1950

Grouting and freezing unconsolidated and water-bearing strata

Robert Walter Heins

GROUTING AND FREEZING UNCONSOLIDATED AND WATER-BEARING STRATA

BY

ROBERT WALTER HEINS

A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE, MINING ENGINEERING

Rolla, Missouri

1950

Approved by J. D. Forrester
Professor of Mining Engineering

ACKNOWLEDGEMENT

This work was made possible by a graduate assistantship at the University of Missouri School of Mines and Metallurgy. The writer is grateful to the School of Mines for receiving this assistance. The author wishes to express his sincerest thanks to the staff of the Department of Mining Engineering at the Missouri School of Mines and Metallurgy, in particular, Dr. J. D. Forrester, Professor of Mining Engineering, for their invaluable aid and advice in writing this thesis.

PREFACE

The problem of controlling ground water is becoming more important to the mining engineer. In many cases, large amounts of time and money are being spent to enable the mining industry to penetrate unconsolidated and water-bearing rock and soils. The purpose of this thesis is to combine in a single volume all the available information concerning grouting and freezing as methods of solving this problem. As far as possible, this information has been brought up to date.

An original research was conducted by the author. The experiments were made to determine if freezing a water-saturated sand could be accomplished in laboratory experiment by using dry ice and isopropyl alcohol. The tests are described and the results are given in this paper.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

GROUTING

Introduction

The process of grouting has undergone many changes in recent years. A definition must, therefore, be inclusive. "Grouting" is the process of injecting, under pressure, into soil and rock through boreholes or other openings, any solution or suspension containing materials that harden, stiffen, or swell in void spaces to produce a solid or semi-solid impermeable mass. Various cements, chemicals, asphalts and clays are the materials used in the grouting process. The use of tailings is also considered a type of grouting, since some hardening or stiffening takes place.

Cement grout relies on chemical reaction to bring about setting or hardening in place. Chemical grouting consists of injecting solutions of two or more soluble salts, and it depends on the chemical reaction between the solutions to produce an insoluble salt which is precipitated in the voids. Asphalts are solidified by cooling. Clays depend on swelling caused by absorption of water to produce an impermeable mass.

The liquid in a grouting mixture serves as the transporting medium. The pressure exerted on the liquid forces grout into the voids. Continued pressure holds the grout in place until it hardens or swells.

Uses of Grouting

Grouting can accomplish several purposes. Sturges (1) lists

(1) Sturges, F. C., Introduction-grouting in mines, A.I.M.E. Technical Publication 2427, Symposium on Grouting, February, 1948. p. 1.

them as follows:

1. To stop the passage of fluids and gases.
2. To cement materials together to make them stronger.
3. To prevent consolidation of materials by filling void space with something solid as a replacement for the air and water that could be forced out under load.

Construction Industry

The construction industry uses grouting for all three of the above purposes. Stabilizing soils and rock under foundations, bridges, dam sites, and roadbeds and repairing leaks in concrete and masonry structures constitute its greatest uses. Grouting in foundation work is used to fill void spaces and to bind broken material to reduce settlement and increase bearing strength. Dam site grouting operations are undertaken to reduce hydrostatic uplift by sealing underground water courses. Water leakage from reservoirs can be stopped by grouting. Brick and concrete structures can be made impermeable by grouting.

Oil Industry

The oil industry is primarily concerned with sealing boreholes to prevent passage of fluids and gasses. Cement grout is usually used. It is mixed as a neat cement slurry. This slurry is injected into the borehole for the following purposes:

1. To protect oil and gas bearing zones from undesirable water.
2. To protect casings.
3. To prevent blow-outs.
4. To help support the casing in the hole.

The method used in oil well cementing varies somewhat from other grouting methods. After the cement is pumped into the casing, a plug is placed above the cement. This plug separates the cement slurry and the mud or water which is used to apply pressure on the grout. The cement is pushed down through the casing and back up through the annular space between the casing and rock. When the plug reaches the bottom of the casing, pumping is stopped. This leaves the bottom of the casing surrounded by cement to insure a tight seal.

Mining Industry

The mining industry must meet the same basic problems as the oil and construction industries though mining as a whole has not made the extensive use of grouting that the other industries have. In those mines where the water problems are not too difficult and expensive to solve, grouting is not worth considering. On the other hand, water met while sinking a shaft or driving entries, slopes, drifts, and other openings presents a very difficult problem and one that is expensive to overcome.

Basically, grouting as applied to the mining field is used for the control of ground water whether it is in sinking a shaft or in the extraction of ore. If the problem warrants the use of grouting, the following results can be obtained:

1. Provide stable ground for the shaft to the orebody.
2. Provide additional support for roofs and walls.
3. Improve safety conditions.
4. Lower pumping costs.

Whatever the purpose, only intelligent handling by experienced personnel can make grouting effective and economical.

Two methods of grouting are used in tunnel and mine work. The first method consists of grouting through pipes into the strata which are to be made impermeable before the excavation has reached the water-bearing zone. In the second method, water is temporarily drained away through bleeder pipes until some type of lining is placed. After the lining has been placed, grout is injected through these bleeder pipes or through special pipes left for this purpose. The lining must be designed to withstand high pressure. A cylindrical lining is capable of resisting very high pressures and should be used if high pressures are anticipated.

In existing shafts in which the lining is not impervious, the second method can be modified somewhat. Holes can be drilled along the lining and grout forced into the holes. This method must be used with caution because the pressure might break the lining.

Grouting in slopes is usually a much more difficult problem than grouting in vertical shafts. Since the strata are usually horizontal, the grout must travel over a greater radius to be effective. A test hole which is drilled ahead of, and downward at a greater angle than the slope, is used to determine the presence of a water-bearing stratum or unconsolidated material. If such a formation is reached, grouting is carried on in steps.

Grouting ahead of the excavation is the method usually used to seal underground workings. If loose material is encountered or if water breaks through after advance, the second method will be used.

Grouting Materials and Mixtures

Factors Influencing Type of Material Used

Various factors influence the selection of the type of material to be used in grouting. These factors are listed as follows:

1. Permeability and porosity of the strata.
2. Purpose for which grout is to be used.
3. Water pressure and flow in the strata.
4. Availability of grouting material.
5. Chemical considerations.
6. Temperatures of the water, rock, and soil.
7. Cost of the grouting materials.
8. Type of project.

The permeability of a formation is a measure of the resistance offered to movement of fluids through its pore spaces. The size of the pore spaces between the grains and whether or not these spaces are connected will determine what fluids may enter and will have a marked effect upon the resistance offered to movement of fluids through the rock. In addition to the pore openings between grains in a granular rock, other openings, such as joint and cleavage planes, vesicular openings, solution cavities, and crevices formed by fracturing may also be considered under permeability.

In grouting openings with a permeability greater than one-tenth of a centimeter per second, cements, clays, and asphalts may be used. In most cases cements are used if possible since they provide the strongest and best seal. Where the permeability is less than one-tenth of a centimeter per second, chemicals are applicable. Often, cracks and fissures permit the grout to escape and penetrate a much larger volume than is required to complete the grouting operation. This is cited by Elgin (2) who says:

(2)Elgin, R. A., How Leadville Tunnel is driven through bad ground, Engineering and Mining Journal, Vol. 146, No. 3, March 1945. p. 99.

> When the cement was forced into grout holes through the bulkhead, it was found to be escaping back into the tunnel through numerous cracks in the bottom, back, and sides. However, this problem was overcome by drilling a series of holes through the concrete, beginning 40 feet back of the face, and forcing a mixture of cement, calcium chloride, hot water, and oats, into the area immediately back of the concrete. Because of their ability to expand upon absorping water, the oats effectively sealed the numerous small fractures through which water and cement were escaping.

The oats stopped the flow of water and the calcium chloride accelerated setting time of the cement on the project cited in the above quotation.

Some grouting materials are easily eroded by flowing water. Bentonite clay, for example, can be washed away by flowing liquids. It follows that this material is unsuitable for grouting under these conditions. Cement will resist erosion after it has set, but much will be washed away when grout is being placed in flowing water. Christians (3) says:

(3)Christians, G. W., Asphalt grouting under Hales Bar Dam, Engineering News-Record, Vol. 96, No. 3, May 20, 1926. p. 802.

> Cement grout washes, and even when the flow is very slight enormous quantities are washed away and wasted before a closure is effected.

