

A STUDY OF THE WATER PERMEABILITY  
OF PORTLAND CEMENT CONCRETE

by

JAMES SAMUEL BLACKMAN

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Arch. E., University of Nebraska, 1947

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## INTRODUCTION

Engineers have long recognized that concrete is a porous material, (1) and have expended considerable effort in reducing that porosity to a minimum. When a material is said to be permeable it is implied that connecting passages exist through the body of that material, and that the passages are at least several times the diameter of a molecule of the percolating fluid. For example rubber is permeable to certain gases, and with respect to water, such materials as gravel, brick, soil, clay and concrete are permeable in varying degrees.

The permeability of concrete to water has for many years been a bothersome problem to engineers. Many methods have been devised for treating concrete to achieve the desired degree of impermeability. They may be grouped as follows,

1. Proper proportioning of the concrete mix.
2. The use of proper techniques for placing and curing.
3. The use of integral materials added before the concrete is mixed.
4. The application of surface treatments.

It will be noted that groups one, two and three are directed toward controlling the permeability of the concrete by reducing the size and number of passages available for water movement. The methods of group four on the other hand substitute an impermeable barrier between the concrete and the water. In this latter group the relative permeability of the concrete is of little concern for it acts only as a support for the impervious

membrane. The methods of group four then can be discarded as contributing nothing to the real permeability of concrete. Groups one, two and three include all methods by which the continuous passages through concrete (the pore system) may be reduced to a practical minimum, that is, to a point where the amount of water passing through the concrete is not measurable, or is at least negligible.

The extensive use of concrete in hydraulic structures, irrigation, and water supply has focused attention on the fact that watertightness may be of equal importance with such prime physical properties as compressive strength. The importance of impermeability lies not so much in confining water to its proper channels, for as shown above, almost any concrete made with proper attention to mix design and curing will prevent appreciable loss through percolation. The real need for watertightness lies in its improvement of the durability of the concrete. The disintegrative effect of freezing and thawing of saturated concrete results in the destruction of large mileages of pavement each year, and untold damage to structures of all kinds. In addition to the damage of freezing and thawing, percolating water removes essential ingredients by solution. Ruettgers, Vidal and Wing (6) state that,

assuming that when the lime content has been reduced to 60 percent, one half of its strength is gone, this becomes the estimated value of the lime content at which the concrete must be replaced. Based on Hellstroms data as plotted on Fig. 10 with water equivalent to distilled water incorrosiveness, this value [60%] will be reached when the total discharge through the concrete is about 35 cubic feet per pound of cement. It is thought that this discharge

represents a minimum for which failure of concrete due to removal of salts in solution by percolating water can be expected.

The removal of salts progressively weakens the concrete and makes it more vulnerable to further attack. In addition to the effect of permeability on durability by means of freeze-thaw and dissolution, a third disintegrative effect of percolating water is the redistribution of corrosive or alkali salts. In areas where alkali soil is found, surface water may take the alkali into solution and then upon entering the concrete deposit the alkali in the pore structure of the concrete. In severe cases "blooming" may result. These phenomena result from the evaporation of the alkali laden water from the surface of the concrete leaving a deposit of alkali crystals on and in the surface of the concrete. Recent studies of the alkali-aggregate reaction and its effect on the durability of concrete have raised the question of whether the redistribution of alkali in a concrete may not produce a concentration of alkali that may locally promote the alkali-aggregate reaction. A cursory examination, only, is sufficient to show the destructive effect of frost and permeating salts. It is axiomatic then that permeable concrete will exhibit a distinct lack of durability.

The investigation described in this thesis was limited to the passage of water through two sizes of specimen, to only one concrete mixture, and to one evaporating temperature. The work was initiated in an effort to achieve three things,

1. To determine how water passes through concrete, whether as a liquid or as a vapor.

2. To investigate a simple method of test for determining the permeability of a given concrete.

3. As a pilot investigation, to develop techniques and apparatus that would be useful in extending the investigation.

The investigation as carried out was based on the principle that water will carry salts in solution only while in the liquid state. It would seem reasonable that if water passes through concrete as a liquid it could be made to carry soluble material in solution during passage. If, then, at any point the water vaporized the salts would be deposited. If on the other hand, the water passed through the concrete as a vapor, the distribution of the salts would be in no way altered by the movement.

The original intention, in initiating this work, was to make use of a radioactive isotope in the form of a soluble salt, introduced into a concrete specimen at a known point. The migration of the radioactive salt under the influence of migrating water could be followed by the effect of the migrating radiation on a photographic plate suitably located on the specimen. When it was found that the desired radio isotopes would not be immediately available, it was decided to proceed with a preliminary investigation using chemically pure sodium carbonate as the salt and a chemical analysis of a section of the specimen by the flame photometer method to evaluate any redistribution of the salt due to percolating water.

The present method is intended to be exploratory only, and will serve to determine such details as size of specimen, arrangement of apparatus, and the techniques of preparing specimens for

test. Perhaps the greatest disadvantage of the chemical method is in the destruction of a specimen during each determination. It is anticipated that with the arrival of the radio isotope that the work can be greatly facilitated both as to time and the number of specimens tested.

The work has been conducted as a project of the Engineering Experiment Station of Kansas State College at Manhattan, Kansas, and has been under the direction of C. H. Scholer, Professor of Applied Mechanics and Engineer of Tests.

#### REVIEW OF LITERATURE

Many investigators have shown (2, 3, 4, 5, 6) that the permeability is increased with an increase in the water-cement ratio, and with any condition that causes an increase in water-cement ratio. It follows then that proper design of the concrete mix is essential to the production of watertight concrete.

Investigations have also shown, (2, 3, 4) that the effect of curing on permeability is considerable. The longer the time of effective curing the more impermeable the concrete will be. Ruetters, Vidal, and Wing (6) report a ratio of 3 to 1 relative reduction in permeability between the ages of 20 and 60 days curing. Since the majority of field concretes are cured for no where near sixty days this is vast understatement. The estimated gain in watertightness shown by their curve shows a 75% gain in watertightness between 15 and 30 days of curing. Most field concretes receive not to exceed 15 days curing so it

is readily seen from the values above that early and adequate curing is necessary to the production of watertight concrete. A greater gain in watertightness with increased time of curing can be expected in lean concretes than in richer ones.

The majority of investigations upon which reports are available have been confined to concretes made up of relatively small maximum size aggregate. The work of Ruetters, Vidal, and Wing, (6) at the U. S. Bureau of Reclamation laboratory, was initiated in connection with preliminary investigation on the concrete for Boulder Dam. Consequently the investigation was extended to include the larger sizes of aggregate that would be used in the mass concrete, (up to and including the 9 inch maximum size). The data reported show a consistent increase in permeability accompanying the increase in maximum size of aggregate. This may be explained, at least in part, by the settlement of the progressively smaller particles away from the larger particles of the mass during the plastic condition. This settlement produces voids of relatively low hydraulic resistance under the aggregate particles, and under pressure would permit water to pass quite readily.

Attempts have been made to improve the watertightness of concretes by the addition of certain integral materials to the mixture. (2, 3) Such additions may be subdivided into (a) those that are chemically active, and (b) those that are inert. There is controversy on the interpretation of data from experimental work with the use of admixtures to control permeability (2, 5).



It seems reasonable from the data of references (2, 3) that the influence of such additives would be less than those that would derive from the use of adequate amounts of cement and proper curing methods. Further it must be noted in connection with the addition of inert materials, that any material added to a plastic concrete is in no sense a void filler since it must necessarily occupy space, and must be surrounded by an impervious paste if the resulting concrete is to be watertight. Where "active" additions are made to the concrete mixture the resulting products of hydration may prove to be beneficial in the closing of voids to the passage of water.

Nearly all of the published literature on the subject of permeability of concrete describes the results of investigation on the passage of water through concrete under pressure. The pressures that have been used vary from 40 pounds per square inch (4) up to 500 pounds per square inch (6). Quite obviously the permeability characteristics of a concrete will appear to vary as the pressure acting to force the water through the pore structure varies. For this reason it is difficult to correlate the results of the several investigations except in any but very general terms. At least two investigators (3, 7) have tried to develop simple tests that could be used to evaluate a concrete on the basis of its permeability. It appears however that little has been done with either method after the results of the investigations have been published.

The great bulk of concrete that has been put in place in Kansas, and for that matter elsewhere, is not required to resist

the passage of water due to any such pressure as even 20 pounds per square inch, the lowest pressure used in any of the investigations found. Such concretes are used in pavements, bridges, sidewalks and structures for other than hydraulic purposes. The bulk of concrete then should be watertight, not to confine liquid water to certain channels but because its low permeability will improve durability. The concrete for pavements is subject to saturation from ground water originating largely from the earth fill on which it is laid. The construction of the Autobahns in Germany is unique largely in that the earth fill was placed in alternate layers of pervious and impervious soils to reduce the rise of ground water to the concrete pavement (8). In this way the durability of both the pavement and the fill was improved. In the northern United States as much as one half inch of pavement thickness may be lost in one winter due to freezing and thawing and consequent disintegration of the surface. The use of salts to reduce ice conditions on pavements, contribute to the damage done by freezing and thawing. The salt is taken into solution and passes into the concrete with surface water. As the water evaporates the salts are deposited in the pore structure. The crystallizing salt occupies a greater volume than did the original solution resulting in disruptive forces within the concrete. Watertightness thus becomes a companion characteristic to durability; without the first the second cannot exist.

The literature cited thus far has sought to describe the measurement of the flow of water through concrete on the

assumption that it is a homogeneous or nearly homogeneous mass. In a material composed of aggregate surrounded by cement paste the mass cannot be considered homogeneous. Percolating water may pass through the paste, through fissures in the paste, between the paste and the aggregate, through the aggregate, or by a combination of these.

Powers (9) found from studies of fresh paste, that for water-cement ratios up to about 5.6 gallons per sack the flocculated particles formed a continuous structure. The permeability of the mass of the paste thus would depend on the texture of the flocculate. With higher dilution (higher water-cement ratio) the particles tend to form separate flocculates that are more or less independent of each other. The permeability of such a mass is not so much determined by the flocculate texture as by the size of the flocculates and their concentration. During bleeding the flocculates tend to subside and the bleeding water rises forming nonhomogeneity in portland cement pastes due to bleeding,

The homogeneity of a fresh paste, or the lack of it, probably persists to some degree after the paste hardens. Hence it is probable that for hardened pastes having water-cement ratios greater than 0.6 or thereabouts,\* the permeability of a test disk is determined not only by the channels that represent discontinuities in the paste--the discontinuities that developed during the bleeding period.

It is apparent that an increase in the number of fissures per unit area of paste would increase the permeability of the paste

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\* The limiting water ratio depends on the characteristics of the cement particularly its specific surface, and on the character and amount of subsieve aggregate. Air-entraining agents tend to raise the limit.

since such fissures present less resistance to the passage of water than does the texture of the paste itself.

