spinning at synchronous speed and is producing zero torque. In the final state, the magnetic axis would be vertical when the field strength goes through maximum.

If now, friction and windage losses are made appreciable as in a real situation, and we start over again, acceleration occurs, the ball again attains synchronous speed, but with the magnetic axis lagging enough behind its above positions, to enable the ball to produce torque enough to drive itself along. These matters are best thought of, if we replace the ball's actual field with the field of an appropriate magnetic dipole embedded within a sphere made of nonmagnetic material.

We just said that acceleration to synchronism would occur, even with losses present. But this can depend on size. As we consider larger and larger balls, analysis shows that the moment of inertia rises faster than net torque at standstill, for given values of field strength and ball magnetization. In practice, then, balls too large will, at a given frequency, not accelerate: they sit still and vibrate. The frequency should be lowered, to get them into action.

Steel balls of sizes 1/8 to 3/8 inches inclusive are not self-starting on the writer's racetrack, but they all can be made to run if given a start, at 60 cycles. The writer has never been able to make a half-inch ball run at 60 cycles.

The first person to get a 1/2 inch ball into action was D. J. Provine, one of the writer's students, who had the misfortune of becoming so deeply interested in these new things, that he spent the entire week of his spring vacation on them. With his own track, and using an audio oscillator he had already built, he made half-inch balls operate in the 10-to-40 cycle range of frequencies.

Torque Produced

Again think of a magnetized ball rolling on a horizontal plane, driven by a uniform vertical alternating field. Again, let the ball's field be considered as due to an embedded dipole. The instantaneous torque will vary. Average torque for a revolution will be maximum, if the dipole axis is horizontal when the field is maximum. The torque argument that follows is for the maximum average torque condition.

It will be obvious that the forces on the poles of the dipole will be proportional to field strength times pole strength, and that torque will be proportional to force times lever arm. Since the magnetic moment of a dipole is the product of pole strength times pole separation, the foregoing statement can be recast in these terms: maximum average torque of a ball is proportional to field strength times magnetic moment. This is a general statement, true irrespective of the size of the ball.

How the Ball Runs the Course

Referring to Figure 10, think of what happens if there is no field on, and the ball is simply started with a flip of the finger. In rolling around several times, its spin axis S, would have to be inclined as shown. The ball makes contact at two points, with floor and wall. The two contact circles would have to have equal diameters, if there is friction at both surfaces, and if we consider track radius to be large compared with ball radius. Otherwise, there would be slip at one or the other of the contacts, or both. Thus the spin axis would be inclined at 45 degrees.

Now let the driving field be turned on. If the ball is placed in at random and started up, the magnetic axis at first will have any orientation whatever. But if the ball "catches on" and runs, there is a strong presumption (not yet rigorously proved) that soon, the magnetic axis R will be as shown in Figure 10, turning in a plane normal to the spin axis S.

If so, the linear speed of the ball center around the track is easily computed, in terms of synchronous rpm of the ball, and diameter of the contact circles. Actual tests of 1/8 inch balls check the prediction to within 2 per cent or better. This is strong verification for the above presumption.

The ball will, of course, run equally well either way around the racetrack. Together with the coils, it constitutes a synchronous motor, and it might lay claim to being the world's simplest synchronous motor.

The Operating Range

Five Commercial A 1/8 inch balls were tested to determine the coil current range within which normal track behavior takes place. The minimum current, below which the ball would stop, averaged 0.33 amperes (highest and lowest values being 0.44 and 0.25). The maximum current, above which erratic behavior sets in, averaged 18.4 amperes (highest and lowest being 20 and 17). The operating range was then between 0.33 and 18.4 amperes. The range ratio was 18.4/0.33, or 56.

More Balls on the Track, and the Space-Apart Phenomenon

It takes more than one horse to make a race. Likewise...! When a dozen or 15 balls are endlessly thundering around the track, they give an impression of honest effort seldom witnessed elsewhere.