Asphaltic materials will resist this erosion and stop flows under these conditions. If water flow is found in fine-grained materials, one of the chemical methods must be used.

The effect of pressure can be seen in the following illustration. While sinking Eagle-Picher's New Garret Shaft, cement grout was chosen to control the flow of ground water. According to Ritter and Stroup (4):

(4)Ritter, N. E. and Stroup, R. J., Sinking Eagle-Picher's New Garret shaft, Mining Congress Journal, Vol. 24, No. 9, September 1938. p. 14.

> The quantity of water was immaterial to the method; but it was realized that grouting would have to withstand 110 pounds per square inch of pressure at the 439 ft. level.

Cements increase the strength of a formation and can be used where high pressures are anticipated as cited above.

Grouting materials which are close to the operation and which possess properties suitable for the job are the materials used. For example, if clay is close to the project and if it has the properties needed to complete the grouting operation, clay will be used. Freight charges raise the cost of grouting materials and thereby raise the cost of placing the grout. The elimination of these charges reduces the cost of the whole operation.

The chemical constituents of the rock or soil to be grouted determines the type of grout to be used. For example, large quantities of quartz in strata to be grouted with chemicals will produce a better seal and greater strength than if small quantities are present.

In an example cited by Stiefel (5) , ordinary cement gave a set volume of 50 per cent while high early strength cement gave a set volume of 90 per cent. It was this difference that enabled the contractor to seal and consolidate the water-bearing rock.

(5)Stiefel, F. W., Overcoming underground difficulties, Compressed Air Magazine, Vol. 46, No. 12, December 1941. p. 6613.

The effect of temperature is indicated by Elgin (6) in his dis-

(6)Elgin, R. A., op. cit. p. 97.

cussion of the construction of the Leadville Tunnel. The underground water temperature was found to be 37 deg. F. Straight cement mixed with the cold mine waters did not set for several days. This difficulty was overcome with the use of hot water and calcium chloride. All grout used was mixed with hot water and one pound of calcium chloride was added for each 100 pounds of cement.

When the need for grouting has been established beyond a doubt, cost has little effect on the choice of the material to be used in grouting. The choice will depend on the purpose for which the grout is injected. When materials have equal properties to accomplish the desired results, the cheapest grouting material will be used.

Grouting Materials

There are various materials and classifications of these materials used for grouting, but for this paper, the following classes will be considered:

1. Cements
2. Chemicals
3. Asphalts
4. Clays

Cements

The most common types of cements used in grouting operations are listed as follows:

1. Portland cement
2. Modified portland cement
3. High alumina or high early strength cement

4. Gypsum cement

The grouting properties of portland cement vary with different manufacturers so that a definite statement cannot be made. The portland cement referred to here is commonly used in the construction industry. Occasionally, only minus 200 mesh portland cements are used. These materials are obtained by rescreening the cement. This is rather expensive and should be avoided if possible.

The modified portland cement contains an admixture of calcium chloride to accelerate setting. This admixture is usually added by the manufacturer. The consumer may add it if shortening of setting time is desired. The affect of this admixture will be discussed later.

High alumina or high early strength cements are often used because finer grinding permits better penetration, and the high early strength saves time.

Gypsum cement, made from calcium sulphate, sets and hardens at nearly the same time. It takes approximately two hours for gypsum cement to develope full strength.

The two most important problems which confront the engineer in planning a grouting program, are the determination of the grout mix or consistency and the determination of the pressure at which the grout will be injected. Since pressures will be discussed thoroughly in a later section, this discussion will to limited to grout mixes.

Minear (7) states:

---

(7) Minear, V. L., The art of pressure grouting, The Reclamation Era, Vol. 27, March 1937. p. 59.

> The selection of a proper water cement ratio is the most important phase of high pressure grouting and undoubtedly more holes have been lost by inexperienced men attempting to use a thicker grout than the hole would accomodate than from any other cause.

There is no standard consistency of cement mixtures that should be used in initially starting the hole. On one operation, it may be necessary to use a water-cement volume ratio of one to 30; on another, a ratio of one to 10 is the thinnest mixture that can be used. From experiences on Boulder Dam, Minear (8) suggests the following rule of

(8) Minear, V. L., Ibid.

thumb:

> The initial injections should be of grout having a water-cement ratio equal to 0.01P where P is the limiting pressure. Thus a 500 pound hole (9) would be started

(9) This term refers to the limiting pumping pressure at which grout may be injected.

> with a grout whose water-cement ratio by volume, was 5.

The water cement ratio depends on the permeability and porosity of the structure to be grouted. A neat cement paste is ordinarily used for grouting fine fissures or highly faulted rock zones. Large cavities sometimes require that some type of filler be mixed with the cement paste. Oats, hay, straw, beans, sawdust, wood shavings, and manure have been used in places where water is flowing. These materials plug the cavity and retard the flow of water. They also provide a bulkhead against which grout may be injected. This work requires a low pressure until a partial set has been reached.

Sand has been used to fill cavities, seams, and some faulted zones where water was not flowing. When used, the sand should be fine. All should pass 1/8 inch sieve and 50 per cent should pass 50 mesh sieve. While mixing a sand-water-cement grout, care should be taken to insure thorough mixing. Otherwise, the sand may form lenses and fail to make a good seal. Hays (10) states:

(10) Hays, J. B., Improving foundation rock for dams, Civil Engineering, Vol. 9, No. 5, May 1939. p. 309.

> Many grouting specifications have allowed the use of mixtures of sand and cement, especially where the required quantities of grout are large. If it is intended merely to fill large openings and to neglect small seams, and if there is no concern as to permeability of grout, the addition of sand is satisfactory.
>
> In a grouting mixture of sand and cement, the cement serves as a lubricant to convey the sand. Once in the cavity, the sand settles to the bottom and the cement comes to the top, the rate and degree of segregation depending on the relative quantity of water used in the grout and the presence of water in the cavity.

If high strength of cement grout is not required, bentonite may be added to the sand-cement grout. Hays (11) says:

(11) Hays, J. B., Foundation experiences, T. V. A., American Society of Civil Engineers Transactions, Vol. 106, 1941. p. 791.

> Bentonite has a dispersion action on the sand and cement, thus keeping all of the materials in suspension. Without bentonite, the sand would have washed out of the mix and would not have been effective in stopping water.

Rock flour may be substituted for part of the cement used in grouting. When large quantities of grouting materials are required, this substitution may be made to save on the quantity of cement used. The addition of rock flour may have a harmful effect on the cement in that it can cause unsoundness. It also retards the setting time of the cement. Lewis (12) says:

(12) Lewis, J. S., Jr., Foundation experiences, T. V. A., American Society of Civil Engineers Transactions, Vol. 106, 1941. p. 718.

> It may safely be assumed that, in grouting extremely seamed rock at a fixed rate of pumping, the area that will be covered is dependent to a large extent upon the setting time of the cementing material. By the use of a slow-setting material, the distance traveled by the fluid may be increased so that areas completely outside of the region that it is desired to treat will be grouted and the quantity of material necessary to effect consolidation increased appreciably. Obviously, even if the unit cost of grout was reduced by the use of a cheap, inert material to replace part of the cement the total cost of treating a given area might be increased if the quantity of material consumed was appreciably larger.

To accelerate the setting time, calcium chloride can be added to the cement-rock flour mixture. It was found that the addition of three per cent calcium chloride by weight will offset the retardation of the rock flour. Table 1 gives a condensed summary of the results of rock flour-cement grout tests.

Many authors believe the best mixture and the proper consistency cement grout can be found by trial and error combined with judgement and experience. It is usually best to use the thickest mixture that will flow since less material is wasted and the cement will attain its highest strength. The strength of cement varies inversely as the quantity of water used during mixing. The time required for portland cement to set increases as the water-cement ratio increases as shown in Figure 1. Consequently, that percentage of water which will meet the requirements must be used if satisfactory results are to be obtained.

