THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

FLUID MAPPER MANUAL

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FOREWORD

A fluid mapper is a device in which streamline fluid flow in a thin flow space portrays some potential field. The flow pattern is made visible by use of dyelines. Examples of potential fields are current flow fields, magnetic fields, electrostatic fields, and heat conduction fields. Some 60 years ago, Professor Hele-Shaw pioneered in this line of work at Oxford, England. His results were admirable, beautiful, and accurate, and they received much acclaim at the time. Unfortunately, his techniques were so inflexible that they were not carried on. In 1948, on learning to work with plaster, the writer began to revive fluid flow simulations in terms of what he has called fluid mappers. Plaster is an extremely adaptable material, lending itself to the making of a great variety of fluid mapper slabs for many different purposes.

The publication of the papers cited herein aroused an interest measured by the fact that the writer has given, throughout the country, 69 Fluid Mapper Lecture-Demonstrations at conventions, colleges, industrial firms, and government and private research units. So many requests for information came in that in 1952, a Dittoed set of instructions was prepared for sending out, under the title, "Starting a Fluid Mapper Laboratory." It was intended merely as a stopgap, to serve until a Fluid Mapper Manual could be written. This was long delayed, for two reasons. First, time has not permitted. Second, the writer has had fluid mapper techniques under almost continuous development for these 12 years; the invention and development of better techniques and new techniques would have rendered any early Manual obsolete.

Meantime, fluid mappers have increasingly been adopted by industry, for solution of difficult problems; by college departments, for teaching; by students, for thesis projects, or, simply to learn the techniques and enjoy the experience; and by high school students working up projects for the annual Science Fairs.

Fluid mappers have three values, all different, and each very real. First, no one ever gets the "mud pie complex" out of his system, just by growing up; and there is a deep satisfaction coming from working with plaster - it satisfies the creative instinct we all have. Second, and esthetically, fluid mapper patterns have a superb beauty that can only be appreciated by being seen. Third, technically, pattern copies from fluid mappers built to simulate actual cases can be mapped and then analyzed for numerical answers to exceedingly difficult field problems.

No one need be scared away by the thought of starting a fluid mapper laboratory - quite otherwise. Many a "laboratory" has started in the home at the kitchen sink - with a couple of pieces of glass and a very few accessories. Fluid mapper laboratories range from the kitchen sink type, to highly developed industrial fluid mapper laboratories designed to work on specific types of problems.

This Manual sums up 12 years of almost continuous invention and development of numerous fluid mapper techniques. Some of the difficulties of making and operating mappers were quickly solved. Others remained baffling for long periods, waiting for the right ideas to come. The entire story of the development of techniques - failures as well as ultimate successes - would fill a book. It has been a most fascinating and rewarding experience.

What this Manual does is to tell how to make and operate fluid mappers. With it, the high school youngster can soon learn how to make up an exhibit for that Science Fair: or the professional, how to build a highly sophisticated mapper for solving his vexing field problem.

The Manual does not go on to tell the professional how to proceed, after mapper operation, to map the pattern and analyze it for the answers he needs. The writer needs more time for preparing such a work. Meantime, the professional has access, in his company or university library, to those of the writer's published papers that bear on these routines. The papers are listed at the end of the Manual.

The content is arranged so that Part One, the first half, gives the beginner everything he needs to know to make simple mappers and get them into operation. Once the beginner achieves some success, his enthusiasm will carry him into Part Two, to learn additional techniques. Also, Part Two covers more complex Type 1 mappers; Type 2 and Type 3; and other items of more advanced character.

Until 3-dimensional work is taken up in Part Two, all mappers described are 2-dimensional.

One more word: fluid mappers need the interested attention of many workers in many types of endeavor. It is as certain as can be that here and there, still more techniques will be invented or discovered; and we need all of the techniques we can get.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

PART ONE

TYPES OF FLUID MAPPERS

Types of Potential Fields

Potential fields in science and engineering occur in almost endless variety, and it is impossible to type them into a few simple classes. Therefore, since it is the technical purpose of fluid mappers to solve potential fields, fluid mappers likewise cannot be simply classified.

A rough typing is essential, however. A Type 1 mapper has a slab without a sandbed. That is, it has simple sources or sinks, and the field portrayed is all Laplacian. A Type 2 mapper has a slab with a sandbed (one or more), with the sandbed simulating a distributed source; and the field over the sandbed is Poissonian. A Type 3 mapper is all sandbed: all distributed source, with no slab around it.

In applied work with mappers, the solution of a potential field situation of course requires that the mapper be built to scale, either full-size; or else, to a larger or smaller scale as need be.

A FLUID MAPPER

Basic Components of a Fluid Mapper

A fluid mapper's basic components are shown, except for the tanks, in Figure 1. There is a plaster slab, with one or more wells (this one has two round wells). Supported somehow, and slightly above it, is the plate: a piece of plate glass. The combination is in a tray, where it operates completely immersed. Water is the typical operating fluid. The wells have bottoms. A rubber tube is connected to a well, and this tube's other end goes to a tank, not shown. When tank water level is above or below tray water level, streamline flow occurs in the thin flow space between plate and slab. The flow pattern is invisible, until made visible by dye-lines. These are typically made by having sprinkled potassium permanganate crystals, before the plate is put in place.

To create the flow spacing, small spacers can be placed directly on the slab, and the plate allowed to rest on them. Such spacers do interfere, locally, with the flow pattern. In Figure 1, the spacing job is done outside of the slab boundaries, by techniques described later on.

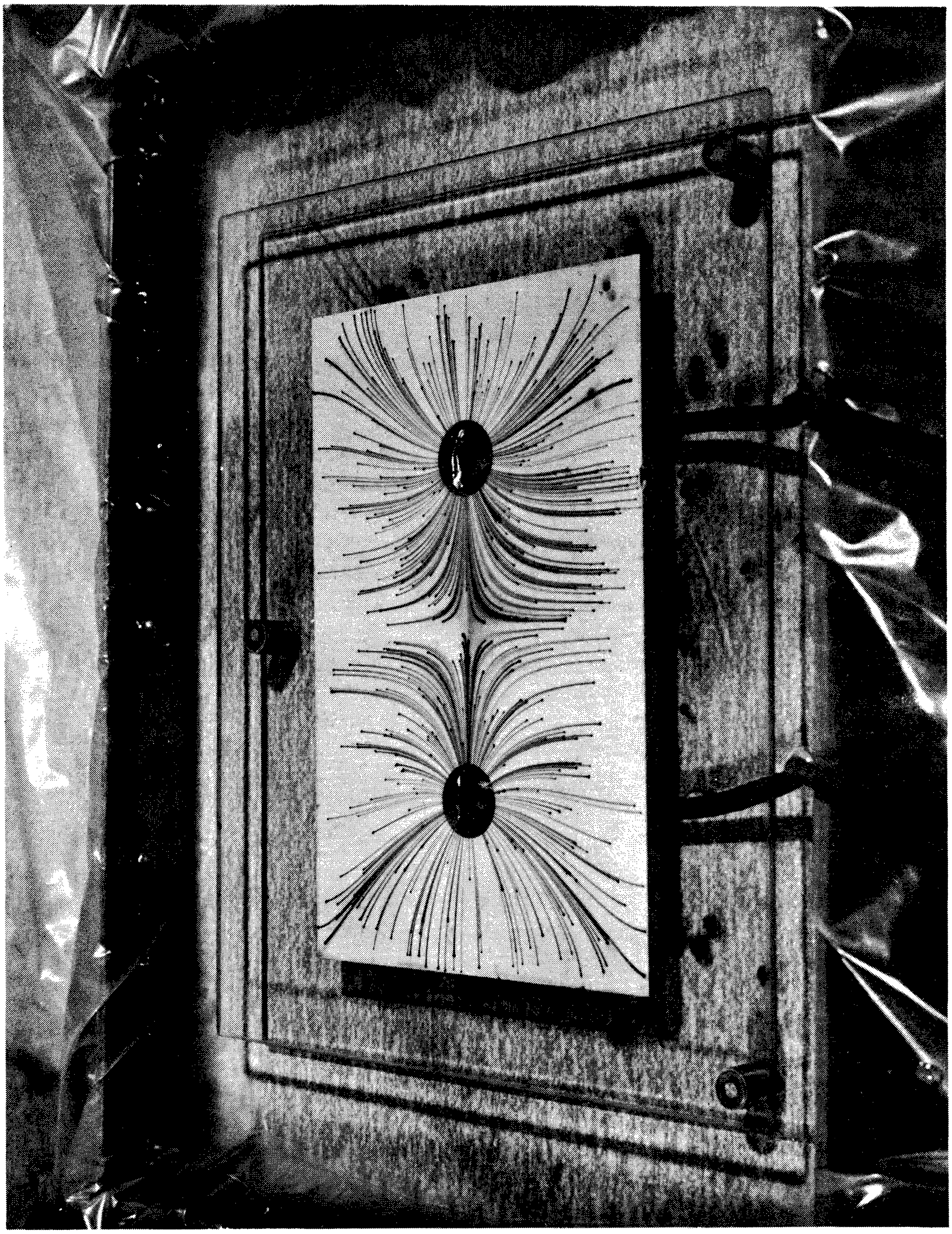

Figure 1. Fluid mapper operating in tray of plastic sheeting and Masonite.

Plates

Good fluid mapper work calls for plate glass, for ordinary window glass is not flat. Plate glass is ground and polished. Nearly all plate glass is flat enough for fluid mappers. Old plate glass, even though somewhat scratched, normally serves very well. However, for accurate work, the glass known as Parallelo-Plate is best: it is simultaneously ground on both sides, so that the two surfaces not only are flat, but also parallel. Firms that install windows can cut plate glass to any size, and also smooth the edges to remove sharp corners.

A typical fluid mapper, Figure 1, needs a uniform thin flow space. Once the plate is bought, the uniformity comes at no extra cost, because the plaster slab itself is cast directly on the plate.

Should the Mapper be Carefully Leveled?

This question is cited here, because so many who witness demonstrations do raise this very point. The answer is: No. The mapper operates completely immersed, and does not need to be level. In fact, with a very deep tray, it could operate in a vertical position, or upside down, or at any angle.

There is one exception to be noted. The foregoing is true, if dyelines have the same density as the surrounding undyed water. Presumably, almost any dye will bring in some slight difference in density, and operating with a grossly unlevel mapper might result in some error. For all practical purposes, any ordinary table, no matter how warped, will serve to make the mapper sufficiently close to level.

PLASTER

Gypsum Plaster

Gypsum is the parent for many plasters. The mined product is heated to drive off water. If water is added to the calcined powder, the result is the plaster mix. Plaster of Paris, wall plasters much like it, and certain industrial plasters, are calcined at atmospheric pressure in the old way. They are excellent for their intended uses, but are weak and relatively porous. They can be used for fluid mapper slabs, and successfully. But much better slabs are made of alpha-gypsum plasters.

Alpha-Gyspum Plasters

A newer method of calcining the natural gypsum is to use heat, and steam pressure. For alpha-gypsums, much less water is needed for the mix, leading to a cast that is much stronger, less porous, and in some cases, having much lower setting expansion.

Dental Stone

Dental stone, so-called in the dental profession, has an alpha-gypsum base. It is strong, hard, and has low expansion. Among the dental stones, Duroc (made by The Ransom and Randolph Co., Toledo, Ohio) is the hardest, strongest, and expands least. It is the preferred stone for slabs. It sets in from 10 to 20 minutes. The cost is roughly 15 to 25 cents per pound (or pint) of powder, depending on quantity. Cast on glass, it has almost a mirror surface. Cast on a piece of wet paper, it will copy the watermark.

Herein, when the word plaster is used, it stands for dental stone.

Getting Used to Plaster

Some experience with plaster should be had, before a slab is attempted. Add powder to a little water in a bowl, and stir. Make it quite stiff. Stir until the lumps are gone. Dump a spoonful onto a plate. The mix is stiff enough to stand up. Jiggle it a bit with the spoon and watch it settle down. Next, add water to the remaining batch, stir, and make the mix quite thin, or runny. Pour some of this onto the plate. Observe that the stiff mix sets first. However, the thin mix will also set. Another thing; the stiff mix will be the stronger of the two. Thus, there is a wide latitude as to stiffness or fluidity of the mix, within which successful castings can be made. In general, the batch for a slab should not be so stiff that it reluctantly flows into place when jiggled; nor should it be so thin that it pours like thin cake batter.

After the two little cakes have hardened, they will be stuck so tightly to the plate that they cannot be removed. Wet them - and they slide off at a touch!

Now mix another little batch of medium stiffness, and make several little plaster cakes on the plate, all alike as to water content.

Watch them. Glistening at first, they all become dull as excess water is taken in during setting. They are still very soft. Then they get harder. When fairly hard, yet easily scratched with a fingernail, wet one and remove it: there will be a smear. It was not really hard-set at all. As setting proceeds, wet and remove the others, one by one, until one of them does not smear. The important lesson to learn here is that a stage comes in the setting of a slab when it seems quite hard; and yet, if wetted and removed from the plate, the accurate surface is smeared by too early removal.

Manipulating Plaster Before Setting

One of the ancient arts is, of course, based on the manipulation of plasters having a delayed setting time, to produce anything from flat plastered walls, to complicated decorative items. Likewise, there are times in fluid mapper work when something can most easily be done by using spatula, knife, spoon, or other suitable tool, to shape some part of the plaster when it is becoming stiff, but before actual setting has taken place.

Properties of Plaster Casts

A plaster slab looks so solid, that those not familiar with plaster casts tend to think that plaster is impervious. The fact is, it is a sponge: it amounts to millions of interlaced crystals, with spaces between. When wet, the spaces are water-filled; when dry, air-filled. When a dry slab is to be used again, it must be completely soaked before use. Otherwise, air continuing to come out will form bubbles in the flow space, and ruin the flow pattern. Soaking may take from ten minutes to half an hour.

A dry slab will keep forever. But calcium sulfate is slightly soluble in water. Therefore, whenever a slab is soaked, or operated with water, the surface is going into solution, and eroding. However, the erosion is so slow that if a slab is to be used only a few times, or operated for a total of perhaps an hour or two, erosion will be too slight to worry about. In fact, the mirror surface of a new slab very soon disappears; and with continued operation, the surface may seem quite rough to the touch. But as long as it is essentially flat, fluid mapper accuracy will be unimpaired.

When a demonstrator slab is to be used many times, as in teaching, then soaking should occur in saturated water. Add a little plaster powder to a vessel of water, and occasionally stir for the first half hour. Then let the excess plaster settle. Saturated water will hardly affect a soaking slab.

Another precaution: do not stack wet slabs, one on top of another. At the pressure areas, some sort of re-crystallization occurs, a transfer of material takes place, and surface flatness will be destroyed. Dry slabs can be stacked.

When new plaster (such as feet) is added to a slab, it will not bond if the slab is thirsty. The slab must be thoroughly water-filled, but not dripping.

Tooling of Plaster Casts

Not only is plaster extremely adaptable for making casts. The casts themselves can be further modified by tooling in one way or another. Carving with a knife can bring a well boundary out to the exact limit, after the well is deliberately made too small when using a convenient but inaccurate well mold material - modeling clay or Styrofoam. Incidentally, with Duroc, carving is much easier when the cast if fresh and relatively weak.

Cutting can be done on the bandsaw. Sanding with a sanding wheel, or by hand, is an available process. When one of the writer's flatfaced demonstration slabs becomes too much eroded from use, it is reclaimed by skating it around, face down, wet, on wet-or-dry grit paper which is supported on a large flat surface.

Using a flexible shaft equipment, grinding wheels, burrs, and fluted cutters can handily make small modifications in a slab cast, that otherwise might be tedious to bring about.

Small round wells: instead of using well molds, these are often best put through the slab blank on the drill press. Plaster can be drilled wet or dry. Flutes in the drill tend to choke up, and this should be watched for.

If several small wells are to be equally fed from a common chamber below, drilling such holes will result in inequality of performance, for the drill will break out, on emerging from the bottom of the cast. It took a long time for the writer to think of a simple way to stop this. The method is to cast a temporary pad of plaster onto the bottom, where the drill would emerge. It is made flat by the squeeze technique, to make it rest flat on the drill press table. The drill now goes on into the pad instead of breaking out. The pad is then knocked off.

Plaster Setting Time

Duroc cast on a plate will set hard enough to permit removal without smearing, in 10 to 20 minutes. Setting is accelerated by having the mix warm and stiff; retarded by being cold and thin.

If plenty of time is needed for manipulating the mix into the mold, on an elaborate slab, setting time can be prolonged by adding a few drops of sodium hydroxide per ounce of water, to the water before adding the powder. Tests should be made with little test slabs, to find the formula to fit the time needed.

Disposal of Extra Plaster Mix

Unless there is a great regard for plumbers, left-over mix will not be washed down the drain. It soon ceases to be a drain. An old, flexible plastic bowl can be assigned to the duty of washing receptacle: mixing bowls and spoons are washed in it. The plaster will harden in the bottom, but this can all be broken out later.

COMPLETING A SLAB

The Slab Blank

Logically, all of the operations for preparing to cast the primary slab or slab blank, and casting it, would now be described. This will be put off until later, in order that the reader may be given a general picture of finishing and operating a slab as early as possible. Also, some finishing techniques can best be described at once, with the properties of plaster fresh in mind. Assume then that the blank is ready. In Figure 1, it is a rectangular blank with two round holes or wells. In Figure 2, it is a five-sided blank with three wells. In all cases, the blank is cast upside down (inverted) on the plate.

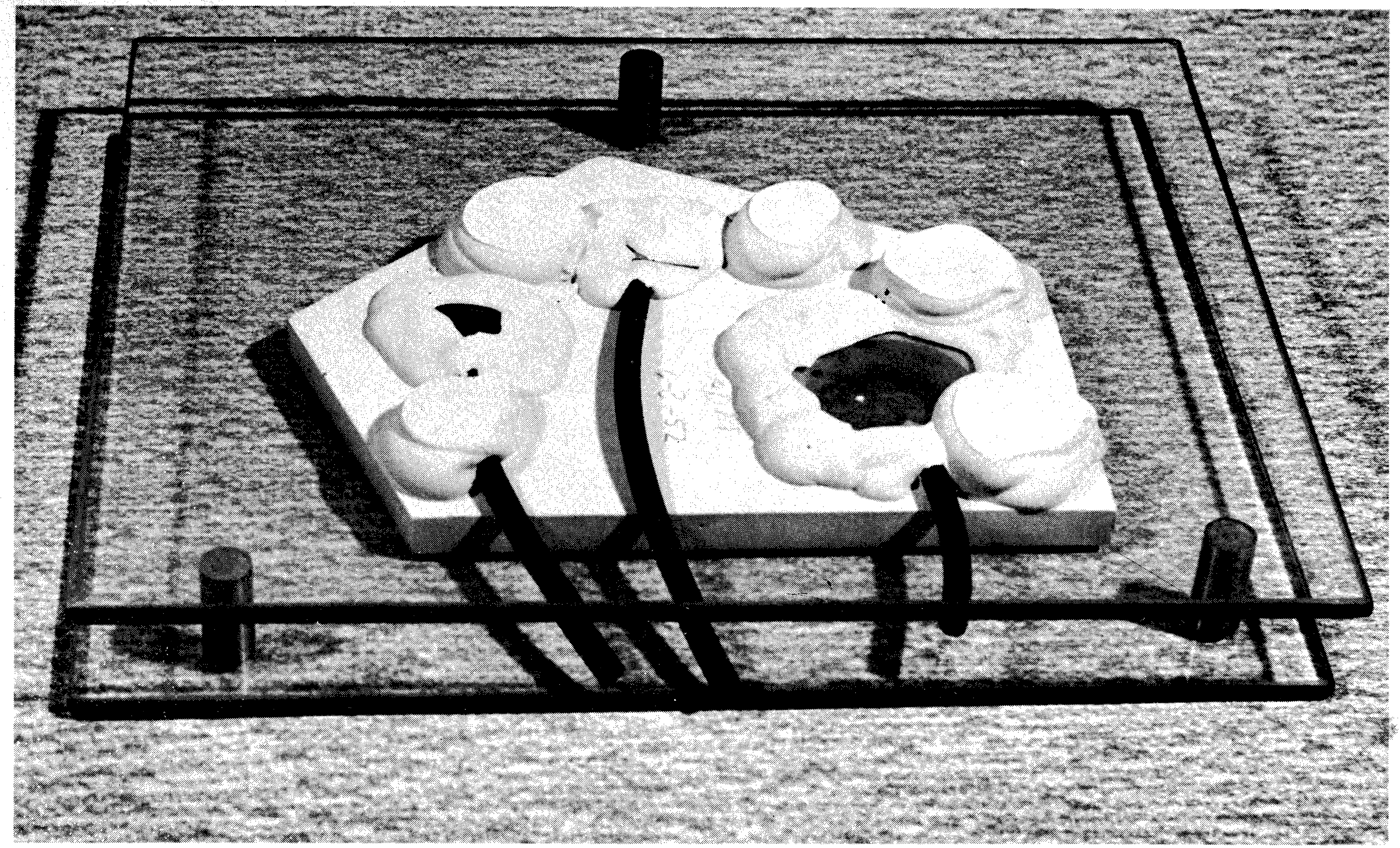

Figure 2. Finished plaster slab, with accurate feet being formed by the squeeze technique.