With respect to the relationship between the permeability of a paste (as discussed above) and the permeability of concrete, Powers (10) states,

Introduction of aggregate particles into paste tends to reduce the permeability by reducing the number of channels per unit gross cross-section and by lengthening the path of flow per unit linear distance in the general direction of flow. However, during the plastic period, the paste settles more than the aggregate and thus fissures under the aggregate particles develop. In saturated concrete these fissures are paths of low resistance to hydraulic flow and thus increase the permeability of the concrete. In general with a paste of a given composition and with graded aggregate the permeability is greater the larger the maximum size of the aggregate. Obviously, the permeability of the concrete as a whole is much higher than the theoretical permeability developed for a homogeneous medium.

A review of the literature would seem to indicate that previous investigators agree on certain points.

1. That permeability is a recognized physical property of concrete.
2. That permeability can be controlled by proper attention to mix design, water-cement ratio, techniques of placing and of curing.
3. That permeability of concrete follows the normal laws of viscous flow through porous materials under pressure.

There seems to be disagreement on the exact effect of materials added to the concrete integrally to control permeability.

The large majority of investigations have been conducted by inducing water to enter concrete under externally applied pressure.

There has been little attention given to the mechanisms by

which water passes from one point to the next in its passage through concrete, except under pressure. Since a substantial proportion of concrete disintegration occurs as a result of exposure to water entering by capillarity, some further elaboration of the origin of these capillaries is considered desirable here. Concrete, when in the plastic state and prior to the beginning of hydration, is probably held together by weak forces of interparticle attraction in the paste. These forces may arise both from the attraction of liquid to solid, and solid to solid particles constitute an interconnected system of capillaries (11). After the plastic stage, when the final reactions of hardening take place, the capillary channels in the paste and around the aggregate tend to become filled with the products of hydration of the cement and water. This process rapidly reduces the volume and size of the capillaries but apparently does not destroy their continuity (11). Thus the concrete is susceptible to taking up water from its exposed surface and passing the water through the interconnected capillaries. The rate at which the water will pass, and the volume passed, are functions of the size and number of the capillary channels.

#### THE NATURE OF THE PROBLEM AND THE PROPOSED METHOD OF SOLUTION

Permeability is probably a more complex physical property than compressive strength. Certainly the apparatus for permeability determinations as described by most investigators was complex. The statement of the purpose of this experimentation included the

investigation of a simple test for permeability. This statement was construed to mean the simplest possible apparatus consistent with the gathering of measurable results. The method as originally conceived required a device for saturating one end of a specimen while exposing the other end to conditions that would promote evaporation. With a known uniform concentration of salts throughout the specimen a change in concentration of the salt would be an indication of liquid travel through the specimen. In order to promote uniformity of saturating conditions at the bottom of the specimen, the lower ends of the prisms were inserted through openings in the covers of the pans; and in order to promote uniformity of evaporating conditions at the top surface, a current of uniformly warmed room air was drawn over the top surfaces. The side surfaces of the prisms were sealed to avoid any evaporation except that at the top surface. It was realized that the water in the prism, if it migrated as a vapor, would be more likely to travel toward the cool surface. On the other hand if the water migrated as a liquid it would tend to travel toward the warm surface. Since the temperature differential between the saturated and the dry surface was small it was felt that the temperature effect would be small in either case so it was decided to warm the dry end of the prism. To make the salt concentration readings more positive, (if they occurred) additional alkali salts of the same nature as those in the cement were introduced near the bottom of the prism in a capsule large and porous enough to require the water to flow through and dissolve

them. The cabinet was built to accommodate six sets of three prisms, twelve 2 x 2 x 12 inch, and six 3 x 3 x 12 inch. It was planned that for the first series the mix and water-cement ratio would be held uniform, and that the following six treatments would be given, one to each set of three prisms.

Set 1. 2 x 2 prisms, with sodium capsule, immersed  $\frac{1}{2}$  inch in distilled water at lower end.

Set 2. 2 x 2 prisms, with sodium capsule, supported  $\frac{1}{4}$  inch above water surface.

Set 3. 3 x 3 prisms, without sodium capsule, immersed  $\frac{1}{2}$  inch in distilled water at lower end.

Set 4. 3 x 3 prisms, with sodium capsule, immersed  $\frac{1}{2}$  inch in distilled water at lower end.

Set 5. 2 x 2 prisms, without sodium capsule, immersed  $\frac{1}{2}$  inch in concentrated solution of sodium carbonate in distilled water.

Set 6. 2 x 2 prisms, with sodium capsule, immersed  $\frac{1}{2}$  inch in distilled water at lower end.

{ Set one was intended to show whether water migrates as a liquid or a vapor, and set 6, identical in every respect, was intended as a check on set 1.

Set two was intended to demonstrate any substantial difference in water migration between liquid and vapor saturation at the lower end of the prism.

Set three was intended as a control set. No sodium capsule was cast in the prism, consequently any variation in the uniform

distribution of the sodium present in the cement would constitute a correction to be applied to those beams containing the capsule.

Set four was intended to be a check on the size of specimen. It is identical in every respect with set one except for size.

Set five was intended to furnish information on whether a difference existed between the migration of salts in a concentrated solution differed from that of a partial solution.

Prisms were used as the specimen shape rather than cylinders because of the potentiality of using radio isotopes with the apparatus in later determinations. The square cross section prism is somewhat easier to attach photographic plates and holders to than the cylindrical specimen.

#### CONCRETE MATERIALS

The materials for the concrete to be tested were selected not so much to produce the most impervious concrete possible, but rather to produce a concrete that would compare reasonably well with commercially produced concrete in current use.

Blue river sand-gravel from Florena Switch, Kansas was used as a combined aggregate. Physical properties of the sand-gravel are as follows:

Specific Gravity	2.62
Absorption	0.5 percent
Unit weight (dry rodded)	116.4 lb. per cu. ft.

Sieve analysis	Percent retained
No. 4	16
No. 8	45
No. 16	60
No. 30	79
No. 50	96
No. 100	99



The aggregate was separated into the six fractions and recombined in the percentages shown. The small percent of particle sizes passing the No. 50 sieve (4 percent) was used because most sand-gravels in this area are deficient in these small sizes.

The cement used was a standard brand Type I Portland cement, purchased on the open market, having the following physical and chemical properties.

#### Physical Properties

Normal consistency	25 percent
Specific surface	3380 Sq. cm. per gm. (Blaine)
Autoclave (soundness)	0.102
Initial set	4 hours, 50 min.
Final set	6 hours, 00 min.
Tensile strength	370 lb. per sq. in (3 days) 470 lb. per sq. in (7 days)

#### Chemical Analysis

##### Major components

Silicon dioxide	20.77 percent
Aluminum oxide	5.90 percent
Ferric oxide	2.82 percent
Calcium oxide	63.23 percent
Magnesium oxide	2.77 percent
Sulphur trioxide	2.30 percent
Ignition loss	1.07 percent

##### Minor components

Sodium oxide	0.28 percent
Potassium oxide	0.59 percent
Insoluble residue	0.38 percent

The water used in mixing the concrete was from the college supply obtained from wells.

## APPARATUS

The apparatus for inducing flow of water in the concrete specimens is shown on Plates I and II. Construction details are shown on Plates V to VIII, in the Appendix.

The apparatus was an arrangement whereby concrete prisms were supported with the lower ends immersed in water while the upper ends were exposed to a draft of warm dry air. The entire exterior surface of each prism was sealed except for the two ends with a coating of hot asphalt and a jacket of .001 thick copper foil. Reference to Plate I shows (a) the cabinet with upper compartment for heat source, and the lower compartment for exposure of the top end of the prisms. (b). The blower, arranged to pull air at room temperature over three, two hundred watt light bulbs (d), and thence over the exposed end of the prisms (h). (c) Copper pans with cutout covers to receive the lower ends of the prisms. The thermocap control (e), arranged to actuate one of the three light bulbs was controlled by the thermometer (f). The college electric current operates at 220 volts so a step down transformer (g) was required, since the thermocap control operated at 110 volts.

Light bulbs were used as a heat source because the volume of air to be warmed was not large, and the required temperature was not high. The temperature of the air was arbitrarily established at 100° F to approximate summer exposure in the local climate.

The full flow of air induced by the blower was such that the 600 watts was not sufficient to heat the air to the designated

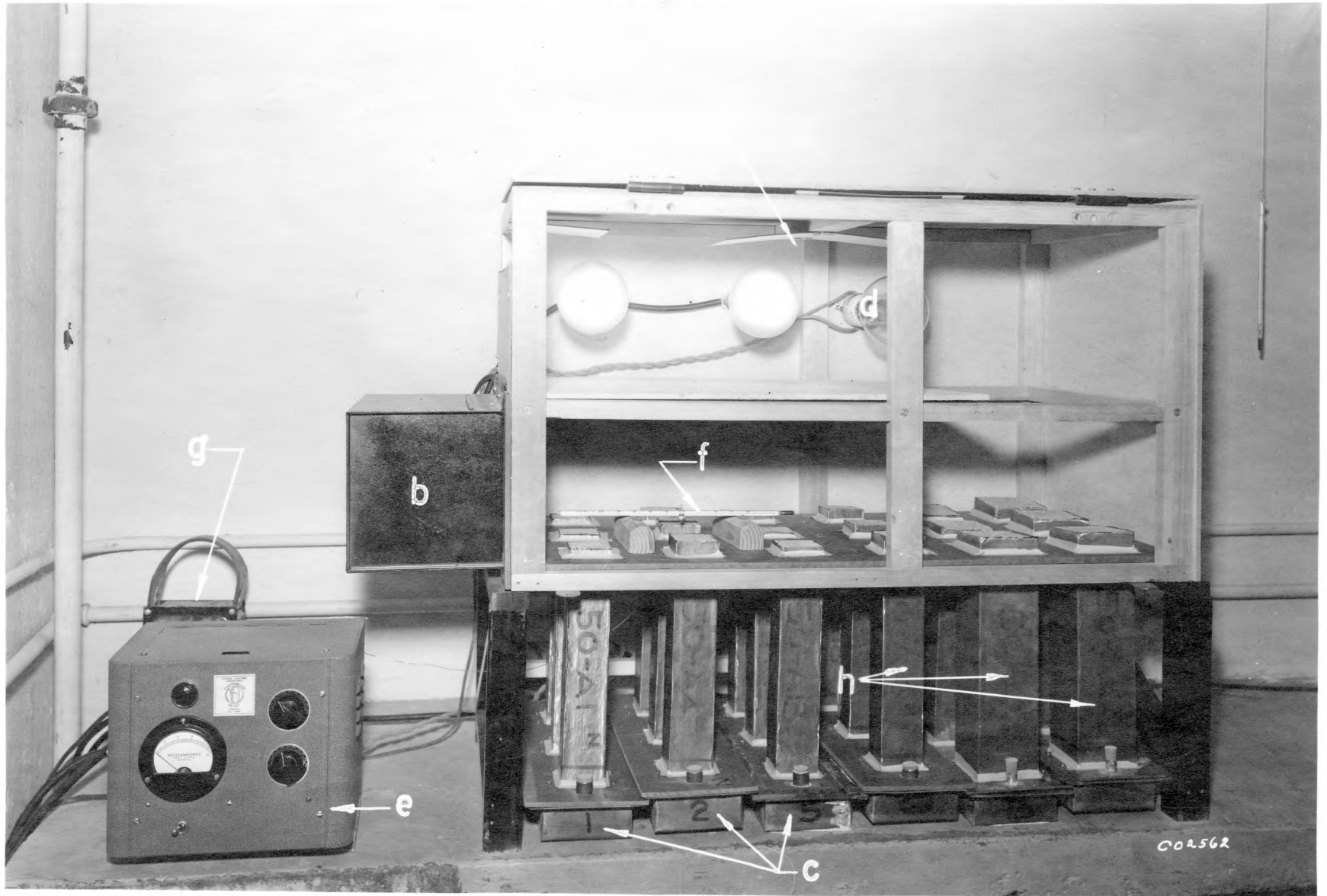
EXPLANATION FOR PLATE I

APPARATUS FOR INDUCING FLOW OF  
WATER IN CONCRETE PRISMS

(Door Open)