While grout is setting, it undergoes considerable shrinkage, even

TABLE 1

SUMMARY OF NORMAL CEMENT AND ROCK FLOUR [13]

Test no.	Mix by volume cement	rock flour	water	Time of setting in hours and minutes initial set	final set	soundness	Calcium chloride
5	1	1	23% by wgt.	3:15	6:50	ok	----
6	1	1	"	2:45	5:00	ok	3% by wgt.
9	2	1	"	2:50	6:35	ok	----
10	2	1	"	1:45	3:25	ok	3% by wgt.
11	2	1	1.5	11:00	22:00	ok	----
12	2	1	1.5	4:05	10:30	ok	3% by wgt.
13	1	2	23% by wgt.	4:30	6:45	ok	----
14	1	2	"	2:15	4:20	ok	3% by wgt.
15	1	2	1.5	16:00	36:00	ok	----
16	1	2	1.5	10:00	18:00	ok	3% by wgt.

(13) Lewis, J. S., Jr., *Ibid.*

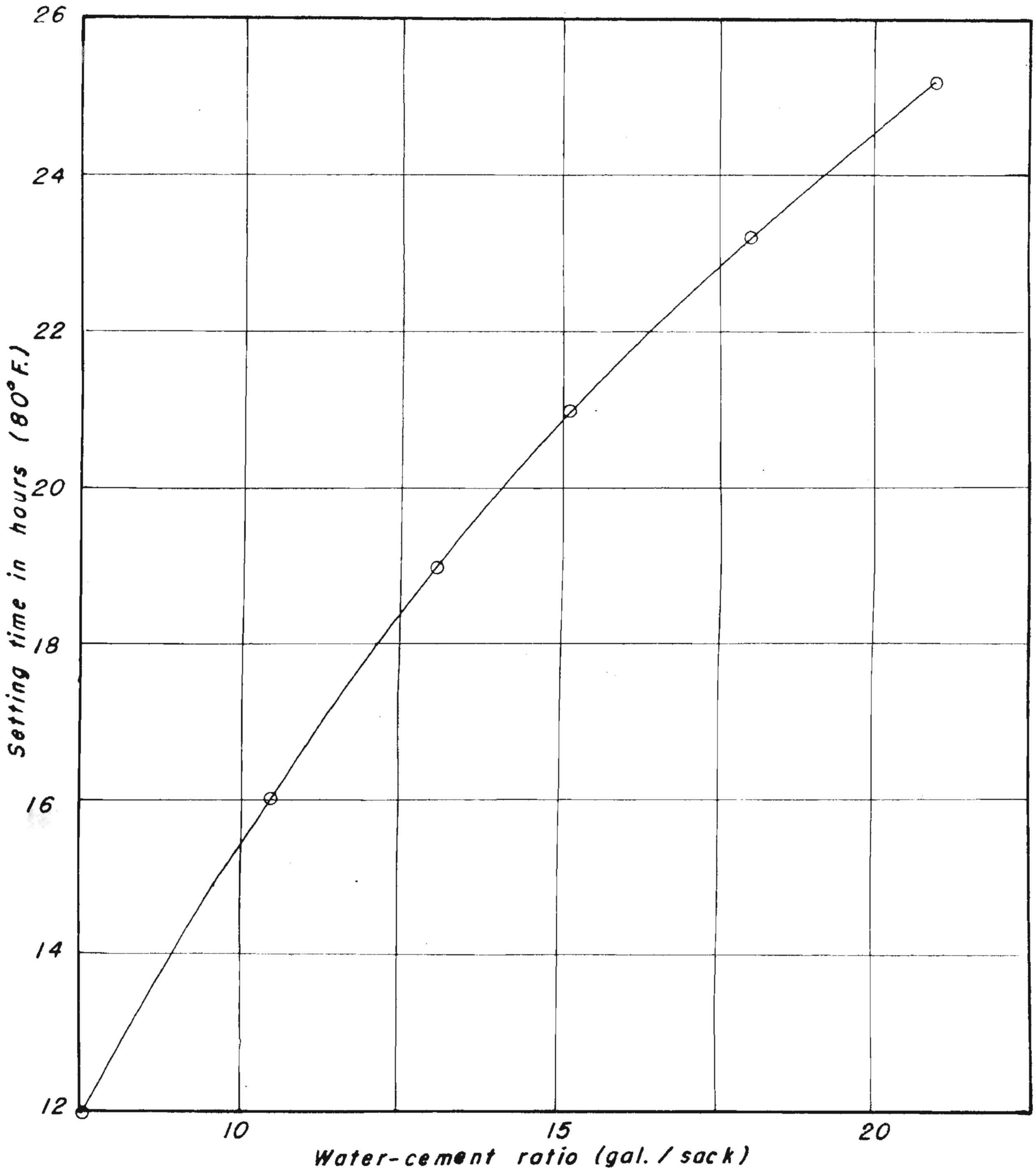


Figure I. Effect of water-cement on setting time of portland cement.

(After U.S. Bureau of Mines)

though the minimum amount of water was used in the mix. When a thin mix is pumped at low pressure, the surface of the grout will shrink from the top of the hole up to one-third of the depth of the hole after grouting has been completed. This same condition exists underground around fissures, cracks, and crevices when the grout is too thin or when it is injected with too low a pressure. When thicker grouts are used, less shrinkage takes place. Higher pressure displaces more water from the grout after it has been injected.

It should be noted that there is no greater tendency for grout to settle out in tanks or pipes with thick mixes than there is with thin mixes. Settling can be minimized or stopped by maintaining a flow of grout of sufficient velocity. This can be most easily accomplished by using flow and return pipes with a small diameter.

The time required for setting of cement grout is dependent on: (1) quality or type of cement, (2) age of cement, (3) water-cement ratio, (4) temperature, (5) curing conditions, and (6) quality of water.

There are several cements having decidedly dissimilar properties. For cementing water-bearing ground, a hydraulic cement is required. Such cements are represented by portland, modified portland, calcium-aluminate, and gypsum cements. The time required for a hard set to form may vary within wide limits in similar types of cements. Setting time is no criterion of quality, but it is important in grouting because it indicates whether or not a given cement can be used advantageously.

In tests conducted with fresh portland and calcium-aluminate cements, it was found that the setting time lengthened as the age of the cement increased. All hydraulic cements will absorb moisture from the air, which moisture, in time, will be sufficient to retard setting time. This property was particularly noticeable in the calcium-aluminate cement tested in the field.

Certain grouting jobs require a high water-cement ratio to insure proper placing, workable mixtures, and penentration of the grout into the ground to be treated. As previously pointed out, tests on portland cement show that the rate of setting decreases as the water-cement ratio increases. However, similar tests conducted on calcium-aluminate cements indicate that hardening is not materially affected when water is added in quantities varying from 7½ to 21 gallons per sack.

Natural conditions in the borehole control the temperature and curing conditions of the cement grout. Some control can be exerted by regulating the temperature of the mixing water and cement. Calcium chloride may be added to lower the freezing point and insure the complete chemical reaction between cement and water. Care should be taken because too much calcium chloride can cause unsoundness.

Abrams (14) when making comprehensive tests of impure mixing water

---

(14) Abrams, D. A., Test of impure waters for mixing concrete, American Concrete Institute, Proceedings of the Twentieth Anniversary Convention, Vol. 20, 1924.

---

did not find an unsound sample of cement. Tests by the Bureau of Mines (15) on water from the Christmas Mine indicated that the setting

---

(15) U. S. Bureau of Mines, Report of Investigations 4559. p. 7.

---

times of both portland and calcium-aluminate cements were retarded by the impurities in the water. The setting time of portland cement was retarded as much as 10 per cent.

Various admixtures have been used to change some of the properties of grouting cements. It should be noted that an admixture having a favorable affect on one cement might have the opposite affect on another cement. The Bureau of Mines conducted tests with admixtures to determine the affect on portland and calcium-aluminate cements. Some of the tests were not carried to completion because of the lack of materials, but they do give an indication of the affect. Table 2 summarizes these tests.

The affect of admixtures may be harmful or helpful. It is desirable that pressure cement grouts harden rapidly, but set slowly, to attain highest possible strength. It will be noted that barium chloride and calcium chloride gave these desirable results when used with portland cement. Under certain conditions, soda ash, hydrated lime, and sodium hexametaphosphate are desirable admistures when used with calcium-aluminate cement. Other cements were tested but the results were not conclusive.

Many types of grout mixers have been used on grouting operations, including hand-operated machines, concrete mixers, and specially designed grout mixers. Since hand-operated machines have limited capacity and since concrete mixers tend to waste considerable grout, the most satisfactory would be the specially designed mixer. Any machine which has the desired capacity and which mixes the grout mechanically until a uniform consistency is obtained is suitable. Manual mixing is not satisfactory except in an emergency.

