V. CATHODE SPARKING

At normal operating temperatures the electron emission from oxide cathodes is frequently limited only by the phenomena of sparking. Although a small physical loss of coating accompanies each spark, this process is generally not injurious to the cathode emission. Many cathodes appear to spark under space-charge-limited conditions,[20] although a slight deviation from the true space-charge line due to a small interface and coating voltage may be undetected in these measurements. When the tube is operated in the region of sparking, measurements of V_{ic} should yield information regarding the effect of the interface on this phenomena particularly when the coating voltage is negligible.

A comparison of points 1, 5, and 9 of Fig. 15 shows that sparking does not occur at a fixed value of V_{ic} as the temperature is changed. Figure 5b and Fig. 7 show variation of the sparking point at several temperatures and is a general characteristic of all Ba_2SiO_4 interface cathodes. If it is assumed that the voltage deviation from the theoretical space-charge line represents only V_{ic}, i.e., space-charge limited operation, a correlation between sparking and the i^2R dissipation in the interface and coating is possible. The dash curve of Fig. 7a represents the products $iV_{ic}=900$ watts/cm^2 and offers good agreement with the variation of the sparking points. A similar treatment of the sparking points for this cathode, Fig. 7b, shows best agreement with $iV_{ic}=4800$ watts/cm^2. The three sparking points in Fig. 15 cover too small a temperature range to justify curve fitting; however, a computation of iV_{ic} yields values between 2200 and 4200 watts/cm^2.

This correlation would seem to favor a sparking mechanism based on heat energy dissipation within the cathode. Since most of the cathode resistivity is located in the interface region of thickness 10^{-3} cm, a considerable local temperature rise is expected. The above correlation (in Fig. 7) is based on the assumption that deviations from the space-charge line represent only values of V_{ic}. Points 9, 10, and 11, Fig. 15c, show that this assumption may lead to erroneous conclusions. Similarly, the agreement in Fig. 7a between the sparking point at 840°K and the dashed curve is doubtless fortuitous since this implies a 7.8 kv value for V_{ic}.

Wright[7] has assumed that the potential drop in the emitting oxide cathode occurs at the interface and has estimated the interface thickness to be such that at sparking a voltage gradient of 10^6 volts/cm exists in this region. An assumed interface thickness of 5×10^{-4} cm and the observed value of V_{ic} permit a check on this estimate. Point 9, Fig. 15c, near sparking, would lead to a value of 6×10^5 volts/cm. In other measurements, values of V_{ic} up to 850 volts have been observed, leading to gradients of 1.2×10^6 volts/cm. In view of the probable existence of thin spots in the interface layer through which the voltage gradient is in excess of these average values, the fundamental mechanism of sparking may be a simple dielectric breakdown.[29] Sufficient information is not available at the present to decide between these two possible mechanisms. The presence of a definite interface compound of low conductivity is certainly responsible for sparking and accounts for the difference in sparking currents observed in Fig. 5a, b.

ACKNOWLEDGMENT

The author expresses his appreciation to the Frank B. Jewett Fellowship Committee and to the Research Laboratory of Electronics whose joint support made this work possible.

Fields from Fluid Flow Mappers

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Fluid flow within the streamline (viscous) range, made visible by appropriate means, may be made to simulate fields occurring in electrostatic, magnetic, electric current, heat flow, chemical diffusion, and other situations. Simple, reliable, and inexpensive techniques for setting up the desired fluid flow situations have been worked out, and are described herein.

Two-dimensional fields with one, several, or many non-distributed sources (or sinks) may usually be made up and operated with ease. Techniques for the simulation of certain three-dimensional fields with axes of symmetry have also been developed.

Through the invention of the "sandbed" feature, the fluid flow method has been greatly extended: fields due to distributed sources can be simulated, not only outside the sources, but inside them as well.

Numerous photographs of fluid mappers in operation, illustrating all of the foregoing types of cases, are included.

1. INTRODUCTION

In fluid mechanics, very broad use has been made of fluid flow made visible, for solving the problems of fluid flow itself. However, the use of streamline flow for simulating other phenomena, and solving their problems, has seen little development. Nearly half a century ago, some beautiful pioneering work was done in England,[1] making fluid flow portray magnetic fields.

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[1] Hele-Shaw, Hay, and Powell, "Hydrodynamical and electromagnetic investigations regarding the magnetic-flux distribution in toothed-core armatures," J. Inst. Elec. Eng. 34, 21–53 (1904–5).

Why has this method—with its great potential value for teaching and problem-solving—remained undeveloped through all these years? From the writer's recent experience in perfecting the techniques described herein, it is suspected that lack of simple and reliable techniques has been the main handicap.

In seeking a way to get a visual simulation of field phenomena concerned with a distributed source, the writer invented the sandbed mapper in 1943. A model was at once built and successfully operated, first with air as the fluid, and then with water. Only recently has time permitted the fuller development of the sandbed mapper. Fortunately, the same techniques needed for a sandbed mapper are, aside from the sandbed feature, applicable to any number of simpler fluid mappers.

Many of the flow patterns are of great beauty, appealing to the layman as well as the scientist or engineer (see Figs. 11, 13, 30). In fact, one who sets up a fluid mapper laboratory will have to resign himself to running a dynamic art gallery in addition to handling the technical interests.

The writer has concentrated for many years on graphical field mapping, and probably has had the privilege of teaching graphical techniques to more students, than any other. The numerous fluid mapper cases operated for classes during the present school year have amply demonstrated that a student's speed and comprehension in grasping the nature of a field are greatly accelerated by these devices. The student may sketch directly from the mapper; or again, the flow pattern may be photographed, enlarged, duplicated, and handed to the student. This does not mean that he is handed a complete solution of his problem: plenty of work remains to be done to put in the orthogonal system, and to subdivide the map so that it is ready for making numerical solutions.

2. BASIC ELEMENTS OF FLUID MAPPERS

The components of a fluid flow mapper are a slab, such as any slab in Fig. 1; a piece of $\frac{1}{4}$-in. plate glass, larger than the slab, parallel to the slab surface, spaced upward from the slab by a constant distance—thus creating a two-dimensional flow space; a tray for immersing the combination in water, Fig. 3; one or more tanks with any desired water levels, Fig. 3; rubber connector tubes ($\frac{1}{8}$-in. I.D. with $\frac{1}{16}$-in. wall), each connecting a tank to the sealed bottom of a slab hole, or source; crystals of potassium permanganate sprinkled on the slab prior to placing the plate, to make the flow visible; and barriers within the flow space, if called for. A sandbed component will be described later.

3. THE SLAB

The problem of easily creating a flat uniform flow space was solved by casting a plaster slab against plate glass. At first, patching plaster, mixed with white sand, was used. Better results came when the sand was omitted. Very good slabs can be made of patching plaster only. The next and final step was to learn how to use what the dentists call artificial stone. Actually a plaster also, it is a high quality, uniform product, with a setting expansion of the order of 0.1 percent. It comes as a powder, in ivory or white. Either color will do. The writer prefers a white slab, with additions (such as bottom seals and feet) made of ivory. The powder must be added to the water, and not the other way around.

By now, the writer has used well over 100 pounds of powder. Powders from four different firms (Albastone, Castone, Rapid Stone, Crestone) have been tried, and all are satisfactory. However, the formula given for dental use is too dry for slab-making. Five pints of powder to two of water is best for slabs, and these actual volumes are used for the square slabs shown herein. These are one foot square and about $\frac{7}{8}$ in. thick. Such a slab will cost a dollar or less, for powder. The cost for patching plaster would be about half that, but the saving is not recommended.

For permanent slabs, or high accuracy slabs, cast aluminum may be the best material. For use with separate barriers, the top would be milled flat; or to dispense with separate barriers, the desired flow space would be milled into the slab face.

4. CASTING THE SLAB

In Fig. 2, a number of techniques for casting the slab used in Figs. 14–17, 25, and 26, are shown. The slab is cast on the drawing board, literally speaking. This slab is to have four little holes in a row, and one large rectangular hole, any one of which may become a source or a sink. On the drawing board is a drawing, showing the outlines of the slab, the rectangular metal core, and the four brass tubes to be cast in the slab and left as inserts. The tubes, now bottoms up, already have caps soldered to seal the bottoms, and side-tubes soldered in to take the rubber connectors. Resting on the drawing is the 14-in. square plate (plate glass). Resting on it are the metal parts, located by eye above their outlines. Also resting on the plate is a brass "fence" or outer mold. It is of brass strip, 1 by $\frac{1}{16}$ in. in section. Two opposite corners of the fence have had corner pieces added on and soldered. The other two corners come apart later. Their (loose) corner pieces may be temporarily held on with paper clamps, until a plaster slush is applied.