- a. Cabinet
- b. Blower
- c. Pans
- d. Light Bulbs (Heat Source)
- e. Thermocap Control
- f. Thermometer
- g. Transformer
- h. Concrete Prisms

PLATE I

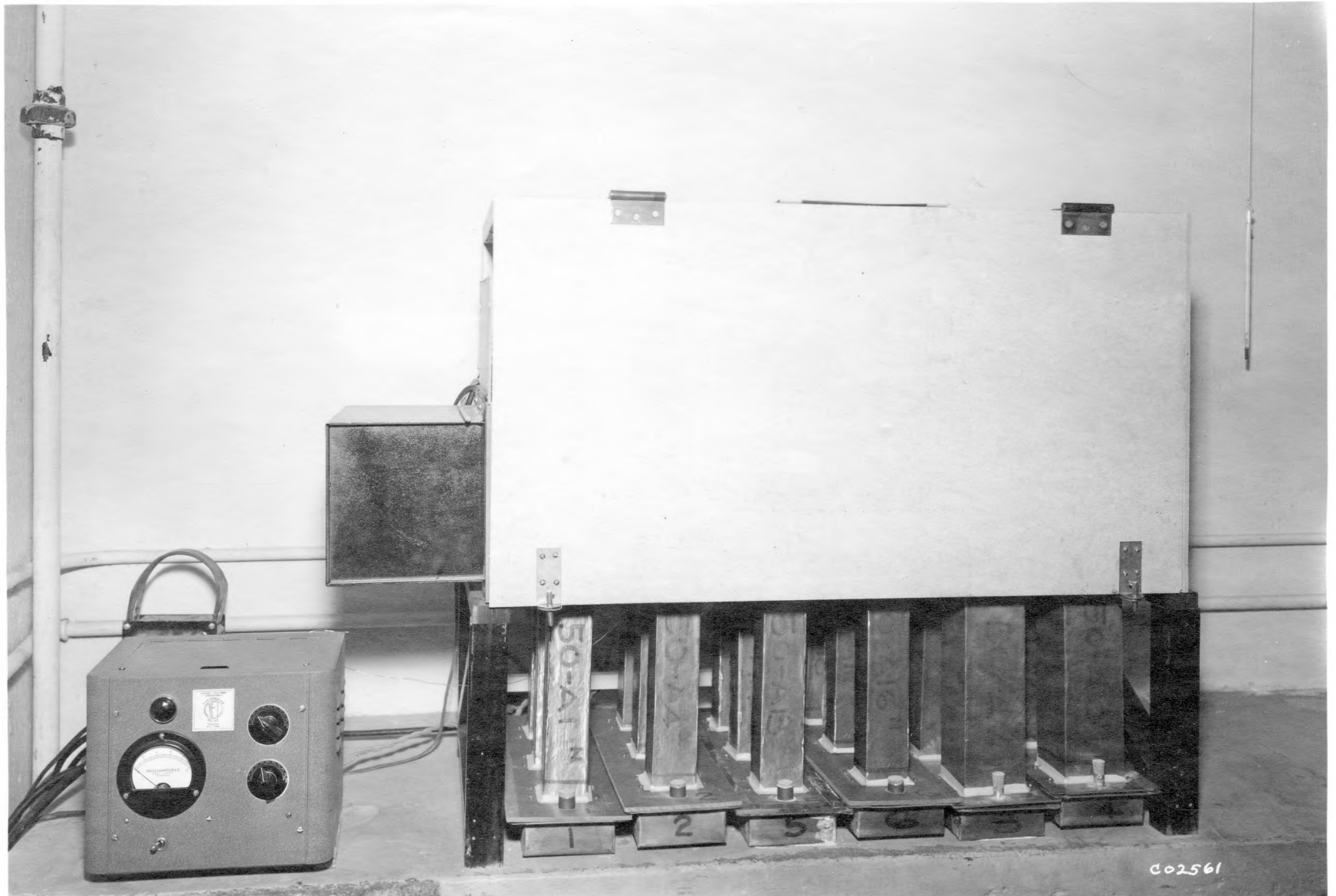


EXPLANATION OF PLATE **ii**

APPARATUS FOR INDUCING FLOW OF  
WATER IN CONCRETE PRISMS

(APPARATUS IN OPERATION)

PLATE II



temperature. The flow was reduced by blocking the inlet opening with heavy cardboard. By trial and error the flow of air was brought to an amount that room air at 80° F would be raised to approximately 102° F. The thermocap control was then connected to one bulb so that one third of the heat source was automatically shut off when the temperature arrived at 100° F. As the temperature began to fall from 100° F the third bulb was automatically turned on again. This arrangement, governed by an ordinary laboratory thermometer (0 to 220° F) read one inch above the exposed ends of the prisms, was accurate to a fraction of a degree. When the room temperature rose above the point where one intermittent and two constant bulbs were required to supply the heat, it was necessary only to disconnect one of the constant bulbs.

The prisms were each supported on two brass strips attached to the inside of the lid (Plate VI). Each strip was fitted with two round head brass screws to hold the lower end of the prism above the surface of the strap. In this way the water was assured of unobstructed access to the entire exposed end of the prism. The small openings between the sides of the prisms and the edge of the holes through which they projected into both the pans and the cabinet were sealed with short strips of scotch tape. Needless evaporation from the pans was thus reduced as well as excessive loss of warm air from the cabinet.

The use of ordinary 3 x 4 x 16 beam molds was not feasible for two reasons; first, since radio isotopes were to be used in

the specimens later, the radiation distance from the capsule to each side face should be uniform. This condition dictated a prism of square cross section. Second, the capsule of soluble salts was to be placed two inches from one end of the prism thus necessitating the filling of the mold from the end, instead of from one side as is the usual practice. Temporary molds were designed and built of Masonite on wood frames. (Plates III, IV and IX). These molds were given two heavy coats of linseed oil, allowed to dry and then given a light coat of No. 2 cup grease after each use. These molds show no signs of warping or distress after ten uses. One set of six molds was made for each of two sizes. One set for 2 x 2 x 12 in. prisms, and the other for 3 x 3 x 12 in. prisms. (A part of the pilot investigation was to determine if there was any preference between a cross section of four and nine square inches).

#### MOLDING THE PRISMS

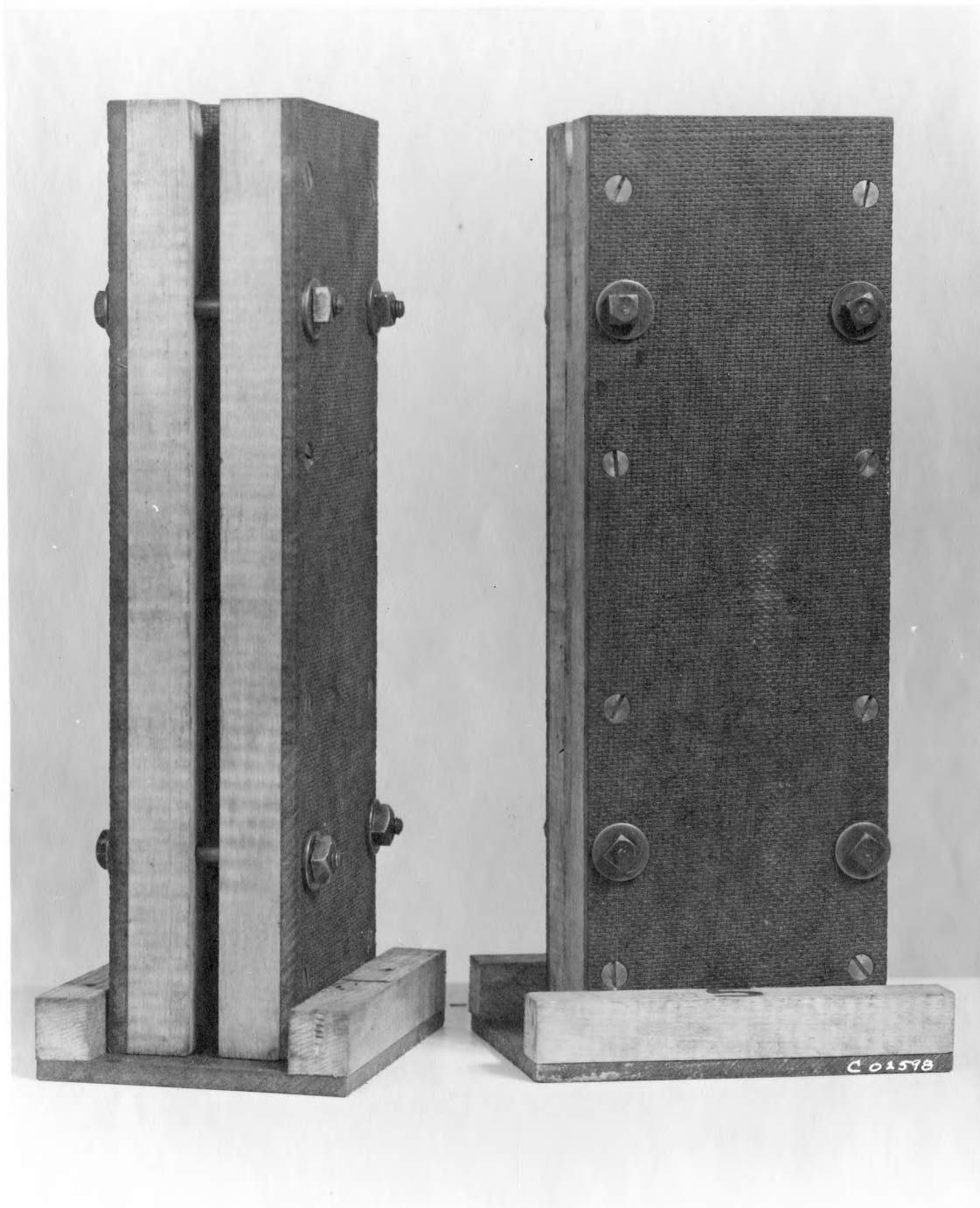
It was pointed out in the Introduction, that in this pilot investigation no effort would be made to test highly impervious concrete. It was desirable at this stage of the investigation to use a concrete that was neither impervious nor excessively permeable. Conforming with the findings of several other investigators and with good practice in concrete making, a water-cement ratio of  $6\frac{1}{2}$  gallons per sack was selected. This value was known to be somewhat higher than that required for concrete having high durability in severe climate. A mix of one part of cement