TABLE 2 [16]

SUMMARY OF TESTS USING VARIOUS ADMIXTURES

ADMIXTURE	PORTLAND CEMENT	CALCIUM-ALLUMINATE CEMENT
1. Calcium chloride	When used in quantities of one to one and one-half pounds per bag and a cement-water ratio of 10 gallons per bag, shortened hardening time 27 to 36 per cent.	No data available
2. Barium Chloride	When added in quantities of one to one and one-half pounds per bag, shortened setting time 18 per cent.	No affect
3. Hydrate of lime	No affect	When added in quantities of six ounces per bag, acted as accelerator. Five pounds per bag caused unsoundness.
4. Soda Ash	No affect	When added in quantities of six ounces per bag, acted as accelerator. Five pounds per bag caused unsoundness.
5. Caustic Soda	No affect	No affect
6. Trisodium Phosphate	No affect	No affect
7. Sodium Hexametaphosphate	When added in quantities of six ounces per bag, increased hardening time 200 per cent.	When added in quantities of three to six ounces per bag at temperatures below 75 degrees Fahrenheit, proved to be a retarder. Acted as accelerator when same quantity was used between 80 and 90 degrees F.

(16) U. S. Bureau of Mines, Ibid.

Figure 2 shows a small, 8 cubic foot capacity mixer used by the Bureau of Reclamation on the Central Valley California project. This light weight mixer can be easily set up and operated. It was constructed at nominal expense. Figure 3 shows the mixer designed by the Bureau for the Hoover Dam project. This machine was operated by a 2.65 horsepower air motor. The air consumption was approximately 85 cubic feet per minute. These illustrations and data give some idea of the various designs and sizes of mixers.

It must not be assumed that the injection of cement grout under pressure is an infallible insurance against all leakage. Although grouting is successful in most cases, many authorities prefer to view it as a cure rather than a preventive measure. According to Freeman,[17]

---

[17] Freeman, M. H., Discussion on the Astoria Tunnel, American Society of Civil Engineers, Vol. 80. 1916. p. 677.

---

the following are the requisites for successful grouting:

1. An impervious bulkhead against which to grout.
2. A grout tank (or pump) pressure considerably above that of the rock pressure against which grout is injected.
3. Adapting the consistency of the grout to the size of the cavity.

While the pressure and mix used vary to suit conditions found on the job, they also vary within the limits set by the engineer responsible for the operation. The pressure and mix used by one engineer may bear little relationship to those used by another engineer under similar conditions. Other major points of difference include the positions of the grout pipes in the hole, the use of a return pipe, and the time at which grouting should stop.

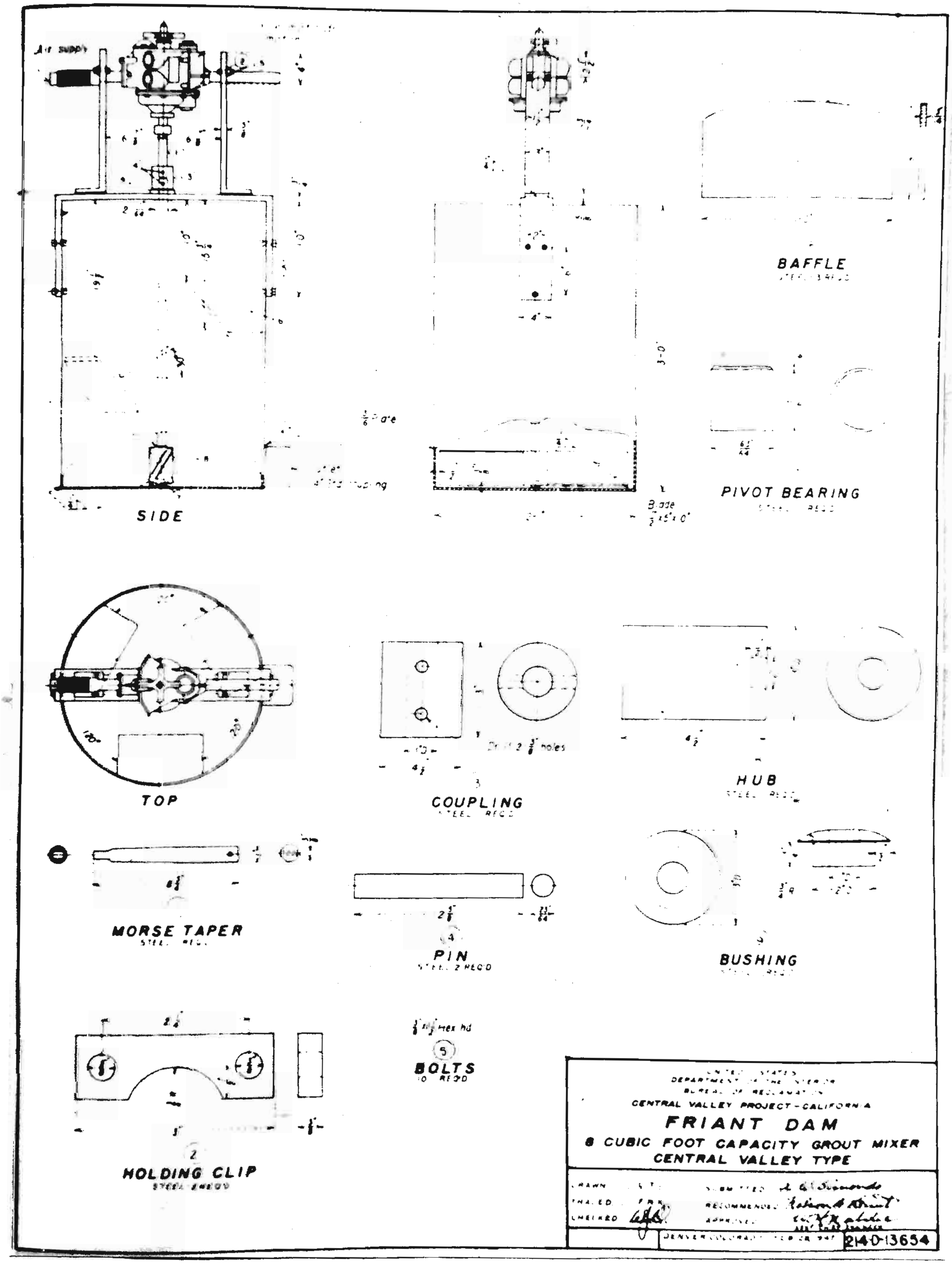

SIDE
BAFFLE
PIVOT BEARING
TOP
COUPLING
HUB
MORSE TAPER
PIN
BUSHING
HOLDING CLIP
BOLTS
CENTRAL VALLEY PROJECT - CALIFORNIA
FRIANT DAM
8 CUBIC FOOT CAPACITY GROUT MIXER
CENTRAL VALLEY TYPE
214-D-13654