One way to get two balls into action is to start one ball, place the second on the track, and let the first running ball kick it ahead. It will not kick it ahead until coil current is brought up to about 2.5 amperes. It is interesting to note that this is 7.5 times the minimum current, and that the square root of 56 (the range ratio) is also 7.5. The meaning of this is certainly obscure.

With two balls in action, they will kick a third ahead, and so on. Thus the running parade can be started.

Another way to start the parade is to pour in a lot of balls, turn on a favorable current, sweep most of the mass ahead with the finger, and have them all go into action at once.

When a mass start is made, almost any spacings may occur at first. But soon, slipping occurs. Groups of balls will begin to close up their spacings; or, all of them may begin to close up the formation. It will seem that they are bound to run closer and closer until they rub, and perhaps stop the race. But then, a new thing enters in. When they get to be two or three diameters apart (see the four balls on the track, Figure 11) they cease the approach, and run thus, spaced apart. Were it not for this space-out phenomenon, we could not have a continued race. What is its explanation?

Explanation of the Spaced Race

First, the tendency of two or more balls to approach must be taken up. These balls are all synchronized with the field, and with each other. Any two balls running close together have their magnetic axes parallel at all times. If we replace a ball's field with dipoles, and analyze the varying forces between two rotating, synchronized dipoles, we find that the force between them varies through plus and minus values, but that there is a net force of attraction taken over the whole cycle. Hence, two balls, near each other, will tend to slip and come closer together.

Since they do not come together, some other force must hold them apart. And this, of course, is magnetic repulsion. It is easily demonstrated. If two unmagnetized steel balls are placed together on the track, they will move apart when the coil current is turned on. Or, if two magnetized balls are placed on the track and allowed to stick together, turning on a sufficient current will make them come apart and separate.

The running balls, then, if too far apart, will draw together until a balance is reached between the attraction and the repulsion force. If too close together, they will separate to that same spacing.

It was magnetic repulsion, as witnessed at the racetrack, that furnished the stimulus to dream up the ball crystals later to be described.

The Steeplechase

Cut out a square of paper, an inch or so each way. Trim one edge rounded, to fit the wall of the racetrack. Place it on the floor, slide it over to the wall, and let the racing balls run over it. Then, with thumb and finger, press down on the ends, and slide them a little towards each other to bulge the center upward about a quarter of an inch. The balls will take the hurdle, and add to the merriment.

Inclined Racetrack

These balls willingly climb a slope, as demonstrated when the entire track assembly is tilted. When tilted until a ball can barely make it on the upgrade, it is obvious that the ball continues to spin synchronously, but slips and decelerates. The winning hill-climber was not defeated until a tilt of 16 degrees was reached.

Measurement of Magnetic Moment of a Sphere

If there is now no convenient way for measuring the magnetic moment of a sphere, a modified racetrack might offer a method. There would be a smoothly accurate track of large diameter, with the V-groove opening upward. Drive coils would be designed to give a uniform vertical field. Resistance to the ball's movement would be almost all due to air resistance, which can be found by experimentation. In fact, the writer has already experimented with balls rolling down an inclined groove under water. A very good dimensionless correlation between Drag Coefficient and Reynolds Number was obtained for considerable ranges of ball diameter and track inclination.

In measuring magnetic moment, the minimum current that would just barely keep the ball going at full track speed would always be determined. The ball then would always be so synchronized that its magnetic axis is horizontal when field strength is maximum. For larger balls, lower frequencies could be used. By using the above correlation curve together with the known properties of air, ball velocity and cross sectional area, the drag would become known. Thus the torque would be determined, and from this and the known field strength, magnetic moment could be computed.

Ball Force Measured

Only two direct measurements have been made. A 1/4 inch Alnico ball, magnetized, was placed on the writer's racetrack. It had a minimum operating current of 0.5 amperes. It was allowed to run against the end of a Mylar strip, deflect it, and continue to deflect it by standing there pushing against the Mylar while spinning at synchronous speed. The strip deflections were later reproduced by weights.

At coil current of 3.5 amperes, the force was about 150 milligrams; at 7 amperes, about 300 milligrams.