Connector Tubes and Well Bottoms

In Figure 2, imagine that there is nothing to see but the slab blank resting, bottom up or inverted, on a plate. It is fully wetted, but not dripping.

Well bottoms have been prepared. In this case (a 1952 slab) they are celluloid, cut big enough to cover the wells and with some excess. They have been heated, then bent up at one side to admit the rubber connector tube. Aluminum bottoms are nowadays preferred. Pies and cakes now come to the home in thin aluminum containers - admirable stuff for well bottoms. After cutting a bottom, one side is placed over the lead end of a pencil and pressed down over it, to form a place for admitting the tube.

Some plaster is now mixed. A tube is wetted near one end, to make plaster "take" to it. A plaster coating is applied to its outer surface for a half inch length at the well end. It is laid in place, with the tube end at the well edge. The bottom is placed over it, and plaster is applied all around the well bottom. This operation alone shows how very easy it is to do things with plaster, that could otherwise be costly and time-consuming.

Special Bottoms

Unusual problems can arise with some slabs, as to well bottoming. It is sometimes necessary to manage a streamlined approach, from connector tube mouth to a well; or, a common chamber to feed several small wells may be needed, and presence of other well feeds may interfere with building a simple large chamber. These special needs are often met by the techniques now described.

Roll out modeling clay to about 1/4 inch thickness. Then cut a strip from it, long enough, and about 1/4 inch wide. There can be wide departures from these suggested measurements. Now lay a strip on the upturned bottom of the blank, from one side of the end of the connector tube, to the well, around the well, and back to the other side of the tube. Plaster the tube end in place, and put plaster all around the outside of the strip. Let this plaster set.

Now cut an aluminum bottom to lay onto the strip, cutting it so that its edge is everywhere (very roughly) halfway out over the strip, and the end covers the tube for half an inch. Plaster all over it, and down over the tube and the strip. Complicated chambers are easily constructed in this manner.

This device can also be used to increase the depth of a well, in the rare case when a half-inch well depth is not enough to make flow resistance in the well negligible.

Accurate Feet: The Squeeze Technique

The slab needs feet. And, for the off-slab spacing technique, it needs accurate feet, such as are shown in Figure 2. If the plaster mix just now used is a little too thin to stand up well, some powder is stirred in to stiffen it.

Before adding the feet, inspect the blank again for wetness. If this is a new blank, being finished as soon after casting as possible, it is still in the very late stages of setting, and of taking up water. By now, it may be thirsty again. Water can be added most easily by painting it on with a brush. Mop off the excess.

Four piles of plaster are now dripped from a small spoon, piled up (Figure 6) higher than the feet will eventually be. The three posts, all of the same height, are set out on the plate, Figures 2 and 6. A second plate is now gently lowered to rest on the posts, thereby squeezing the piles to accurate level. As soon as the added plaster is set, the slab can be operated.

Removing Added Parts

Added plaster parts, such as bottoms and feet, can easily be removed. Simply place the slab face down, put the edge of an old chisel to a foot where it joins the slab blank, and give the chisel a smart rap with a light hammer. The bonds are weak enough to let such added parts pop off. Thus, repairs or remodeling can be handled. Also, record slabs, described later, are more easily stored, handled, and shown, if the added parts are removed.

ASSEMBLING AND OPERATING

Assembling

For assembling the fluid mapper, see Figures 1 and 6, the tray is filled with water, enough to cover the upper plate by about 1/4 inch. A plate is placed on the tray bottom. The slab is placed on the lower plate. The posts are set out around the slab. Since those posts made the accurate feet, the top plate, if put down, would rest on the slab and the posts, and there would be no thin flow space. Therefore, the spacers (brass washers of equal thickness) are laid on top of the posts.

The two tanks (not shown), each with its long rubber tube, are set on the table. Each tank tube is joined to the slab's connector tube by a suitable nipple. The tanks are partly filled, then elevated to start flow, in order to clear all air out of the system. The tanks are set down again.

Next, potassium permanganate crystals are sifted onto the water over the slab. The wetted crystals sink to the slab surface and wait.

Operating

The plate is now lowered, with one edge immersed first, to avoid trapping air under it. The closer it approaches the slab, the slower it is lowered, to avoid gushing of water that would wash crystals out of the flow space. When it rests on the spacers, the mapper is in operation. Raising or lowering the tanks induces flow. In Figure 1, the tank levels are equally below tray water level, and the wells are acting as equal sinks.

Operating Versatility

Instructors in various technical and scientific areas will be particularly interested in the versatility with which a library of a few slabs can demonstrate field phenomena. Even with one slab, the change of position of islands, or exchange of one island shape for another; changes in temporary barriers; changes in relative rates of flow of two or more wells -- such simple manipulations can visually show a wide variety of effects. Students are invariably fascinated as they see these fields take shape.

SIZE OF FLUID MAPPER EQUIPMENT

Equipment

From having built and operated hundreds of slabs, the writer finds that the equipment now described serves admirably for classroom use, demonstrating to groups, Engineering Open House exhibits, making record slabs, and much of the application work for actual solution of field problems.

The tray (black-finished steel tray for kitchen use), having sloping sides, is 10.5 by 15 inches, bottom measurement, and about 2.25 inches deep. The tray is coated with Krylon, or else painted, to stop rusting. A tray of any size can be made with Masonite strips used as sideboards, Figures 1, 6, and 7, notched halfway into each other near their ends. After erecting the sideboards on a table, the whole is covered with crib lining borrowed from the baby, or plastic sheeting from the 5-and-10. To empty the tank, pick up the four corners and carry the ball of water to the sink. The plates are 10 by 12 inches, and about 0.2 inch thick. Slab blanks, typically 0.5 inch thick or somewhat less, are anywhere from baby size, up to as large as can be cast on a plate. The posts are 1 inch high. The writer's permanent tanks of sheet brass are 3 by 6 by 6 inches high, with nipples soldered into the wall near the bottom. Tanks can be made of tin cans, if coated with aluminum paint to prevent rusting.

The kitchen sink laboratory could reduce the above sized by one-third, reduce the costs, and still get excellent results. In some professional application work, the above sizes may need to be increased.

Next, we take up many of the details of accessories and techniques that up to now have been passed over.

FENCE MOLDS

Straight Mold Pieces

A wide variety of slab blanks having straight sides can be cast in molds assembled from straight pieces. Figure 3 shows how a fence mold rectangle can be assembled from four Ell pieces (L-shaped). An Ell is made of 1/8 by 1/2 inch brass strip, with a brass angle soldered to the side at one end. These are of course completely adjustable for any size slab, up to the limits of the lengths used.

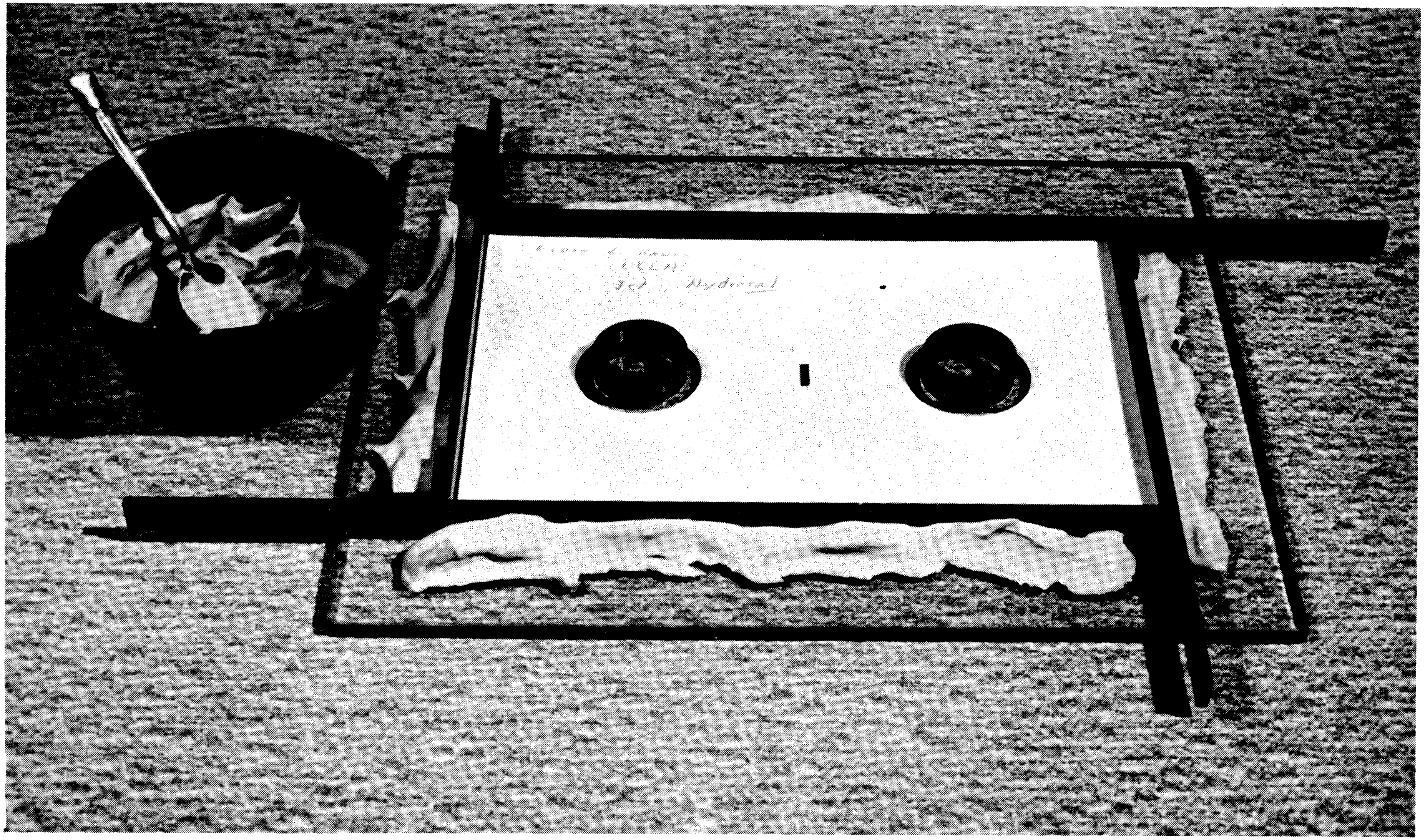

Figure 3. Ell mold parts against template, hollow well molds in template windows. Holding plaster already applied.

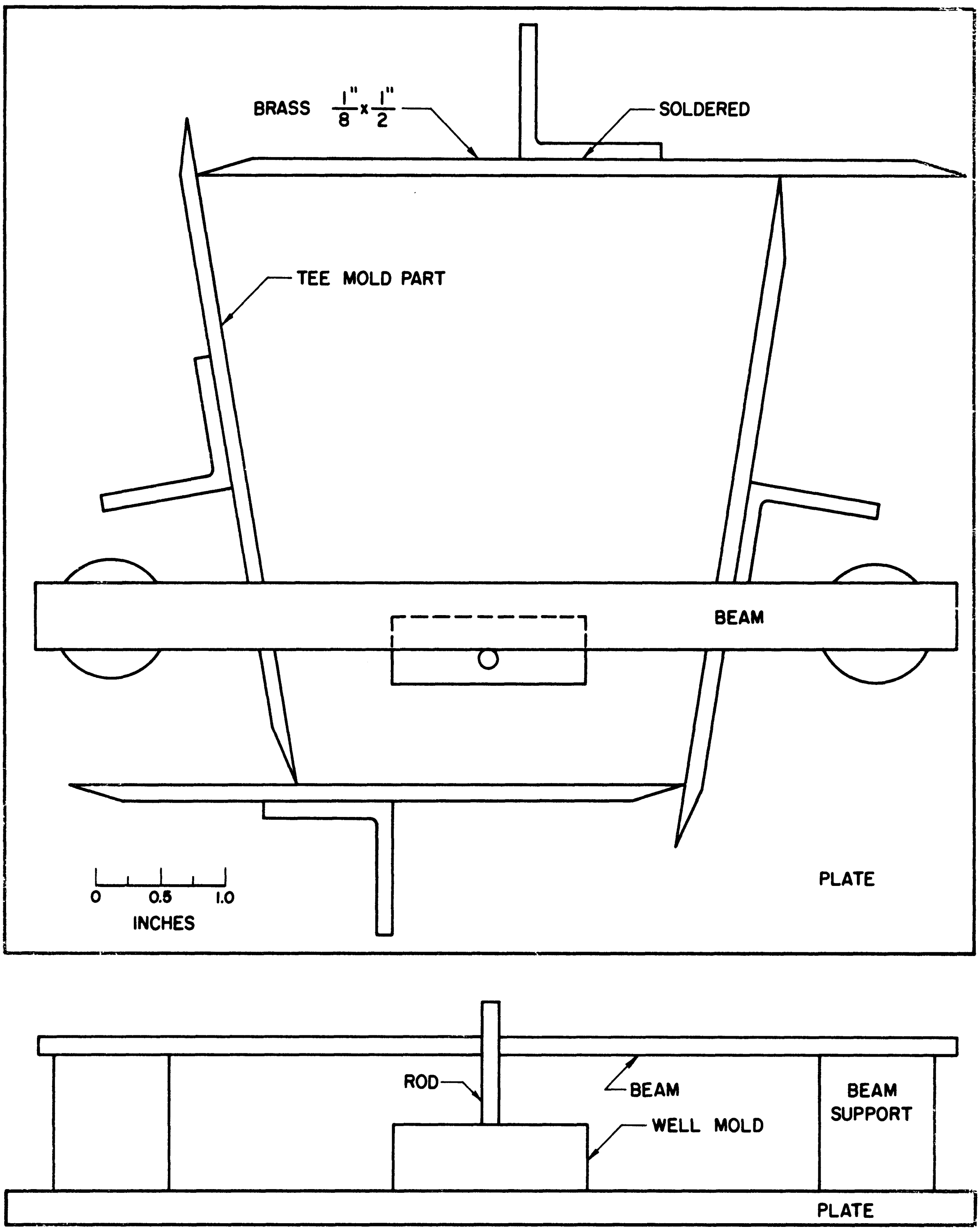

Figure 4. Tee mold parts, arranged to form a trapezoidal slab with a rectangular well. Also, bridging technique for holding well mold. Holding plaster yet to be added.

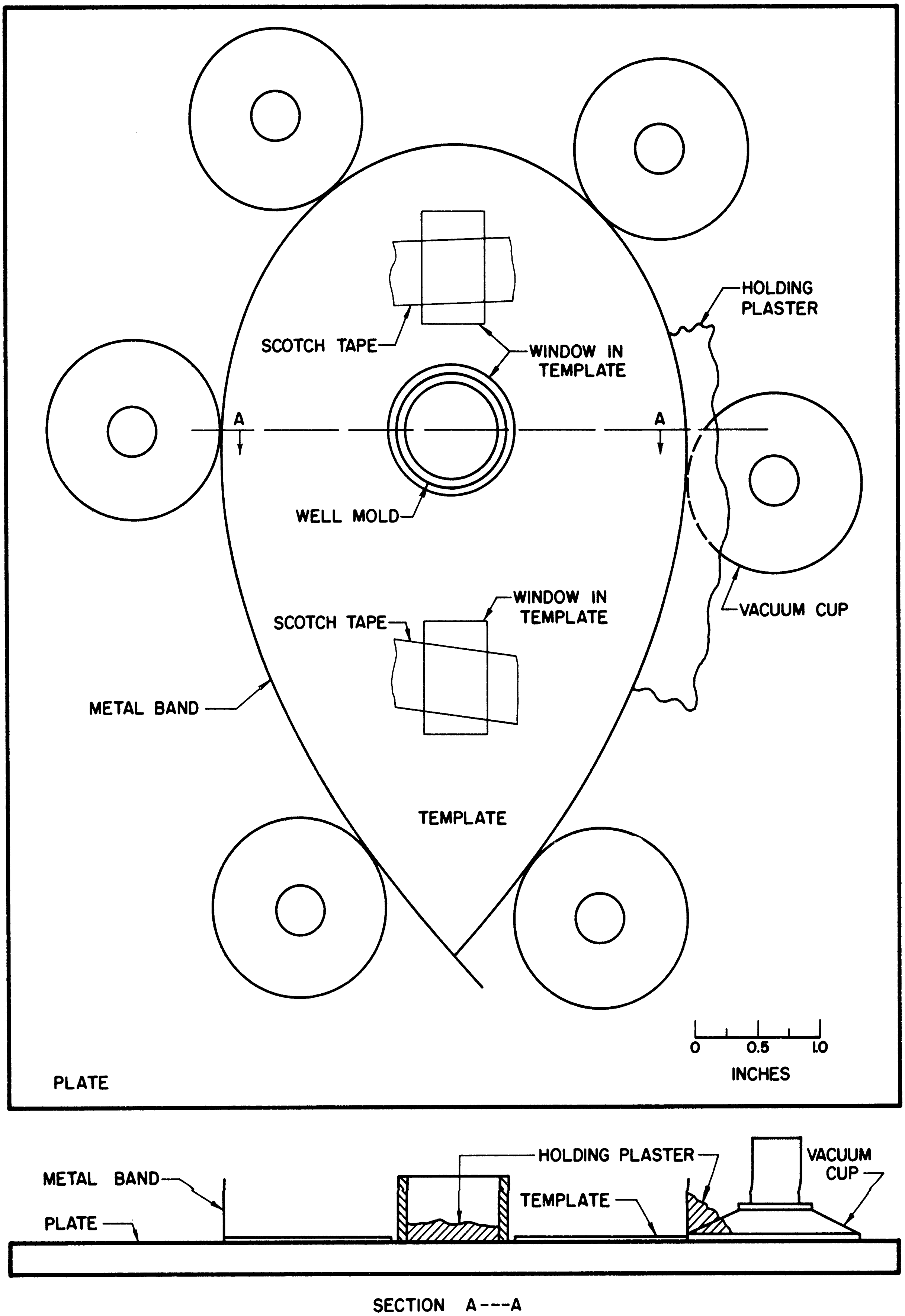

Figure 5. Template and flexible band technique for a curve-sided slab. Vacuum cups on plate hold band to template.