Unless metal parts are anchored, pouring the mix would always slide them out of place along the smooth plate. A small batch of plaster is mixed, and applied as a slush with a spoon, all around the outside of the fence, letting it pile up against the fence and also run out on the plate somewhat. First, on setting (in 10 minutes or so) it firmly anchors the fence. Second, it acts as a seal, preventing seepage of water from slab mix out under the fence—thereby giving a better edge to the slab. Slush is also laid down inside the metal core in like fashion. Any such core as this had better be slightly tapered. As to anchoring the metal tube in-

FIG. 1. Slabs of artificial stone, and some accessories.

serts, plaster techniques again furnish the easy way. In Fig. 2, a light metal bar has been laid on top of the tubes and plastered to them. This bar extends over the fence, and metal blocks standing on end are plastered to the bar, and to the fence and plate. Anchorage plaster is easily cracked off after the slab pouring. Metal parts in contact with the slab itself are painted with a thick soap solution to prevent sticking; or Silicone DC4 Compound, which works better than soap, may be used.

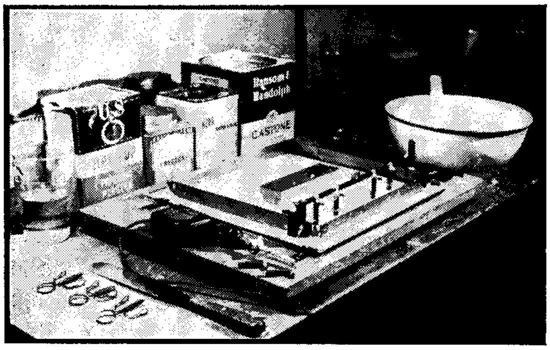

FIG. 2. Preparation for slab-casting. The brass containing fence or mold rests on plate glass, which rests on the drawing on drawing board. Central metal core is in place, as are four metal tube inserts.

All the water is put in the bowl, Fig. 2. The powder, already measured, is poured in while rapidly stirring. Stirring will take about a minute. Some small lumps may then remain, but these will be fully wet, and they will cause no difficulty. Mechanical mixing would be desirable. The resulting mix is soup, like pancake batter. It can be poured with little care; it is spread around with the paddle, and is evened up by jiggling with the paddle.

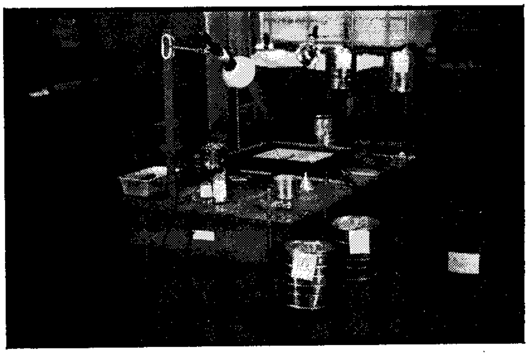

FIG. 3. Fluid mapper in operation. No. 2 photofloods are in place, for photography.

Within a few minutes after setting, the anchorage plaster is cracked off, the fence is removed, and the plate and all that it bears is set in water. The plate is then slipped off with ease. The metal core is tapped out; sometimes, it can simply be lifted out.

While the slab is still soft, a sloping channel is cut into the bottom, running into the side of the central hole. It is to take a rubber connector tube. A thin aluminum plate, about $\frac{1}{4}$ in. larger all around than the hole it is to cover, is placed over the bottom of the hole. It and the rubber tube running in under it are plastered to the slab by additional mix, which is slushed around and over the edges of the plate. At this time, low feet are also plastered on by piling up plaster where desired. The slab must be completely wet—but not dripping—when any such plaster is added. Any such additions hold with ample strength, but may easily be cracked off at any time with a chisel, to make repairs or changes.

5. OTHER SLAB TECHNIQUES

One thinks of the hard ways first—and this applies to the above method of getting four little sources by means of metal inserts. Someone may sometime need metal inserts, and therefore, the details were described. However, such inserts are most unwelcome if the slab surface becomes imperfect from use, and needs to be ground flat again. Also, small holes are more easily made by drilling, from the top down, with bottom seal and rubber connector to be plastered on. For $\frac{1}{4}$-in. round holes, the rubber connector is wetted with plaster and stuck directly into the hole bottom. Large holes are best made with hollow metal cores, internally anchored with plaster.

Artificial stone offers many advantages: it may be sawed, carved, routed, drilled, reamed, end-milled, and so on, after firmly setting, either when new and still damp, or when air-dry. When dry, it can be ground or sanded.

The one bad quality of the stone is its erosion in use. The mirror finish it has when first cast, rapidly disappears when immersed. The slight roughness resulting is of no importance whatever, but the erosion is. In several hours of use, the areas of higher fluid velocities may erode as much as 8 or 10 mils. Many of the photographs shown herein were taken before erosion was recognized, and such patterns must be taken as good demonstrations rather than accurate simulations. An eroded slab can be retrieved by first letting it dry, then grinding it by turning it face down and moving it against emery cloth. Flatness is tested for by slipping feeler gauges under plate glass applied to the slab sur-

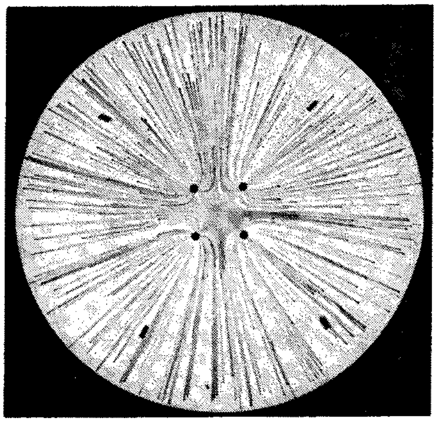

FIG. 4. Four equal sinks. Each streamline begins at a crystal of potassium permanganate. The plate glass or plate, spaced $\frac{1}{16}$ in. above slab, does not show. It is covered with water.

face. Some of the writer's experience indicates that once the first few mils are thus removed, erosion may proceed more slowly. Often, it will be easier to throw the slab out and build a new one. Prevention of erosion by finding a suitable surface treatment is due for further study.

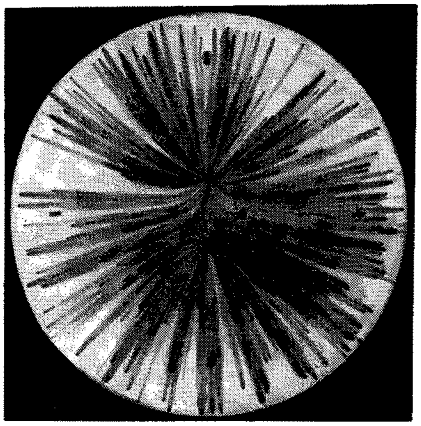

FIG. 5. Two unequal sinks, approximately 2:1 in strength.

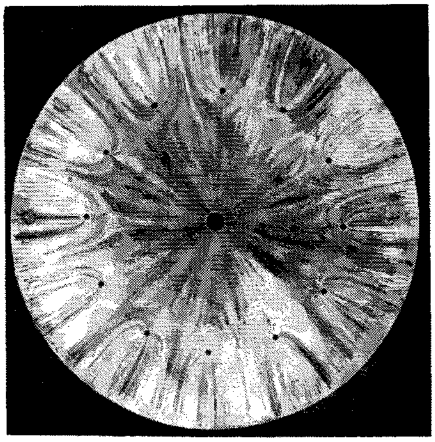

FIG. 6. Simulating a triode's field. Central cathode, 12 axial grid wires. All holes operated as sinks.