Erratic Behavior

When coil current is raised above the top of the operating range, a ball's behavior becomes erratic. It may run "steady by jerks", but continue going the same way. It may occasionally reverse, or even cut across the floor.

Oscillation

As coil current is gradually increased above the operating range, erratic behavior sets in. With further increase, erratic behavior usually continues; but occasionally, the ball begins to oscillate. Time and again, oscillation was observed, but at first, it could never be induced at will.

Eventually, reliable oscillations were produced. First, the glass plate between coils is removed, and replaced by a much thinner plate of plastic or aluminum. An aluminum plate .05 inches thick works very well. Second, a 1/4 inch Alnico ball is used, with coil current of from

3 to 10 amperes. The ball smoothly oscillates back and forth along the track, over a space range of one to 6 inches.

The factors involved are highly speculative. The shape of the field through the ball is such that the field pulls the ball into the groove; and the greater the field strength, the greater the pull. High contact forces may mean high friction forces. In some complex way, these forces may, coupled with the ball's spin, bring in gyroscopic effect, and cause the spin axis to precess. Thus, as the ball reaches the middle of its travel, the ball may begin to turn over, with friction at contacts putting on the brakes to bring it to a standstill; whereupon, it reverses its travel, and goes through the whole thing again in the other half of the oscillating range.

It is to be hoped that someone will approach this problem with adequate experimental techniques and theoretical analysis. It might be that this phenomenon could serve as a rough analog for some other situation - such as magnetic resonance?

Alnico Balls on the Racetrack

It was predicted that Alnico balls, much more strongly magnetized than the steel balls, should run the track at much lower coil currents. Industrial Tectonics, Inc., of Ann Arbor, kindly made up and supplied two special samples of Alnico balls, 1/8 and 1/4 inches in size. They came already magnetized.

The first trial of a ball was made with high anticipation, but the ungrateful little thing responded with dismal failure: nothing but erratic behavior. Then it was realized that the current used was too high. Alnico balls have their own operating range.

Tests on 7 balls, 1/8 inch, gave an average minimum operating current of 0.03 amperes, an average maximum of 1.8 amperes. The operating range ratio is 60, average value. It is rewarding to find how closely this compares with the operating range ratio of 56, for the steel balls - even though the currents are far different.

Comparing maximum currents, 1.8 for Alnico and 18.4 for steel, the ratio here is about 10:1. It is a good presumption that the magnetic moment for these Alnico balls was about 10 times that of the steel balls.

The larger the ball, the narrower its operating range, at 60 cycles. Five 1/4 inch Alnico balls averaged 0.54 and 1.2 amperes for minimum and maximum currents, the ratio being only 2.2. Three steel balls of the same size gave about 4 amperes minimum, 20 maximum, and an operating range ratio of 5.

The 1/8 inch Alnico balls can be made to run the course, two or more, spaced apart, at currents high in the operating range. But in the low part of the range, magnetic attraction predominates over the repulsion coming from a weak field, and the balls will bump each other, and go into a state of confusion.

Subnormal Track Speeds

Steel balls run the track in normal fashion, or else become erratic at currents above the operating range. But on a very few occasions, above the range, balls were found going for a little while, at subnormal track speeds. At first, the guess was made that the ball had chosen to spin at a submultiple of synchronous rpm. And this still might happen at times. Many efforts to induce subnormal speeds ended in failure, until a 1/4 inch Alnico ball was tried, together with an aluminum sheet

(.05 inches thick) for a floor and coil separator, used in place of the glass plate.

This ball had a normal track speed of 114 rpm, at coil current of 0.5 amperes. At higher currents, it consented to run at subnormal speeds instead of oscillating. The data will be given in pairs, the first figure being current; and the second, rpm around the track: 2.5, 24.9; 3.0, 40.6; 3.15, 43.8; 3.7, 57.5; 4.4, 65.0. Normally, one would present the data in tabular form, and also plotted. The curve is indeed fairly smooth. One hesitates to dignify the data with such treatment, because: at 1 ampere, the track rpm jumped to 86!