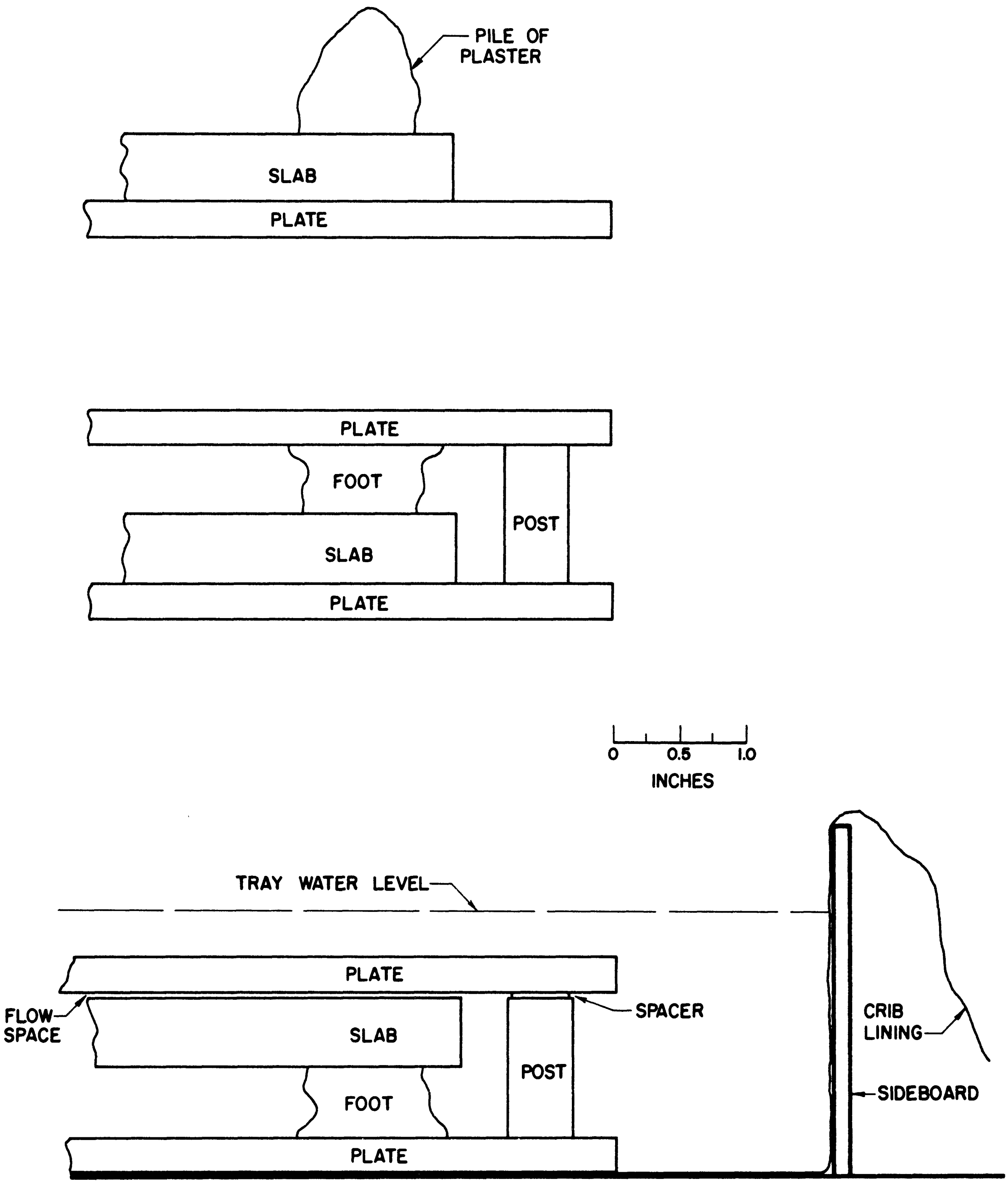

Figure 6. Above, squeeze method for accurate feet. Below, slab in operation; spacers on posts give thin flow space.

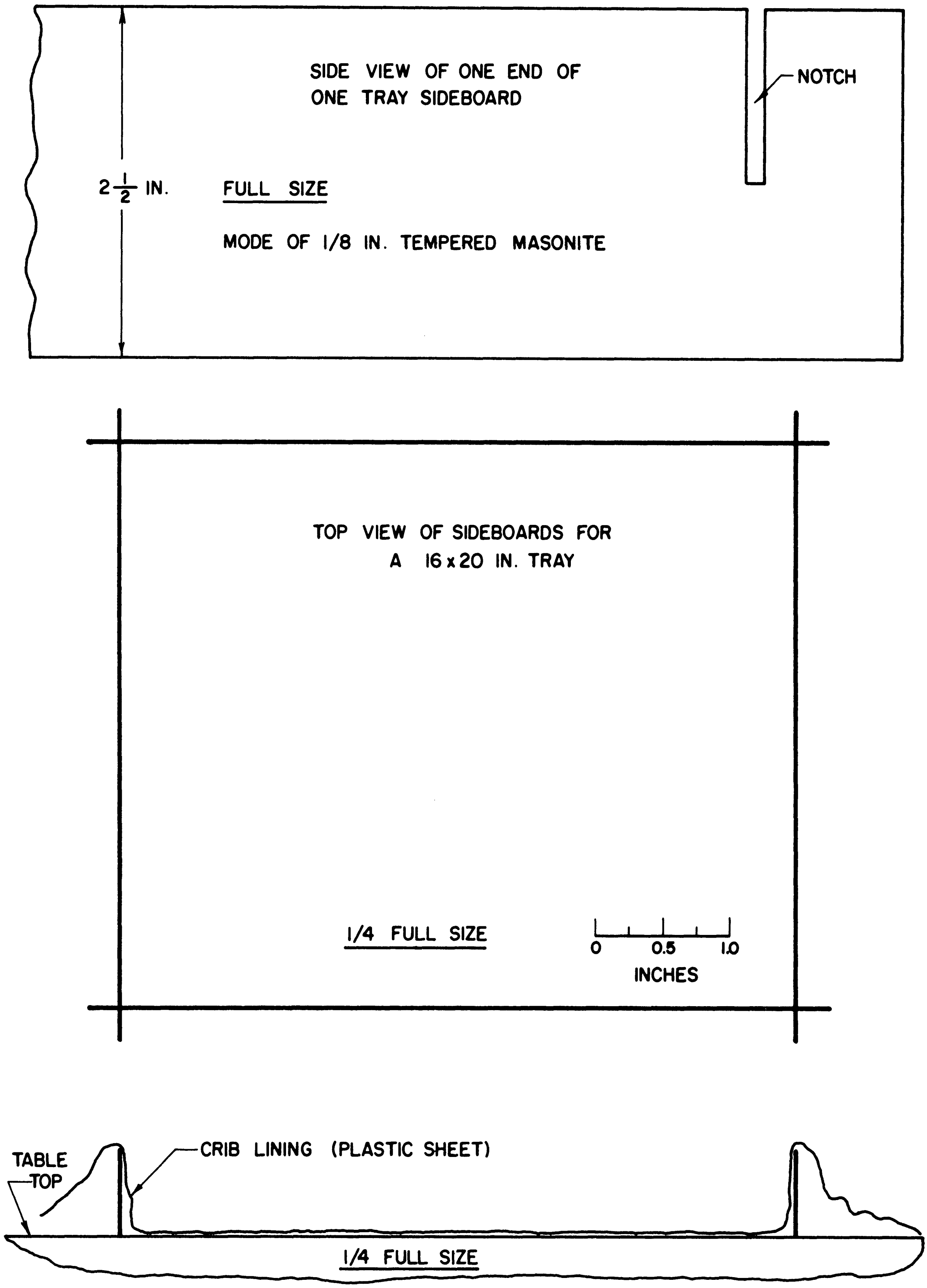

Figure 7. Tray of any size: notched Masonite sideboards, covered with plastic sheet.

Figure 4 shows Tee (T-shaped) mold pieces, with the ends sharpened. These can be assembled to form slabs of polygon shapes.

It is by no means necessary to use the above material, and design, for mold pieces. Square brass tubing would do a job. Stiff strips of Lucite or Bakelite can serve. Sometimes extruded aluminum can be found that can be adapted.

The surfaces of metal mold pieces against which the slab plaster is poured can be lightly greased with petroleum jelly, to prevent sticking.

Placing and Holding the Fence Mold

A drawing of the slab blank can be laid under the plate; mold parts can then be located directly above the lines of the drawing. A different method is to cut a template from pasteboard, Figure 3, lay it on the plate, and bring the mold pieces up to its edges. Windows are cut in the template for well molds.

Holding the mold parts is very simply done with plaster, Figure 3, used as holding plaster. Just lay down some plaster on the plate and up against a mold piece. It is not necessary to go all the way around with the holding plaster.

Molds for Slabs of Any Shape

This is where the mold must conform to a template of any shape, and such a mold must of course be flexible. Thin ribbon of zinc, copper, or aluminum, half an inch wide as it comes, or cut to that width, can be had. Or, one can use strips cut from a sheet of celluloid or thin stiff plastic sheet. The template, Figure 5, has windows cut in it, with sticky tape pasted across to hold the template rigidly in place on the plate. The ribbon or strip is bent around the template to make an approximate fit against it.

Next, Figure 5, we take some rubber vacuum cups (auto supply store is a source), moisten them slightly with soapy water to insure against leaks, and press them down onto the plate. Push them in where needed, to push on the strip wherever it bulges away from the edge of the template, and force it to conform. Holding plaster is now mixed. For this mold, it is laid all the way around. In going over a vacuum cup with the plaster, the cup need not be covered: a ribbon of plaster up over the inner edge will suffice. When the holding plaster is set, the template is lifted. After the slab is poured and set, wetting the holding plaster will let it all come loose, after the continuous ring is cracked at one or two places.

WELL MOLDS

Turned Well Molds

The round wells seen in slabs pictured herein were formed by brass ring molds, turned in a lathe. The outer surface, making plaster contact, has a slight taper. If this surface is lightly greased, such a mold is easily tapped out of the slab blank. These rings are like the Ell and Tee molds - half an inch high. When a template is used, the ring mold is located within a template window, with its small diameter down on the plate. Thus, it is tapped out of the slab bottom, not the face.

To hold the ring mold, holding plaster is dropped into the ring. There is a risk involved in this holding technique, for when the slab is poured, water from the mix may sometimes go under the ring mold, loosen its holding plaster, and let the mold be moved sidewise when - as covered later - one goes after bubbles. Usually, a ring having an inner diameter of an inch or more does not come loose. Smaller rings had better be touched with care; or, checked for position after slab plaster is poured and jiggled; or, the ring can be rigidly held by bridging, as described later.

Modeling Clay

Modeling clay is very popular in early school grades, because it is so highly adaptable. An experimenter should never overlook a highly adaptable material. Wells of varied shapes can be molded from clay. However, if perfection is expected, there will be disappointment. Modeling clay simply refuses almost all efforts to make it accurate, in fluid mapper work.

Once this fact is learned and accepted, modeling clay becomes a welcome addition to our family of materials. A cake of the clay can be rolled or pressed to the half-inch thickness, approximately. When the thickness is down near to that, lay a piece of paper on a plate, lay the cake on the paper, and finish getting it down to the desired thickness.

Next, a paper template is cut to the desired well shape, but: it is made about 1/16 inch too small, all around. This is lightly pressed onto the cake. With a sharp, thin-bladed knife, remove slashes of clay until there is no more than about 1/8 inch to remove. Now, without much deformation resulting, the remaining clay around the template can be shaved off. The template is removed. The cake is lifted, and the lower paper removed. Without the lower paper, the cake would be stuck to the plate, and might be considerably deformed when removed.

The clay mold is now placed on the plate where the slab is to be poured - above its position on the drawing, or within a template well window. It will stick, if gently pressed down. Any serious deformations can now be dressed up with a knife point.

The well thus formed is deliberately made too small. While the slab blank is still fresh, one takes a knife and carves the upper lip of the well to correct dimensions. It may be necessary to have an extra template at hand, to use for putting a pencil mark on the blank's face, thus accurately laying out the line to which to carve.

The kitchen sink laboratory can have an advantage in hot weather, for warm modeling clay can be vexing stuff to work with. Too soft and sticky. Chilling in the home refrigerator will cure that trouble.

Styrofoam

The writer's latest answer to the any-shape-of-well problem, is Styrofoam. It is available in thick slabs, especially at Christmas time. The writer built a hot-wire cutter which has a large smooth surface. Across one end is a spring-stretched No. 24 Nichrome resistance wire, adjustable as to level. This is the slabber. With a few amperes, the wire is hot enough to slice half-inch slabs from the large parent slab. Near the other end is the trimmer: a vertical wire, for trimming the mold piece's sides to any desired shape. An even better job of trimming is done on a Dremel jigsaw. Trimming can also be done with knife or razor blade. This requires practice, for Styrofoam tends to pile up ahead of the blade, crushing and tearing.

Like clay, Styrofoam is inaccurate stuff. Such well molds are made a little small, and well boundaries are later brought to correct limits by carving, grinding, use of high-speed cutters, and so on.

Styrofoam on glass is a very slippery combination. Also, unless rigidly held, it is so light that when plaster is poured around it, it would float. It must be held in place by the bridging technique, described below.

Styrofoam well molds have to be slashed and cut out of the slab with a sharp knife.

Bridging

The purpose of bridging is to hold objects - such as well molds - fixed, while slab plaster is being poured and manipulated. It may sound complicated. In fact, it is very simply and easily carried out.

Suppose, Figure 4, we wish to use bridging to fix the well mold. On each side of the fence mold, out on the plate, we set down a beam support - a post about an inch high. These two posts can be anything handy. Then a strip or bar of something fairly rigid is laid on the posts, as a beam, spanning the fence mold, and located above the well mold. The writer often uses one of the brass Ell mold pieces for the beam. Next, a piece of scrap metal such as a brass rod is placed so that its lower end rests on or in the well mold, with its upper end leaning against the beam. Now comes holding plaster. Some of it is dripped down over the posts onto the plate, with the beam also covered where it rests on the posts. Some more is carefully dripped on the beam above the well; coaxed from there down the piece of scrap metal; and onto or into the well mold. When plaster sets, the mold is firmly anchored to the beam, and the beam to the plate. The holding plaster is easily cracked off after the slab blank is cast and set.

CASTING THE SLAB BLANK

The Plaster Mix

After the mold is ready, plaster for pouring can be mixed. The quantity needed is figured from knowing the cubic inches required, there being about 29 cubic inches to a pint. A pint of powder will make about a pint of mix. Allowing 6 ounces of water to a pint of Duroc powder will usually give a satisfactory mix. Pour the powder into the water, and stir with a spoon until the lumps are gone. As mixing proceeds, water or powder can always be added, if the mix is too stiff or too runny.

Ladle the mix from bowl into mold with a tablespoon. Use a smaller spoon, or a small spatula, for putting plaster into narrow mold spaces. If there is a large open area, pour directly from the bowl. Spread the mix around until all of the plate area in the mold is covered. Proceed thus, to place a half or two-thirds of the mix.

Removing Air Bubbles

Air bubbles will now be trapped in the corners, and on the plate. Using a small stiff brush, rapidly probe down into the plaster, all along the mold parts. Probe down in, jiggling the brush as it is moved along. Bubble cavities at the edges of the blank's face are thus prevented.

Now add the remainder of the mix, or as much as is needed, placing it where needed. Use the spoon, with spreading and jiggling movements, to make the plaster spread fairly uniformly. Next, go rapidly all over the mold area, with spoon bowl partly immersed, making small up-and-down movements. Air bubbles trapped on the plate are made to rise into the mix, where they will do no harm.

Finishing the Slab Blank Bottom

The bottom of the blank is now, of course, on top, since the blank is cast inverted. The bottom of a Type 1 slab needs no special attention as to finishing. If it is fairly level and smooth, accessories such as well bottoms can be plastered on with entire success. If the blank is 3/8 inch thick or more, wells (unless very large in area) will be deep enough so that flow resistance in a well is negligible compared to resistance in the thin flow space - thus insuring that the well boundary will be an isopressure line.

A Type 2 slab (with a sandbed) is a different matter. A representation of a uniformly distributed source calls for a uniform sandbed, and that calls for a sandbed of the same thickness everywhere. In this case, the mold is filled pretty uniformly to its full half inch height; and around the sandbed well mold, slightly over-filled. Then, as the plaster reaches a soft set, the excess plaster around such a mold is scraped down to a uniform level with the edge of a putty knife. It is against this surface that the sandbed screen will be placed, and to which its margin will be plastered.

Also at the time of soft set, a pencil can be used to write into the slab, its identification: date, number, and so on.

Final Operations on the Blank; Finishing the Slab

The reader is again warned about wetting and removing a blank from the plate too soon, for smearing of the flat face may ensue. First, the slab blank will become quite hard; but only later will the heat of setting become quite evident to the touch.

When the heat is quite evident, it is safe to wet the fence mold holding plaster, and remove the fence mold. The blank is still tightly stuck to the plate. It is now convenient to run the point of a knife along the edge where needed, to cut away any fin, due to mix running out under a mold piece. Any further dressing down of the exposed blank bottom is also easy at this stage.

The whole blank is now wetted and slipped off. Well molds are removed. The blank is inspected for any remaining fin to be removed. If clay or Styrofoam well molds are used, they are dug out; and the fresh, weak slab is carved to bring well boundaries to their precise limits.

Next, it is most important that all bits of plaster be washed from the blank. If one tiny fragment of loose plaster is left on the flat face, it will spoil the accuracy of the accurate-foot technique.

The blank is now placed face down on a clean plate, ready for the addition of connector tubes, well bottoms, and accurate feet, as already described.

Warning repeated: this is a fresh slab, and for quite a while to come, it will get thirsty. Make sure it is wetted before adding new plaster, else the bond will be weak, or entirely absent.

Baby Slabs

When the beginner has read this far, he may feel ready to go right ahead and make a full-fledged slab. It is recommended that instead, he should get some more experience with plaster in a very simple way, by making baby slabs. For the well, press a lump of modeling clay onto the middle of a plate, squeezing or carving it to make a cake an inch or so wide and roughly a half inch high. Cut a piece of rubber tubing, perhaps six inches long. Stick a short piece of 1/8 inch brass rod (or wooden stick) into one end, letting it project a little from the tube. Push this combination into one side of the clay cake. Mix some plaster, fairly stiff. Pour it down over the well mold and out onto the plate in all directions. Be sure the plaster makes an all-around seal for the rubber tube at the well. The tube at the well mold should be wetted to make sure it takes the plaster.

Now pile up plenty of plaster on top of the mold region. Set out the three posts on the plate. Bring down the second plate to rest on the posts. If enough piled plaster is used, it will be squeezed out into a broad enough "flat" to make an accurate base - really, a single broad accurate foot.

When set, wet and remove the baby slab, dig out the clay, withdraw the plug in the tube, and proceed to operate.

For practice, as many as four baby slabs can be made at once, on plates of the size recommended. Such experience adds much to one's confidence, when the first formal slab job is attempted.

(NOTE. Logically, we would continue with slab-making, and take up slab techniques for more complicated slabs. But this would be to ignore the interests of those beginners who wish to make simple slabs and get them into operation. Also, highly trained professional workers needing mappers for advanced work, nevertheless should have initial experience with simple slab-making and operating techniques. Therefore, we turn to consideration of posts, spacers, crystals, staining, and so on, at this point.)

ACCESSORY ITEMS

Rubber Tubing and Nipples

The best tubing for connectors from tanks to slab wells is the so-called Handmade rubber tubing (outside rough, rather than smooth), either red or black, 1/8 inch I.D., 1/4 inch O.D.

Maximum flexibility of manipulation comes by using a two-piece connector. One piece is plastered to the well, and it extends, Figure 2, two or three inches out from the slab edge. The other piece, perhaps 40 inches long, permanently attaches to a nipple on the tank. The two parts are joined by a nipple. (Incidentally, except for sandbeds, nearly all of the flow resistance in the system is in the connectors; the flow resistance in the thin flow space is comparatively very small.)

The best nipples are short lengths cut from thin-wall brass tubing, 1/8 inch I.D., 5/32 inch O.D. (obtained from Besly, Chicago). However, other types of nipples can be used: glass tubing; or, stiff-type plastic soda straws, when they can be found.

Tanks

In place of permanent metal tanks, temporary tanks can be used, such as plastic food containers (used for storage in the refrigerator).

Instead of attaching a nipple at the bottom for connecting the rubber tube to the tank, the tube is carried up over the rim and down into the tank water. Some way of holding the tube to keep it in place must be devised. Flow is started by suction, before a tube is connected to a well.

Posts

Permanent-type posts (Figures 1, 2, and 6) can be cut from 1/2 inch brass or aluminum rod, on the lathe, to the preferred length. The writer prefers a length of one inch. Three are needed, and they should quite accurately agree as to length.

Temporary but entirely suitable posts can be made of plaster. Assume that the inch length (or height, when the posts stand on end) is adopted. Make up three temporary pieces which we may call supports, each fairly close to an inch high, but not accurately so. For instance, these can be flathead screws, standing on their heads, and with the other ends ground off until they pretty well match. Next, prepare three little paper collars or tubes, about 3/4 inch in diameter, and roughly 15/16 inch long. Use tape to keep the paper from unrolling. Wet the collars, and stand them close together on the center of one plate. Stand the supports as far apart and out as far as possible, on the plate. Pour the collars nearly full of plaster and jiggle it down. Then add plaster, piling up some excess on top. Take a second plate, and lower it gently and horizontally, until it rests on the supports. It will squeeze down the excess and make the plaster posts flat on top, just as in making accurate feet on a slab. If these posts are not considered to be in sufficiently accurate agreement as to height, repeat the process, using them as supports when making the next set.

Erosion through use under water will, of course, spoil the plaster post's accuracy in the course of time; but it is a simple matter to make new posts.

Spacers; the "Thin Flow Space"

The spacers resting on the posts to form the thin flow space between plate and slab, Figures 1 and 6 are about 35 mils (0.035 inch) thick. Various ideas for making spacers readily come to mind, but most of them are no good, or troublesome, or expensive. These spacers are ordinary brass washers, of about 7/16 inch diameter, and originally thicker than the final 35 mils. They are somewhat flattened by rubbing first one side, then the other, on grit paper. To make a set of four (only three being usually needed for operation) we start with seven. Both sides of all of them are somewhat ground, as above.