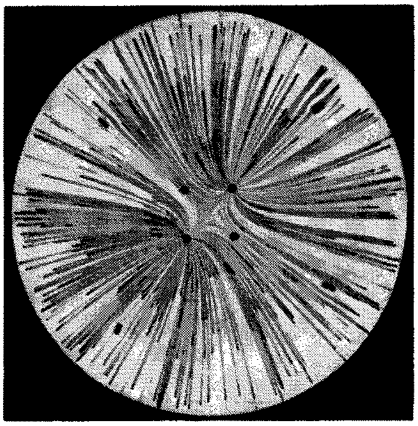

FIG. 7. Two equal sinks.

6. SPACERS, BARRIERS, SEALANTS

In all but one (Fig. 29) of the two-dimensional cases shown herein, a flow spacing of about $\frac{1}{16}$ in., or about 60 mils, was used. Spacers are cut from sheet rubber or from brass strip.

The best material for general barrier purposes so far

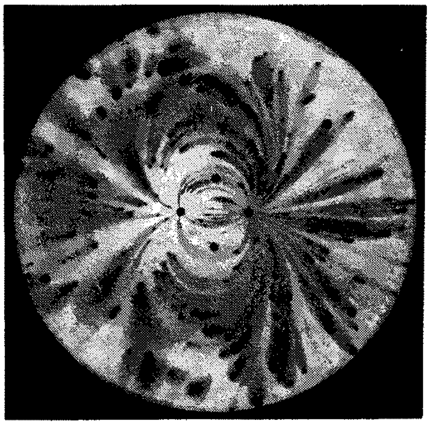

FIG. 8. Source and sink, equal.

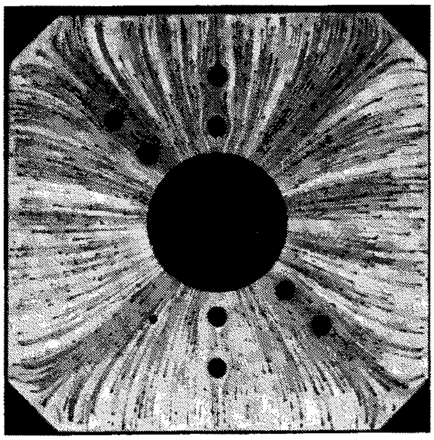

FIG. 9. Simulation of a heat flow case. Round black rubber pieces represent thermocouple wells.

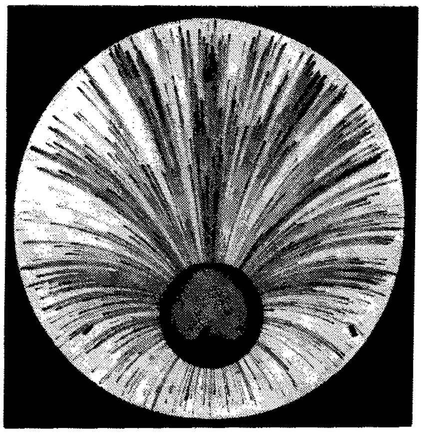

FIG. 10. Open-edge slab, large round sink eccentrically located. Screen for supporting a sandbed is seen in the hole.

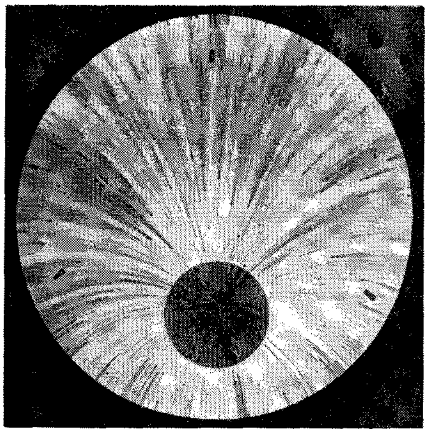

FIG. 12. Sandbed operating as a distributed source. Note displacement of kernel upward from source center.

FIG. 11. Square slab, open edge. Four small equal sinks, large round central source.

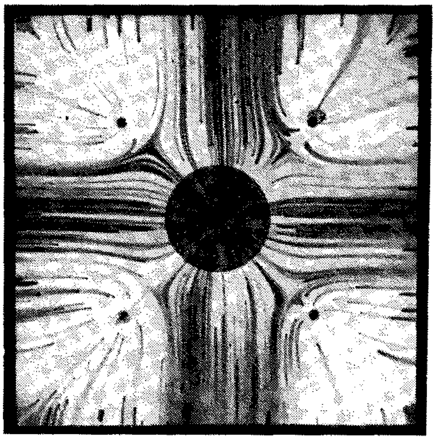

FIG. 13. Central sandbed as a distributed source, and four other small equal sources.

found is $\frac{1}{16}$ red sheet rubber; even though not finished smooth, there usually has been no leakage on account of the finish. At one time, some smooth black sheet rubber, with cloth insert in the middle, had to be used. It was so stiff that permanent set prevented it from lying flat willingly. Brass strip, flattened by hand bending and hammering, and polished, works nicely: it is heavy enough to remain located better than rubber, when water movement occurs due to placing the plate. However, for a variety of purposes not calling for high accuracy, high grade sheet rubber is most easily worked up.

Leakage across a barrier due to barrier or slab imperfections may be absent, or too slight to worry about. When bad enough, a sealant is called for. Some success has been achieved by smearing Vaseline on the barrier before placing it. It is not an invariably convenient and reliable sealant. One night, when it failed, the writer turned in desperation to a sample tube of anti-fogging material that was accidentally at hand. It worked well, and later on, did so again. This stuff, now obtainable at filling stations, is a clear, viscous something made "to prevent fogging on glass surfaces." At this writing, it is the only sealant that can be recommended. It should not be applied so that it will be squeezed into the flow space: it is nearly invisible under water, and might become an undetected block to the flow.

A search is now being made for some rubber-like sheet plastic, which, it is hoped, will be smooth-finished and highly uniform.

7. MAKING FLOW LINES VISIBLE

Much fluid flow work in applied mechanics is done with a free surface; thus, injectors, injecting colored streams of fluid such as Malachite Green, are feasible. Such a technique could seldom be easily applied to fluid mappers, where no free surface exists. Potassium permanganate crystals therefore are used. These come in mixed sizes. After crushing somewhat, they are screened to eliminate the finer particles. Those remaining should freely come through holes of about 1 mm diameter in the head of a saltshaker. Such crystals will

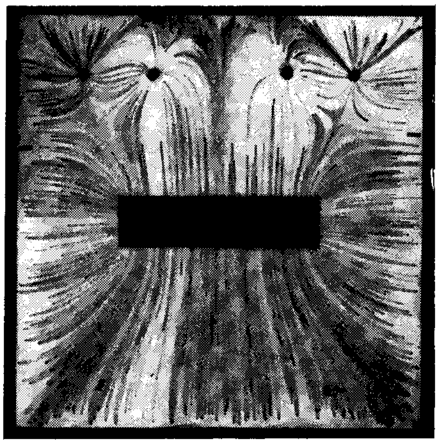

FIG. 14. Square open-edge slab; large rectangular central sink; two outer holes, equal sinks; two inner holes, equal sources.

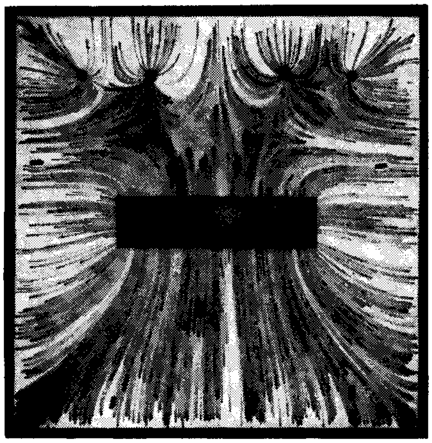

FIG. 16. Square open-edge slab; four small equal sinks, large central sink.

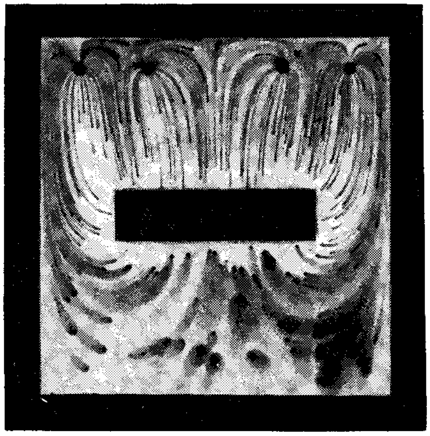

FIG. 15. Flow contained by sheet rubber barrier all around edge. Large central source, four equal sinks. In lower part where velocities are low, lines are broad due to sidewise diffusion of dye.