This thing is full of unknowns. The writer certainly believes that the ball continued to spin synchronously. If so, then something happened to shift the spin axis away from normal, and permit a smaller contact circle to give the traction, while the other contact slipped freely. That is merely a spectulation. The only facts are in the data given. Further investigation is needed.

Pandemonium

If one or two dozen of 1/8 inch Alnico balls are placed in the track, and a current of 3 or more amperes (above the operating range) is used, pandemonium ensues. The balls frantically run in all directions, bump each other and rebound, and do all sorts of wild things.

Climbing the Prison Wall

This piece of drama was discovered quite by accident. Using only the upper coil, 150 or so of 1/8 inch steel balls, unmagnetized, are poured onto the floor of the racetrack. They are prisoners, aimlessly standing around in the prison yard. But they await only the "signal", to make a break for liberty. The signal: very suddenly turn on a high current, 10 or 15 amperes. There is a mad stampede for the wall. Faster than the eye can see, the prisoners stack up, as in Figure 12. Suddenly cut off the current. Equally dramatically, the prisoners fall down, run out into the open, and collide all over the place with much noise. The prison break can be repeated time and again, but no one ever escapes.

MAGNETOSPHERICS: CRYSTALS

Dendritic Crystals

The little "trees" described in the Cycle Events and seen in Figure 6 are shaped like pine trees. Branching or tree-like crystals are called dendritic. The sparse young forest growth of Figure 6 can be turned into a thick forest, Figure 13, by pouring a quantity of cast iron shot into the ballroom bowl while the bowl is sitting on the plate, and with the coils arranged and connected as for the ball ballet.

When hard shot are slowly poured into the bowl with about 8 amperes flowing, a beautiful spectacle develops. The growing mass of shot takes on, and maintains, a rounded mound shape, being covered densely with little pine trees which move - they all march slowly outward as the shot is poured. At around 14 amperes, the trees are much higher and slimmer, as seen in Figure 13.

Very long, needle-like dendritic formations occur when the shot are allowed to grow in a more nearly rectilinear field. When a hollow solenoid is used, about 4 inches long and about 2 inches in diameter, and placed upright, great long strings of crystals can be formed.

The same general effects occur at lower currents when malleabilized cast iron shot is used.