Next, lay three on one plate, sufficiently separated, and lay a second plate on top. Slide the others, one at a time, between the plates to test for fit. Soon, by trial-and-error, the three thinnest washers are found. From here on, use these as the separators of the plates. There follows the business of rubbing the set of four, one at a time, on grit paper, until each goes between the plates at the same place, with just a feeling of fitting, without binding. The set of four can, if desired, now be checked against each other, using any three for supports, and testing the fourth.

Just what value of flow space is best? There is no answer to that question. It depends on several factors. A space as small as 10 mils would call for extreme accuracy, as to spacer thickness, slab flatness, and so on. Going up to around 100 mils invites difficulty: flow space velocities are so low that dyelines become broad and diffuse - and then, speeding up the velocities may cause fluid from a well or slab boundary to wander uncertainly. This is when flow in the third dimension of the flow space becomes appreciable, and spoils the pattern. The upper limit also depends on how large the slab is, and on viscosity of the operating fluid.

DYELINE TECHNIQUES

Potassium Permanganate

This compound rates as a poison, but ordinary precautions remove all risk. Avoid getting it in the mouth, and avoid inhaling the dust when grinding and screening the crystals. Avoid getting permanganate dust in the air where it can settle on articles prone to rust - it may greatly accelerate rusting.

The coarse crystals are first ground with mortar and pestle, then put through a 30/inch screen. That which is passed contains much dust and many too-small crystals. Put it next through a tea strainer (about 40/inch, obtained at the 5-and-10). The crystals not passed by the strainer, averaging about one millimeter long, have the size the writer has found to be most useful for making fluid mapper patterns visible. The writer does use a coarser crystal on occasion, to make patterns show up better at a distance, in demonstrations.

A plastic saltshaker, with one hole open (the others taped shut) makes the best device for sprinkling the crystals.

(NOTE. At this point, the beginner has covered everything he needs to know, to make and put his first fluid mapper into operation.)

Stained Slabs and Stain Removal

Permanganate makes a "floor pattern". The crystals rest on the slab itself, and the dyelines move along the floor of the flow next to the slab. Therefore, after operation, the face of the slab will show bright pink spots and lines, where crystals rested, and dyelines flowed. It is a fuzzy copy of the flow pattern. Set the wet slab aside and soon, the pink stains turn to brown, as permanganate converts to manganese dioxide. The staining rate can be reduced if the slab, fresh from operation, is immersed in plain water for a few minutes, to dissolve out some of the permanganate before it converts. However, brown staining is inevitable. But it can all be cleared up.

The remedy is a bleach made of 5 parts acetic acid, 95 parts of hydrogen peroxide, and 100 parts of water. Any rough approximation to this formula will turn the trick. Brush it on the stained slab, and usually, all but very bad stains will disappear almost at once.

Do not operate a slab immediately after this treatment. Give the peroxide a change to decompose first. Otherwise, it will come out into the flow space, react with the permanganate lines, and make a precipitate.

Methylene Blue Crystal Dyelines

Crystals of methylene blue (non-poisonous) attached to the under side of the plate will form a "ceiling pattern" of sharp lines. These dyelines form high up near the ceiling of the flow in the flow space. Being of low density, they do not sink to the floor as permanganate would. But they do sink somewhat, thereby getting into faster flow levels, are thus carried faster, and remain sharper.

Before the plate is placed in position for operation, the crystals are attached to it. They are attached by means of what the ladies call nail polish - sold in small bottles at the 5-and-10 under various trade names, such as Cutex. It is clear and colorless, and dries quickly.

An applicator is needed. A plastic knitting needle serves admirably, but one can use a slim wooden stick, sharpened at both ends. One end is reserved for the Cutex, the other for the crystals. Dip one end in Cutex, apply it to the plate, and leave a small dot of the cement on the plate. Apply the other end of the applicator to the tongue; thus moistened, one can pick up a single crystal and stick it to the aforesaid dot of Cutex. Many crystals can be applied fairly rapidly. In cleaning up, the Cutex dots are scaled off the wet plate with the edge of a putty knife or other such instrument.

MBM Dyelines

For 8 or 10 years, the writer tried numerous times to think of a way to attach numerous methylene blue dots, rapidly, to the plate; and with no success whatever, even though the materials eventually adopted were right in his laboratory for most of those years. The "MBM" idea finally came. The initials stand for a Methylene Blue-Methocel mixture. Methocel, a Dow Chemical Company product, is remarkably useful for fluid mapper work, in several ways.

Methocel

Methocel has many commercial and industrial uses. Initially a white powder, water is added. There are several grades, giving differing degrees of viscosity. The writer uses Methocel 1500 cps (cps stands for centipoises). Dow Chemical has kindly supplied the writer with an ample quantity, to meet requests from fluid mapper workers. The writer will be glad to forward some Methocel, on request (no charge).

Methocel paste can be made up as follows. Put, say, 50 cc. in a bowl, add a little warm (not hot) water, and stir. The water is taken up at once, and a stiff, messy mixture results. Add more water and stir. And keep it up, time and again. In a few minutes there will be perhaps half a pint of pasty mixture, shot through with any number of white flakes of unwetted powder. Continue to add water and stir, until it grows to a pint. Most of the Methocel is now reduced to paste, but many white flakes remain. Stirring will not reduce them, but time will: water will slowly diffuse into them and turn them to paste also. This may take an hour or so. Occasional stirring will help. The thick, sticky paste may then have a milky appearance due to a vast number of air bubbles. These do no harm. If the paste is kept in a jar with a tight lid, it will keep indefinitely.

Making and Applying MBM Paste

Using a spatula, put one or two cc. of Methocel onto a plate. Dump onto it a roughly equal volume of methylene blue - which can be either in crystal or powder form. Spatulate the mixture thoroughly. In a minute or so, the MBM paste is ready. A quantity can be pre-mixed and stored, in a tightly sealed container.

To apply single dots, use the applicator mentioned above, dipping it into the paste, and applying a dot at a time to the plate. This goes quite rapidly.

Warning: do not let the MBM dots dry before use. If dried out, they come loose when the plate is immersed.

To show again how slow some ideas come, the writer yearned for a way to apply MBM dots in multiple, as soon as the single-dot technique was worked out. It was some months before the use of a pocket comb was thought of -and again, one was available all that time! To use the comb, break off and discard the fine-tooth half, and retain the coarse half for use. With the spatula, smear out the MBM paste to perhaps 1/16 inch thickness. Bring the piece of comb down vertically, and without sideslip, dip the teeth into the paste. Apply it likewise to the desired place on the plate. The edge of a slab can thus be quickly ringed with dots, and extremely striking, as well as useful, patterns are obtained.

Removing Methylene Blue Stain

Few of the MBM lines of a ceiling pattern ever get down to slab level, where they stain the slab. But an especially thick dot will do that, and cause a blue flowline record on the slab. To remove it, get a bottle of Chlorox (a bleach) from the grocery store, and paint it on the slab. Some stains may take quite a while to clear up, but the Chlorox always wins. It does not damage the slab.

Warning: use methylene blue powder with much care. It is most pervasive, and later on, will show up in unexpected places around the laboratory, if carelessly handled. After a plate, loaded with MBM dots has been used, take it to the sink and let water run over it until all dye is washed away. The sink will be stained by this. To avoid sink stain (especially the kitchen sink) replace the foregoing process by smearing the dots off with wetted paper towels. Then be careful of towel disposal, or there will be a blue wastebasket.

RECORD SLABS

Rubber Paints

Glidden's Spred-Satin was the first synthetic rubber emulsion paint to appear on the market. The writer applied some of it to a wet slab, hoping to prevent erosion of the face. It was operated with permanganate. On removal, the startling discovery was made: the flow record was imprinted or recorded in the paint on the slab. Thus, the record slab technique was one of those fortunate accidental discoveries. The permanganate reacts with the latex to make a brown trace of a dyeline - very likely, manganese dioxide. Other companies soon followed with rubber paints. At present, the writer is using Sherwin Williams' Super Chem-Tone (white).

Prior Test

A new slab is first tested out in operation, for two reasons: first, to see if it is all right in all respects; second, to learn how to sprinkle it - how to place the crystals to best effect for the slab's particular flow pattern. The slab is then removed, for painting.

Painting

Slab wetness has much to do with painting success. The dripping slab is mopped with a damp cloth to remove surface water. The one-inch varnish brush is wetted in water, then brushed on a cloth to remove its excess water. A stick or spatula is dipped deep in the paint can, to bring up some of the settled, thick paint. A little of this is gotten onto the tip of the brush. The slab surface where flow will occur (and not any barriers, if present) is quickly painted, all over. The paint will now be quite uneven, and full of brush marks. Working steadily, the brush is applied crosswise of the first strokes. After that, stroke the surface slantwise, all over; then across these strokes. Thus, by crosswise stroking, evenness is produced; and all the time, water is being evaporated and the paint is getting tackier. In a very few minutes, no more brushing can be done, for the paint is so stiff that the brush would begin to dig into the paint. All this does not give a smooth paint job, free of brush marks. But it is a pretty smooth matt surface, and quite uniform.

There is no reason to be worried about spoiling the job. If something does go wrong, simply scour the paint off with a damp cloth and do it over again.

In another two or three minutes - depending on heat and humidity - the paint is firm enough to stand immersion and recording. However: it is extremely weak and tender. Do not touch it. After recording, do not run tap water directly onto the face, to wash away a remaining crystal. Run the tap water slowly into a well. A camel hair brush can safely urge a crystal to go away, when slow water from the well is flowing over the face.

Recording the Pattern

The painted slab is installed in the mapper, then permanganate-sprinkled and operated as usual. The reaction begins at once, and the record should be complete within a minute. The brown first appears at the dye pool around a crystal; later, the pink dyelines begin to show some brown. The slab is now removed and gently washed, then set aside to drain, and to let the paint harden.

In watching the record form, it may sometimes be noted that an area where pattern lines are needed, was insufficiently sprinkled. This also is no cause for worry. Finish the recording being done. Sweep the crystals slowly off the slab with a soft brush. Sprinkle anew, in the place that was missed, and record again.

Acidity of the operating water can be important. For some years, the writer's record slabs showed much variability as to darkness of line, and sharpness. Of the many factors that might be involved, he was lucky enough to guess that acidity might be the key, and research showed that it was. Ann Arbor tap water is roughly at pH 9. By adding 25 or 30 drops of HCl to the tray water, the writer gets the pH down to 2 or 3, and with two fine dividends: the pattern is much darker; and the lines, for reasons no one is as yet sure of, are much sharper. Also, the pattern bids fair to be more permanent.

Record slabs are very beautiful display items. The writer has many of them for use in teaching.

Record Slab Protection

To protect the record slab, let it dry thoroughly, and spray the painted face with clear Krylon. This treatment has the added advantages of making the pattern of recorded dyelines darker, and making them show up with greater contrast.

Recording on the Slab Face Itself

This was another accidental discovery. For some reason, the writer once wetted a dry record slab, softened the paint, and scoured off the paint which had the record on it. He was surprised to find that the record not only went through the thin paint film, but also remained on the slab after the paint was removed. Now, there may be slabs made, for which accuracy will be somewhat impaired by adding even a thin paint film to the surface. It is comforting to know that we can have records, with no paint on the slab.

The process is simplicity itself. Just paint the slab any old way, and let the paint remain for a minute or so. Then rub it all off with damp cloths. Enough of the paint has gone into the pores of the slab to make a record, and a very good record, too.

PART TWO

COMPOSITE SLABS

Composite Slabs, Assembled

When two or more parts of a slab are pre-cast and then joined with plaster to make one slab, it is an assembled composite slab. Figure 8 shows the pattern of a two-member job, in which there are two values of flow space. It portrays the potential field in two mediums of different physical properties.

After the two rectangular slab parts were cast, the large one was laid inverted on the spacers, on a plate. The small one was placed against it, and enough plaster was laid along the common region on the upturned bottom where they joined, to weld them together.

The accurate feet and the ultimate spacing used for operating this slab were arranged so that the two flow spacings were in the ratio, 1:2 (actually, 35 and 70 mils). Cube these numbers, and we get the ratio 1:8, which is the ratio of the two thermal conductivities if heat conduction is represented; or the ratio of permeabilities if it is a magnetic field; or the ratio of dielectric constants, if an electrostatic field. There is refraction at the interface of the flow spaces, or of the two media.

The design for a straight-flow mapper is shown in Figure 9, made of four pre-cast parts. In assembly, the central part is supported above the plate on spacers. The other three parts, resting on the plate, are brought up to it as shown, and arranged so as to form a rectangular well at one end of the flow space. The drawing does not show the joining plaster, or the bottoming plaster.

The Spacing-Cubed Law

To make clear how this law or rule applies, first consider a thin conducting sheet of metal, rectangular in form, with electrodes attached all along both ends. For a given voltage difference between electrodes, a certain current flows. Do it all again, with a sheet of double the previous thickness, and for the same voltage drop, twice the current flows.

Now pass to a fluid mapper with a rectangular flow space, there being a well at one end and a mouth at the other end. Operate it: for a

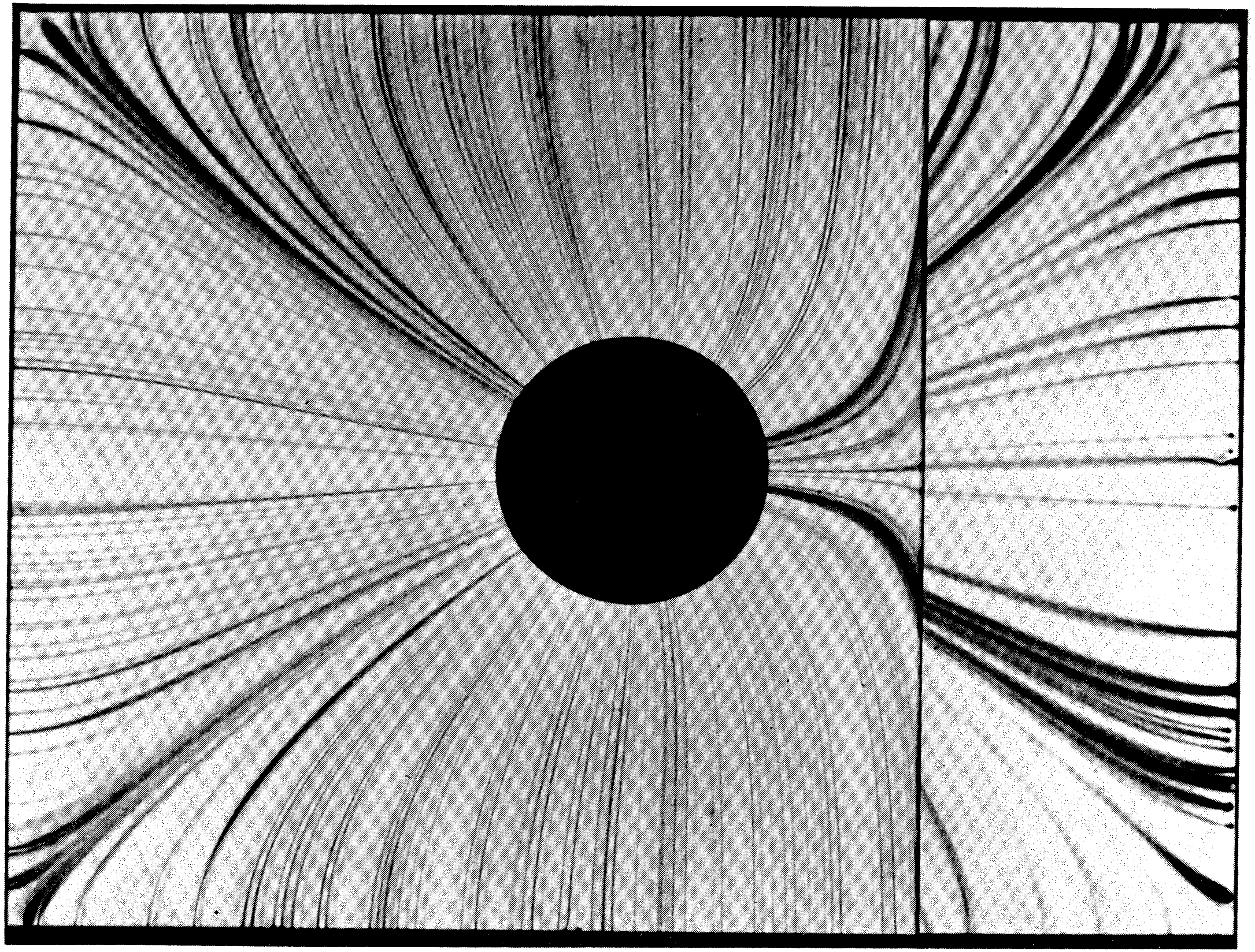

Figure 8. Composite slab, two parts, stepped, showing a potential field in two mediums. Ceiling pattern, from crystal-on-plate technique.

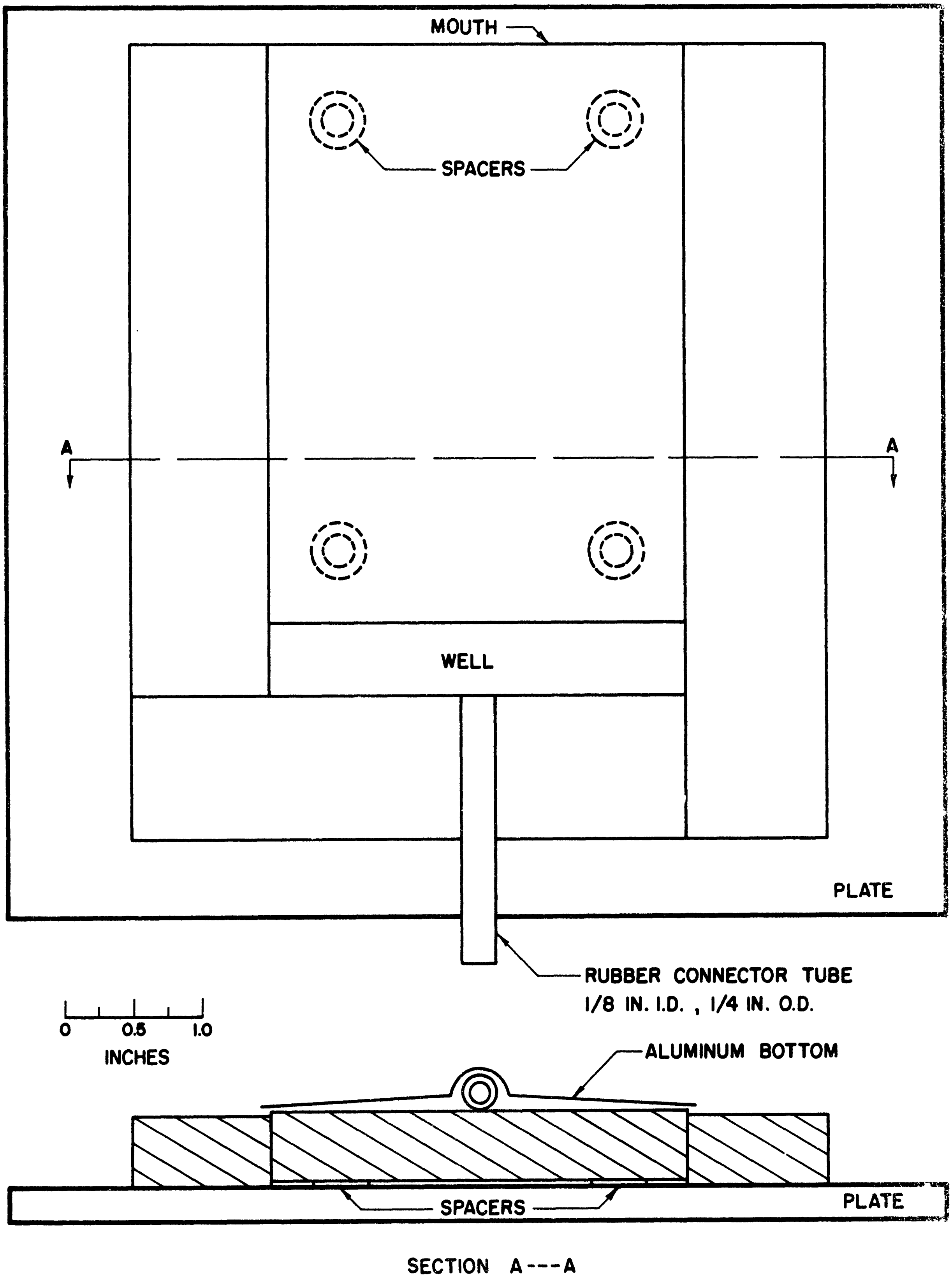

Figure 9. Composite slab, pre-cast, ready for joining plaster, and added parts. A straight-flow slab; the three outer pre-cast parts form the barrier.

given pressure drop for the flow space, a certain rate of fluid flow occurs. Now arrange to double the flow space thickness: for the same pressure drop, the rate of fluid flow is not twice, but <u>eight</u> times as much. The laws of fluid mechanics for streamline flow dictate this result.