FIG. 17. As in Fig. 15, but with sandbed simulating a distributed source.

last for many minutes, each crystal forming the head of a streamline of color.

In fluid mapper use, the permanganate often changes fast enough to form a brown stain; in prolonged operation, the MnO_2 formed may appear as a precipitate, moving along with the stream flow. A stained slab can be completely cleared in a short time by brushing its face with this mixture: 95 parts of 3 percent hydrogen peroxide, 5 parts of acetic acid, 300 parts of water. Any rough approximation to the formula is effective. The slab is of course raised above water for this treatment. If immediately put into service again, brown precipitate will copiously appear: peroxide, diffused into the slab, diffuses out again to unite with the permanganate. After clearing a slab, it should be flushed with water, then allowed to soak in water for a while.

In spite of diligent inquiry among chemists, the only other material now known to the writer which might be suitable, is methylene blue. For years, the writer has had a little of this in crystal form, has used it for making streamlines in water many times, and found it better than permanganate in sharpness of line. Recently, the supply was all used up. Then—no one had any more, and no chemist yet approached knows of methylene blue being successfully made into large crystals of 2- or 3-mm size. It may be that the "crystals" one had were fake—made by boiling the dye with soluble starch, gelatin, etc., spreading the mixture out to harden, then cracking it up. It is to be hoped that some such crystal coloring agent, better than permanganate, may be found. MnO_2 precipitate is not an asset to fluid flow devices.

A very striking and often valuable technique is to color a whole area of flow. Instead of using crystals in the flow space, one of two flows, say, is colored by coloring the water in its feed tank; and the other flow is left clear. This was done in Fig. 20, the set-up being the same as in Fig. 18. The two sources at the right were supposed to be equal, and the sinks at the left, equal. The horn of colored fluid extending leftward from the inner sink may be partly due to set-up imperfection;

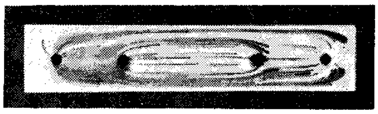

FIG. 18. Equal sources at right, equal sinks at left.

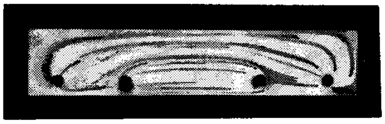

FIG. 19. As in Fig. 18, but sources and sinks displaced downward. The particles are MnO_2 precipitate.

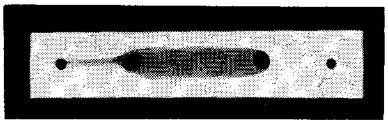

FIG. 20. Case of Fig. 18, but no crystals used. Entering fluid colored for one source, but not the other.

but also, this effect can ensue due to lateral diffusion of the dye, from the colored part to the uncolored flow area.

8. THE TRAY

A rustproof tray should be used. However, the tray of Fig. 3 is a cheap black steel kitchenware tray, with sloping sides. It is repainted from time to time. It is 3 in. deep, and about 15 by 16 in. horizontally. For convenience, several junction tubes are provided. These are thin-wall brass tubes, $\frac{5}{32}$-in. O.D., piercing the tray wall and soldered into it. Rubber connectors from the slab join to the inside projections; connectors from tanks go to the outer ones. Thus, connectors need not be brought out of the tray by coming up over the edge.

9. OPERATION

The slab is put into the tray, with enough tap water used to cover the plate when it is in place. Rubber connectors are hooked up. Water is put in the tanks to make their levels, at first, about the same as tray water level. Barriers or spacers, as the case may be, are put onto the slab surface, under water. Crystals are

FIG. 21. One source at lower right, and three sinks.

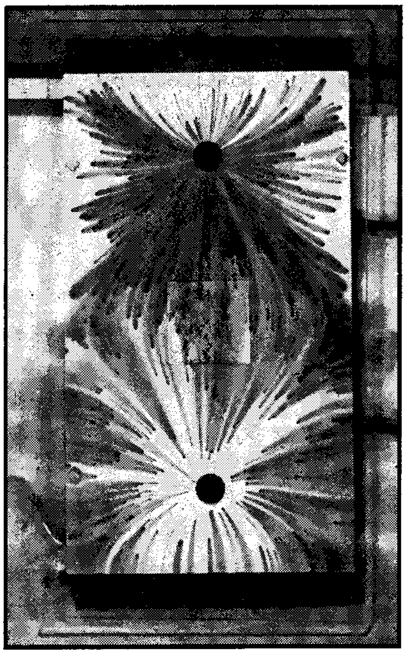

FIG. 22. Open-edge slab; source and sink equal. Paraffined bristol board embedded in slab still in place; uniform flow space. Note swirl effect on flow lines leaving the source.

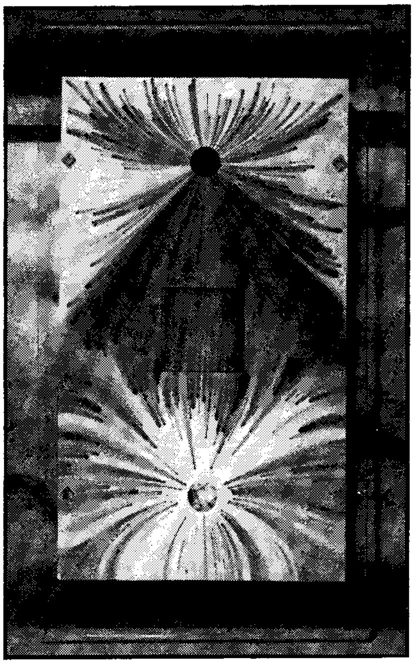

FIG. 23. Flow space increased in center square by removing embedded insert shown in Fig. 22. Note the refraction. Note also the gauze crowded into lower half of source hole, curing swirl effect.

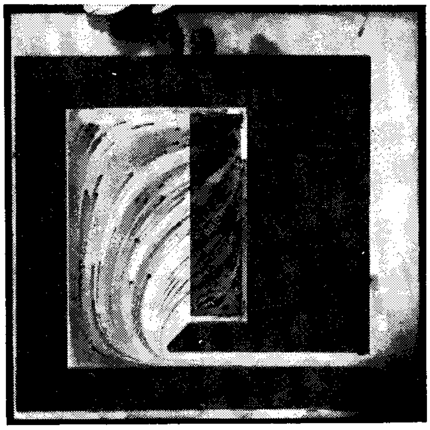

FIG. 24. Sandbed mapper simulation of equipotentials of magnetic field due to current distributed in field coil wall section.

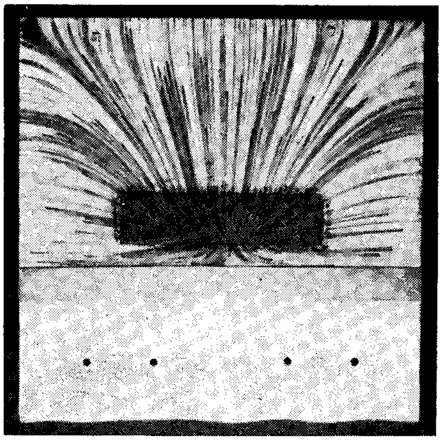

FIG. 25. Sandbed sink, brass barrier below. Crystals on slab. Others attached to plate above sandbed edge, to get good delineation over sandbed.

sprinkled over the exposed slab areas; they promptly sink to the slab. The plate, preferably cleaned with Glass Wax or its equivalent, is slowly lowered. On placing the plate, water is displaced outward, and a "placing pattern" is formed. After operation is started, part of the placing pattern may remain for quite a while, in low velocity regions.

Consider Fig. 4, an open-edge case. The four holes are to become equal sinks. Equal lengths (each about 50 in.) of rubber connectors have been used. Tank levels have been made the same as tray level. All four cans are now picked up together, moved off the table, and lowered a few inches. The pattern at once begins to form. With the flow space and rubber connectors as described, most of the flow resistance will be in the connectors. Connector inequality will occur for three reasons, in spite of using equal lengths. First, rubber tubing is not uniform; and in a long round straight duct, resistance, or ratio of pressure drop to flow rate, varies inversely with diameter to the fourth power. Second, there are bend effects. Third, there are pressure drops at entries and exits. The second and third factors rise, relatively, with rise in velocity. Even so, many nearly symmetrical patterns, in symmetry cases, can promptly be obtained by simply using near-equality of equal-length connectors. When better symmetry is desired, a little water can be added or taken from one or more tanks.