EXPLANATION OF PLATE III

VIEW OF PRISM MOLDS, ASSEMBLED

PLATE III



EXPLANATION OF PLATE IV

VIEW OF PRISM MOLDS, DISASSEMBLED

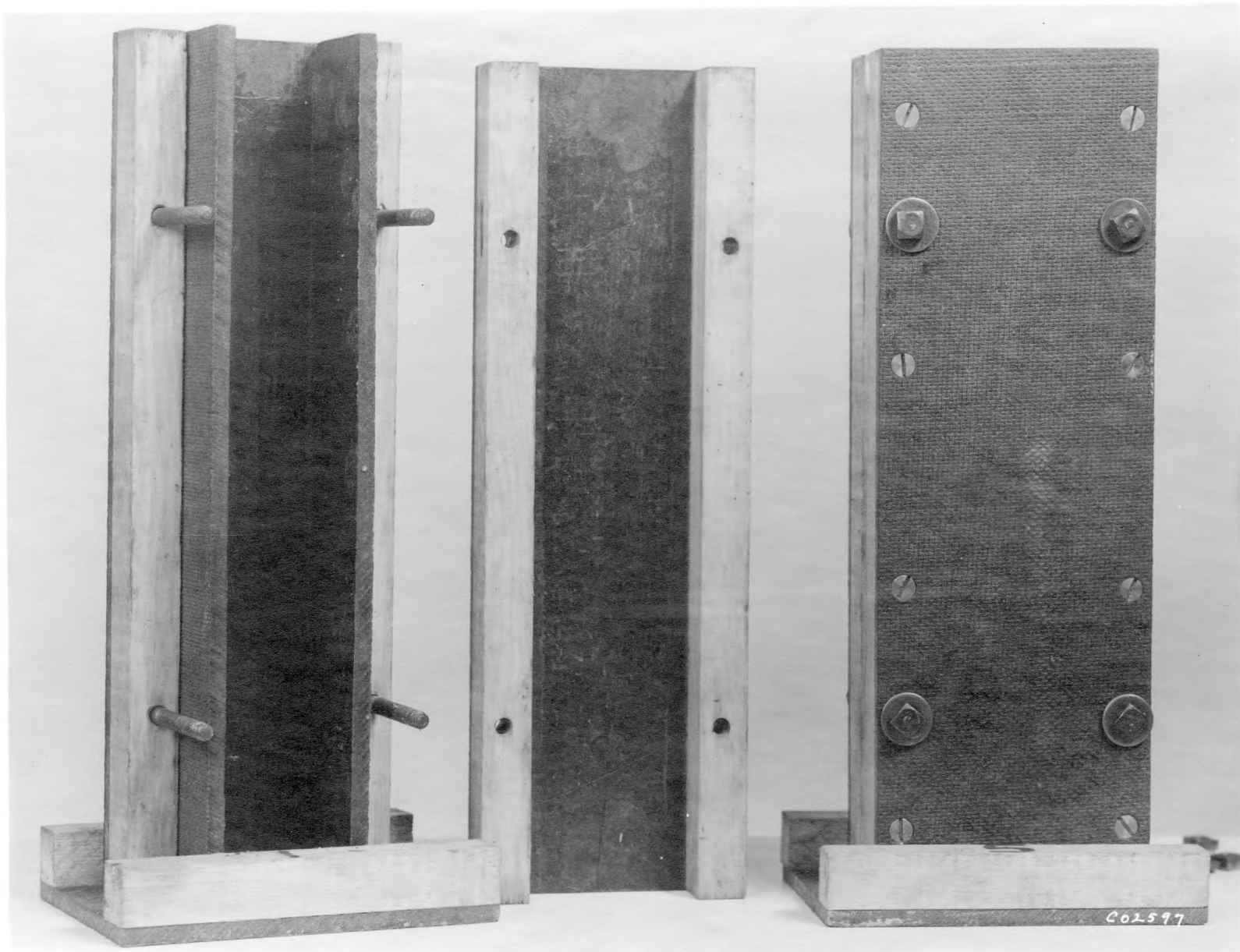


PLATE IV

to five parts of combined aggregate by dry weight was selected. This mix was somewhat leaner than good practice would dictate. It will be noted that in the selection of both the water-cement ratio and the proportion of cement to aggregate values were used that would increase permeability very slightly over what would normally be required of concrete exposed in a severe climate.

The materials were weighed (see mix computations in Appendix) and mixed in a Lancaster open bowl laboratory type mixer. Cement and aggregate were mixed dry for one minute and then mixed for two minutes after the water was added. The  $6\frac{1}{2}$  gallons, 1 to 5 mix had a slump of  $\frac{3}{4}$  and 1 inch in the two batches that were run. The concrete was somewhat harsh and did not place easily in the molds. The first set of molds to be filled (3 x 3 x 12 inch) was filled in three levels with 25 tamps of a bullet nosed tamping rod at each level. These specimens showed poor corners and honeycomb spots when removed from the molds. The second set of molds to be filled (2 x 2 x 12 inch) was filled in the same manner and when removed from the molds showed even poorer corners and larger areas of honeycomb. A second batch was made using the same mix and water-cement ratio resulting in a 1 inch slump again. In this trial a capsule of sodium carbonate was introduced into the prism two inches below the top of the mold. Considerable difficulty was experienced in securing good bond of the concrete at the edges of the capsule, and again poor corners and honeycomb characterized the finished specimens. It was quite evident that the concrete was not sufficiently plastic to be properly compacted in such small molds, and around the capsules

of sodium carbonate.

In the third batch the mix was reduced to one part of cement to four and one half parts of aggregate by weight. This mix resulted in a concrete having a  $1\frac{3}{4}$  inch slump and very much better placeability in both sizes of molds. The corners were clean and sharp and there was no evidence of a lack of bond around the edges of the capsule. The molds were filled in three layers, each layer being tamped 25 times, and in addition each layer received 10 vertical strokes of a kitchen spatula inserted between the concrete and the mold on each of the four faces. After the molds were filled and before the concrete was struck off, each mold was given 24 smart raps with the wooden handle of the trowel beginning at the bottom and progressing upward. The treatment resulted in almost complete absence of air bubbles or other surface imperfections. The extra effort to produce prisms having as nearly perfect lateral surfaces as possible was required in order that the asphalt seal might be applied with reasonable assurance of continuous bond.

Preliminary to the preparation of prisms for testing, a batch was prepared in which the sodium carbonate was dissolved in the mixing water instead of being introduced into each prism in capsule form. The purpose of this procedure was to check the chemical analysis when a known amount of sodium carbonate was present. The original sodium oxide content of the cement was 0.28 percent. An amount of sodium carbonate was added to the mixing water to produce a sodium oxide equivalent of 0.84 percent.

This amounted to adding twice the sodium oxide equivalent for the weight of cement in the batch (see computations in Appendix, page 44). If the flame photometer showed a reasonable check on the amount of sodium originally in the cement plus the amount added, it was felt that credence could be placed in similar readings which showed a redistribution of sodium in the test specimens. The preliminary check specimen showed 0.78 percent sodium oxide equivalent in a sample calculated to have 0.84 percent. The test value should be lower than the calculated value for two reasons, namely,

1. Since the sodium carbonate was dissolved in the mixing water an undertermined amount would be lost by bleeding.

2. The sample for test in the flame photometer was taken from the lower end of the prism as cast. This would result, again due to bleeding, in a somewhat lower concentration of mixing water in the lower end of the beam. Thus a correspondingly lower amount of sodium could be expected in the lower part of the beam.

The results of the flame photometer test thus were judged to be sufficiently accurate to expect it to detect even small migrations of sodium in the test prisms.

#### SPECIMEN PREPARATION

The mix that was used for the prisms to be tested was one part of cement to four and one half parts of combined aggregate by dry weight. A water-cement ratio of six and one half gallons

per sack with a 0.5 percent allowance for absorption in the aggregate. The revised molding procedure was used. It was found that when a small depression to receive the capsule was made in the top of the concrete, that the insertion of the capsule was made considerably easier, and that bonding with the last two inches of concrete was more firm. Twelve prisms were molded on the first day, and six on the day following. In all cases the prisms remained in the mold for one day, and then were cured in the fog room for three days. At the end of the third day in the moist room the prisms were set out in laboratory air to dry for four days before the asphalt and copper foil seal was put in place.

It is known that concrete adjacent to a mold surface will have a slightly higher cement content than concrete very slightly deeper in the mass. A similar effect but to a greater degree occurs due to trowelling a surface. The higher cement content results in a more impervious surface. Since it was the intention of the test to induce water to pass from one end of the prisms to the other, it was judged that the end effect\* could be reduced by grinding the ends of the prisms. Accordingly both ends of each prism were ground on a power grinding wheel until the exposed surface showed that the maximum diameter of aggregate was visible. In most cases the grinding removed  $\frac{1}{8}$  inch or less of concrete.

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\*Ruetters, Vidal and Wing (Ref. 6) pp 393 state that the end effect in a specimen adds the equivalent of three inches of length for each end considered.



Great care was exercised to avoid overheating the specimens during grinding.

In order that there would be no evaporation from the twelve inch sides of the specimens, those faces were covered with a brush coat of 160° F melting point asphalt cement, applied hot. The asphalt coat was then covered with a jacket of copper foil to further seal the surface of the asphalt and to stop any pin-holes that may have been present in the asphalt surface. It was found that only one face of the prism could be coated at a time before the copper foil was applied, if proper adhesion to the copper was to be secured. Copper sheets were cut in advance and when one face of a prism had been coated with asphalt, the edge of the sheet was aligned with the edge of the prism. Firm pressure of the palm of the hand over the copper foil was sufficient to make the copper adhere satisfactorily. The prism was then laid on the finished surface, and the next face treated similarly. An overlap of one full face was provided. When covered, the prism identification number was lettered on the copper foil jacket and a heavy line drawn on all faces opposite the position of the capsule of sodium carbonate. It was necessary that the position of the capsule be known for each prism, in order that it could be placed in the apparatus with the proper end exposed to warm air.

The amount of sodium carbonate to be placed in the capsule for each prism was problematical since there was no way of knowing the rate at which percolation would take place. It was

finally decided that each capsule was to contain four times the sodium oxide equivalent of the cement in the prism in sodium carbonate, (See computation in the Appendix). This amount was arbitrary and was used to assure that an excess of salts would be present throughout the test. Much smaller amounts of sodium salt will be required in the capsule when the migration is to be measured by the radiation from radio isotopes. The present supply of radioactive sodium chloride is dissolved in water. One millicurie is present in 17 milliliters of liquid. It is anticipated that this amount will be diluted to 24 milliliters and that one milliliter of the liquid will be evaporated on a small square of filter paper. With the evaporation of the liquid, the salt (sodium chloride) will be deposited on the filter paper, which in turn will be placed in the concrete specimen in the same manner as the capsule for the present investigation. Probably a smaller quantity of the radio isotope could be used than one twenty fourth of a millicurie, but the best advice available indicates that at least for the first run, that amount should be used.