FIGURE 2

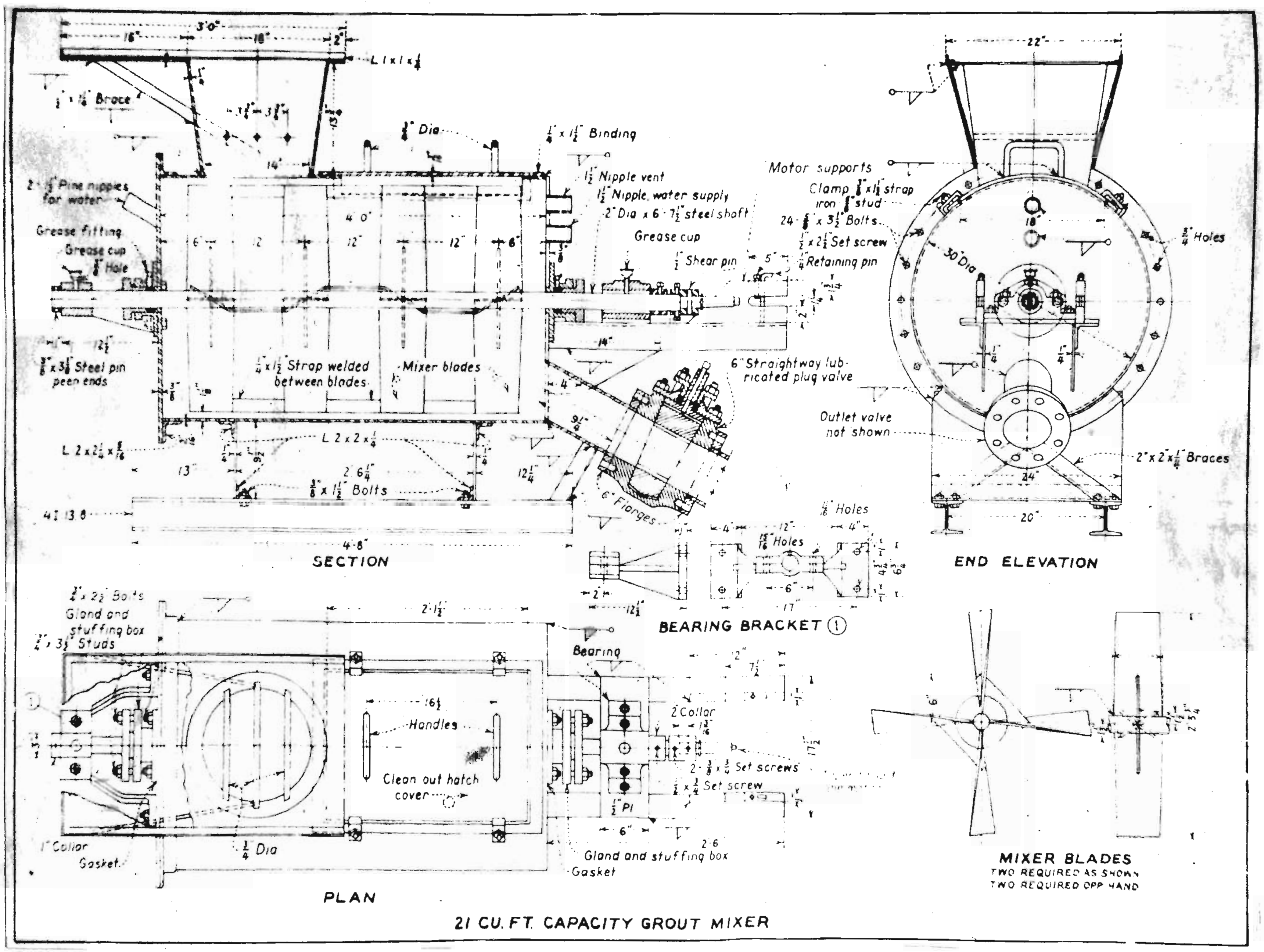


FIGURE 3

(Reprinted From U. S. Bureau of Reclamation)

Grouting may be sub-divided into stages, namely, single and multi-stage. The single stage grouting process consists of injecting grout into a hole until the hole refuses to take further quantities of grout. In the multi-stage process, grouting does not stop with one injection; instead, grouting continues day after day, or hour after hour, until the hole is passed as tight. On some projects, as many as 10 stages have been used, with each stage a little more grout is forced in. This system tends to overcome shrinkage. Multi-stage grouting has the advantage over the single stage in that a complete seal is more likely to be effected.

With the above points in mind, the actual grouting procedure should be considered. Since the procedure for shaft sinking is similar in most respects to the other grouting operations, it is felt that shaft sinking would serve as a good example of this procedure. In this example the shaft is to be sunk in stages.

Where water is present and the water level is known, sinking is stopped at a distance 15 to 20 feet above this level. The grout holes are started with a bit, the diameter of which is slightly longer than the diameter of the pipe. The holes are drilled from 6 to 10 feet. The pipes are caulked or cemented into place and tested under pressure. This is done so that they will not be lifted or displaced during the grouting operation, and it also serves to wash and clean the hole. This same procedure may be followed upon completion of grouting to see if the formations are thoroughly sealed. Each pipe is fitted with a stop-cock and drilling is continued through the pipes. Boreholes have been drilled more than 60 feet. These holes have been treated as one stage. Grouting to great depths is uneconomical; effective grouting calls for shallow treatments.

When water is found, the drilling is stopped and the holes are tested and washed. There seems to be some disagreement about the use of air or water for this test. Beanfield (18) states:

(18) Beanfield, R. McC., Technique of pressure grouting foundations, Western Construction News, Vol. 3, No. 19, October 10, 1928. p. 636.

> The use of water force in the hole is of questionable value, as the water may form air or water pockets in the voids and otherwise occupy the void space instead of the grout. Air will certainly penetrate and clean better than water.

Minear, (19) on the other side, says:

(19) Minear, V.L., op. cit. p. 58

> Some engineers question the use of water, particularly in the case of tight rock, as the water fills the pockets which would otherwise be occupied by cement. On the other hand, it may be maintained that under pressure the water is forced into the rock pores; or if there is no escape of water, there is no need of grout in that particular crevice. All high pressure holes at Boulder Dam were pressure washed with water or thin grout and the superiority of the former for local conditions was definitely established.

After drilling is stopped, cement grout is forced in to refusal. After sufficient time has been allowed for setting, the holes are cleaned. If water is still present, additional injections are made until the water is sealed. The holes are deepened to a predetermined distance and treated as already described. A second series of holes are drilled and grouted in the same manner as the first. Figure 11 indicates this method. In this way, work can be carried on continuously in either of the series of holes. As soon as both series of holes have been completed excavation is begun immediately and is continued to a distance of from 15 to 20 feet above the bottom of the treated section. Another section is prepared for grouting following the procedure outlined above. This method described is commonly called the advancing method.

It has been found that the penetration of the grout is in a horizontal direction rather than vertically downward. Therefore, the bottom of the treated section is the bottom of the hole. The 15 to 20 feet allowed between the bottom of the excavation and the treated section is a factor of safety.

There are two general methods of connecting supply lines to grout holes. The direct connection may be made similar to Figure 4. In this method, the supply line is connected to the hole. There is no provision for a return line. The circulating system uses a return line from the manifold to the agitator, as illustrated in Figure 5. The pump is operated at a constant speed and the pressure is regulated by valves at the manifold connection. This arrangement is useful in grouting holes where the rate of penetration is low.

Chemicals

The choice of materials used in the chemical grouting processes is dependent on the method employed. There are four major methods, namely, Joosten, Francois, K. L. M., and the Jorgensen processes.

The Joosten method uses solutions of sodium silicate and calcium chloride. The silicate solution is injected first and the chloride solution second. When these solutions come in contact, they react to form insoluble calcium silicate and soluble sodium chloride. The silicate which forms is a sticky substance which gradually hardens as it looses some of the liquid. Upon further hardening, the mass becomes