When one pattern is changed into another, as by setting up Fig. 4, then clamping two connectors to get Fig. 7, the effect is indeed striking. Nearly every spectator comments on it. First, there is the old pattern; then apparent indecision; then the new pattern suddenly seems to appear everywhere.

For Fig. 5, the two tanks may be lowered by different amounts, to get operating heads of 2:1. Or, Fig. 8, equal positive and negative heads can be used, to give a source and a sink of equal strength.

Inertia effects are nil when the flow space is operated within the viscous (laminar or streamline) range. This is strikingly shown by setting up, say, the Fig. 4 pattern with half-inch heads; then suddenly lowering the tanks to the floor, to give about 30-in. heads: the pattern is unchanged. A large majority of cases can be operated with heads of 2 in. or less.

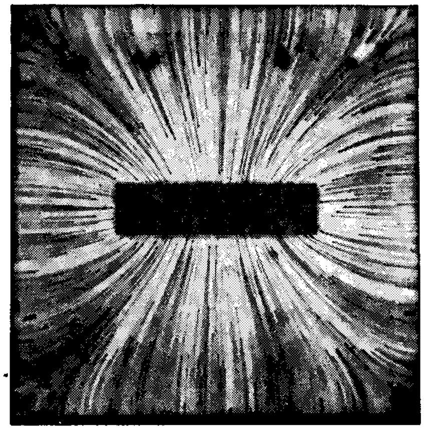

FIG. 26. Open-edge slab, central sandbed as source.

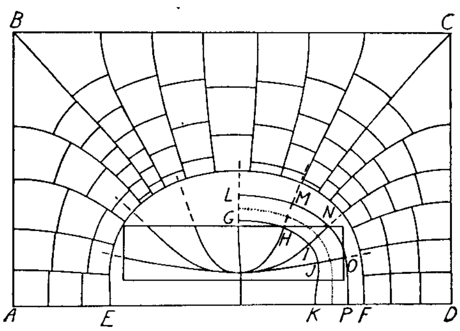

FIG. 27. Mapping study of the case shown in Fig. 25.

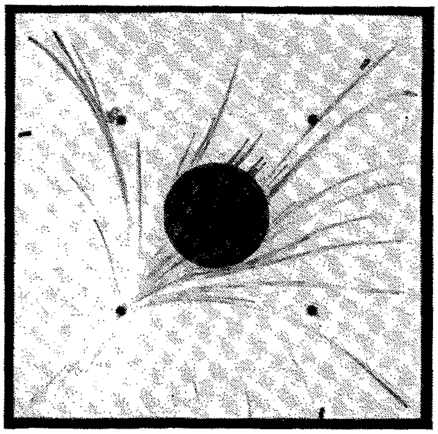

FIG. 28. One small sink, dead sandbed. Refraction at sandbed edges, and lines avoiding it, show that sandbed is high.

10. SWIRL EFFECT

In all cases not involving a sandbed, the streamlines should approach or leave the edge of the sink or source orthogonally. Likewise for an open slab edge. However, in Fig. 22, it is seen that whereas the fluid approaches the (upper) sink at right angles to the edge, it is not leaving the (lower) source properly. If the hole were large compared to the flow spacing, this trouble would not occur. As it is, water entering the tube at the bottom retains a swirling movement, and local velocities in the hole are large enough to affect nearby flow in the flow space. The cure was to stuff gauze into the lower half of the hole, to even up the velocities in the hole. In the (lower) source, Fig. 23, the gauze can be seen; and it has also been used in the two sources of Fig. 35.

FIG. 29. Same as in Fig. 28, but flow space doubled. Lessened refraction shows that the larger the flow spacing, the less the effect of spacing inequalities.

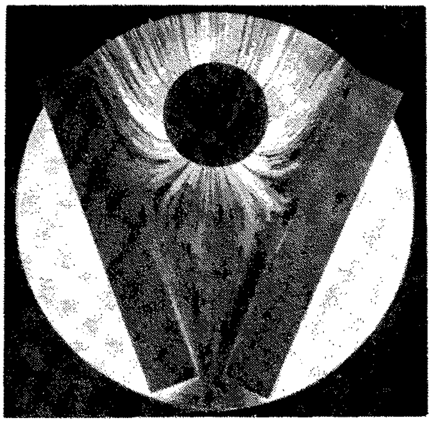

FIG. 30. Sandbed and rubber barriers. Possibly the most beautiful of all the patterns yet photographed from these mappers.

Figure 6, simulating a triode with central cathode and 12 axial grid wires, at first suffered from swirl effect, when holes were sources, distorting part of the field near the grid wires. That was when this slab looked like a Portuguese Man-of-War, with 13 rubber tubes trailing out from underneath. This was changed by removing the 12 separate connectors; beveling the 12 holes from below with the end of a large drill, to equalize hole lengths and approaches; and installing underneath a common plenum chamber. Several baffles of fine screen were mounted in front of the tube feeding the plenum chamber, in the chamber itself. Symmetry of pattern at once resulted.

11. SIMILITUDE

In Fig. 4, the open slab edge is an isopressure boundary. Calling the sinks equal, their edges are isopressure boundaries, all at the same pressure. Then the flow set up in the uniform flow space must be normal to these boundaries. Also, what we may think of as flow resistivity offered in the flow space is constant everywhere. Reinterpret it as a current flow case; current is flowing in a uniform homogeneous sheet between boundaries made into equipotentials by suitable electrodes. The conditions are such that similitude occurs between the flow pattern and the current pattern. Interpret again as a heat flow case in a sheet, when equipotentials are isothermals, and similarity again prevails. Or again, four small parallel cylinders, all at one potential, set up an electrostatic field between them and an enclosing cylinder. Or, interpret as a magnetic case, a chemical diffusion case, and so on.

Returning to the current-in-sheet interpretation, if we go vertically through the conducting sheet, constant current density is found; whereas, in the fluid flow space, a parabolic velocity distribution occurs. This departure from similitude is of no concern, for the streamline pattern set up in any one level duplicates that at another level.

Figure 9 had its origin as a heat flow case. Mr. J. L. Schweppe, Ph.D. candidate in Chemical Engineering, is preparing to do research on evaporation of liquid in a central hole in a metal bar, heat being forced into parts of the four sides of the bar. The round spacers represent thermocouple wells. In order to know the facts about the heat flow pattern and the meanings of thermocouple readings, slabs were built and operated for three sizes of holes. To show how speedily some cases can be carried through, take this case. The hole cores were turned out in advance, and the barriers and spacers cut. Then, beginning one morning at 9:00, the writer, with help from Mr. Schweppe, cast all three slabs, operated and photographed them, and had the films developed by 5:15 P.M.

Figure 35 may be thought of as a three-phase line in an iron conduit, at the instant when one conductor has maximum current. Fluid flow lines correspond to magnetic equipotentials. The writer recently carried the materials, mold, cores, and suchlike to class; in one hour—lecturing meanwhile—this slab was cast, and the appendages added; in the next hour, it was operated.

12. MAP COMPLETION

This paper can merely mention map completion steps. From a fluid mapper, a flow pattern is taken off, photographically or otherwise. The orthogonal system can sometimes also be set up on a fluid mapper; if not, the operator must put it in himself by suitable graphical methods. In the end, the map consists of selected lines in both systems. A two-dimensional map is commonly made up of a regular array of curvilinear squares. Moore[2] may be referred to for graphical field mapping techniques. Numerical results are easily obtained, once the map is completed.

13. THE SANDBED MAPPER

The invention which was the major incentive for developing these fluid mapper techniques, was the sandbed feature. Consider Fig. 10 as a heat flow case in a long solid cylinder having an eccentric axial hole. If hole and cylinder surface are isothermals, heat flow lines would be as in Fig. 10. Next (Fig. 12) let the cylinder be without the hole, and let heat be produced constantly throughout that part of its volume where the hole was. Heat would flow away from every point where it originates, in some direction, *seeming* to originate at a point called the kernel. To simulate, the hole in the slab is provided with a screen, halfway down, visible in Fig. 10. A uniform bed of sand is filled in on the screen, with top sand leveled off just flush with the slab surface. Flow spacing, sand grain size, and sandbed depth are so selected that the horizontal flow space resistance is negligible compared to that of the sandbed. Operating as a source, fluid would have to appear uniformly above the sandbed, then flow away in the flow space. This corresponds to heat appearing uniformly within the volume described, and there will be similitude.