Therefore, as a simple illustration, if we build a mapper having a stepped face on the slab, and it has then two values of thin flow spacings, we must recognize that it is simulating some potential field in two adjacent mediums; and, that the conductivities of the mediums (or whatever physical constant corresponds to heat or electrical conductivity) represented are <u>not</u> in the ratio of the flow spaces, but in the ratio of the <u>cubes</u> of the flow spaces.

<u>Composite Straight-Flow Slab, with Barrier</u>

Figure 10 shows such a slab, but with a round well cast in it. In the operation shown here, it is a "dead" well: the well is there, and it modifies the flow as shown; but it is not "working", either as a source or sink; its connector is clamped off. This slab can demonstrate straight flow if the well is plugged with modeling clay, which is shaved down to slab face level.

Note that in operating this slab, <u>no spacers are used</u>. The plate rests on the raised, outer slab level, or <u>barrier</u>. The purpose of this assembled construction was to have a slab with a barrier around three sides, and an open mouth opposite the well.

This barrier can be subject to some slight leakage, which reflects the fact that plaster does expand on setting. Even the very slight expansion of Duroc will let the plaster which joins the assembly together, cause some slight deformation, and prevent the three outer parts from having their faces perfectly in one plane.

<u>Sealing the Barrier: Methocel</u>

Barrier leakage in cases like the above may be so slight that it can be ignored. If not; or, as in a closed-barrier case where sealing against leakage must be used, a successful sealing technique is mandatory. It took the writer some years to find the one and only material he has yet found to lick this problem: Methocel paste. Before the plate is put down, a brush is used to lay Methocel paste along, fairly uniformly, where it will pretty well cover barrier widths. A template as a

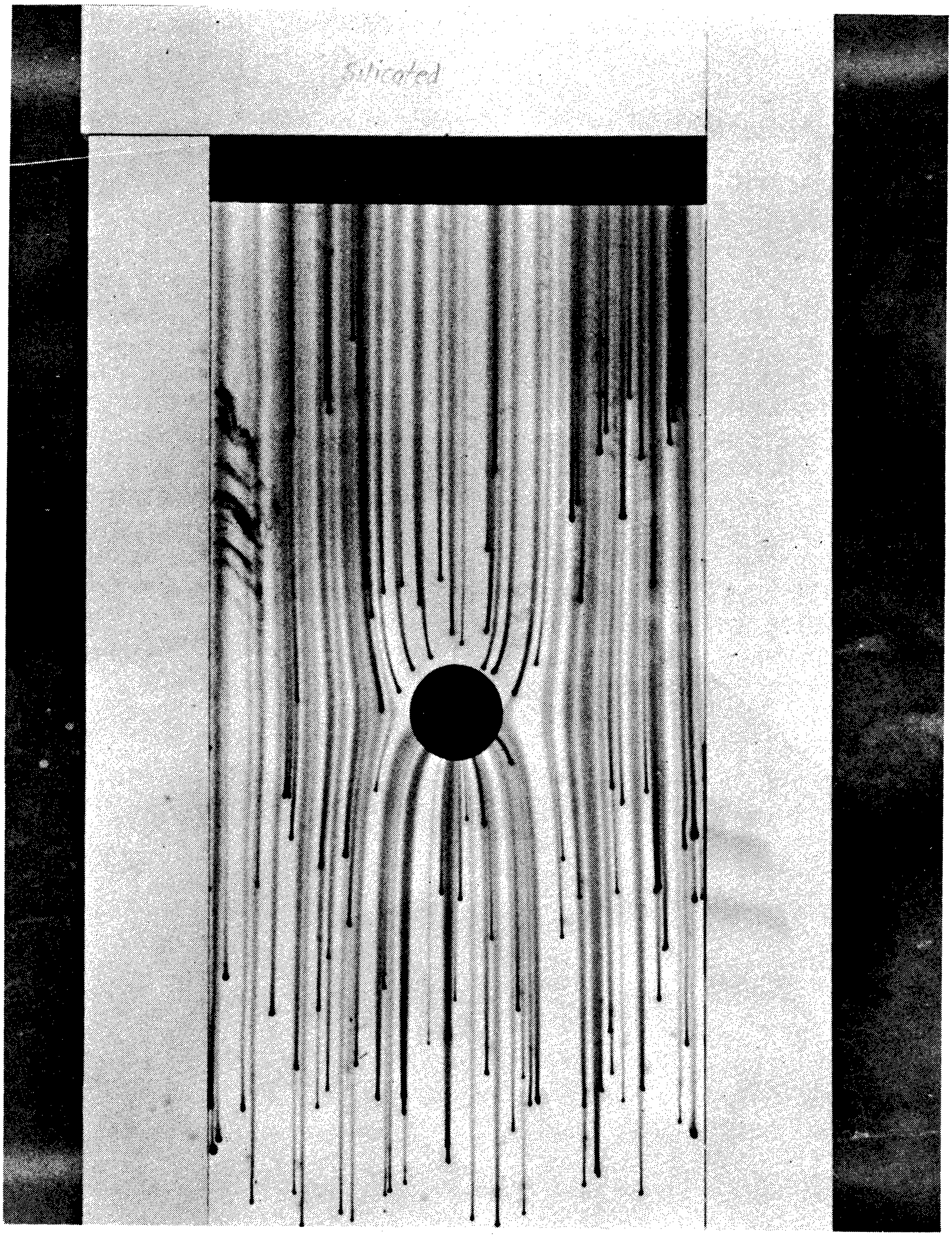

Figure 10. Composite slab, pre-cast, in operation, with dead well. Well connection clamped off.

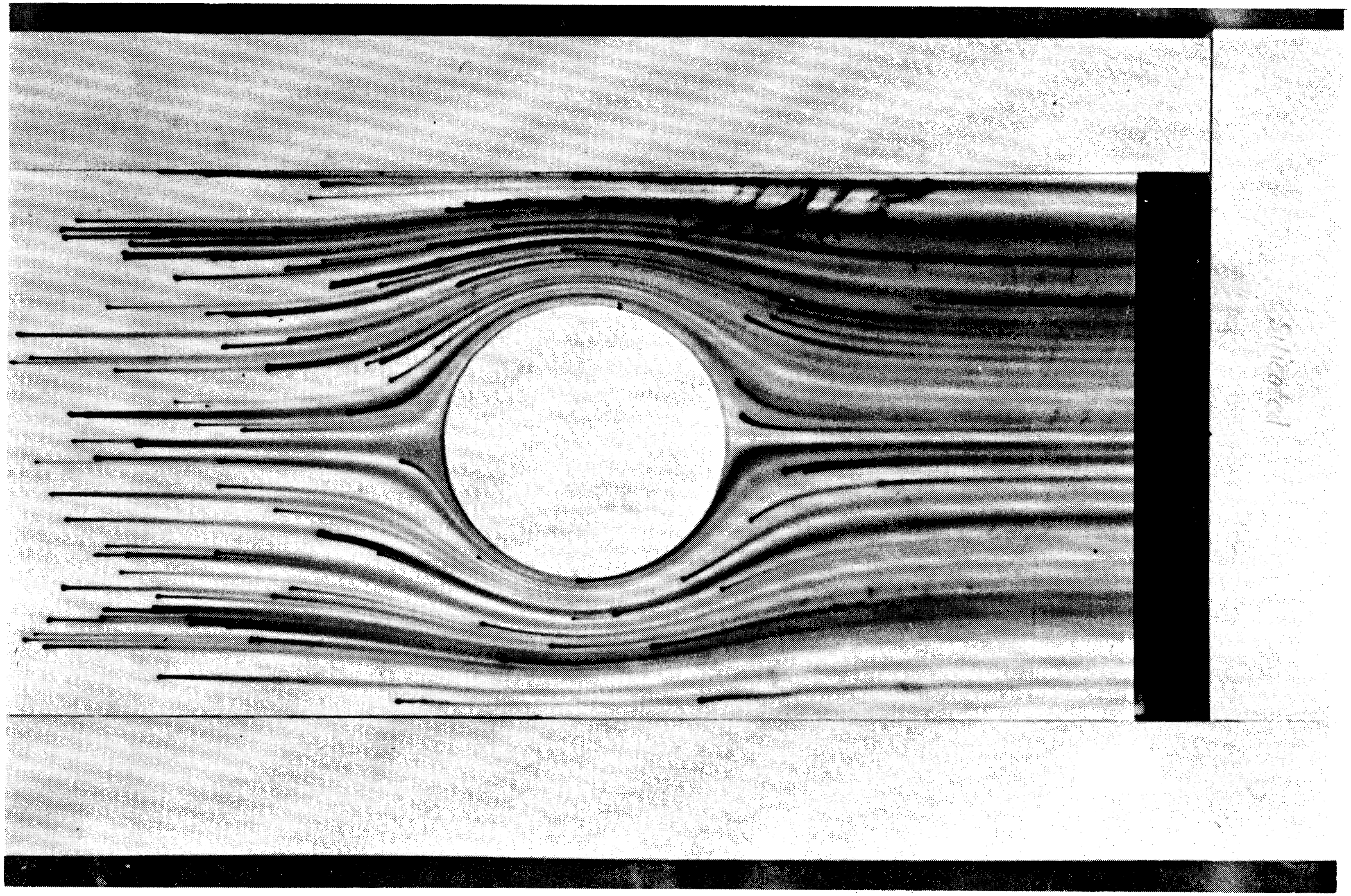

Figure 11. Flow around an island. Plaster island made by the squeeze technique.

guide may be needed in some cases. After placing the plate, shift it slightly, and with pressure, to even out the layer of Methocel. Some practice may be needed. Usually, a perfect seal is obtained.

Composite Slab Distortion from Expansion of Joining Plaster

When the two or more pre-cast parts of a composite slab are integrated by laying a trail of joining plaster on the joint lines, the composite slab inevitably will be distorted. The expansion of the joining plaster is the cause. The face planes of the parts, initially parallel as laid down on the plate, or on spacers on the plate, will turn out to be not quite parallel planes.

With small composites, say 8 by 10 inches or less, the distortion can usually be ignored, using the low-expansion Duroc plaster. With other plasters of higher expansion, it may be bothersome. Larger slabs may show serious distortion.

The distortion is virtually eliminated by a "sandwich technique". To illustrate, if a thin slab is pre-cast, laid face down, and plaster to an equal thickness is poured all over it, the resulting two-layer slab will be somewhat warped. But if, after adding the second layer of plaster, another pre-cast slab is laid on top of what now becomes a middle layer, the resulting three-layer slab will come out flat.

If distortion is feared, this distortion-neutralizing technique can be used. Its application will depend on the details of slab design, for provision must be made for installing well bottoms and so on.

Composite Slabs, Sequence-Cast

Rather than pre-casting all slab parts and then welding them together, some slabs can be made faster and better by sequence-casting: cast one part, then cast a second part against it or inside of it or around it.

The slab of Figure 12 was sequence-cast. First, the part-slab for the flow space was made, using flexible fence mold parts. Inverted, it was placed on spacers on a plate; the mold for the outer addition (to be the barrier) was constructed; the slab part was thoroughly wetted; then the outer part was cast against it. In this process, two problems arise.

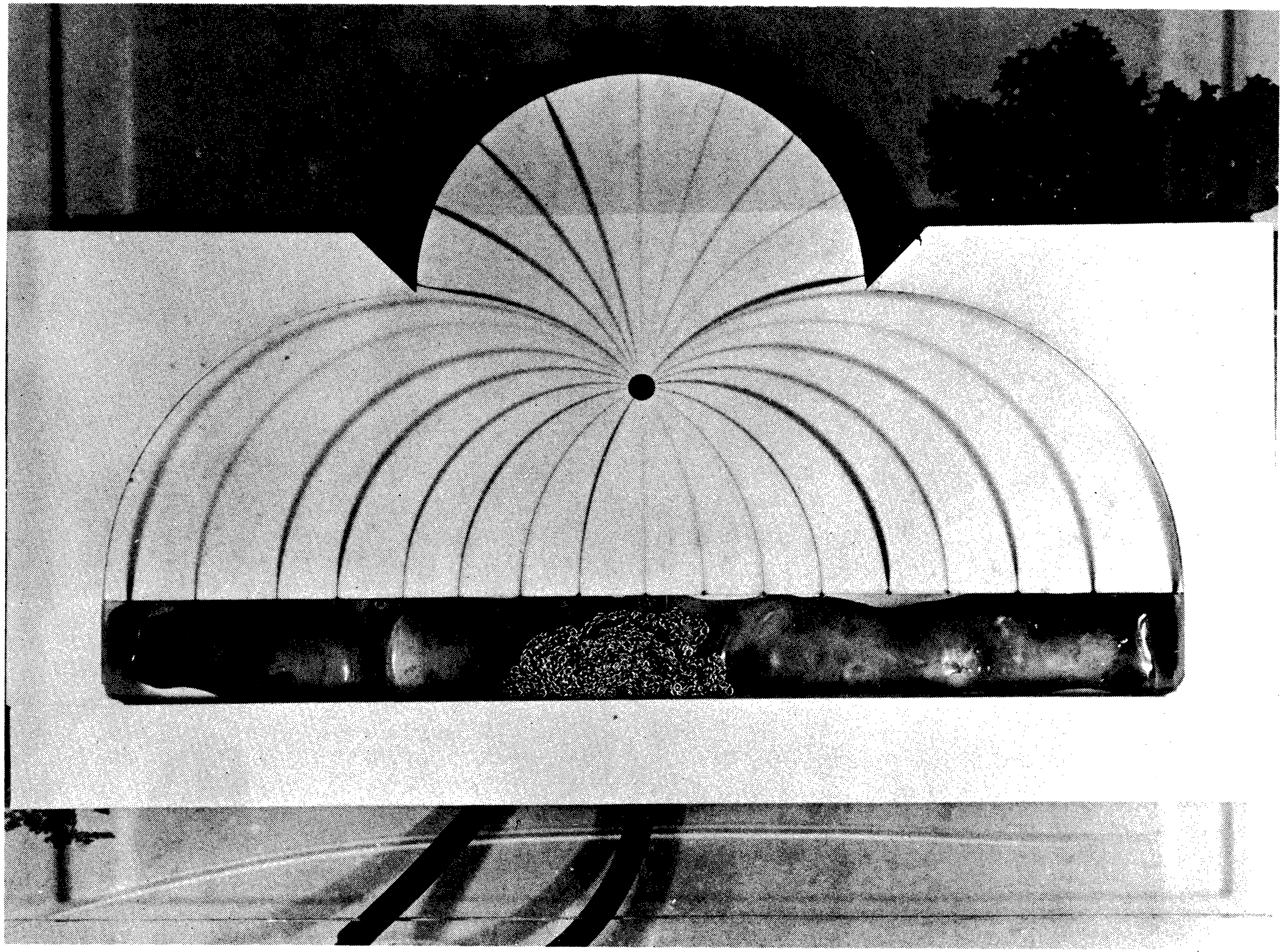

Figure 12. Composite slab, sequence-cast. In well, note brass chain laid over connector inlet mouth to kill swirl effect.

First, due to plaster expansion, the bond between the first and second parts sometimes comes loose and permits leakage. A bit of back plaster added along the bond line will stop the leakage. Second, and treated next, is the under-run problem.

Handling the Under-Run Problem

When casting the barrier in Figure 12, use of the probing brush to remove bubbles, and make sure that barrier plaster everywhere comes up to the flow space edge, will drive plaster in under the pre-cast piece. Some of it would run under anyway. There are three ways to handle it.

First, let it run under and set. After removal of the slab, remove the under-run or trespassing plaster. Its bond with the smooth face is weak. Use a knife point to score into the new plaster where the joint occurs (use a template for accurate guidance). Then, with the plaster wetted, jab with the knife to start breaking the unwanted plaster away. Soon the knife can be inserted under the trespass plaster, lifting it and causing it to break at the scoring line.

Second, prevent under-run. Use bridging to hold the pre-cast part rigidly. Roll modeling clay into long thin rolls, lay a piece along the edge, use a knife point to crowd some of it in under the edge. Then trim off the excess. A perfect dam is thus formed, and under-run does not occur.

Third, permit under-run, but prevent it from forming a bond. Here, Methocel paste again gives the solution. Cut a strip of paper, perhaps an inch wide, that will go against the pre-cast face <u>before</u> it is put down on the spacers - and cut it so that its edge just comes to the margin. (If necessary, cut windows where spacers will be placed.) Wet it. Mop off the water, then paint it, both sides, with Methocel paste. Apply it to the pre-cast piece. The paste acts as a temporary glue to hold it to the face. In casting the barrier, under-run freely occurs, but the paper separates it from the pre-cast face. After set and removal, score as above; wet the region; insert the knife blade under the paper and lift. The under-run and paper will come up in large pieces.

<u>Warning</u>: all paper expands when wetted, and more in one direction than the other. If the slab layout is such that this will affect the results, test a piece of the paper first; find its degree of expansion; and then lay out the protector paper to allow for expansion.

THE SQUEEZE TECHNIQUE

Squeezed-on Barriers

Accurate plaster-squeezing operations have already been discussed, as to making accurate feet, and plaster posts. There are further important uses for the squeeze technique. Often, much the easiest and best way to make a barrier, or to make a slab of two or more levels, is to add squeezed-on plaster to the face of the slab blank.

In Figure 10, suppose we first cast the entire slab blank in one piece, using a well mold to form the well. The blank face will be flat, with no barrier around three sides. With the slab blank face up, a trail of plaster mix is laid all along the middle of the barrier space. This can be done with spoon or spatula; but a much better trail is made by applying the plaster from a plastic squeeze-bottle. Four spacers, meanwhile, have been laid out on the flow space area. A plate in now lowered, with a bit of sidewise shifting to help the plaster spread, until it rests on the spacers.

Enough plaster is laid on to insure that it will cover the barrier areas. Therefore, it will freely run out over the edge, where it can be trimmed off. And there will be over-run, in and onto the flow space face. Like the under-run problem covered above, the over-run is neatly taken care of by laying down protective paper strips, glued on with Methocel paste. Locate the spacers so that over-run will not reach them.

Squeezed barriers are highly accurate, and are preferred over barriers achieved through other techniques.

In putting on a complete barrier (entirely surrounding the flow space) provision must be made for air trapped in the flow space to escape through a well. Otherwise, the squeezed plaster will run out, but not in; and here and there, the barrier will not come up to the edge of the flow space.

Plaster Islands, Squeezed

The slab in Figure 11 is the same as seen in Figure 10, put with a plaster island laid on. Two-dimensional viscous non-inertial flow around a cylinder is thus demonstrated.

Making such islands offers good experience in the squeeze technique. Lay a plate on the table, with three spacers set on it, far apart. Drop a blob of plaster mix in the center of the plate. Lower another plate until it rests on the spacers. Warning: if the mix is somewhat stiff, one may think the complete squeeze has taken place, but be mistaken. Tap the upper plate to help the spread; also shift it slightly back and forth, and sidewise. When the plate really is on the spacers, no further spread of plaster is observed.

Large spreads, up to several inches across, are easily made. They are quite fragile, but can be safely handled if not abused. A desired island shape is laid out on the very thin casting. Scoring with a knife along a straight line permits a piece to be broken off. Most of the excess can thus be removed. Careful scoring along the desired line now enables small bits to be broken off to bring the island to near completion. Small modifications of the edge can follow by carving, filing, or grinding. Leakage under or over an island can be stopped by thin applications of Methocel paste.

If desired, the island in Figure 11 can be squeeze-cast directly onto the slab, using protector paper (with Methocel paste) outside of it, for removal of over-run.

Edge Effect

In the thin flow space, fluid velocity is zero at the plate and slab surfaces, and in between, has a parabolic velocity distribution. The exception comes at edges, where, if a barrier or island is present, the velocity is zero at the vertical surface of barrier or island. At such edges, then, there is a source of some error, if the slab is built precisely to scale.

In the writer's first published paper, edge effect is covered. It is shown that it is largely eliminated by moving barrier edges or island edges back from the flow space by an amount equal to 1/4 of the flow spacing. Such a correction is so small that it need be done only for exceptional cases.

OPERATING TECHNIQUES - TYPE 1 SLABS

Trying Out a New Slab

Before serious work is atempted - such as, to photograph the pattern for later analysis and problem solution - one should get acquainted with it. Sprinkle it and test it out. Get used to its performance. Find where to sprinkle crystals lightly, and where more densely, to get a good pattern. Find what tank levels to use, to avoid, on the one hand, flow space velocities so high that dyelines are thin and crystals are moved along; and on the other, to avoid velocities so low that dyelines are too broad and diffuse. Find how long it takes for colored water, left over from the period before the plate is placed down, to be moved out, leaving a clear pattern; and then learn how much time there is left to make a picture, before some crystals are used up and their dyelines disappear.