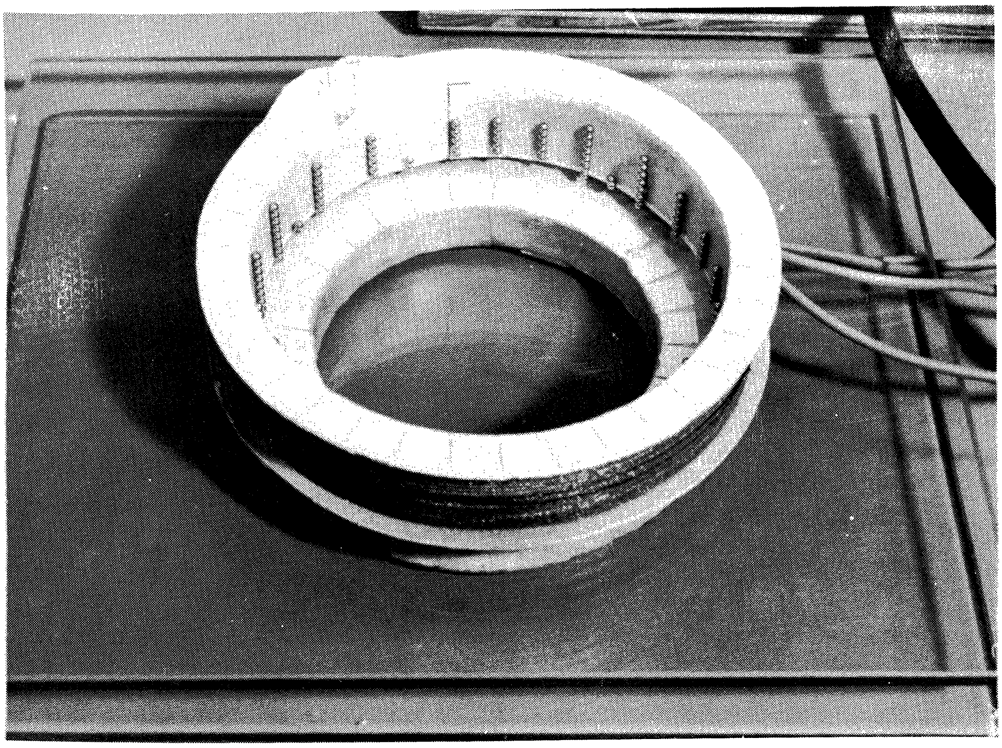

Figure 12. Balls Stacked Up the Wall By Strong Field of Upper Coil Only.

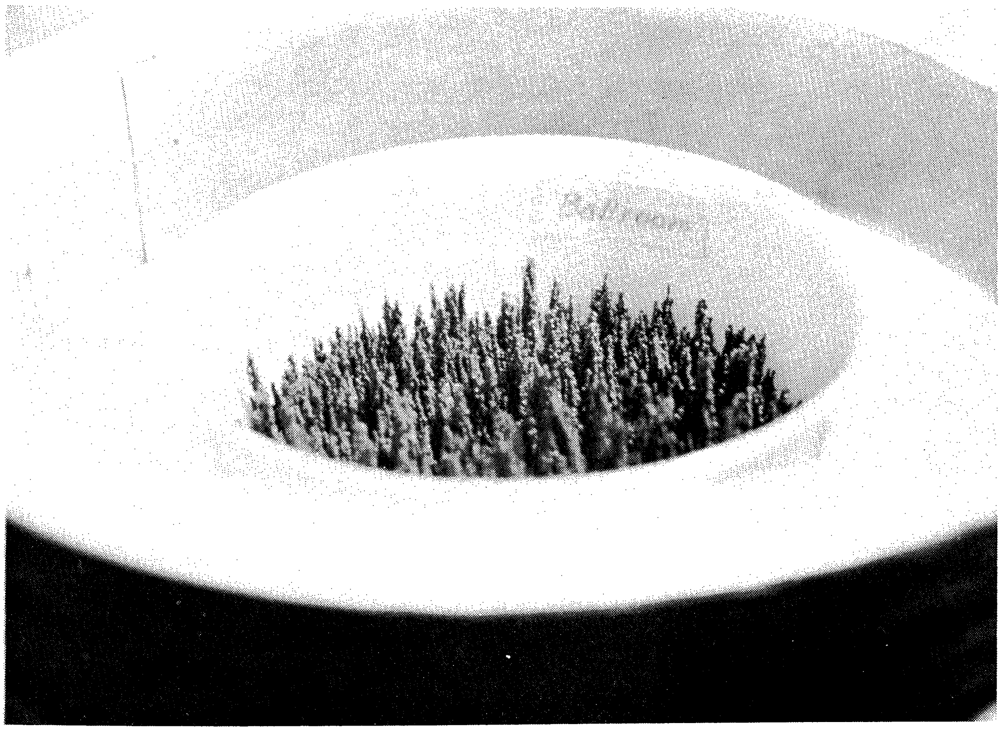

Figure 13. Dendritic Crystal Formation of Cast Iron Shot in an Alternating Magnetic Field.

Ball Crystals

Spheres of equal size that are allowed to form a monolayer of closest packing, will assume the hexagonal formation. Earlier experience with magnetospherics, in which magnetic repulsion made the balls space away from each other, brought on the idea that if proper boundaries were furnished, repulsion might make a set number of balls space themselves apart and take hexagonal form. This application of magnetospherics came through with spectacular success. In Figure 14, 61 steel balls, 1/8 inch, unmagnetized, have formed a "ball crystal". There are four shells around the center ball. The count, starting with the center, is 1:6:12:18:24.

The complete set-up is shown in Figure 3, where pieces of rubber sheet with notched hexagonal opening are seen at the left. The ballroom bowl is shown there in the coil assembly. Remove this, place the rubber boundary piece at center on the plate, pour in the 61 balls, and suddenly turn on about 10 amperes. No matter where the balls may have been, they rush to positions, and form the crystal.