The kernel cannot occur at the sandbed center, but is displaced upward, toward the region of higher flow space resistance. Foreseeing the probable location of the kernel in a new case seems to present the mind with an unusually difficult puzzle. When a kernel which otherwise would be at a center of a symmetrical source is to be displaced by change of barriers or what not, students at first (and others too!) almost invariably predict a displacement opposite to what really occurs.

FIG. 31. Isolated sandbed, 2 by 8 in. Sand: cast iron shot copper plated. Operated as source, and crystal-sprinkled in usual way.

Re-interpreting, the sandbed becomes the equivalent of a uniform space charge; a distributed current setting up a magnetic field; a uniform and changing flux piercing a disk, setting up eddy currents both outside and inside the source; and so on. Problems in these situations typically defy mathematical solution; approximation methods can be used, but cause a great deal of work to be done. The very small literature measures the lack of progress to date. The sandbed mapper can yield a very good first approximation with simple techniques; or certainly can solve a case with high accuracy, if accurate devices are built.

FIG. 32. The case of Fig. 31 operated as a sink, crystals attached to plate by "nail polish." Better lines obtained.

The figures show a number of sandbeds in operation. Figure 24 shows (developed) half a pole pitch of a machine, the sandbed simulating the coil wall section current. The slab of Fig. 34 was built to solve for Foucault currents in a round disk. Take the radial

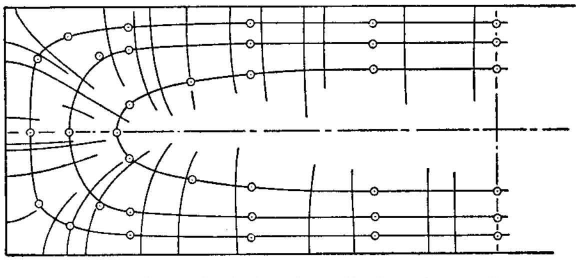

FIG. 33. Lines from the isolated sandbed, orthogonally crossed by contour lines of soap film produced on top of the empty sandbed frame.

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[2] A. D. Moore, *Fundamentals of Electrical Design* (McGraw-Hill Book Company, Inc., New York, 1927).

FIG. 34. Open-edge slab, small narrow sectorial sandbed used as sink. Solving for Foucault (damping) currents in a round disk, rotating through a flux piercing the disk.

dimension of the little narrow sectorial sandbed, and sweep it clockwise to 12 o'clock. Imagine the other half to be present, with a similar area. Fill this total area with uniform flux, and rotate the disk through it. Then the Foucault or damping currents would be in the system orthogonal to the fluid flow lines shown here. The theory requires a double substitution. First, the new flux-band-and-pencil-pair concept (Moore[3]) is applied; next, two narrow sectorial sandbeds replace the pencil pairs.

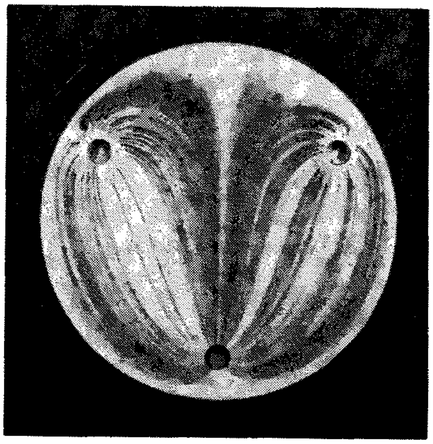

FIG. 35. All-around barrier. Two equal sources (note gauze to cure swirl effect) and a sink. Solving for magnetic field due to three-phase conductors in an iron duct.

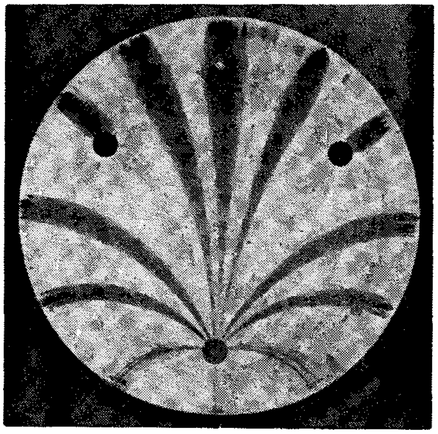

FIG. 36. Sandbed operating as sink, using shotted nickel. Crystals attached to plate in patches, showing how certain pattern effects can be emphasized.

14. SANDBED MATERIAL

The first (1943) demonstrators were made of wood, and used Standard Ottawa sand. The fluid was air. It was loaded with ammonia fumes, to react with hydrochloric acid dotted on the lower surface of the plate and make smoke. The slab surface and the sand were blacked with India ink, to make the smoke visible. But smoke diffuses rapidly, and it may soon clog a sandbed.

The writer has successfully used sand under water, but cannot recommend it. It is too prone to float, too hard to see, and too easily washed out by placing the plate.

Shotted metal is far superior to sand. Shotted copper —also called copper shot, copper powder, copper granules, is spheroidal. All but two of these sandbeds are of copper shot, about 0.02 in. in diameter, kindly supplied as a sample by Metals Disintegrating Company, Inc. (Copper Powder MD34A). This company recently furnished a sample of shotted nickel, slightly smaller than the copper and more spherical: see the lower hole in Fig. 36. (However, the nickel is experimental, and is being closed out.) The beds of Figs. 31 and 32 were larger than the copper supply; as a stopgap, shotted cast iron, copper-plated, was used. Copper darkens rapidly with use, but is brightened again in an acid bath. Nickel is darker, but stable.

15. THE SCREEN

The screen, placed $\frac{1}{2}$ in. down, is a two-piece affair. The round holes seen in Fig. 10 are in the lower member, made of No. 22 gauge stainless steel perforated plate. The upper member is 70-mesh brass or bronze screen. They are in contact. Handwork must be done on both, after cutting, to flatten them. The plate gives flatness and strength; the screen holds the shot. Rigid mounting is required. In Fig. 2, note the enlargement of the metal core, to provide a $\frac{1}{8}$-in. enlargement of the bottom of the source chamber. The screen fits against the offset. It can be plastered at the edges to hold it; or a metal frame can bear against it, with a plate soldered to the frame to seal the bottom. The frame is plastered in.

16. MAKING THE SANDBED

The sandbed must be built under water. When water is brought into a dry-made bed, further settling occurs, and some of the surface will float away. Entrapped air is Enemy Number One. Air will always be trapped under the screen, after immersing the slab. Every bit of it must be sucked through, using the end of a rubber

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[3] A. D. Moore, "Eddy currents in disks: driving and damping forces and torques," Trans. A.I.E.E. **66**, 1–11 (1947).

tube as a siphon, and rubbing it all over the screen. The wetted shot is kept at hand in a beaker. Plenty of detergent, such as Aerosol or Tergitol, is used in the water in the beaker, and detergent must be used in the tray water. Even then, shotted metal will sometimes float and cause trouble; in that case, add more detergent. After spooning enough shot into the bed to fill it, roughly, a probe is inserted all over the bed to water-settle it. If this is not done, packing effects, especially at walls and corners, will leave local voids thereat, causing an unwanted extra flow at the sandbed edges. Proper settling cannot be obtained with angular shot, as was found by trying shotted zinc and shotted bronze. Copper works well; nickel, being smoother and rounder, is still better.

Shot getting out on the slab is pushed back to the bed with the edge of a piece of Celluloid. Every such grain must be taken care of. As grains are added or taken away to make the surface nearly right, some tedious work is faced. The plate is placed directly onto the slab, to find high and low areas. When just right, moving the plate will slightly move most of the top grains; also, localized grain arrangements, with grains in circular arcs, will form and be recognized.