Also, if it is really intended to use the MBM dyeline technique, a trial run with permanganate is easily carried out. It can be highly instructive as to placing the MBM dots later on.

If the design of the slab has symmetry, by all means take advantage of it: the pattern should then be symmetrical. If it is, then one may be pretty sure that all steps taken that have a bearing on accuracy, have been well carried out. If not, look for the trouble and correct it.

Multi-Color Operation

Again using Figure 1 as the example, suppose the wells are made into equal sources. The two flows would each cover their halves of the slab, meeting at the axis line across the middle. Now let some permanganate powder be stirred into the water of the righthand tank, and dissolved. Soon, as this colored water enters the flow space, the whole right half of the flow space will be colored pink.

Better yet, use food colors, red for one tank, green for the other. (Burnett's colors will do it. The writer has found no other brand to be satisfactory.) The two colors will meet at the center, but with such a sharp dividing line that even those who are thoroughly conversant with streamline flow are struck with the sharpness of the division.

Then, by slowly manipulating tank levels, various striking color effects are obtained.

The writer has a triode slab, the technical purpose of which is to portray the electrostatic field in a vacuum tube. Its central well, the cathode, can be fed with red water. Part way out to the round slab boundary, several equally spaced wells (the grid wires) are fed with green water. The writer always ends a Fluid Mapper Lecture-Demonstration with the "Color Show", using this slab. Going through extended evolutions with tank levels, and getting changing hues as colors become mixed in different ways, this magnificent spectacle can even make the Aurora Borealis ashamed of itself. On-lookers are invariably spellbound.

Excessive Velocities

If a fluid mapper is to represent some potential field properly, it must meet several requirements. Two of these are, first, that the flow must be streamline (no turbulence); and second, inertia effects must not be present in enough degree to affect the flow patter appreciably. The first requirement is normally met when the "thin flow space" is less than 1/16 inch, using water as the fluid, and operating the tanks with no more than a few inches of head - provided the connector tubes are of the recommended length. However, even though streamline, the flow still may show inertia effect.

The practical test for absence of inertia effect is to operate with some given tank level; observe the flow pattern; then suddenly double the difference in head. If there is no sensible change anywhere in the pattern, inertia effects are virtually absent.

When present, reduce the excessive velocities by reducing the head, until inertia effects disappear.

High Viscosity Operating Fluid

Professor Hele-Shaw used glycerol (glycerine) for his operating fluid, and its high viscosity no doubt eliminated inertia effect from his devices. It is not necessary to use such an expensive fluid. The sugars, in solution, are "Newtonian" (the viscosity has the simple, ideal behaviour). Thus diluted corn syrup makes a highly acceptable high viscosity operating fluid. At the same tank operating head, velocities can be tremendously reduced; inertia effects disappear; and fortunately, the same dyeline techniques as described for water, still apply, and with equal success.

Swirl Effect

When a well is used as a sink (downflow) the dyelines normally do as they should: approach the well boundary everywhere at right angles to it. This orthogonality means the boundary is what is should be: an isopressure line. Now, at sufficiently low velocities, a well acting as a source (upflow) will behave likewise. But get the incoming velocity high enough, and the pattern near the well boundary will be seen to be distorted. Water shooting into the well from the connector tube is causing inertia effect, which in this case, the writer has called swirl effect.

It is usually not necessary to go to a high viscosity fluid to cure this trouble. If velocities cannot be reduced enough to eliminate it, then use some such remedy as is shown in Figure 12: a piece of fine brass chain has been dropped over the mouth of the inlet tube, to quell the incoming spurt of water. The chain, or whatever is used, should pile up over the inlet, but should not reach up close to the flow space level.

Reversibility

In theory, all fluid mappers are reversible. For example, in the operation shown in Figure 1, the tank levels are below tray level, the wells are sinks, and all dyelines go from crystal to sink. If the tanks are now raised, the flow is reversed but the pattern is unchanged. It is most interesting to watch a dyeline reverse itself, following its own track, and to see the beginnings of dyelines, at each crystal, moving out and starting for the outer boundary.

This is more than just a matter of interest. If a photograph is needed that will show lines all the way from boundary to wells, flow-reversal is one way to turn the trick. Use double exposure. Expose once for the inward flow, in this kind of example. Then reverse the flow, and expose again for the outward flow when the lines have reached the boundary. The writer has not, it so happens, used precisely this technique, but feels sure it will give results. Or again, flow reversal will put a complete pattern on a record slab.

Troubles

At times and places, an operator may be plagued by a trouble that may be anywhere from small, to devastating. Suppose a dry slab has been properly soaked. No more air can come out of it. Yet, put in operation, the flow space slowly becomes loaded with bubbles. The pattern is ruined. Whence these bubbles? Some tap waters are so charged with air that bubbles keep forming for a long time - especially if the tank levels give a negative head, tending to cause a partial vacuum in the flow space. Such water must be heated to drive off air, or else drawn well in advance, and allowed to stand.

Next, there is local trouble that is bound to become more prevalent, as the country's water supplies get into more precarious states: the water may be so chemically loaded that it is unfit for use with permanganate. In demonstrations at Cornell University, the writer had to give up using Ithaca water because of precipitate, and call for bottled spring water instead.

There is another kind of bubble trouble that can show up, if, in assembling the mapper, air has not been completely cleared from all parts of the system. Air can lurk under ledges of well chambers, and in odd places like that. An ear syringe should be obtained: a rubber bulb with one part of itself shaped to be a nozzle of ear-entry size (the drugstore has it). With this tool, one can probe down into wells; with a tank lifted high to get high water speed, alternately use water injection and suction, to move bubbles out of hiding holes and wash them up out of there.

Sometimes, after a new slab has been started on its career, the pattern is approaching perfection, and a photograph is about to be taken, the operator is distressed to see a cloud of dyed water coming up out of the tray and slowly moving over the plate. This means a well is being fed from a tank with water warmer than tray water. Naturally, the warmer water rises, even if it is loaded with color.

SLABS WITH SANDBEDS - TYPE 2

The Distributed Source

Type 1 mappers have no distributed sources. In such mappers, having ordinary wells, the mapper is so designed that fluid pressure drops in wells and in tray water is negligible. Well and slab boundaries then become isopressure lines, with the result that fluid flow arriving at or departing from such boundaries are orthogonal (at right angles to) the well boundaries. Any actual flow in wells and tray is ignored. The region of interest is confined to the flow space, in which the flow phenomena simulate the phenomena of some potential field.

The writer invented the sandbed in 1943, in order to simulate potential field phenomena within a distributed source, and the phenomena as thereby affected in any surrounding medium. The sandbed idea was promptly proved in, but the real opportunity to begin serious development of fluid mappers did not arise until 1948. Learning to work with plaster was the main key to making progress.

In Figure 13, a slab with a round sandbed, matters are so arranged that the surface of the sandbed is a uniform source or sink. Fluid appears, or disappears, uniformly all over this area. Thus, we have here a distributed source of fluid. One potential field interpretation - in terms of heat flow - will now be made. Let the slab surface, plus sandbed surface, represent the cross-section of a cylinder of such a section, it being one single, continuous medium; and by some means, let heat be generated uniformly within the circular cylindrical part where the sandbed is. Then the fluid mapper flow lines everywhere show where the heat flow lines would be; and the fluid mapper's isopressure lines would be copies of the isothermal lines of the heat flow case.

Distributed-source fields can be, and usually are, extremely complicated, and they normally defy any attempt to get good solutions mathematically. As a result, the entire world supply of really good pictorial representations of such fields was highly limited, until sandbed mappers opened the door to visual portrayal of these difficult phenomena.

Construction

The construction is shown, slab inverted, in Figure 14. With the aid of that wonderfully adaptable material - plaster - every step becomes simple. First, the slab blank is cast, with a well. To have a uniform sandbed source, the sandbed must be of uniform depth. Therefore, the half-inch high mold is slightly overfilled in the well region, and the slab is then scraped down to mold level.

A screen, described later, is plastered onto the slab bottom, by painting thin plaster mix onto its margin, which overlaps the well

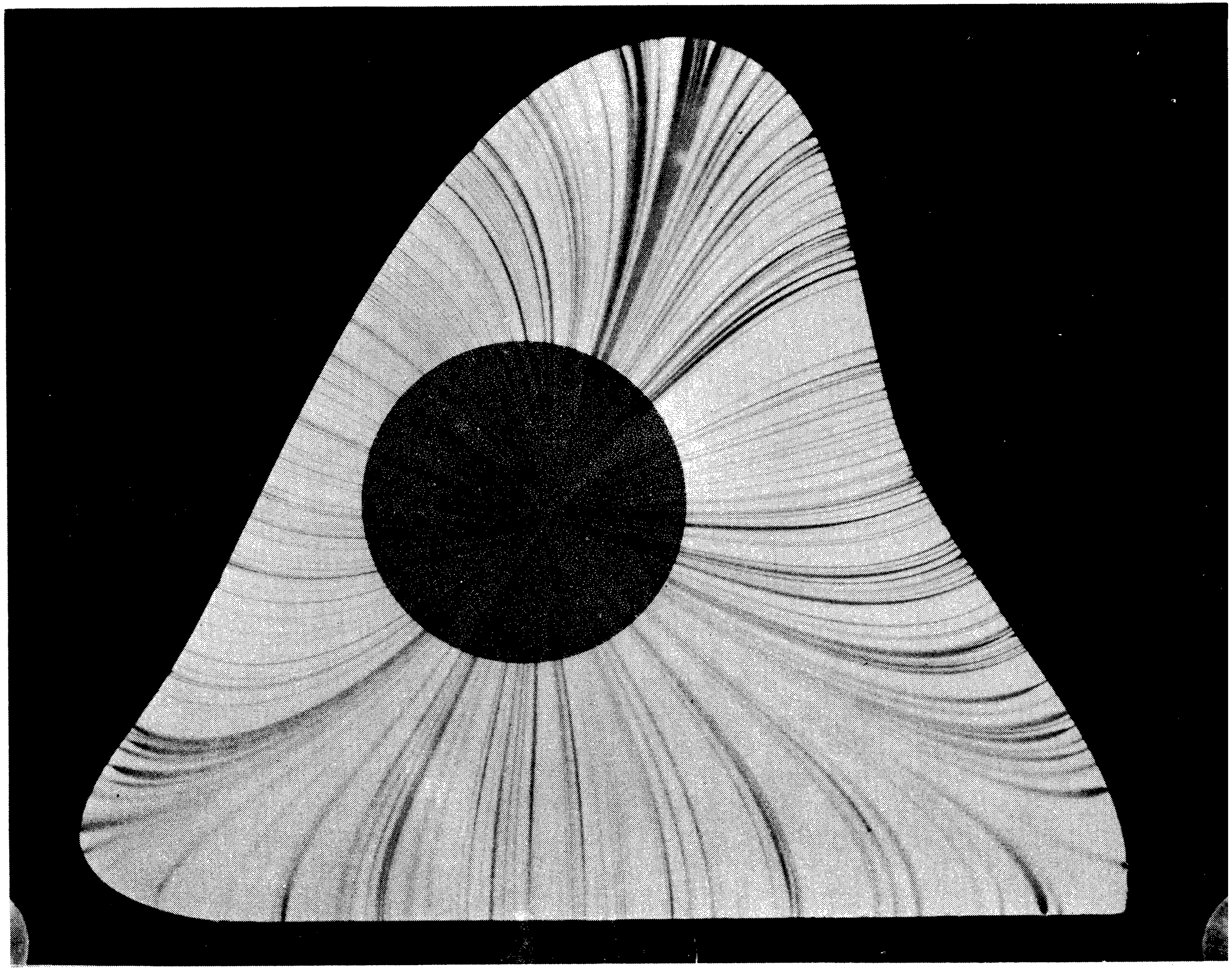

Figure 13. Slab with sandbed. Ceiling pattern, via crystals-on-plate. The sandbed is a uniformly distributed sink.

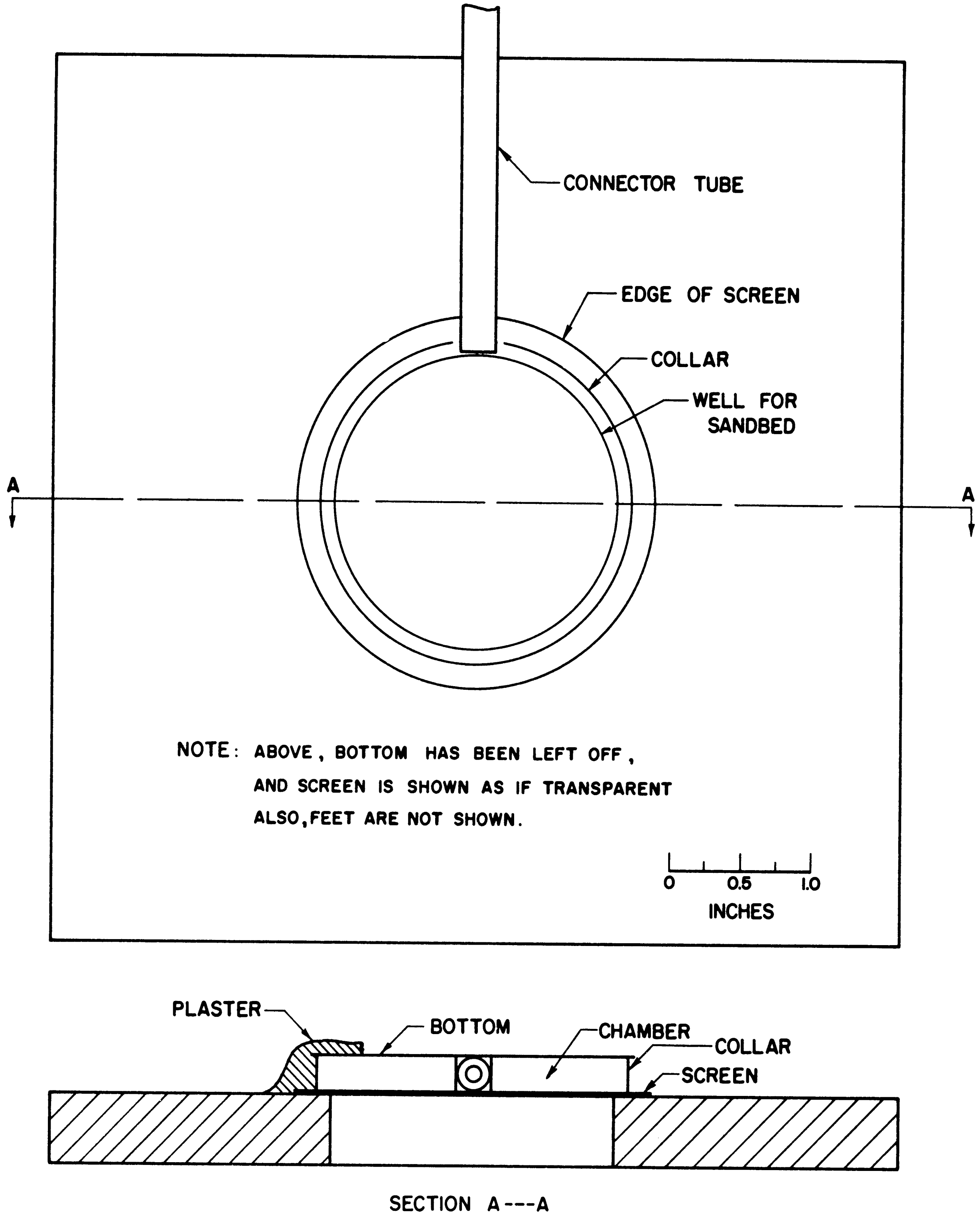

Figure 14. Slab with sandbed - construction techniques.

boundary. Do not let the brush wander too close to the boundary, lest plaster fill some of the screen mesh under the well. Let this plaster set. Take a metal strip about 1/4 inch wide, bend it to make a collar, leaving an opening where its ends nearly meet, to admit the connector tube. Put plaster around the base of the collar, and plaster the end of the tube in place; let this plaster set.

The aluminum bottom comes next. The foregoing work need not be fussy; hence, the collar will no doubt be somewhat irregular. To make an easy job of cutting a bottom that will overhang the collar slightly, lay a piece of paper onto the collar and press it down to get the collar imprint. Hold this to the aluminum sheet, using it as a template for cutting. Lay on the bottom, and cover the whole job with plaster. We now have a slab with a well; a screen at well bottom; and a chamber below the screen, with tube attached. Feet are added, of course. The slab is ready for the sandbed.

Screen; Additional Screen Support

Any screen that will hold the sandbed material can be used, but preferably, it will be non-rusting in character. After cutting it to size, the screen will almost certainly have to be flattened by some handwork. Even so, it may require some judicious weighting down here and there, to hold it flat while the margin plaster is painted on.

For small sandbeds, the screen alone will be stiff enough. But a large well, using some kind of thin, fine-mesh screen, may require that the screen be kept flat by extra support. Pieces of brass rod, 1/8 inch, will do the job. Before the screen is plastered on, these are laid onto the screen (slab inverted), spaced an inch or two apart. Weight them if necessary. Their ends are plastered down at the same time as the screen margin is plastered. Their lengths are such that the collar goes around their ends. After completion, if the screen waviness causes it to bulge up here and there, tie it down to the rods beneath, with thread.

If suitable metal screen is not available, there is another way to make up a screen job. Instead of screen, cover the well bottom with brass rods, spaced one rod apart, and plaster their ends. These will support the screen, which now is made of two thicknesses of cheesecloth. Stretch the cloth, spray it with Krylon to stiffen it, let dry, then cut it to fit down onto the rods, with a little margin to spare. Still another expedient is to plaster on a piece of perforated metal sheet where the screen should be, then cover it with cheesecloth.

Sandbed Materials

Standard Ottawa Sand is what the writer used in his original sandbeds. Hence the name. Sand is too low in density. It is hard to see, difficult to put in place, and too easily disturbed. Nevertheless, it will work, and can be used if better stuff is not obtained.

Smooth metal balls of around 18 mils diameter make the best sandbed. The size should be between about 16 and 24 mils. Ball bearing balls of a non-rusting metal would be excellent, but prohibitively expensive. We must look to other types of materials, and two such are available. One is shotted metal (also called metal powder); the other is cast iron shot.

Metal shot (not made in shot towers!) can be had from companies such as Metals Disintegrating Co. Inc., Elizabeth, N.J., makers of metal powders. Copper shot of their MD34A designation, if most of it is reasonably smooth, serves very well. It may need cleaning, to take out defectives. The writer uses their nickel shot. It is admirable for sandbeds, but this shot was from an experimental batch and is probably unobtainable. We live in a fast-changing technology, and it is rather useless to specify a company and product precisely; a change in the company's customers needs may at any time wipe one product off the market, and replace it with another that would be unsuited for sandbed work. This is a good reason for knowing about cast iron shot.

Cast iron shot is made by the ton, for shotpeening surfaces, and cleaning up castings with an air blast to deliver the shot. It should continue to be available. Smooth round shot, averaging somewhere around 18 or 20 mils, should be specified. It will have a goodly amount of debris and bad shapes in it. Sifting small quantities slowly down an inclined plane will do a sorting job. Many defectives are left behind.

Dark or rusted cast iron shot can be brightened considerably by acid, using equal parts of water and HCl, and stirring for a while. To minimize rusting after use, the batch should be dried on paper towels, moving it from one towel to another; and stored dry.

The test of a good sandbed material comes in seeing how it manipulates when being made up into a sandbed.

Making a Sandbed

In assembling the mapper, methods used for getting air out of Type 1 systems will not suffice here. A fine screen can trap large bubbles under it, which no amount of tank elevation will remove. Use the ear syringe, and apply suction all over the screen, repeatedly. If, by construction, there are places down in the chamber where bubbles may lurk, use jetted water from the syringe to go after them and get them to where they can be sucked up through the screen.

Place enough shot in a handy little bowl, and cover it with water. Now add some wetting agent, and stir. Also add wetting agent - some suitable detergent, of which many are available - to the tray water. Metal shot do not wet easily, and many would otherwise float, and cause much trouble.

Pour from the bowl into the well, or use a spoon, until the well is nearly full. If the metal shot are suitable for sandbed work (smooth enough and uniform enough) they will settle into place, under water, with hardly any urging by the spoon. Add more, to near fullness, but do not over-fill. Now place a small piece of plate glass down over the well, to flatten the hill of shot, and reveal unfilled areas. Fill these with the spoon; or, for tiny amounts, use a medicine dropper, with the snout broken off to make it large enough to take the shot.