#### TESTING

The apparatus was put through a two day test during which time a record was kept of the temperature variation. At no time did the temperature drop below  $99^{\circ}$  F or rise above  $100^{\circ}$  F. This was considered to be an adequate test run of the apparatus, and proof that the thermocap regulator would maintain the temperature

of the air flow at the required 100° F. Actually the temperature variation was less than the one degree F indicated, but since a thermometer graduated in degrees was used, the variation could be read to only one degree.

It was planned that the first test run would be for a period of approximately 10 days after which one prism from each treatment would be removed and tested for migration of the salts. The second of the three prisms in each treatment was to be removed at the end of approximately 20 days, and the third at the end of 30 days. It was hoped that this arrangement would give some clue to the time required for water movement take place. It must be emphasized that no information was available that indicated how long a time would be required for perceptible flow to be established; thus the 10 day increments of time were arbitrary.

Ruettgers, Vidol, and Wing (6) found that maximum flow was established in their investigation at approximately 400 hours. Withey (4) shows variations in flow at 10 hour intervals. In both these investigations, however, the water entering the concrete was under pressure. It was reasonable to assume that water entering the concrete by either capillary action or by vapor diffusion would move at a very much slower rate than when under pressure.

The weight of each prism was taken just prior to being put in place in the apparatus, and was weighed again upon being removed. The weights and the gain in weight are shown in Table 1.

At the end of each period of testing the proper specimens were removed from the apparatus and after weighing, a two inch

long section was broken out of the prism one inch above the center. The copper foil and asphalt were scraped off, and each specimen in a marked porcelain dish was introduced into a muffle furnace at 800° F. This temperature was sufficiently high to burn away any remaining asphalt but not high enough to volatilize the sodium in the specimen. When the specimens had cooled they were placed separately into a hand mortar and pestle and reduced to a size that would all pass a No. 4 sieve. Each sample was then passed through a sample splitter until it was reduced to a 50 gram sample. Each 50 gram sample was then ground in a Weber hammermill until the entire sample passed the No. 50 and the No. 10 screen. Since the samples were each from a different treatment, the grinder and all attachments were cleaned with a compressed air stream between grindings of each sample.

Sodium determinations were made by means of the flame photometer apparatus, and were based on the sodium oxide equivalent of the original cement sample. A tabulation of both sodium and potassium determinations are shown in Table 2.

#### DISCUSSION OF RESULTS

From the limited amount of data taken in this pilot investigation it does not seem possible to draw extensive conclusions. The data in general show, however, that the apparatus as now constructed will operate as intended, and that further experimentation will improve the accuracy of the data obtained.

1. The rather uniform increase in sodium oxide content of

Table 1. Prism weights.

	Prism no.	Wt. when placed: in apparatus (lbs)	Wt. when removed: from apparatus (lbs)	Gain: (lbs)	Time in apparatus (hrs)
set 1	50-A1	3.865	3.880	.015	255
	50-A2	3.850	3.870	.020	519
	50-A3	3.935	3.965	.030	759
set 2	50-A4	3.930	3.950	.020	255
	50-A5	3.925	3.935	.010	519
	50-A6	3.860	3.875	.015	759
set 3	50-A7	8.930	8.950	.020	255
	50-A8	8.960	8.995	.035	519
	50-A9	8.885	8.910	.025	759
set 4	50-A10	8.884	8.865	-.019	255
	50-A11	8.915	8.940	.025	519
	50-A12	8.995	9.020	.025	759
set 5	50-A13	3.805	3.815	.010	255
	50-A14	3.785	3.795	.010	519
	50-A15	3.870	3.875	.005	759
set 6	50-A16	3.920	3.925	.005	255
	50-A17	3.830	3.840	.010	519
	50-A18	3.910	3.915	.005	759

Table 2. Alkali test values.

Age (hrs)	Sodium oxide,* percent of cement											
	Set 1		Set 2		Set 3		Set 4		Set 5		Set 6	
	total	gain	total	gain	total	gain	total	gain	total	gain	total	gain
255	0.33	0.05	0.32	0.04	0.32	0.04	0.33	0.05	0.32	0.04	0.32	0.04
519	0.34	0.06	0.34	0.06	0.35	0.07	0.35	0.07	0.33	0.05	0.33	0.05
759	0.34	0.06	0.33	0.05	0.35	0.07	0.34	0.06	0.33	0.05	0.33	0.05

Age (hrs)	Potassium oxide, percent of cement											
	Set 1		Set 2		Set 3		Set 4		Set 5		Set 6	
	total	gain	total	gain	total	gain	total	gain	total	gain	total	gain
255	0.63	0.04	0.59	0.00	0.56	-0.03	0.61	0.02	0.61	0.02	0.59	0.00
519	0.59	0.00	0.64	0.05	0.64	0.05	0.63	0.04	0.60	0.01	0.60	0.01
759	0.67	0.08	0.63	0.04	0.64	0.05	0.64	0.05	0.63	0.04	0.64	0.05

\*Original Sodium Oxide in Cement 0.28 percent

Original Potassium Oxide in Cement 0.59 percent

Set 1 With Sodium capsule, immersed in water

Set 2 With Sodium capsule,  $\frac{1}{4}$  in. above water surface

Set 3 Without Sodium capsule, immersed

Set 4 With Sodium capsule, immersed

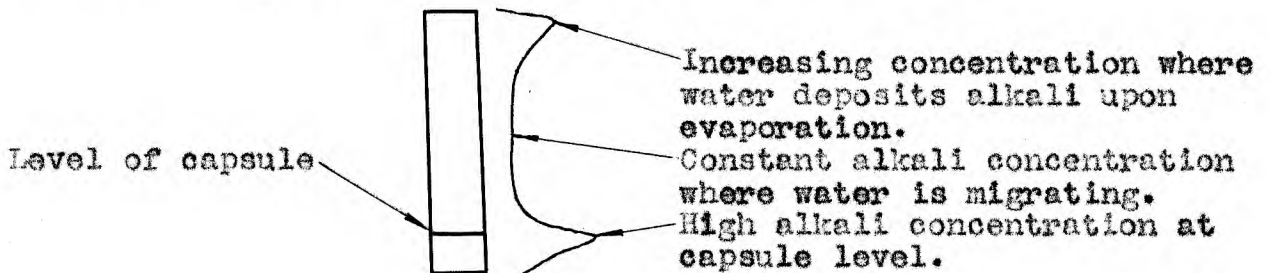
Set 5 Without Sodium capsule, immersed in Conc. Sol.  $\text{Na}_2\text{CO}_3$

Set 6 With Sodium capsule, immersed

of all specimens is taken as an indication that migration of water in the anticipated direction was induced in the prisms. Substantiation of this statement is found in Table 2. All 18 test prisms, excepting only the 759 hour readings for Sets 2, 3 and 4, show an increase in sodium oxide content after testing. It is not probable that the additional sodium could have come from the aggregate because the solutions for test in the flame photometer were prepared at room temperature. Normally the alkalis in feldspar aggregates are dissolved in acids only at considerably higher temperatures.

2. There is no apparent difference in the movement of water in the 2 x 2 prisms and the 3 x 3 prisms as measured over the short time of this test by means of the change in either sodium or potassium concentration.

3. It is probable that the concentration of alkali at any level in the prism is indicated by the following diagram



the fact that the prisms were tested from a section taken out just above the middle and after a relatively short period of time would justify at least to some extent the small increase in sodium.

4. The small gain in alkali concentration and the small in-

crease in weight (Table 1) indicate that the length of time required for migration of water under these conditions is much longer than was originally supposed.

5. The gain in weight of the prisms of Set 1 and Set 6 is not similar and no explanation is offered. The gain in sodium however is almost the same, and in addition both sets show a movement of potassium oxide.

6. Set 2, exposed to saturated air showed an 0.05 percent gain in sodium oxide and some gain in weight due to absorbed water. Apparently flow is induced by water saturated air as well as by saturation in a liquid.

7. Surprisingly, Set 3 with no sodium capsule showed the greatest concentration of sodium oxide of all six sets. It is suggested that the sodium carbonate of the capsules in all other sets, upon being first exposed to water formed a rather impervious cake that retarded the percolation of water in all sets except number 3. Set 3 having no capsule was enabled to take up and pass on more water than the others.

8. It is noteworthy that the gain in the percent of potassium oxide on the average was nearly as great as that of sodium oxide, though no potassium was added over the amount present in the cement. This fact leads to the inference that the source of gain in the sodium was not the capsule but the sodium already present in the cement. The 759 hours was apparently not long enough for continuous flow to be established throughout the full length of the prism.



The movement of water through concrete is possible under two conditions, with the specimens saturated, or at some degree of partial saturation. An example of the first is the usual permeability test, where the moving water enters the concrete under pressure. Water moving through unsaturated concrete may move by vapor diffusion motivated by a difference in vapor pressure on the opposite faces of the concrete. Since the capillaries of the concrete are not of uniform size it is probable that lenses of water form at points of constricted crosssection of the capillaries. In this case, however, the movement from lens to lens would be largely by vapor diffusion. This process is bound to be very slow. The concrete prisms subjected to the test described in this thesis were in a partially saturated condition, that is, they had been subjected to drying in laboratory air for four days prior to testing. It should follow then that a long time would be required to establish flow through the entire length of the specimen.

#### CONCLUSIONS

In the light of the purposes of this investigation, as stated on page 4, it can be said,

1. That the apparatus as developed and described, operates satisfactorily, and that the techniques of specimen preparation are apparently adequate, though some modifications may be desirable as the investigation continues.

2. Data from the investigation are not sufficient to warrant a definite conclusion on the state in which water moves through

concrete. The definite and consistent, though small, increase in sodium oxide concentration seems to indicate that with longer periods of test more definite values may be obtained.

3. Suggestions for changes in techniques of specimen preparation and testing are enumerated as follows.

a. The prisms could probably be coated with paraffin in place of asphalt. This suggestion is made because the asphalt does have some sodium content, and care must be taken that it is entirely removed. Paraffin burns at a much lower temperature with consequent less chance of altering constituents of the cement and aggregate.

b. Capsules for prisms need not contain so great an excess of sodium carbonate; possibly only two times the sodium oxide equivalent of the cement in each prism, per capsule.

c. Since the effect of temperature gradient is somewhat obscure, it may be desirable to test the specimens with no difference in temperature between the two exposed surfaces, relying only on the difference in vapor pressure to provide the moving force for the water.

d. Since it is known that the degree of saturation of the concrete, as well as the vapor pressure gradient between the exposed surfaces has an effect upon the permeability, it may be desirable to begin the test with the prisms in a fully saturated rather than a partially saturated condition.

e. The lids to all pans should be sealed to prevent unnecessary water loss.

## ACKNOWLEDGMENT

Indebtedness is acknowledged to Professor C. H. Scholer, Head of the Department of Applied Mechanics for guidance and encouragement during this study; to Dr. Gerald Pickett for counsel and suggestions; to Dr. R. H. McFarland of the Department of Physics, for suggestions for making the apparatus adaptable for use with radio isotopes; to Mr. R. F. Childs of the Kansas Highway Department Testing Laboratory for all flame photometer tests; and to Mr. J. E. McConnell for technical assistance.