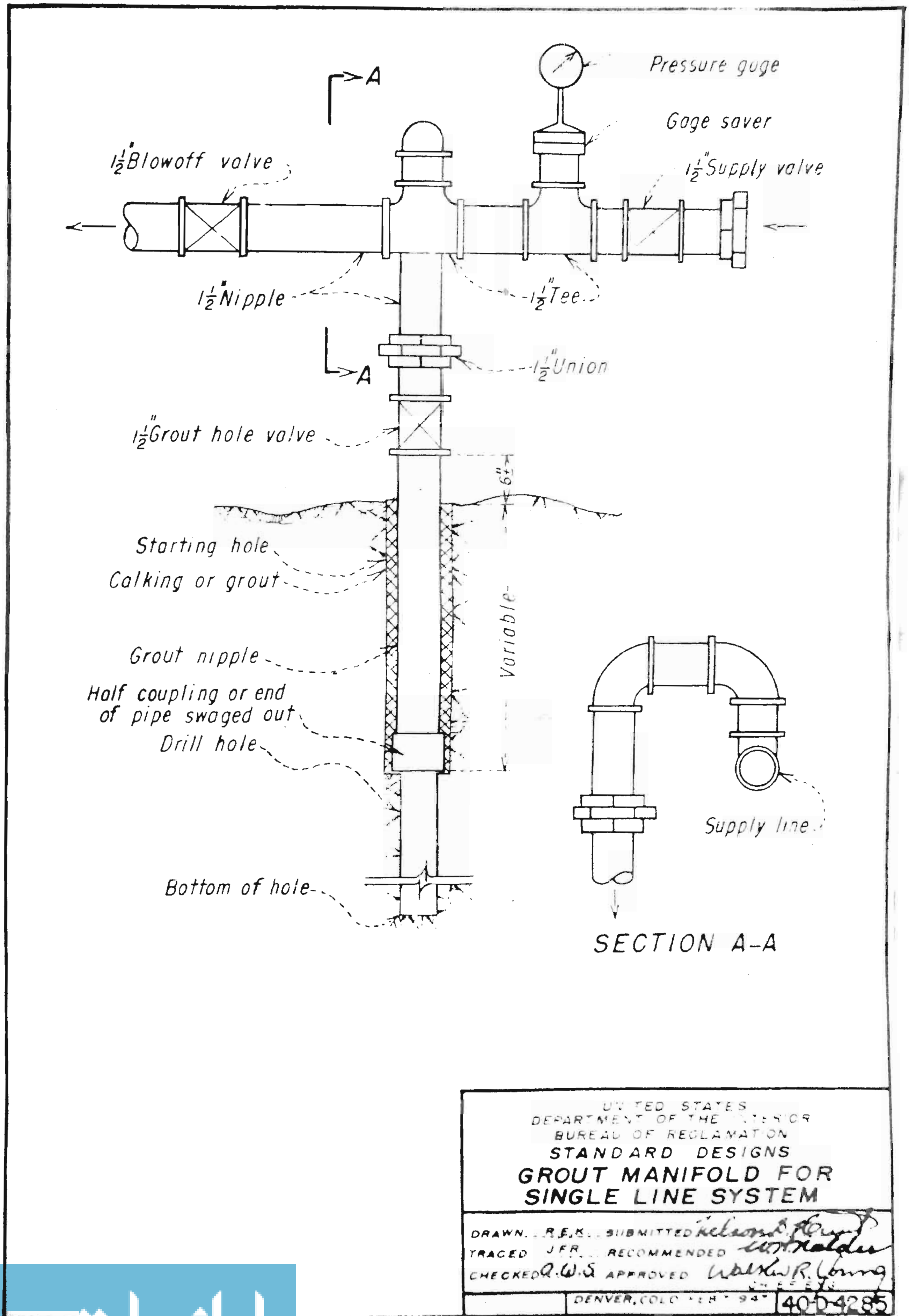

A
A
Pressure gage
Gage saver
1½" Blowoff valve
1½" Supply valve
1½" Nipple
1½" Tee
1½" Union
1½" Grout hole valve
6"±
Starting hole
Calking or grout
Grout nipple
Variable
Half coupling or end of pipe swaged out
Drill hole
Bottom of hole
Supply line
SECTION A-A
STANDARD DESIGNS
GROUT MANIFOLD FOR SINGLE LINE SYSTEM
DRAWN R.E.K. SUBMITTED
TRACED J.F.R. RECOMMENDED
CHECKED Q.W.S. APPROVED
DENVER, COLO.
40-D-4285

FIGURE 4

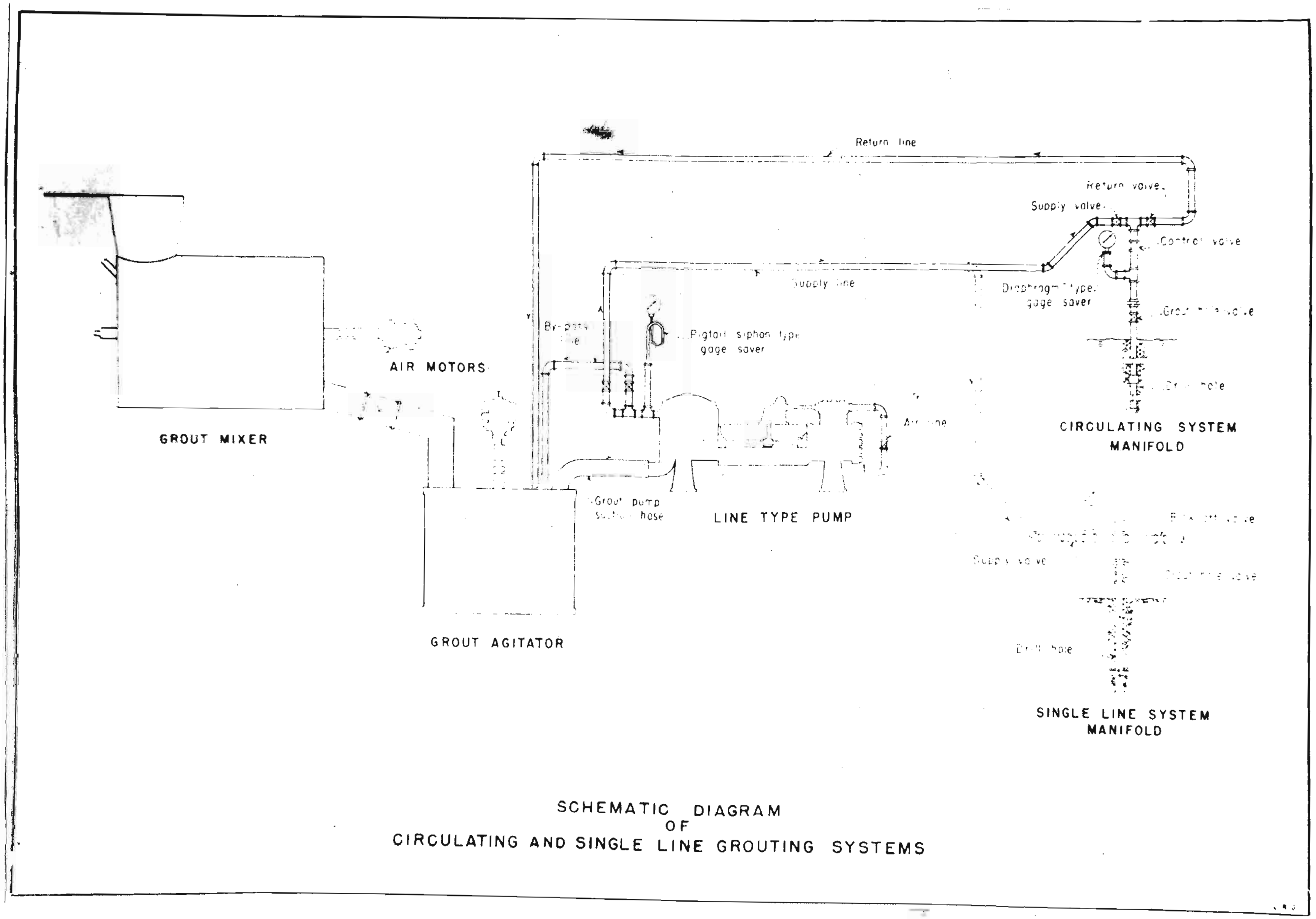


FIGURE 5

(Reprinted From U. S. Bureau of Reclamation) impermeable and the strength approaches that of sandstone.

The Francois process combines both cement and chemical grouting. Crawhall [20] states:

---

[20] Crawhall, J. S., Tunneling a water-bearing fault by cementation, Engineering News-Record, Vol. 102, May 30, 1929. p. 874.

> Whenever rock does not accept liquid cement readily, (due to fine fissuration, sand filling the fissures, pores or other causes), it is treated by chemicals. Under a patented process, silicate of soda and sulphate of aluminum are injected as two independent clear solutions; they meet in the rock and form a colloidal precipitate which lubricates the fissures with a jelly-like substance and, along with the subsequent injected cement, sets and forms a water-tight filling.

From a bulletin published by the U. S. Waterways Experiment Station, [21] the K. L. M. process is explained as follows:

---

[21] Soil Mechanics Bulletin No. 9, U. S. Waterways Experiment Station, Vicksburg, Mississippi, March 1939. p. 8.

> The reagents used in the K. L. M. process include a number of different metallic salts and acids. Demonstrations are being made, for example, with sodium silicate and a reagent consisting of copper sulfate and dilute hydrochloric acid. Use of the process is advocated for sands where permeabilitites range from 0.1 to 0.0001 centimeters per second.

Gutmann [22] says:

---

[22] Gutmann, I., Algerian rockfill dam substructures, Engineering News-Record, Vol. 120, May 26, 1938. p. 749.

> The K. L. M. process offers these distinct advantages over the older methods: (1) the water glass and salt solutions, pre-mixed and pre-treated, are injected simultaneously in one operation; (2) The time of set of the injected colloidal mixture can be regulated at will to occur at the end

of say, one minute, 20 minutes or 2 hours after it has been prepared.

The Jorgensen chemical process, as given by the U. S. Waterways Experiment Station, (23) is as follows:

(23) U. S. Waterways Experiment Station, op. cit. p. 8.