A larger crystal was, of course, an imperative, and Figure 15 shows a ball crystal of 7 shells, 169 balls. Turning on about 15 amperes will form this crystal. Even if all notches are emptied, and the balls are deliberately massed anywhere at will with current off, the onset of the alternating field gives them the repulsive forces that promptly result in the orderly array. Of all these magnetospherics phenomena, the ball crystal is perhaps the most arresting.

If the inner edges of the rubber boundary are left smooth, repulsion forces will crowd an excess number of balls into the outer shell. Hence the need for notching.

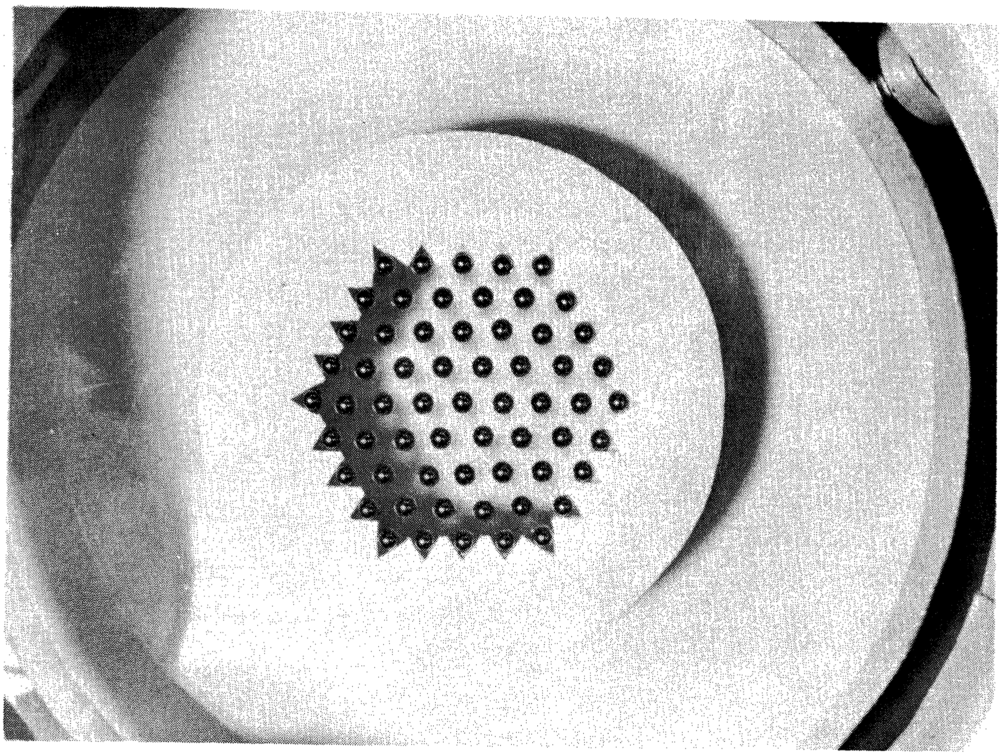

Figure 14. A 4-Shell Ball Crystal of 61 Balls.