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APPENDIX

## REFERENCES

The following list of publications provides supplementary material relating to the permeability of concrete and other porous materials. For one reason or another they have not been included in the references cited in the Review of Literature. They are presented here for the convenience of those who may wish to use them.

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## CONCRETE MIX COMPUTATIONS

Blue River Sand-Gravel - Sp. G = 2.62

Unit Wt. 116.4 lb. per cu. ft.

Absorption 0.5 percent

Mix 1:4 $\frac{1}{2}$ Water Cement Ratio 6 $\frac{1}{2}$  gallons per sack.

1 Sack Batch

Weights

$$\text{Cement} \quad \frac{94}{3.17 \times 62.4} = .48 \text{ cu. ft.} \quad 94.0$$

$$\text{Aggregate} \quad \frac{116.4 \times 4.5}{2.62 \times 62.4} = 3.21 \text{ cu. ft.} \quad 524.0$$

$$\text{Water} \quad \frac{6.5 \times 8.33}{62.4} + \frac{2.62}{62.4} = 0.91 \text{ cu. ft.} \quad \underline{56.8}$$

Absolute volume 4.60 cu. ft. 674.8 lb batch wt

30 lb. Batch

60 lb. Batch

$$\text{Factor} \quad \frac{30}{674.8} = .0444$$

$$\text{Factor} \quad \frac{60}{674.8} = .0888$$

$$\text{Cement} \quad .0444 \times 94 = 4.18 \text{ lbs.}$$

$$.0888 \times .94 = 8.36 \text{ lbs.}$$

$$\text{Aggregate} \quad .0444 \times 524 = 23.30 \text{ lbs.}$$

$$.0888 \times 524 = 46.60 \text{ lbs.}$$

$$\text{Water} \quad .0444 \times 56.8 = \underline{2.52} \text{ lbs.}$$

$$.0888 \times 56.8 = \underline{5.04} \text{ lbs.}$$

$$\text{Total} \quad 30.00 \text{ lbs.}$$

$$\text{Total} \quad 60.00 \text{ lbs.}$$

Sample Computation for Determining the Sodium Carbonate  
Equivalent to Four Times the Sodium Oxide in the Cement

Sodium oxide equivalent in the cement = 0.28 percent.

1.710 gms sodium carbonate equivalent to 1 gm of sodium oxide.

4.18 lb. cement per batch for 1 set of 6 prisms.

$$(4.18) \times (454) \times (.0028) = 5.31 \text{ gm}$$

$$(1.710) (4) (5.31) = 36.3 \text{ gm of sodium carbonate per 30 lb. batch.}$$

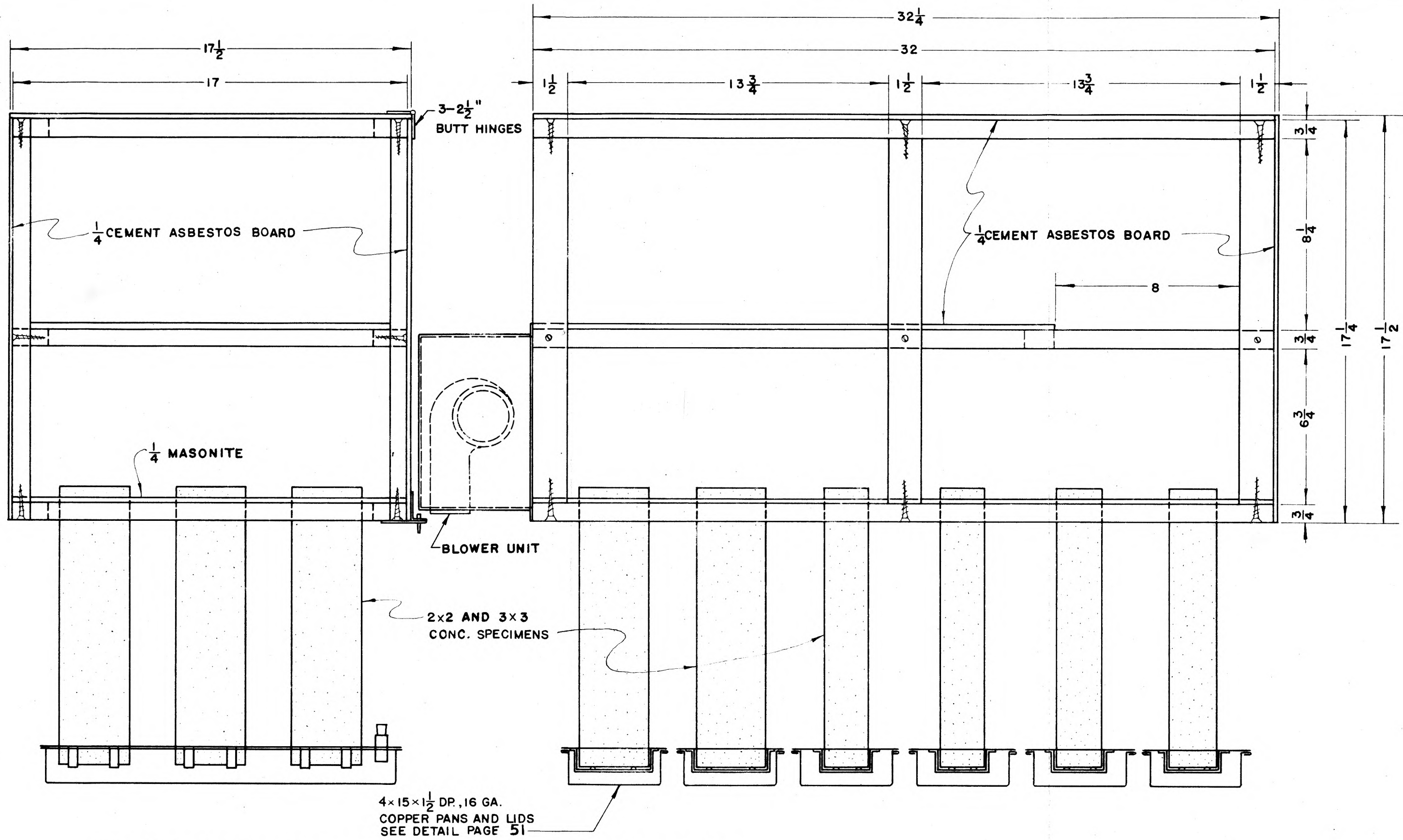
Each 2 x 2 x 12 prism weighed 4.1 lbs (fresh concrete)

$$\frac{30}{4.1} = 7.3 \text{ prisms in each batch.}$$

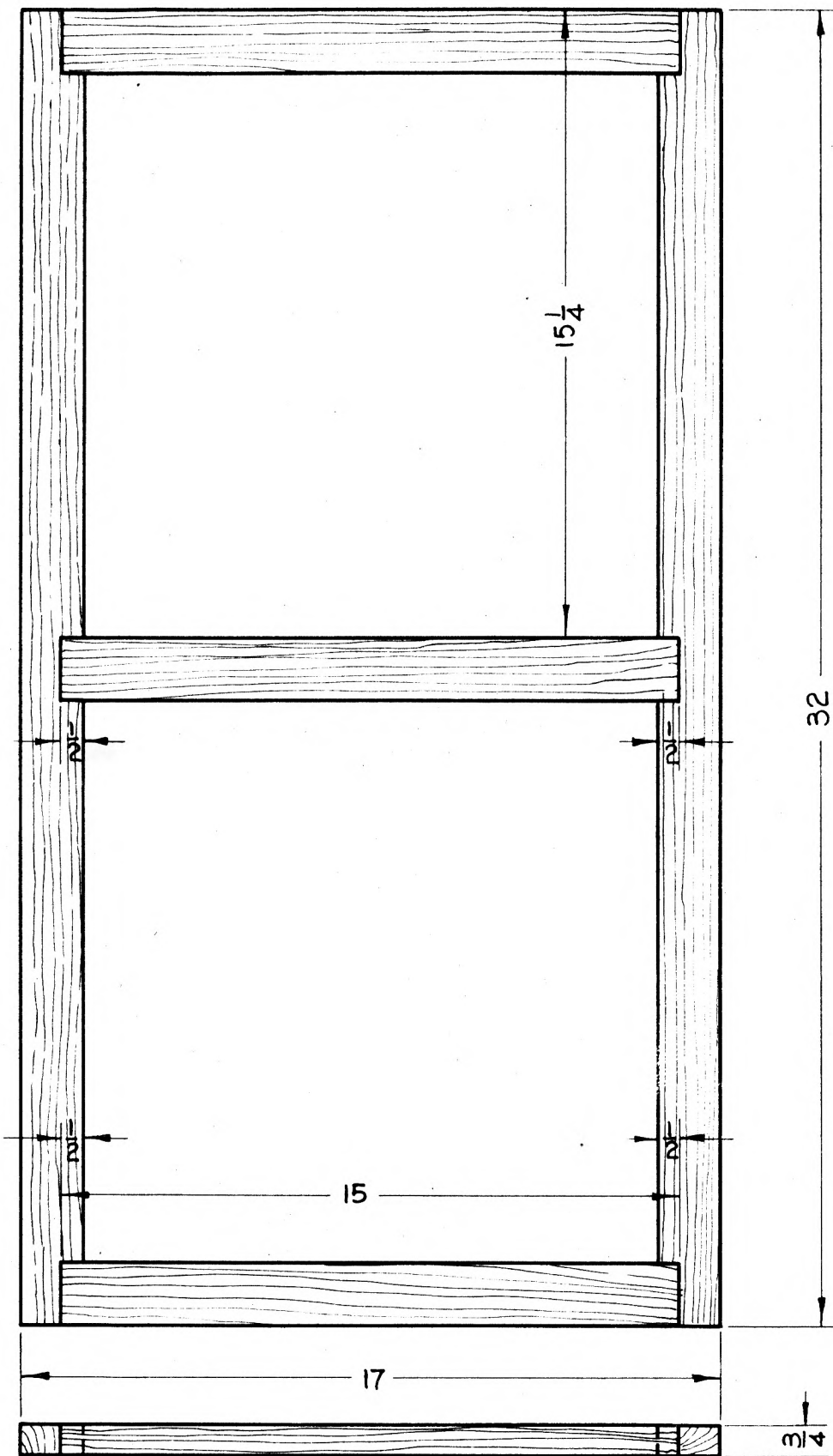
The capsule for each prism was prepared to contain