> The reagents used in this procedure are sodium silicate, calcium chloride, and carbon dioxide gas. The use of this process is recommended by the patentee for petrifying granular materials and for strengthening weak rock formations. The chemicals are injected separately in two or three stages depending upon whether the carbon dioxide is introduced with the salt or separately. The gas is claimed to be valuable in water-tight work, making the solidified mass denser.

It has been determined that the silicate of soda used in the chemical grouting processes should have a density greater than 41 deg. Baume' and a ratio of one part sodium oxide to not less than 3.22 parts silica. For best results, the soil or rock to be treated should contain 20 per cent or more quartz. This was brought out by tests conducted by the Corps of Engineers, U. S. Army. (24) In these tests, sand, which

(24) The U. S. Engineer Sub-Office Hydraulic Laboratory, War Department, Corps of Engineers, U. S. Army, November 1937.

contained a high quantity of silica, was treated. A sample of river sand, when treated the same way, did not show appreciable bonding. Small lumps of gel were found scattered in the specimen, but otherwise the material was just as plastic and sticky as it was before treatment.

In general, the following materials are suitable for chemical grouting: (25)

(25) Riedel, C. M., Chemical joint sealing and soil solidification, Engineering News-Record, Vol. 127, August 14, 1941. p. 77.

1. Loose, not too fine sand, dry or under water pressure.
2. Layers of sand and gravel with a limit of clay content, about 20 per cent, since clay cannot be impregnated.
3. Other alluvial soils shown suitable by laboratory tests.
4. Quicksand, even under high water pressure.
5. Poor, pervious concrete or brickwork.

As already pointed out, the main difference in the various chemical processes is in the type of materials used to effect solidification. The method of application is much the same except that the K. L. M. process permits simultaneous injection of the chemicals. According to Jorgensen: [26]

(26) Jorgensen, L. R., Solidifying gravel, sand, and weak rock, Western Construction News, Vol. 6, November 10, 1931. p. 591.

> The general procedure (Joosten Process) is to drive the perforated pipe down into the material to be solidified, say 20 inches; then pump the first solution (sodium silicate) into this layer; then drive the pipe another 20 inches and inject chemical I and so on again. When the full depth has been reached and all the solution I desired has been forced in, the salt solution (chemical II) is injected in 20 inch lifts, as the pipe is pulled out. The gel is formed immediately, but remains in such a condition for sufficient time for the salt solution to penetrate to the outer strata, there to find the atoms of silicate. Both liquids are heavier than water, and have a tendency to displace all the water in the voids of the gravel and reach rock bottom, even if the end of the pipe does not.

The solidified mass is water tight and insoluble. The distance of penetration from the injection pipe depends on the size of the void spaces. The distance that the chemical grouts penetrates is directly proportional to the pressure used.

Asphalts

Asphalt materials used for grouting are obtainable in several varieties. They range from a thick fluid to a brittle or oxidized grade. As a general rule, the best type of material is one which stiffens after cooling, but does not become hard and brittle.

Asphalts are used where water is flowing through cracks and crevices at a high velocity and at a high pressure. This material will solidify enough to resist moving water, but remains soft enough so that continued pressure will expand the asphalt against the sides of the cavity. The asphalt is injected hot and when it comes in contact with water, the outside is cooled. Inside this covering, the asphalt remains liquid. Continued application of pressure tends to fill the cavity. After filling takes place, the asphalt is forced along the long dimension of the opening. When the required section has been treated, the pressure is reduced and the remaining liquid asphalt is allowed to cool. The distance traveled by the asphalt is dependent on the size of the opening, type and shape of the cavity, the grade of asphalt used, the amount of pressure applied, and the length of time over which the pressure is applied.

There are three general methods used for asphalt grouting. The first or Christians method uses an electrical resistance wire suspended in the injection pipe. When electricity is applied, the wire becomes incandescent, the heat generated keeps the asphalt hot. Grouting operations, which have been stopped for a period of time, may be resumed by applying a current to the wire a few minutes before starting the pumps. Christians [27] states:

---

[27] Christians, G. W., op. cit. p. 802.

> By altering the grade of asphalt, adjusting the rate of flow, controlling the temperature in the pipe line, operating intermittently and to determined pressures, it is possible to adapt the method to various local conditions so as to obtain maximum results with minimum effort and material.

The second method uses a circulating steam system to keep the asphalt hot during injection. The steam unit is lowered into the hole to be grouted; asphalt is forced in. This method is particularly applicable where it is necessary to fill large cavernous openings.

The Shell Oil Company, Incorporated, recently announced the use of an asphalt-in-water emulsion in a method for control of subsurface seepage. This is being used under the trade name of "Shellperm". The following method of use is quoted from the Petroleum Refiner: [28]

---

[28] Underground dam, Petroleum Refiner, Vol. 28 No. 3, March 1949. A Gulf Publishing Company Publication. p. 114.

> Shellperm is a process employing an emulsion of asphalt-in-water, which is pumped under low pressure through a metal pipe driven into the ground. After the emulsion emerges from the pipe, it spreads out roughly in the form of a ball. Then chemicals mixed with the emulsion cause the asphalt to coalesce and the resulting mass is impermeable to water.
>
> When the first or bottom injection has been made, the pipe is raised and additional shellperm pumped down to form the second impermeable mass. Repeated injections produce a vertical asphalt column. The pipe is then moved and injections made to form a second vertical asphalt column. By repeating the process of building the overlapping or abutting vertical columns, an impermeable underground dam is formed.

Clays

The most common type of clay used in grouting is bentonite. Most bentonites have a strong affinity for water, absorbing from eight to 15 times their volume. Bentonite forms a plastic gelatinous mass which resembles soft soap. When it is agitated in water, it forms a more or less permanent suspension. An electrolyte coagulates or flocculates the suspension and bentonite settles out rapidly. These properties make bentonite suitable for use as a grouting material. From experience, it has been determined that the clay used in grouting should contain less than five per cent plus 200 mesh sand.

Other clays have been used for grouting. These materials must be tested in a laboratory to determine if they are suitable. Tests were conducted on clays to be used in grouting the Madden Reservoir [29] to

---

[29] Madden Dam Project, Alhajuela, Canal Zone.

---

determine their properties for use on this operation. Kellog [30] states:

---

[30] Kellog, F. H., Clay grouting at Madden Reservoir, Engineering News-Record, Vol. 109, No. 14, October 6, 1932. p. 396.

> The objects of this group of tests were: (1) to determine what type of clay mix would make the best grout; (2) to note the distance through which the grout would travel underground; (3) to note the sizes and types of openings in the rock that could be grouted; and (4) to check the efficiency of the methods used in stopping leakage.
>
> The results of these experiments indicated that a pure clay-water mix would serve the best. The best results were obtained with grouts containing about 55 per cent water (by weight). The minimum distance underground through which grouts of this consistency were seen to flow was 13 feet. The maximum distance observed was 50 feet. Grouts containing about 55 per cent water were found to penetrate seams with widths as low as one-half inch.

The clay used on the Madden operation, according to Randolph: [31]

(31)Randolph, E. S., Sealing reservoir lakes with clay grouting, The Military Engineer, Vol. 28, No. 159, May-June 1936. p.209.

> ...tested out 26 per cent clay, 33 per cent silt, 41 per cent fine sand, and between three and eight per cent was retained on a Number 200 sieve. This material was difficult to break down from its natural compact form into the creamy paste needed for grouting, but once this was done it remained in suspension very well.

The injection of clay grout closely resembles methods used for cement grouting. In general, holes are drilled into the water-bearing strata or stratum. The injection pipes are wedged and caulked into place. The grout is then forced in at the required pressure until the hole refuses to take more grout. Pressure is maintained until the grout stiffens. Pressure is released, and the hole is tested for leakage with water or air. If leaks are present, the process is repeated until the strata are tightly sealed.

INJECTION

Drilling Patterns

In grouting operations, the first task is to drill the holes. The patterns used in drilling will depend on the type of opening being excavated, the type of material to be grouted, and the depth of the rock or soil below the surface. The number of holes required may vary from one to forty.

There are various patterns, one of which may fit the needs of the project. In most cases, these patterns may be used interchangeably for cement, chemical, asphalt or clay grouting with only small modifications.