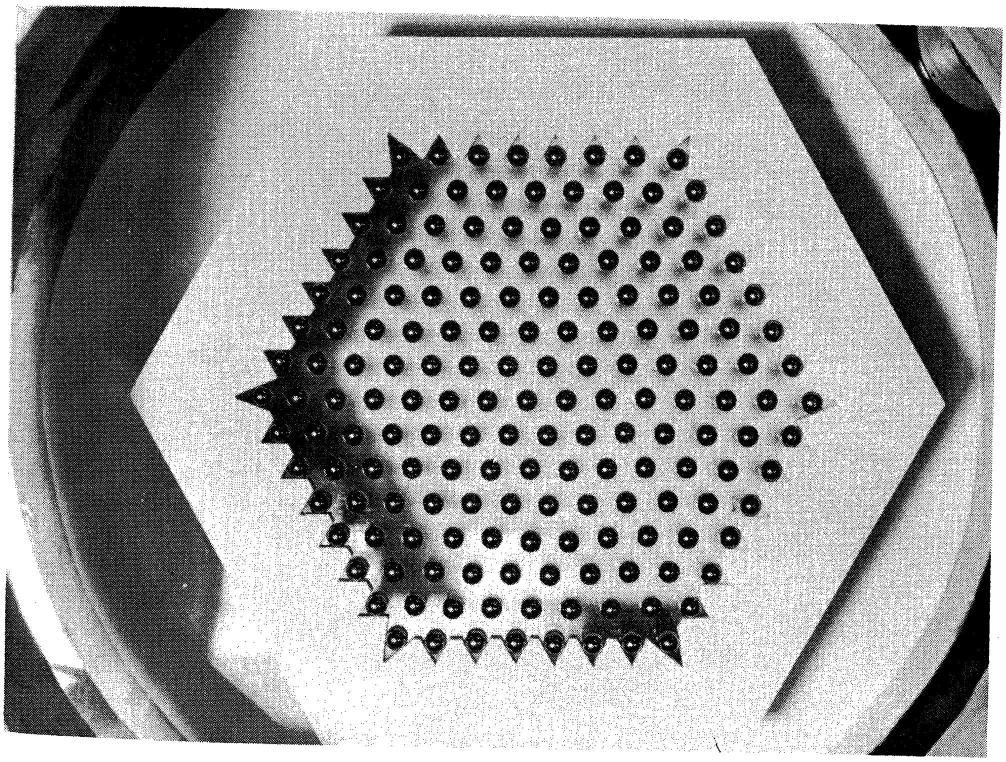

Figure 15. A 7-Shell Ball Crystal of 169 Balls.

Ball Crystal Defects

Let a ball crystal be formed, and held by maintaining the field. If a ball is picked out, there will be local readjustments where the defect appears, but the major pattern elsewhere is retained, or one or more balls may be added. There will be defects, but the hexagonal pattern does a brave job of forming where it can.

Grain Boundaries Shown in Ball Crystals

Grain boundary phenomena are of major interest nowadays, and something of their nature may be seen in terms of ball crystals. In Figure 16, the lower three sides of the opening belong to one hexagon, while the upper two sides belong to a differently-oriented hexagon. A lot of balls were poured in, and the results are as might be expected. The two crystals growing out from the two different boundaries disagree, come to a compromise, and show defects and grain boundaries.

These ball crystals need further investigation. Using notched sides, smaller balls, and many more of them, the grain boundaries might show up much more clearly. New light might be cast on actual crystal phenomena.

Waves and Eddies in Ball Crystals

Consider the ball crystal in Figure 15. There are elastic forces between balls, and the balls have mass. Therefore, wave phenomena should be capable of demonstration.

If a pencil is used to give the rubber boundary a sudden short push sidewise, a wave travels across the crystal, and is reflected from the other side.