$$\frac{36.3}{7.3} = 5.0 \text{ gm of sodium carbonate.}$$

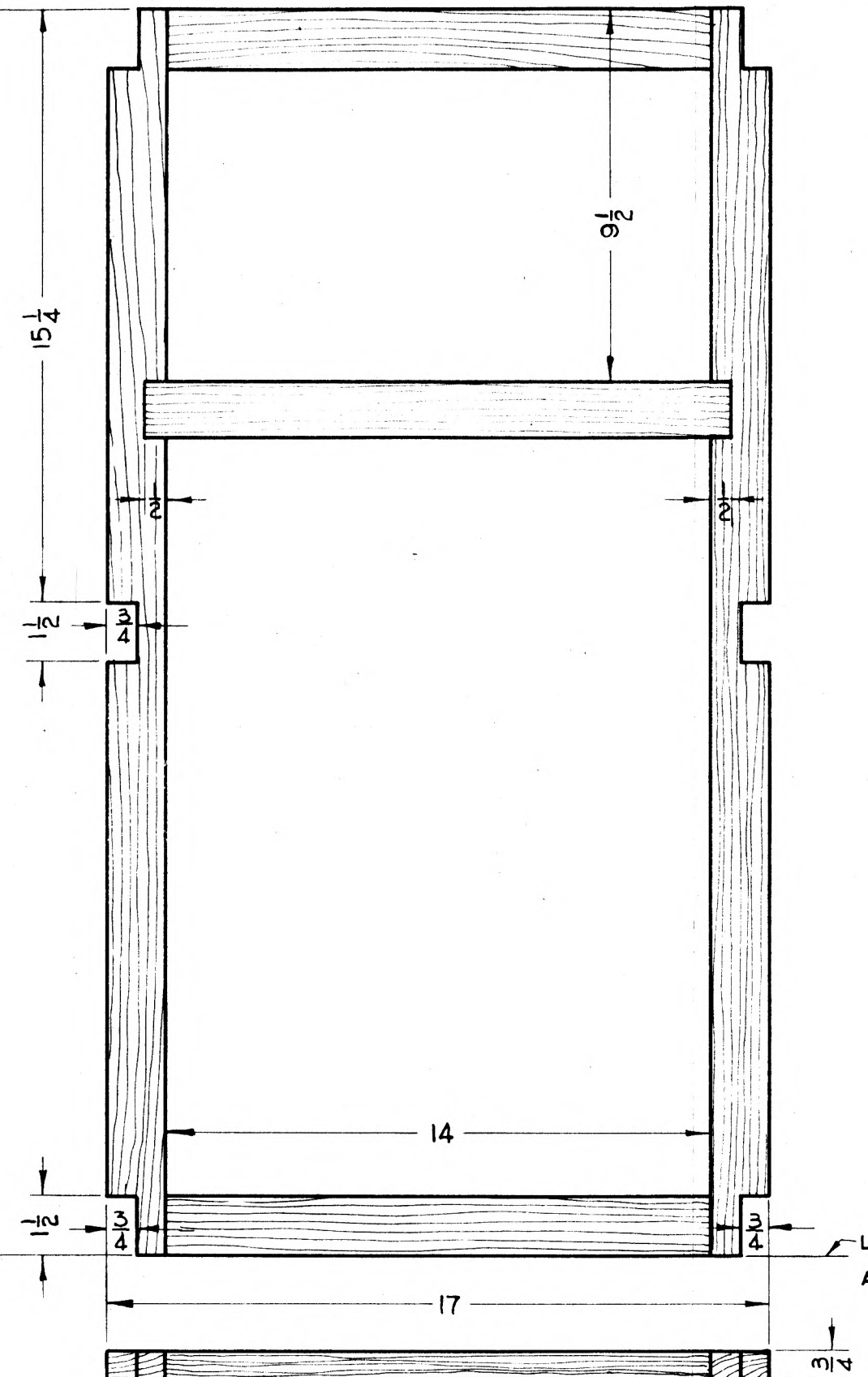




TOP, MIDDLE, AND BOTTOM FRAMES ASSEMBLED WITH 6° FINISH NAILS. SEE DETAIL PAGE  
 FRAMES AND POSTS ASSEMBLED WITH 1 1/2 IN. NO. 9 FLAT HEAD SCREWS C'TS'NK.  
 1/4" CEMENT ASBESTOS BOARD ATTACHED WITH 3/4 IN. NO. 9 FLAT HEAD SCREWS C'TS'NK.

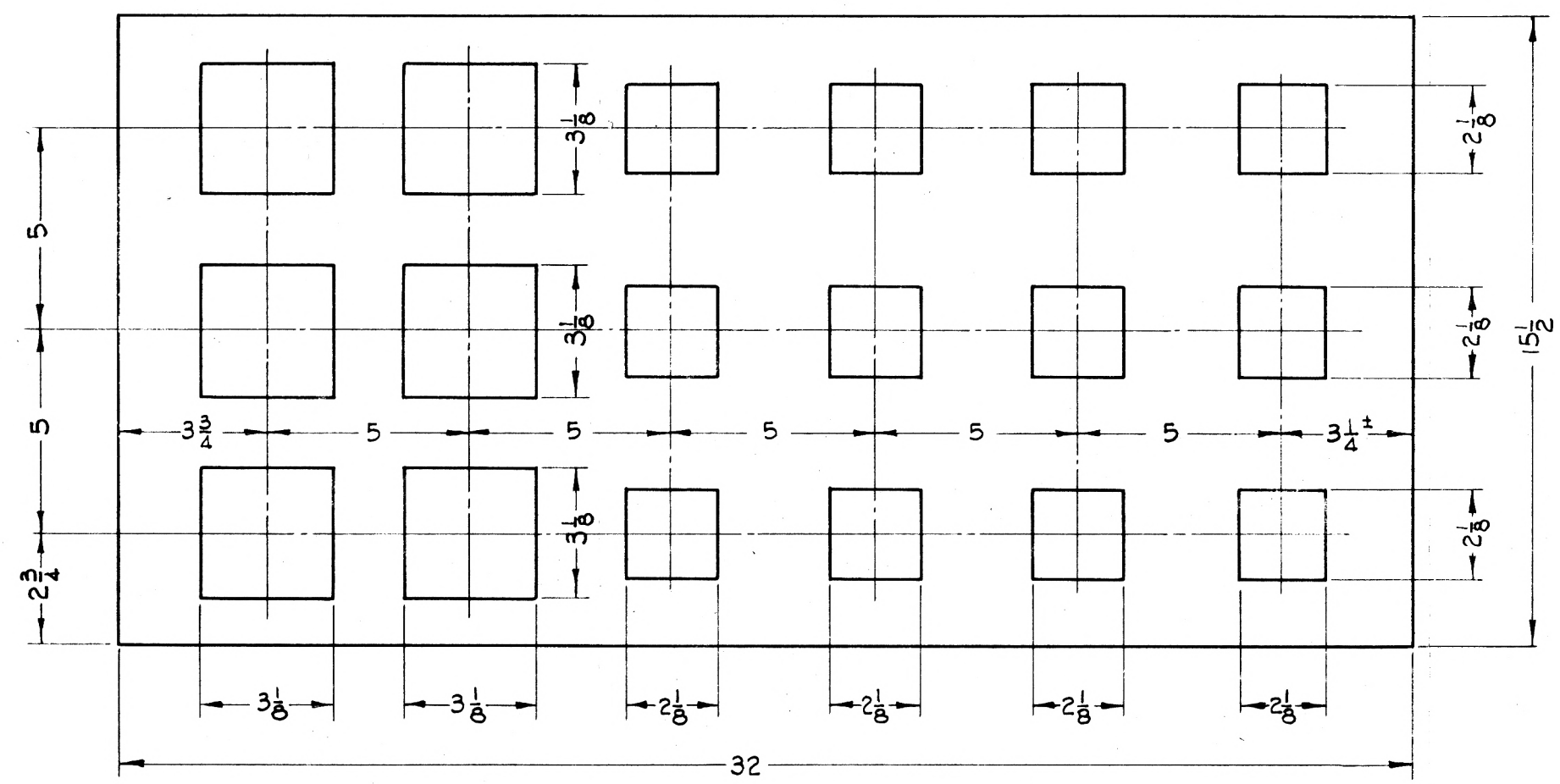


TOP AND BOTTOM FRAMES  
(MAKE 2)