A single loose grain on the slab will hold up the plate, resulting in a high sandbed. Figure 28 shows a high sandbed, which was due to another cause: this slab had been eroded in the central area. When enough grains were added to touch the plate, the sandbed surface was above the slab. The streamlines are refracted, tending to avoid the bed. Such a test should be made of any important sandbed. In Fig. 29, the flow space has been doubled: less refraction occurs, showing that the larger the spacing, the less the effect due to spacing inequalities.

In a given flow space, the resistance varies inversely with the cube of the spacing. In a given sandbed, it varies inversely with the square of grain diameter (assuming like kinds and relative sizes of grains). Therefore, there is plenty of design latitude for building sandbed mappers, in seeing to it that sandbed resistance is always high compared to flow space resistance.

The idea of fixing a sandbed, to avoid the nuisance of building it anew each time, is seemingly attractive. However, the writer has gone to considerable lengths to develop cemented types of fixed beds. Due to packing and other effects, no success was achieved. Permeable materials such as alundum, fritted glass, etc., are available; but there are problems of cutting to size, cementing in, and plugging of pores in operation. No generally good answer to the fixed-bed problem is anticipated.

17. ISOLATED SANDBEDS

A rectangular, isolated sandbed is shown in Figs. 31 and 32. Since no slab is present, ears are attached to the metal frame, with pads. The spacers are laid on the pads to support the plate. The top of the frame is beveled all around to give a sharp edge.

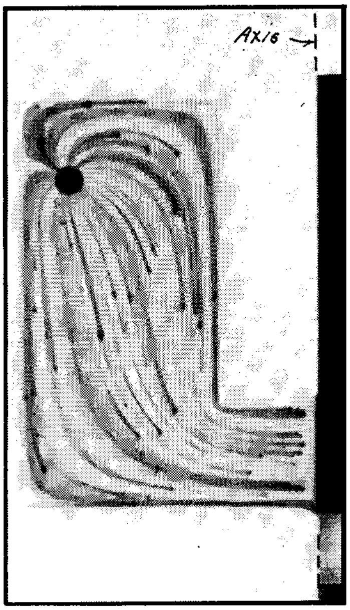

FIG. 37. Three-dimensional, with axis of symmetry. Flow space cut into flat slab by end-milling and hand scraping. Note curved mouth, to take care of edge effect.

Figure 31 shows the bed as a source, with crystals placed by sprinkling directly on the bed. Much sharper lines can be obtained, Fig. 32, by using the bed as a sink, and applying the crystals differently. Before the plate is placed, its lower surface, when dry, is painted with cellulose acetate (clear "nail polish" at any drugstore). This is applied in a band, to locate at the sandbed edge. Crystals are sprinkled on it while it is sticky. The streamlines thus formed are high in the flow space. They carry far, and are sharp.

These flow lines duplicate heat flow lines in an axially long solid having such a section, when heat is uniformly produced throughout the volume, and the surface is an isothermal. Or they simulate the equipotentials for the eddy currents in a rectangular disk uniformly and

FIG. 38. Three-dimensional of the other type, with axis of symmetry. Note gauze to kill swirl effect.

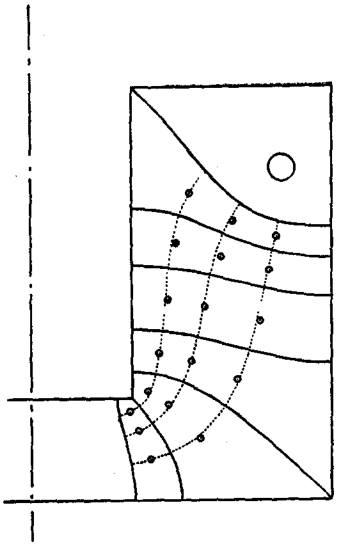

FIG. 39. Mapping study of the case of Fig. 37, to check its accuracy. If strictly accurate, the points shown would fall on their respective dotted lines.

completely pierced by a changing flux; or for eddy currents in a lamination of like section, granted constant permeability and sufficiently low frequency.

The orthogonal system would normally be secured by graphical work. However, the writer has proved, theoretically, that this system occurs as soap film contour lines. To demonstrate, a soap film was placed on the top of the empty frame, and blown up to a maximum elevation of $\frac{1}{4}$ in. at center, the frame being 2 by 8 in. The points shown in Fig. 33 were obtained (in one quarter only) with apparatus devised by the writer. Note that the four contour lines (the boundary being one) are reasonably orthogonal to the flow lines. Soap films have seen some use in solving for stresses in shafts of odd sections. Since soap film techniques are notoriously difficult, it may be that in some cases they can be discarded in favor of sandbed techniques.

18. EDGE EFFECT

In a number of the figures, the flow space is constrained, or even entirely contained by barriers placed on the slab. In Figs. 18–21, the flow is entirely confined. These lines simulate the equipotentials in a field set up by currents in conductors, entirely surrounded by iron of infinite permeability. Or, think of the fluid flow as simulating current flow in sheets shaped like the confined spaces shown, flowing between electrodes attached to the sheets. In this last case, as we approach the edge of a sheet, current density retains a finite value. But in the fluid flow space, as we approach the edge or barrier, velocity falls to zero. Here is a lack of similitude, and it must be discussed.

Interestingly, we can call on and use the sandbed mapper of Figs. 31 and 32 to help the analysis. Taking up Fig. 33 again, the writer has been able to prove that, along with other interpretations, the isopressure lines of the fluid case (or the soap film lines) coincide with isovelocity lines for axial streamline flow occurring in a long duct having this rectangular section. Therefore, we have here a picture of the fluid flow taking place near the edge of a flow space. Note that very largely, the effect of the edge is confined to a square that can be fitted into the flow space at the edge. Using data from Fig. 33, the writer has found the average velocity for the duct; and has found that the same total flow would occur, were there no edge effect, in a rectangular duct made narrower at each side by an amount equal to 0.27 times the spacing. Adopting $\frac{1}{4}$ in place of 0.27, this means that approximately, when cutting barriers, if the flow space at any edge is made *larger* than the boundaries being imitated, by $\frac{1}{4}$ of the spacing, edge effect on the fluid pattern within the simulated boundary should be very small. In a great many cases, edge effect can be ignored.

19. STUDY OF A SANDBED CASE

Interpret Fig. 25 as heat flow, heat production being distributed uniformly throughout the sandbed part of the solid. Below, a perfect heat barrier blocks all heat flow. Otherwise, all heat produced flows to the isothermal boundary (ABCD, Fig. 27), which is simulated by the open slab edge. This slab was badly eroded from previous use. Presence of metal inserts made it very difficult to grind its face flat again, and its flow space lacked uniformity by several mils. Another defect came

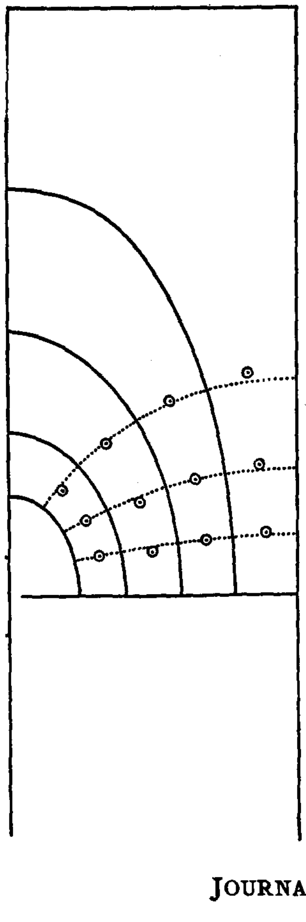

FIG. 40. Mapping study of case of Fig. 38. If accurate, the points shown would fall on their respective dotted lines.

in when the film was projected to get an enlarged full-size image for hand-copying the flow lines: the film warped due to heat. Completing the map of Fig. 27 by graphical techniques would introduce other small imperfections. Therefore, we can by no means expect the map to check perfectly.

Tracing paper was put down over the hand-copied picture. Starting at E, isothermal EF was put in, orthogonal to the flow lines. Arbitrary flow lines were next adopted and drawn in, thus dividing the total heat flow from EF to ABCD into 18 arbitrary, unequal, tubes of flow. The curvilinear squares were then constructed. By finding the conductances of these tubes, adding them, and dividing by 8, the total flow was divided into 8 equal parts, thus locating the flow lines that are drawn to the kernel. These lines divide the heat source or the sandbed into 8 areas which, in a perfect solution, would be equal. Actually, the areas, as read directly from the planimeter (starting at lower left and going clockwise) are: 0.75, 0.80, 0.70, 0.73, 0.70, 0.61, 0.62, 0.64. The largest departure from average is 15 percent. The errors largely arise from flow space inequalities. With a new slab, uneroded, far better accuracy should result.