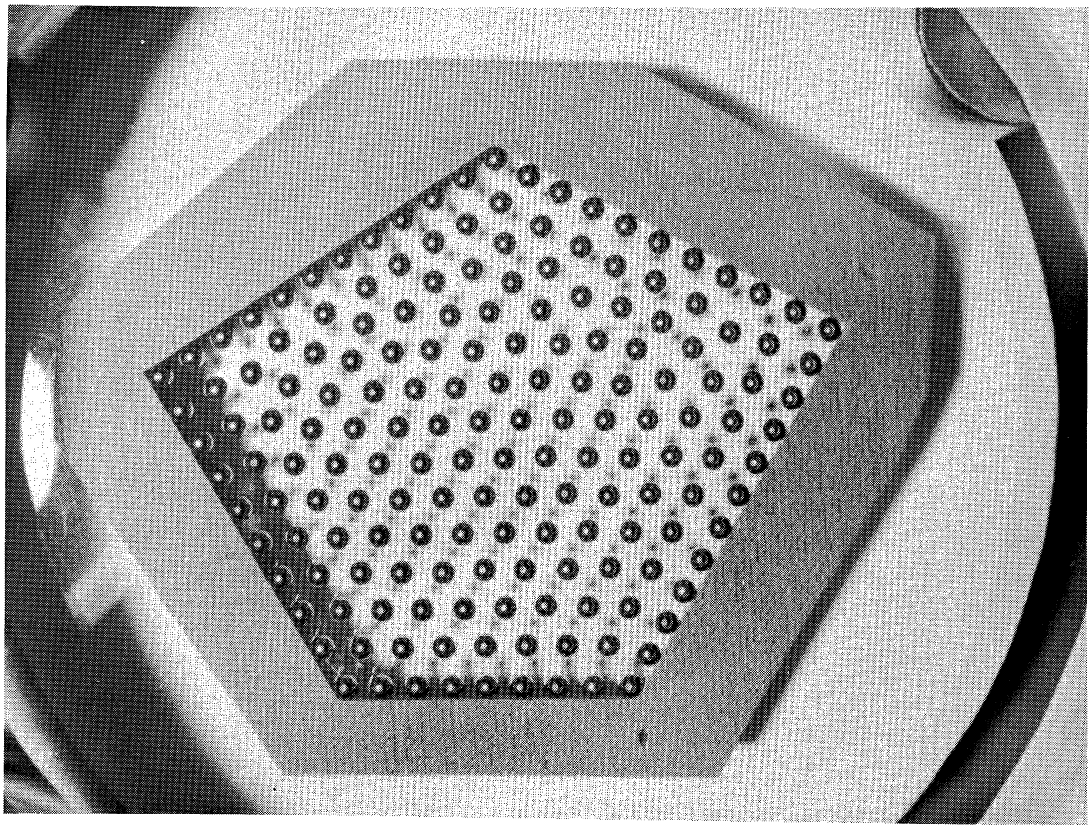

Figure 16. Grain Boundary Phenomena. With Parts of Mismatched Hexagons for Boundaries, Two Crystals Attempt to Grow, and Have to Reach a Compromise.

Moreover, a striking effect comes of stirring the balls with a paddle. The balls flow around the paddle, and form eddies behind it. The effect is so convincing that it is difficult not to think that one is stirring a liquid.

CONCLUSIONS

Electrospherics

1. Several static and dynamic electrospheric phenomena have been discovered and described, in which metallic spheres, electrified by rolling contact with a dielectric surface, are attracted by the surface but are mutually repellant. The several behaviors are interesting in their own right; and some may at least roughly serve as visual demonstrations of other phenomena such as crystal formation, electrons attempting to leave a cathode, molecular movement, Brownian movement, and so on.

Magnetospherics

2. The simple equipment for demonstrating magnetospheric phenomena has been described.

3. In the ball ballet, anywhere from one to thousands of tiny magnetized balls in a plastic bowl are made to dance, under the influence of an alternating magnetic field.

4. The ball ballet, with the aid of electrospherics, becomes an eddying, streaming, or circulating phenomenon, with properties simulating those of a liquid.

5. The balls are shown to be acting as synchronous motor rotors.

6. At low field strengths, the ball ballet is turned into various chained-up configurations in which one might seem to see bacterial chaining, and growth and tearing down of crystals.

7. At high field strengths the balls form dendritic "crystals".

8. The ball ballet can take place under water.

9. Techniques have been worked out for floating unmagnetized and magnetized balls on water, in static and dynamic formations. Standing waves appear. Formations of balls, some in contact and some not, can swim around under their own power. The mobility of these "organisms" derives entirely from vibration, not from ball rotation.

10. From one to many steel or Alnico balls will run a circular racetrack; and a ball on the track can be made to oscillate.

11. The racetrack, properly modified, might be turned into a simple method for measuring the magnetic moment of a magnetized sphere.

12. Large numbers of balls in any chaotic array can be snapped into the perfectly ordered form of the hexagonal ball crystal, merely by turning on the field. The ball crystal seems to offer possibilities for studying crystal defects and grain boundary phenomena.

13. Undoubtedly, still other electrospheric and magnetospheric phenomena remain to be discovered and devised. Those discovered so far are endlessly fascinating. Some are readily understood. Others will require much effort before they are fully explained.