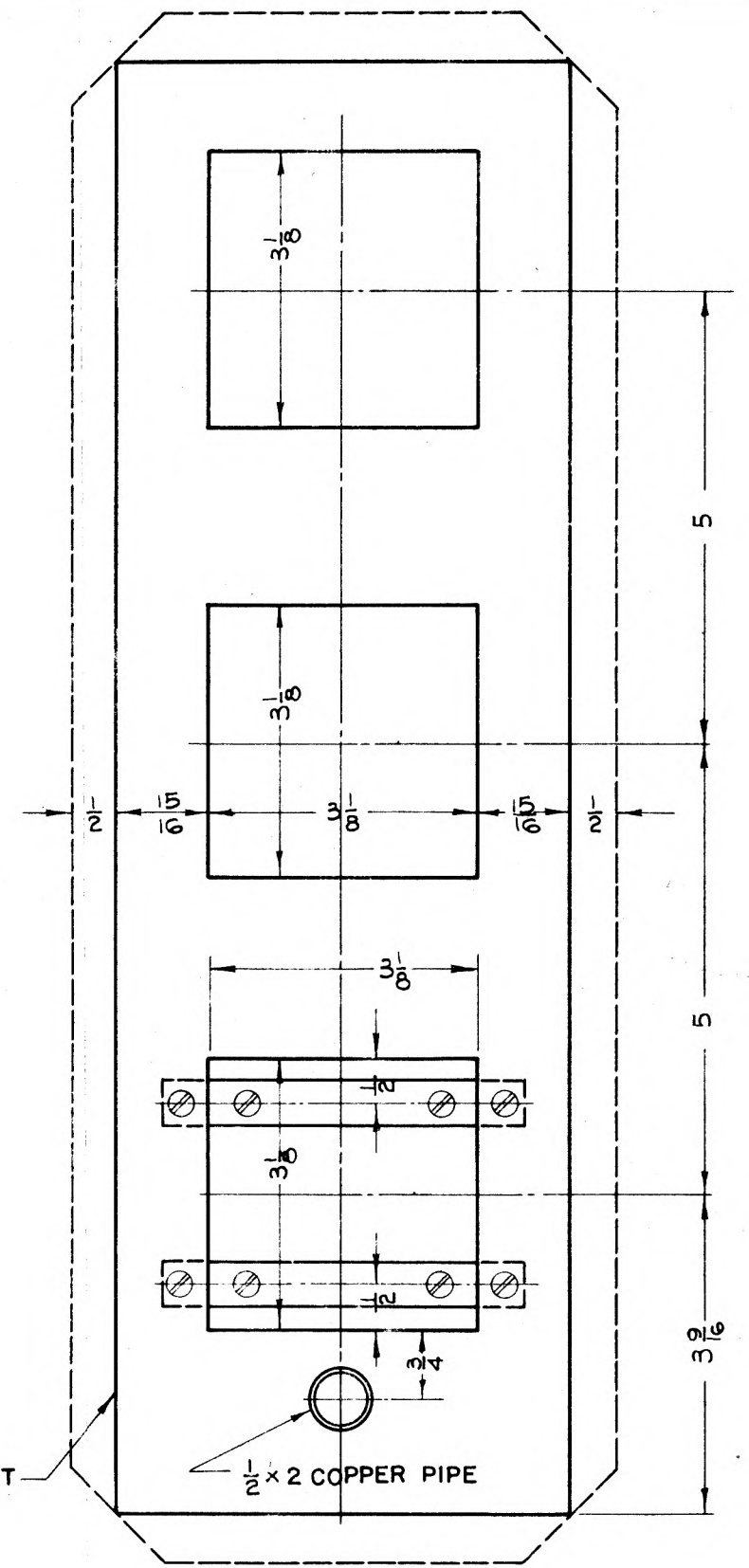
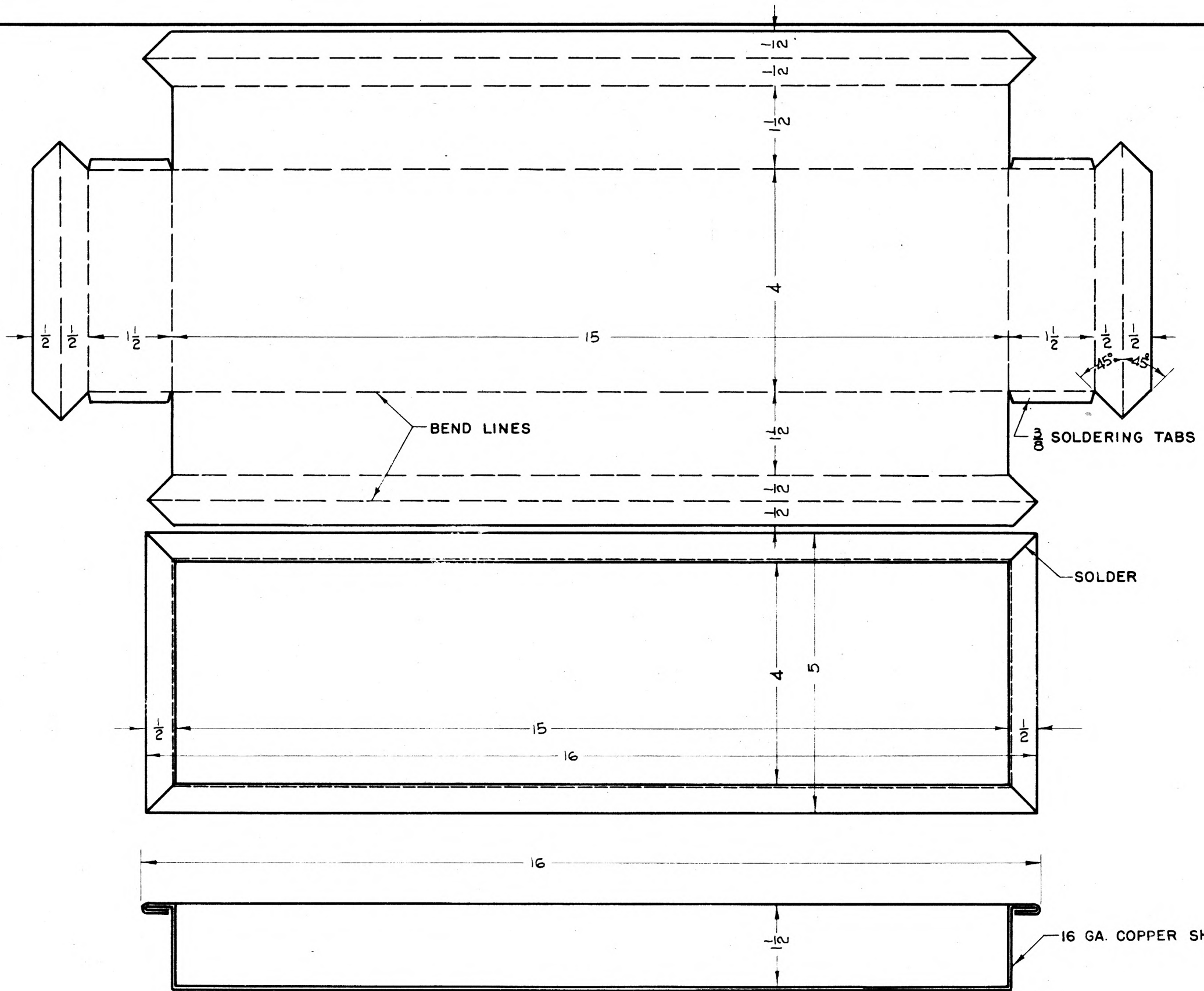


MIDDLE FRAME  
(MAKE 1)

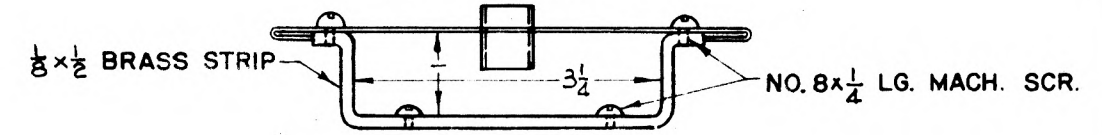
LEFT FACE OF CABINET  
AS SHOWN ON PAGE



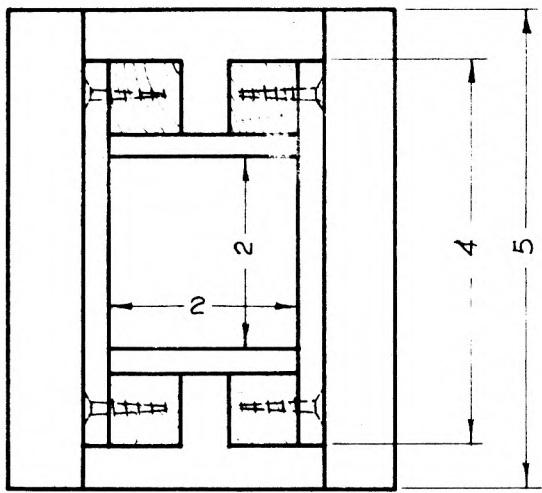
BOTTOM CUTOUT DETAIL  
1/4" MASONITE (MAKE 1)



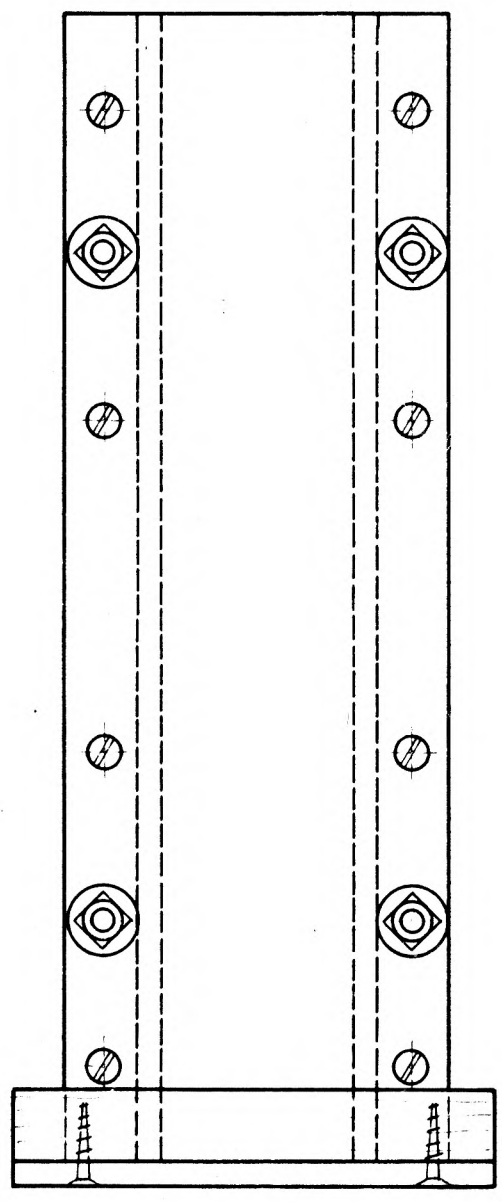
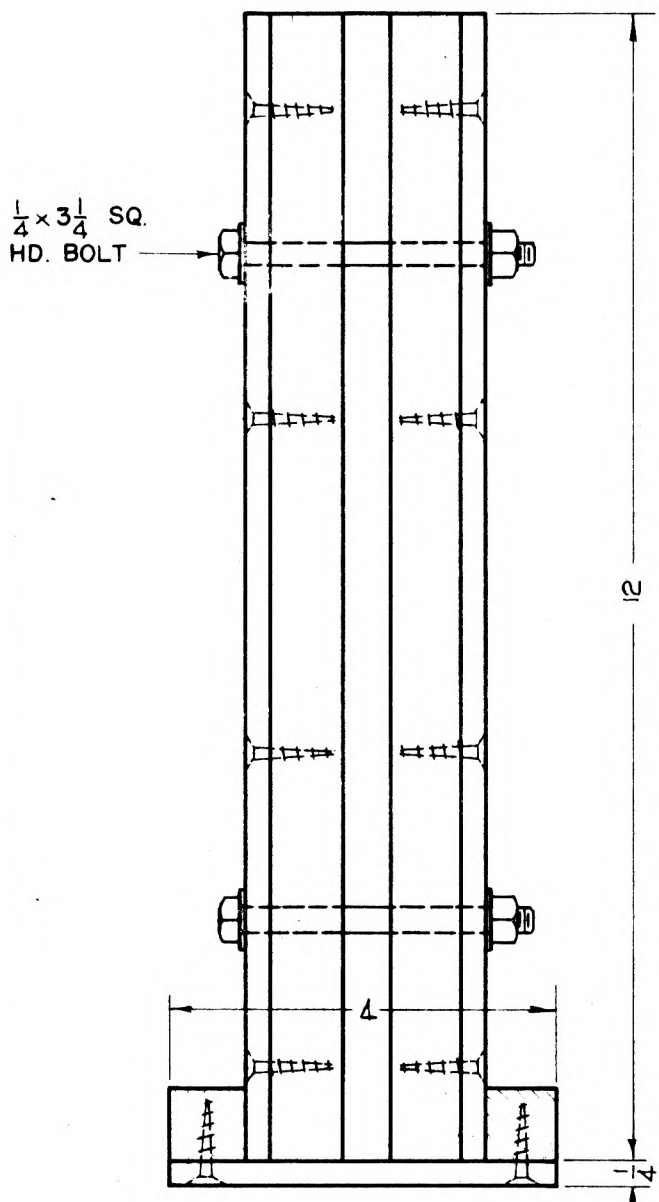
PAN  
 SCALE 6=1-0  
 NO ALLOWANCE FOR BEND RADIUS  
 MAKE 6



COVER  
 MAKE 2 AS SHOWN; 4 WITH  
 2 1/8 x 2 1/8 INSTEAD OF 3 1/8 x 3 1/8 HOLES



NOTES.  
ASSEMBLED WITH  $\frac{3}{4}$ " x NO. 9  
FLAT HD. SCR. THROUGHOUT.  
ALL WOOD STRIPS  $\frac{3}{4}$ " x  $\frac{3}{4}$ " IN  
CROSS SECTION,  
MOLD FACES  $\frac{1}{4}$ " MASONITE.



PRISM MOLD DETAIL  
SCALE 6"=1'-0"  
PLATE IX