Analysis was carried further by putting in the two isothermals GK and LP in the right half, which cross the sandbed or heat source. In the "isothermal tube" thus laid out, the dotted midline was put in; this being the isothermal that is halfway in temperature between the two other isothermal temperatures. The parts of the four heat source areas inside this midline can be taken, approximately, as dictating the heat flow that must be conducted out from GH to LM, HI to MN, and so on through four conductances. The four conductances are found by mapping the areas with curvilinear squares (not shown). They are, going clockwise, 2.00, 1.36, 1.03, 1.45. The source part-areas inside the midline, same order, are 0.70, 0.59, 0.38, 0.58. Respective ratios of conductances to source areas should all be the same. Actually, they are: 2.86, 2.31, 2.72, 2.50. The theory is approximate, and other imperfections have been mentioned above.

Even with its errors, this map is a fine first approximation to the solution, as compared with a first approximation obtainable by methods available heretofore; and with due care taken with techniques, it can be made far better.

20. THREE-DIMENSIONAL TECHNIQUES

The writer has developed theory (not included here) which shows that a fluid mapper should be able to simulate a three-dimensional field having an axis of symmetry, providing the flow space varies either with the one-third power of the radius, or inversely as the same power—depending on which of the orthogonal systems is to be shown by the fluid flow. Both types have been tested.

In Fig. 37, of the "cross-axis" type, the axis is at the right. This could be an ironclad magnet with a central pole, and circular turn carrying the current. Flow space varies inversely with the one-third power of the radius, rising to infinity at the axis. This flow space was made by starting with a flat slab, then end-milling, then hand scraping. Near the axis, spacings become large, and edge effect is large: note the curves on the plaster mouth, cut to eliminate edge effect as outlined above. A mapping study was made, Fig. 39. Each of the tubes (between solid lines) was made to predict the positions of the equipotentials that would divide this total mmf into four equal parts. In a perfect solution, the encircled points would all fall on their respective dotted lines. They very nearly do so.

The other, the "pro-axis" type, is represented by Fig. 38, where the axis is at the right. Here, the flow space varies directly with the one-third power of the radius. The mapping study, Fig. 40, again shows a very good check. This case simulates heat flow in a solid cylinder, when most of the upper half of the round surface is an isothermal, most of the lower half is another isothermal, and the middle band between takes temperatures as dictated by the conditions. No heat flow is crossing the cylinder ends. It is clear that such types of mappers will also apply to electrostatic and magnetic fields.

As far as is known, these are the first such fluid mappers ever to be produced.

21. REFRACTION

When the slab in Fig. 22 was cast, a square of paraffined bristol board was first placed on the plate glass. It is seen, still imbedded, in this picture. In Fig. 23, the insert has been removed, leaving a depression, and demonstrating refraction when a sharp change of flow space occurs. The lack of symmetry shows that this technique for making a depression has its imperfections. However, the point is that, as was pointed out long since by Hele-Shaw,[4] change of flow space, properly effected, can be made to correspond to change of permeability; it also corresponds to change of thermal conductivity, dielectric constant, and so on.

In Fig. 12, for example, the sandbed was level with the slab, and no refraction occurs at the sandbed boundary—merely a change in curvature; and here, the properties of the simulated material are the same, inside the source and outside it. But by inserting a thin lining around this sandbed and elevating it, a high sandbed could be built. Then, in terms of heat conduction, the source volume would be given a lower thermal conductivity than the surrounding solid. Like-

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[4] H. S. Hele-Shaw and Alfred Hay, Phil. Trans. Series A (English) **195**, pp. 303–328 (1901).

wise, it is possible to build depressed sandbeds. Other variations are possible, given the incentive.

22. TEACHING POSSIBILITIES

A great many of the simpler fluid mappers can be made up easily and cheaply. Their visual appeal is very high indeed. There is no reason why these teaching aids should not be adopted wherever a better understanding of field situations can help students, at any level.

Note added in proof.—Since writing the paper, it has been found: (a) that a line of Silicone DC4 applied to the dry lower side of a rubber barrier and gently pressed by the plate, makes a good seal; and (b) excellent 35 mm color slides (Ansco Daylight) are made, using blue photofloods.

High Inverse Voltage Germanium Rectifiers*

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(Received January 17, 1949)

Rectifying current-voltage characteristics going up to several hundred volts inverse have been observed in metal-germanium point contact rectifiers. A reproducible negative differential resistance region occurs in the inverse characteristic. Certain impurities are desirable in producing high voltage material. Surface treatment, e.g., by etching, is very important. The metal used as a whisker has little effect. Increasing the force of contact increases greatly the current of low voltages but has less effect on the high voltage curve. Pronounced improvement of rectification can be effected by treatment of the contact with large currents.

Variation with temperature is very marked, especially for crystals of large inverse resistance; the variation of the inverse peak with temperature indicates that contact heating is responsible for the negative resistance. Time lags in the inverse negative resistance region of the order of 10^{-5} second occur.

When contact is made between two Ge crystals, typical inverse characteristics are observed in both directions. Photoelectric effects are observed and indicate that the barrier thickness is greater the higher the inverse peak voltage.

I. INTRODUCTION

CONTACT rectification between germanium crystals and metals has been known since the work of Benedicks.[1] Merritt[2] also did extensive work on this problem. In 1942, when germanium rectifiers were found, by the Sperry Research Laboratories, to be useful at microwave frequencies, a group at Purdue, working under the direction of K. Lark-Horovitz (contract with NDRC Division 14) undertook to develop such crystals for use in radar.

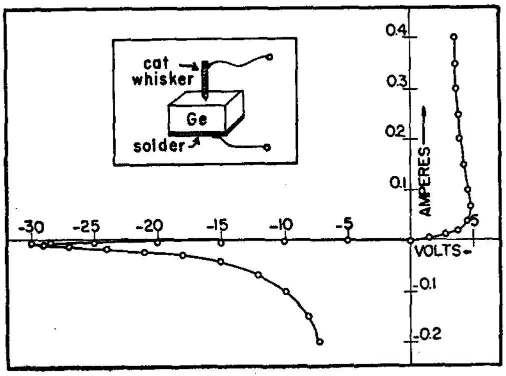

Fig. 1. Double-valued current-voltage characteristic for metal-germanium contact (inset). Polarity of the applied voltage refers to the metal.

In the course of the investigation of these rectifiers, it was necessary to determine the characteristics of germanium in "burn-out," as the destruction of rectifying properties by excessive power is called. When more than a few volts were applied to crystal rectifiers made with germanium, interesting current-voltage curves were observed (1942) which became the subject of this study. Figure 1 is an illustration of the type of characteristic which is referred to. As the current through the crystal was increased, the voltage would go through a maximum and then drop again, thereby giving a negative resistance characteristic which persisted as negative up to high currents. This effect was most marked in the high resistance or inverse direction (metal negative with respect to the germanium), but also could be observed in the forward, although at voltages and currents widely different in the two directions.

There were uses for crystals which would maintain a high resistance up to large voltages of one polarity, while having a low resistance for the other polarity. Thus, the investigation of the properties of these crystals and the mechanism responsible for the high inverse voltage characteristic became of interest. During studies on the effect of air on contact rectification in germanium, Lark-Horovitz and Whaley[3] found that

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* Based in part on Purdue University NDRC report 14–323, November 1, 1944, entitled, "The high voltage germanium rectifier" and on a thesis submitted in partial fulfilment of the requirements for the M.S. degree at Purdue University. This is paper No. 8 of a series of studies from the Purdue Semiconductor Laboratory.

** At present on leave of absence at Oak Ridge National Laboratory.

[1] C. Benedicks, Int. Zeits. f. Metal. 7, 225 (1915).

[2] E. Merritt, Proc. Nat. Acad. Sci. 11, 743 (1925).

[3] See final report (reference 4), also R. M. Whaley and K. Lark-Horovitz, Phys. Rev. 69, 683 (1946); and R. M. Whaley, Ph.D. Thesis, Purdue University, (February, 1947).