When the well is precisely full, shifting the little plate sidewise will make the top layer assume a pattern that is soon recognized; and, the top members will exhibit slight movement all over the surface.

A single shot, stuck in a tiny bubble cavity, or resting on the slab face and serving to keep the plate from going down, will spoil the finishing of the sandbed. The feel of the plate when shifted, will betray the presence of such a shot, if it is not seen.

Type 2 Operation

Let the slab of Figure 13 be sprinkled all over, and the sandbed operated as a sink. The pattern outside of the sandbed will be visible. However, crystals on the bed make dyelines that go down through it, and these lines are not seen. Also, incoming dyelines from the slab form a floor pattern, and these promptly disappear down into the bed near the edge. The sandbed pattern does not show. Now reverse the mapper: the sandbed becomes a source, and the complete pattern appears, as in Figure 15.

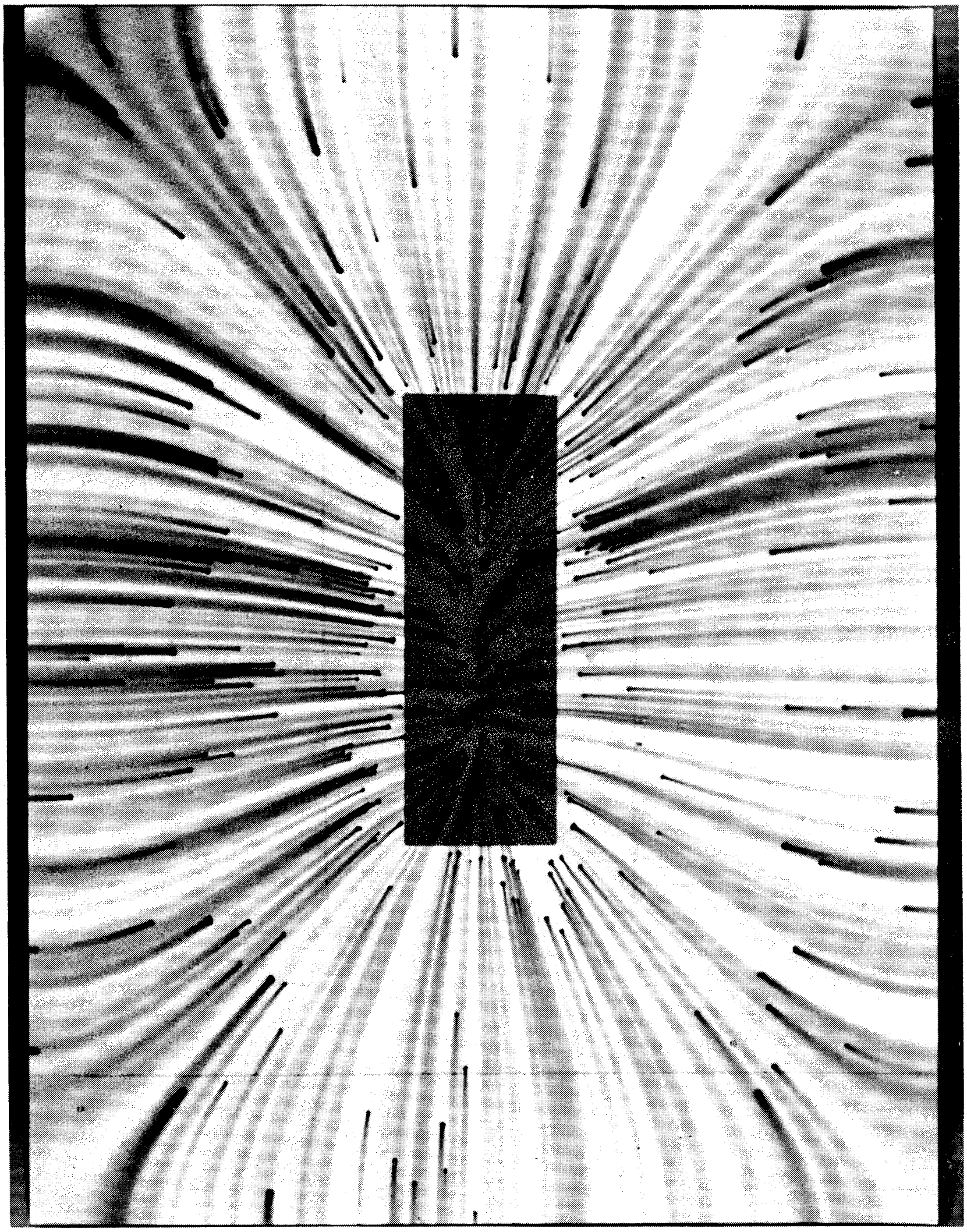

Figure 15. Slab with non-uniform sandbed. Kernel is over the thinner part of sandbed, where source density is greatest.

Better yet is a ceiling pattern, seen in Figures 8, 13, and 17, due to methylene blue crystals stuck to the plate at the slab's boundary. The MBM technique can also be used. These high-up flow lines carry in over the sandbed area before going down (operating as a sink) and some of them reach almost to the kernel.

At the end of operating, the only convenient way to recover the shot is by "fludizing" - using water to make the stuff flow. The slab can be tilted up on edge, and water used to flush out the shot into the tray; from there, with water, it is poured into a bowl. Or again, the sandsucker idea can be used to empty the bed, without disturbing the slab. Take a long enough piece of rubber tube, 1/4 inch I.D., with a piece of thin-wall metal tubing stuck in one end. Dip the metal tube in tray water, let the other end of the rubber tube reach toward a bowl on the floor, and start flow by siphon action. Put the metal tube against the sandbed, move it around, and soon, all the shot are in the bowl.

Non-Uniform Sandbeds

Within limits, non-uniform sources can be simulated by sandbeds having varying depth. In Figure 15, the slab and sandbed are superficially symmetrical; and if the sandbed were of constant depth, the pattern would be symmetrical, with the kernel located at the center.

Instead, the kernel is nearer one end of the sandbed. This is because this composite slab was made with a sloping screen, sandbed depth being three times as great at one end as at the other. The kernel is over the thinner portion of the bed.

The flow density appearing or disappearing over a sandbed of this kind is approximately inversely proportional to depth.

Discussion of Flow Resistances

To achieve the ideal in a sandbed mapper, several requirements would have to be met. First, the chamber below the sandbed would be vastly deepened, with its feed placed at the bottom. Flow in the chamber would rise vertically (sandbed acting as a source), and the bottom of the sandbed would be virtually an isopressure plane. Second, the sandbed would be made of extremely fine particles, so that fluid would appear uniformly on top, in spite of the fact that lateral flow occurs in the flow space, and therefore pressure variations do occur over the sandbed. Also, the extremely fine particles would make lateral flow within the top levels of the sandbed, negligible. It is quite out of the question to meet these requirements in practice, and quite unnecessary. The apparatus as described herein typically will serve to simulate the field being solved, with good accuracy.

In case of doubt, one can run an "upper test" and a "lower test". Operate with, say a 35 mil flow space. Then again, with a larger flow space, say, 50 mils, or anything like that. If there is no appreciable pattern change, then all is well. The sandbed is producing a virtually uniform source. That is the upper test.

The lower test removes worry as to whether the chamber is deep enough: will lateral pressure drops in it affect the uniformity of the source? If there is doubt, simply install two connector tubes to the chamber, as far removed from each other as possible. Operate with one of them used, then arrange to shut it off and shift to the other. If the pattern remains essentially fixed, the worry was unfounded. The fact is that a chamber 1/4 inch deep can adequately serve a remarkable sandbed area - even up to measuring several inches each way.

ISOLATED SANDBED - TYPE 3

The Isolated Sandbed

Talking "slab language", a Type 1 mapper has a slab without a sandbed; a Type 2, a slab with a sandbed. Then a Type 3 mapper has a sandbed without a slab. The sandbed is alone - no slab surface outside of it. The thin flow space is present over the sandbed only. If - as soon described - the construction is such that there does seem to be a slab around the sandbed, it is structural only: it does not play a part in the flow space.

Construction

Again, plaster techniques turn what could be a difficult job, into a series of simple operations. An unfinished unit for a rectangular sandbed is shown in Figure 16. A template of pasteboard is first fixed onto a plate, being taped down by way of windows cut in it. The metal band, 1/2 inch high, is bent to fit around and against the template.

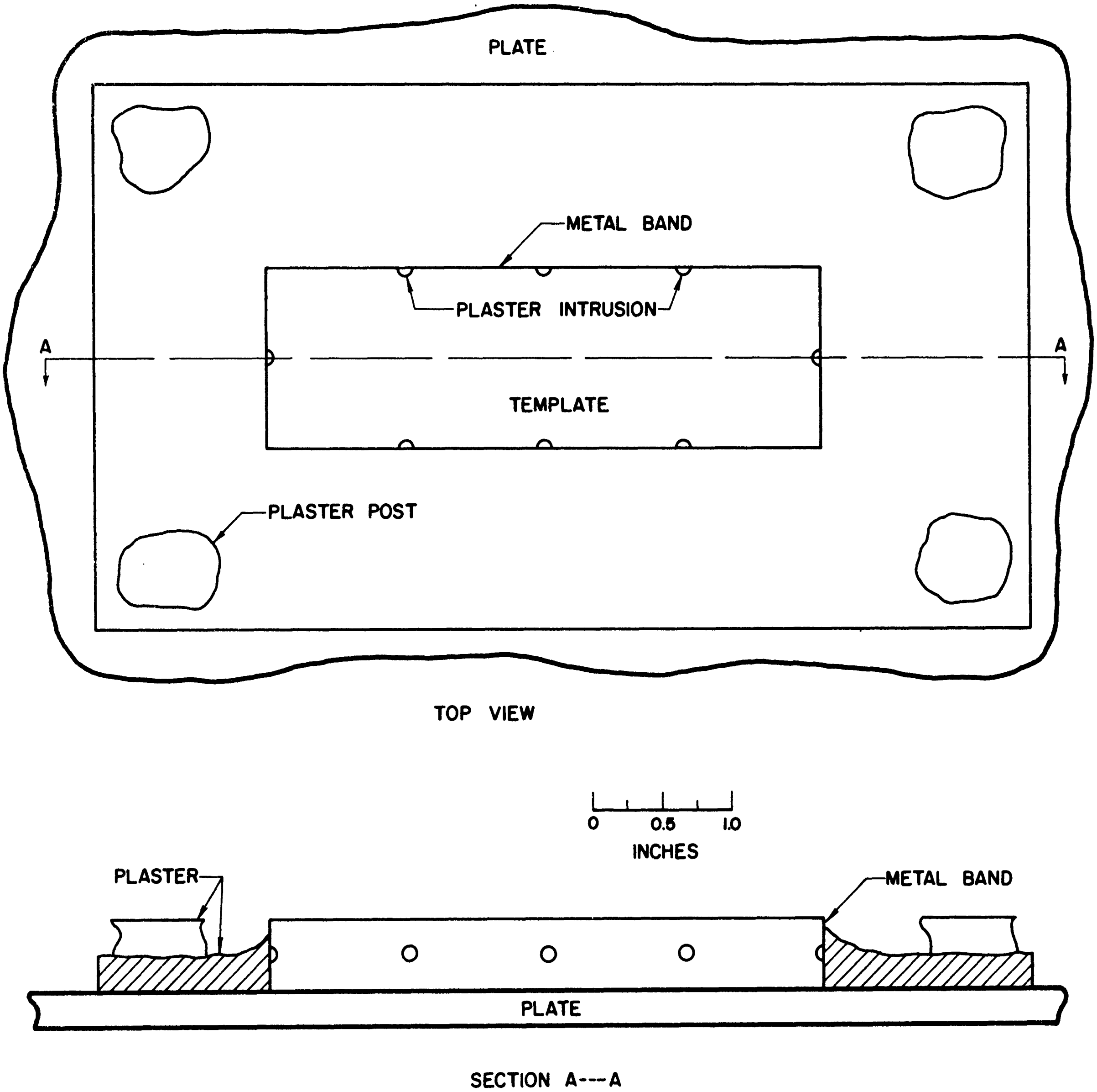

Figure 16. Isolated sandbed construction details. This slab is not shown inverted: the four corner mounds are posts, not feet.

Every inch or so along the middle of the band, small holes are drilled or punched through the band (which will deform it at the time - it will need flattening again). After setting up an outer fence mold, a thin plaster slab is cast around the band. It extends far enough out to provide for the plaster posts shown in the drawing.

Thus a cast, structural, but not functional as to the mapper pattern, is made roughly 1/4 inch thick. While the plaster is unset, a spatula is used to drag plaster up to near the top of the band; in doing so, care is taken to cause plaster to enter the holes, form an intruding knob inside, and thus grip the band to hold it permanently in place.

After the plaster is set, plaster for the four posts is piled on high enough so that, when a plate is gently put down to rest on the top of the band, the posts are squeezed to have flat tops level with the band top.

The unit is next inverted. The screen, collar, bottom, and connector tube are added as heretofore described; and feet are added to let the unit have a firm base for operation.

Operation

The sandbed is made up and finished off accurately as already described except that now, in bringing the sandbed top layer of shot to precise level, the plate rests, not on a slab face, but on the top of the band and the posts.

For operating, the spacers are laid on the plaster posts, to provide the thin flow space.

Figure 17 shows such a unit in operation, using the crystal-on-plate technique for dyelines, and the sandbed used as a sink.

PINHOLE SLABS

Fixed Sandbeds

When making up a sandbed of loose material, one inevitably wonders - why not develop a fixed sandbed, using a block of some uniformly porous stuff? This is a very attractive idea, in theory. In

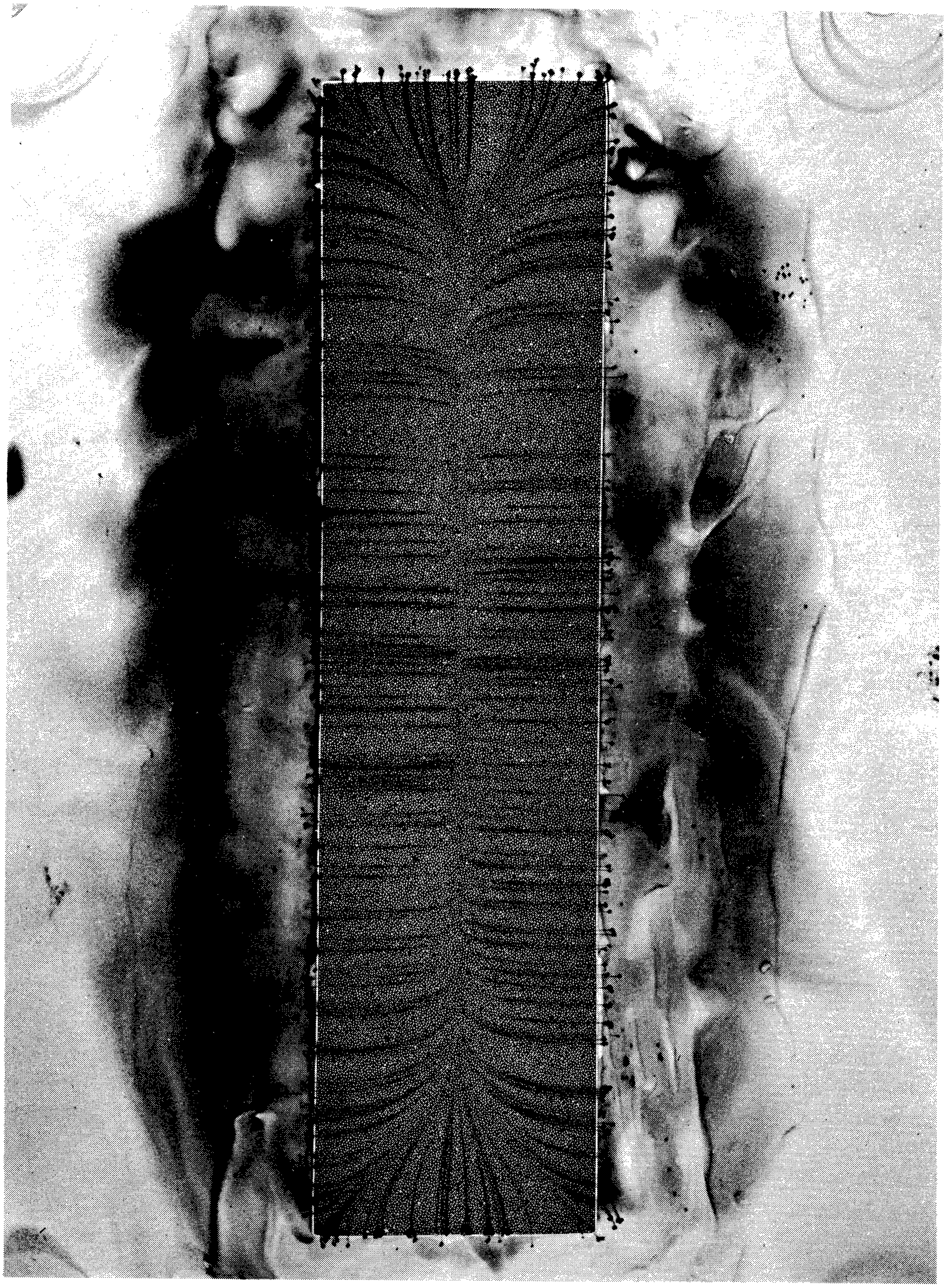

Figure 17. Isolated sandbed operating as a uniform sink, ceiling pattern.

practice, there are hazards and difficulties that have not been surmounted as yet. Let us hope they will be, by someone who finds the right material and works out simple, reliable techniques for using it.

Styrofoam Needlehole Slabs

Pursuing the fixed sandbed idea, the writer once cast an experimental slab around a flat piece of Styrofoam, and put a chamber under the Styrofoam. The hope was that the Styrofoam would prove to have reasonably uniform porosity. It turned out to have no porosity: no fluid came through. Styrofoam is impermeable. Impatient then, the writer determined to get some effect, and did so by punching holes through the Styrofoam with a needle. The results were promising.

Later, this technique was very well developed by Dr. Jun-ichi Fukuoka in the writer's laboratory, when he came from Hokkaido University on a Fulbright Scholarship, and spent his year in the laboratory, learning fluid mapper techniques. On returning home he set up his own laboratory, and through his publications, introduced fluid mappers to Japan. Highly skilled, this brilliant man has done a great deal of beautiful work.

The needlehole-in-Styrofoam technique is promising, but it is quite difficult to cut Styrofoam blocks accurately to dimension. Also, holes punched through bubble walls are not prone to be uniform: their surfaces are ragged rather than smooth, and possible inequality of performance might continue to be a worry.

Drilled Holes

It is entirely possible to replace the loose sandbed of Figure 13 with a fixed equivalent, by drilling holes. Cast the slab to uniform half-inch thickness, without the well. Then drill numerous equally-spaced holes down through the sandbed area, and put a chamber and connector underneath. There are two handicaps. Drilling takes time, especially since a very small drill tends to choke up on plaster. Also, as the drill wears, appreciable hole inequalities might appear.

Pinhole Slabs

To avoid drilling, the next idea was to have the sandbed area studded with ordinary pins, prior to pouring the plaster for the slab;

then withdraw the pins, and thus achieve a suitable hole array. Very good - but how to hold the pins? It was some years before the writer solved this problem, through that other highly adaptable material - modeling clay.

The Pinhole Processes: Clay Preparation

Three plates are used, shown small in Figure 18 to make the drawing clear. They are normally larger. Lay down the lower plate, and place two plates, separated, on it. Put a large enough lump of modeling clay on the lower plate, press and manipulate it down to, say, half an inch high, then start rolling it. Separate the two plates as needed, to give the clay freedom to spread. It spreads irregularly.

With the clay down to near plate thickness, take a knife and cut both sides of the irregular clay margin with two fairly parallel straight cuts. Remove the cut-off portions. Now roll some more, and get the clay still flatter, and closer to plate thickness. Cut margins again. Next, move the two plates in, with edges pressing against the straight clay margins. The clay will never roll down completely; it still bulges up somewhat.

Scraping comes next. This requires practice; also, allowance must be made for the way the clay changes in plasticity and stickiness, with temperature change. The writer uses a piece of square brass tubing, with sharp corners. Tilted slightly, it is drawn over the clay bed, to remove a thin shaving. This is repeated until the clay bed is flat, and level with the plates.

Marking Pin Positions

The clay surface is very delicate and easily disturbed. A way must be found to mark pin positions on it, without damaging the smooth surface. First, elsewhere, lay out pin positions for the desired sandbed array, on a piece of paper. Take a pin or needle, and pierce each pin location. Small holes made thus in the paper have their edges turned down. Lay the paper in correct position, on the clay bed. Lay a plate on it, for pressure, then remove the plate. Lift the paper. Each pinhole margin of the paper now shows on the surface of the bed.

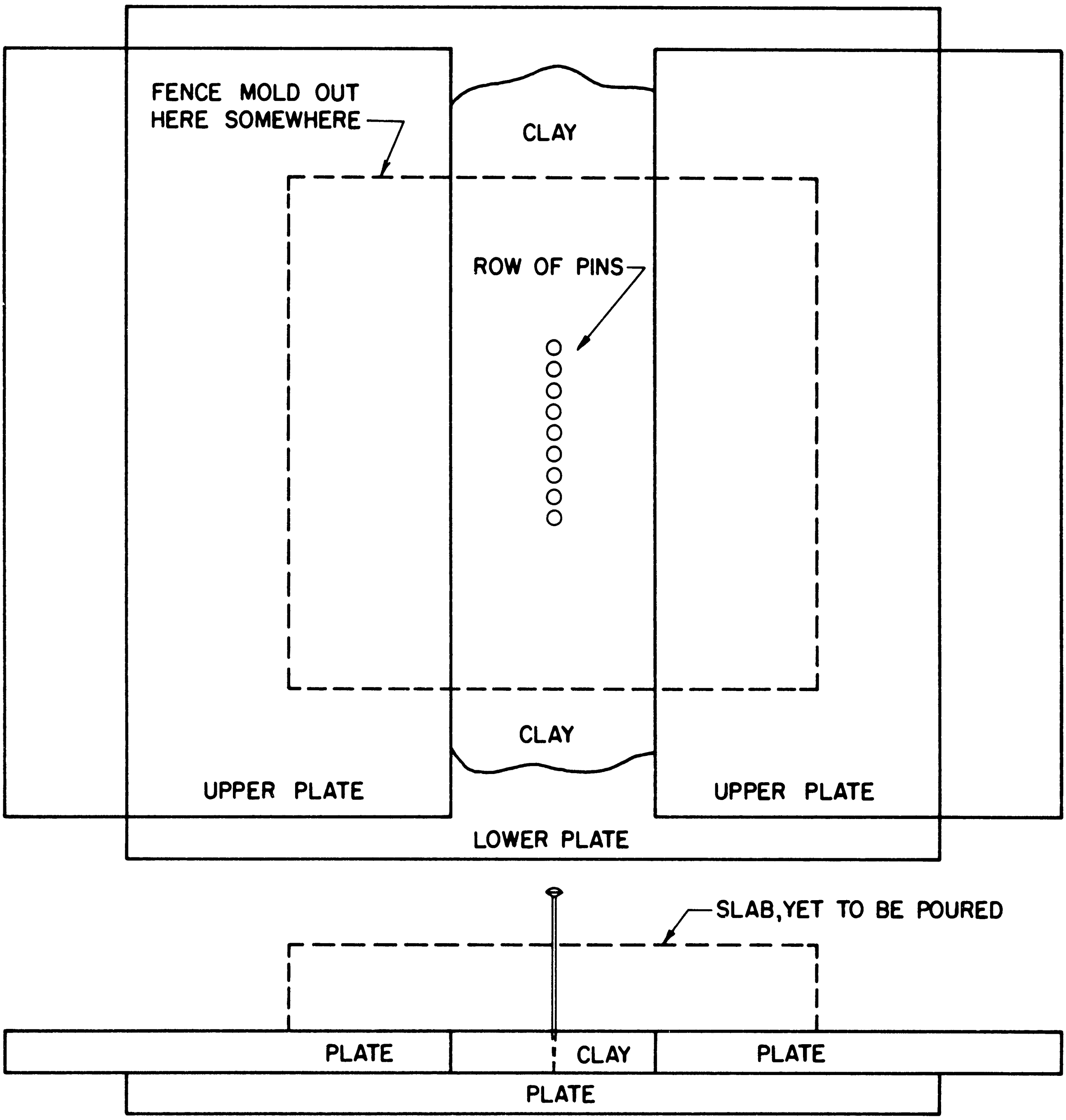

Figure 18. Pinhole slab techniques. (To make the drawing clear, plates shown here are much smaller than usual size.)

Pin Placing

Pins can be placed with the fingers, but a better job may be done with tweezers. These are ordinary pins, bought as a paper of pins at the 5-and-10. Take a bit of petroleum jelly, smeared between left thumb and forefinger. Grasp a number of pins therein, rolling them to give them a thin coat of grease, all at once. Take one at a time from the left hand with the right, and push it down through the clay until it touches the lower plate. If in a row of pins some are leaning slightly this way and that, it is not serious. The more important feature is to get the pin located correctly where it pierces the clay bed.

Slab Pouring and Finishing

Pouring the slab presents a special problem, for an array of pins close together will make a fine bubble trap. It may sometimes be best to give the plaster a setting-delay additive. This will give time for manipulating plaster to flow in among the forest of pins, and for using the small probing brush to bring up bubbles. Also, time is needed for filling in the slab plaster closely to the half-inch level.

After setting, the pins are pulled. Tweezers or pliers may be needed to release them. Wetting the slab may help. The pins can be saved for future use. The wetted slab blank will not slide freely off the plate, for the modeling clay tends to stick; but it does come away easily enough, and the clay can be retrieved and used over and over.

The bottom of the slab cannot be cast to accurate flatness, and it is now ground flat. This is done by skating it around, wet, on wet-or-dry grit paper which is laid on a flat surface. Thus, all pinholes are made alike, both as to diameter and length.

In grinding, the holes will become completely plugged with wet soupy material ground from the bottom. Flushing with tap water cannot be relied upon to remove all of this material. Using the ear syringe, place its opening against each hole, and force water through.

The hole array replaces the loose sandbed, and also the supporting screen. The slab is finished with feet, and the usual chamber and connector tube to feed the hole array.

Pinholes versus Loose Sandbed

If the loose sandbed were replaced by a very large number of pinholes equally spaced, the pattern over the distributed source would look the same. Since pinholes must be limited to a practicable number, with feasible minimum spacings, a difference in operation will show up. The general pattern will be the same, but of course, localized little patterns will occur in the neighborhood of each hole. For technical work involved in actual solutions of potential field problems, these localized effects would be wiped out by smoothing the flow lines in a tracing of the photograph.

The pinhole technique has unique possibilities. If only a line of pinholes is made, as shown in Figure 18, we have a means of simulating, say, the cross-section of a uniform current sheet, and the pattern leads to a solution for the magnetic field at and near the sheet. There are other technical problems that would call for very narrow sandbeds. But very narrow sandbeds are impracticable, when the width of the loose sandbed may be only as great as two or three sandbed sphere diameters.

Furthermore, within limits, non-uniform distributed sources are readily achieved by appropriately varying the pinhole spacings. A still greater variation of flow density over the distributed source area could be had by varying the thickness of the pinhole part of the slab; or, doing a composite job by pinholing two pre-cast pieces of different thicknesses. Approximately, if all holes are quite a number of hole diameters long, hole resistance would vary in proportion to hole length. For more accurate work, calibration tests would be needed.

PAPER LAMINATE TECHNIQUE FOR FLOW SPACE VARIATION

An Experiment

Take a piece of smooth paper, such as is widely used for making Ditto copies. It is perhaps 3 mils thick. Cut out a small piece of it, of any shape. Put the piece under water, to wet it thoroughly. Take it out and lay it on a plate. Use a very damp, almost wet cheesecloth on it, to pick up excess top water; gently rub the paper, to squeeze out any water from underneath. With the paper still wet, and before it has any chance to dry out, pour some plaster all over it and around it. Jiggle the plaster gently to raise bubbles up from below. Let set.

On removing the cast, one finds the wet paper tightly stuck to the plaster. Rub most of it, wetted, off the slab face. Many fibers will remain stuck. Go after these with a stiff brush, and remove them all.

Close inspection now shows that the plaster has not only accurately copied the impressions left by the wire screen used in making the paper - it also will show the watermark of the paper.

Follow this with several pieces of paper, one on top of the other, each smaller than the one below. This is a paper laminate. Squeeze out excess water, but have complete wetness when the covering plaster is poured. When the paper laminate is removed, its stepped-off impression will be left in the slab.

Stepped Slabs from Paper Laminate

Very good demonstrator slabs having two or several steps, showing fields in two or more media, are easily formed in one piece by casting them on wet paper laminates. Each step may be one, two, or more paper thicknesses thick, as desired. Rather than take the time to achieve such results by way of the composite slab, pre-cast, or sequence-cast, this method will give quite good results, even though hastily done.

Warning: the laminate must be wet. Not just very damp, but wet, with pores water-filled. The writer's first slabs cast on laminate of a dozen or so laminations, mysteriously came off the plate with one or more dimples. Two solid weeks went into attempts to find a way to make the paper stick to the plate. Twenty-eight different methods (various glues, adhesives, etc.) were tried, all of which failed. At long last, it was found that in carefully applying one piece of paper after another, earlier pieces had lost water and were partly air-filled. The plaster, at a certain pre-setting stage, exudes water (which is later taken back in). This caused entrapped air to move to one place, bulge the paper up, and make the dimple. The cure was simple: make sure the entire laminate is wet when the plaster is poured over it.

THREE-DIMENSIONAL SLABS FROM PAPER LAMINATE

Circular Symmetry

Fluid mappers cannot simulate generalized 3-dimensional fields. But some of those fields having circular symmetry (symmetry about an axis) can be handled. However, in theory, this demands that the flow space part of the slab's face be curve Applying the Spacing-Cubed Law, the curve ought to be such that the flow space varies with the cube root of the radius taken from the axis; or else, inversely with the cube root, depending on whether it is a pro-axis or a cross-axis slab. Now, the business of getting that curved face, on plaster or anything else, can be an expensive process. The long quest for a simple way to make such slabs ended only with the development of the paper laminate method, by way of throwing away the curve and replacing it with very gentle steps.

Curve Replaced by Steps

Knowing the law of variation, based on cube roots of radii, it is a simple matter to figure out equal-height steps such that the desired curve would pass approximately through the middles of tread and the riser of each step. If a stepped mapper is so constructed, it will operate to give a pattern very nearly the same as it would have with a truly curved face - provided the steps are gentle enough. There will be a slight refraction as a dyeline goes over a step, but so slight that it may even be difficult to find it.

A 3-D Slab

The drawing, Figure 19, shows a 3-dimensional slab cast on a 14-page laminate. It is the pro-axis type: any fluid flow at the axis goes along it. Where the steps become very short close to the axis, two or three have been left out of the drawing. They would not show if drawn in, on this scale.

To explain what this slab's pattern might represent, revolve the case about the axis. The flow space then generates a volume of revolution which is a right circular cylinder. Let it be a heat-conducting cylinder. Let the bottom, and part of the top, be covered with perfect heat insulation. Let one temperature be imposed on the outer circular surface, and a lower temperature be imposed on the circular top area swept out by the well. The mapper's pattern lines would then show the heat flow lines.

If the step lines are laid out on a Ditto master, plenty of Ditto copies can be made. Thereafter, other slabs can be built, without having to lay out new cutting lines each time. In building the laminate, each copy is cut back one step further before being laid down. It is difficult to lay a piece of wet paper accurately in place. Sliding it into place is facilitated by lightly painting a layer with thin Methocel paste, before laying down the next layer.

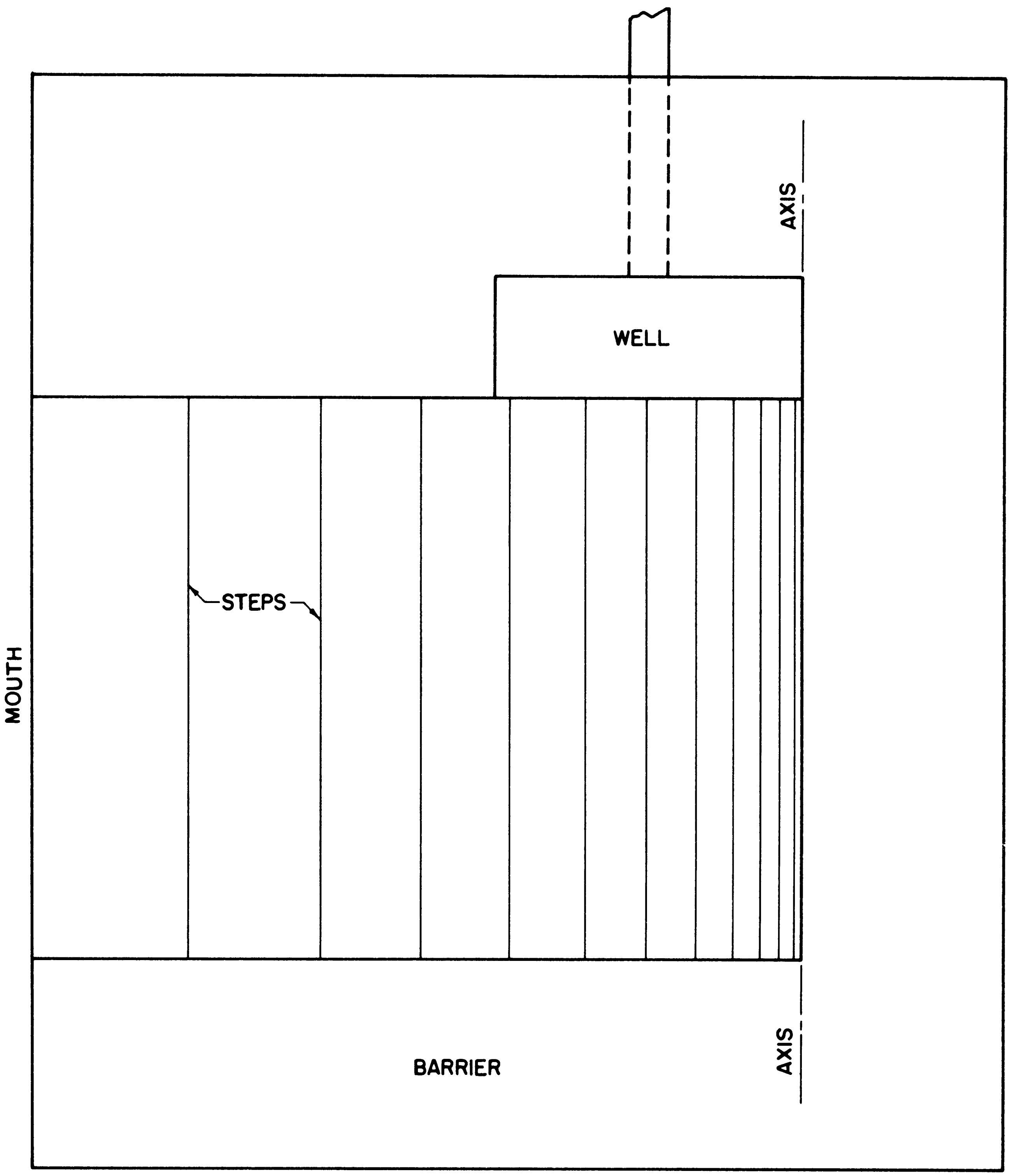

Figure 19. Axi-symmetric 3-dimensional slab, stepped, cast on paper laminate.

Warning: test the paper beforehand, by wetting it, and measuring its wetting expansion each way, before laying out the master. The master can then be made, taking expansion into account.

OPERATION: OBTAINING REQUIRED FLOW OR PRESSURE VALUES

Potential Field Problems

Many potential fields for which solutions are needed, have symmetry. Suppose such a case arises, which calls for a slab with two wells, and it is known that the field will be symmetrical about both centerlines of a rectangular flow space. When tank levels are adjusted to give the double-symmetry pattern, the pattern is ready to be put on record for analysis.

Other cases arise, having no symmetry, and the foregoing easy attack will not serve. Those who work with the several potential fields will recognize that one or the other of two kinds of imposed conditions can prevail in a given case. First, a problem will require of the corresponding fluid mapper that certain relative flow rates of wells must be imposed. Or second, certain relative pressures must be imposed.

Imposing Flow Rates

In Type 1 mappers, it is easy to impose relative well flow rates. Recall that typically, in mappers as described herein, nearly all of the system resistances are to be found in the long rubber connecting tubes. If these tubes are given a minimum length of 20 inches, then by using tube lengths inversely proportional to desired flow rates, surprisingly good results are obtained. Rubber tubing certainly is not accurate stuff, and the way the tubes must curve around to make connections and allow for manipulations must be expected to reduce accuracy still further. But if 1/4 inch I.D. Handmade tubing is used, all cut from same length as supplied, it does a surprisingly good job.

When higher accuracy is needed, the professional operator will calibrate his flow system in some manner.

Imposing Pressures

Imposing pressures in the fluid mapper corresponds to imposed potentials in the potential field problem. This is much more difficult to do, than imposing flow rates. The basic difficulty stems from the fact that pressure drops in the mapper's flow space are exceedingly low.

The direct method would be to arrange small tubes that would end internally in, say, two wells of a two-well slab, with a third tube ending in tray water. Externally, these tubes would go to vertical manometer tubes, where water levels would indicate existing pressures. But this is merely an idea. It cannot be carried out, for the tiny differences in level cannot be read. Two expedients are then brought into play.

First, the manometer tubes are inclined; and second, the operating fluid is made highly viscous. Both changes greatly magnify the change of position of the meniscus in a manometer tube, and readings become possible. The writer has done just enough of this work to know that it has possibilities, but that it calls for careful techniques if good accuracy is to be achieved.

There is a quite different approach to this problem, available when the slab is not too complex. That is to operate with any initially adopted tank water levels, get a pattern, record it, map part of it, and analyze to find what relative pressures did exist. Next, change one level, and go through it all again. Change again, and repeat. Now a curve can be plotted, to find just the level needed in that tank to get the desired relative pressures.

Be it noted that someone may make a welcome contribution, by developing a very delicate but accurate transducer for pressure-sensing, to use in this line of work.

FLUID MAPPER LITERATURE

1. Fields from Fluid Flow Mappers, A. D. Moore. Journal of Applied Physics (New York, N. Y.) volume 20, August 1949, pages 790-804.
   (The first fluid mapper paper. Numerous photographs of all three mapper types, including 3-dimensionals. Numerous materials and techniques described. Some of these early techniques have now been greatly improved, or replaced.)

2. Soap Film and Sandbed Mapper Techniques, A. D. Moore. Journal of Applied Mechanics (New York, N. Y.) volume 17, September 1950, pages 291-298.
   (The soap film analog is furthered by description of the invention of a new photographic method for finding film contours. The illustrative case used is then solved by the fluid mapper sandbed method, with results compared. Film contour lines are orthogonal to sandbed flow lines. A routine for analyzing the sandbed flow pattern is given.)

3. Four Electromagnetic Propositions, with Fluid Mapper Verification, A. D. Moore. Electrical Engineering, volume 69, July 1950, pages 607-610.
   (One of these 2-dimensional propositions shows that even with iron present, any current distributed over the cross-section of a solid conductor may be centered at the axis without disturbing the magnetic field outside of the conductor, if the current has circular symmetry about the axis. Striking verification by way of fluid mapper photographs.)

4. The Further Development of Fluid Mappers, A. D. Moore. AIEE Transactions, volume 69, part II, 1950, pages 1615-1624.
   (Photographs, all three types of mappers. Extended discussion of materials and techniques.)

5. Mapping Techniques Applied to Fluid Mapper Patterns, A. D. Moore. AIEE Transactions, volume 71, 1952, part 1, pages 1-6.
   (The writer's circling-in technique for forming curvilinear squares; mapping of tubes into squares; treatment of remainders; tube evaluation in relative ohms; further analysis of the map. It should be noted that these techniques for dealing with fluid mapper patterns also apply to patterns or maps otherwise obtained, - as from conducting paper methods, the electrolytic tank, and graphical trial-and-error mapping.)

6. Fluid Mappers as Visual Analogs for Potential Fields, A. D. Moore. Annals of the New York Academy of Sciences, volume 60, Art. 6, 1955, pages 948-962.

(Photographs; descriptions of various mappers, materials, techniques.)

7. Fluid Mapper Patterns, A. D. Moore. Overbeck Company, Publisher, 1956, 31 pages.

(Loose sheets in envelope. A work manual for student use in a fields course. Various line patterns drawn from fluid mapper patterns, ready for mapping and assigned problem solution. A number of pages of text content on mapping; including special routines needed to handle fields having refraction (2-medium cases).)

8. Appendix 2, Fluid Mapper Techniques, A. D. Moore, starting page 324 in a book, Introduction to Electric Fields, Walter E. Rogers, McGraw-Hill, 1954.