Figure 6 illustrates the drill hole pattern for grouting a proposed

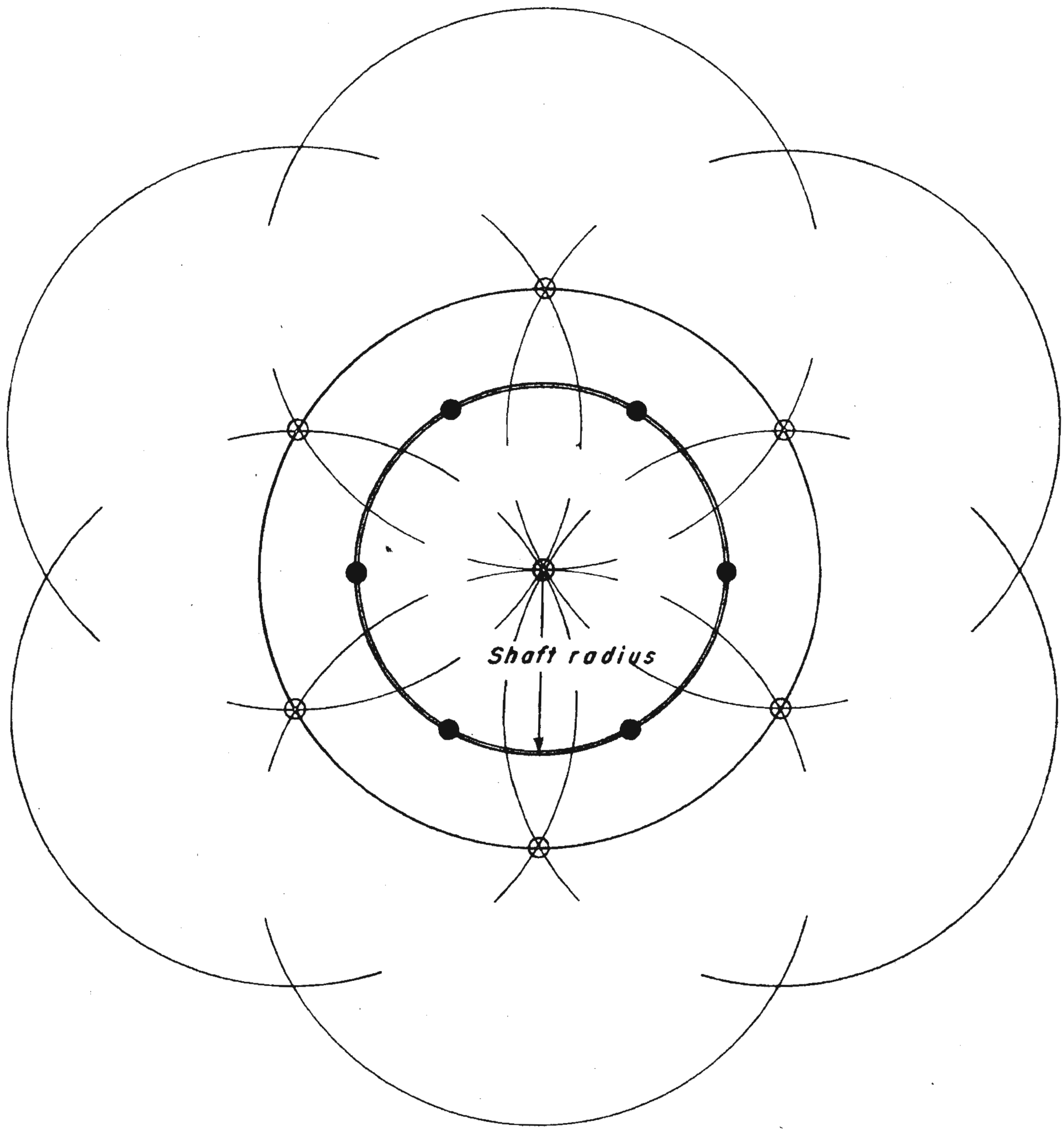


Figure 6. Diagram of drilling pattern for grouting circular shaft.

circular shaft. The broken circles indicate areas of influence for each hole. The number of holes and the spacing between each hole will be determined by the porosity and the permeability of the formation. The outer ring of holes is drilled first. If more holes must be drilled to completely stop water seepage, it is recommended that holes be drilled around the periphery of the proposed shaft. This pattern is used when grouting is completed before the sinking operations are begun. The holes are drilled to full depth. Grouting is then begun at the bottom of the hole and, with the aid of packers, each section is grouted to refusal.

A modification of this method has been used as shown in Figure 7. In this example, a single, large diameter hole is drilled from the surface to the bottom of the proposed shaft. Using packers for grouting various sections, the operation is complete in a retreating manner.

Packers, or expanding plugs, are devices which are inserted into holes for the purpose of localizing the applied pressure to certain zones within the hole. Several packers have been developed. They usually consist of a series of soft rubber collars mounted on a pipe with a device for expanding them against the hole to effect a seal.

A simple and inexpensive packer which can be made in the field is shown in Figure 8. It consists of leather cup washers and pipe fittings as illustrated in the diagram. Packers of this type are satisfactory for hard rock where the hole has been drilled true. The air-expanded packer, shown in Figure 9, is most applicable for holes drilled untrue or in soft and/or broken rock. The rubber tube around the grouting pipe is expanded by compressed air to form tightly in the hole, thereby holding the grout pipe in its proper place.

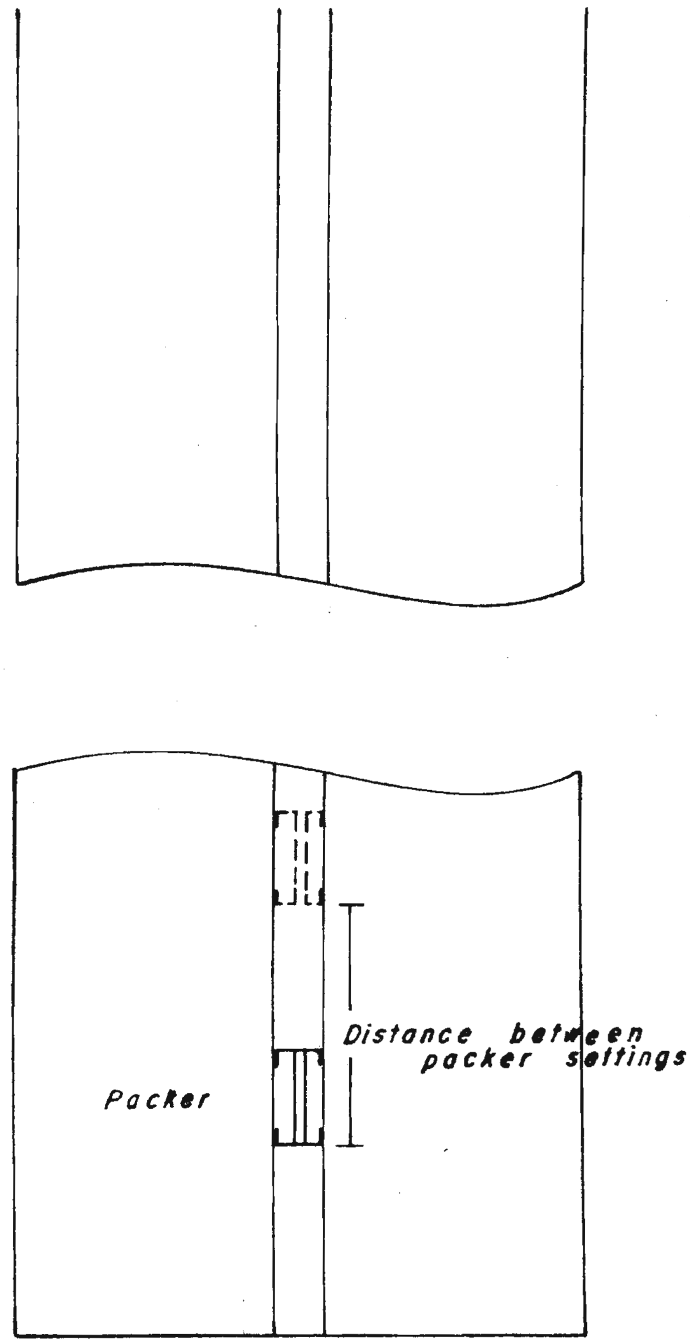


Figure 7. Diagram of single hole grouting with packers.

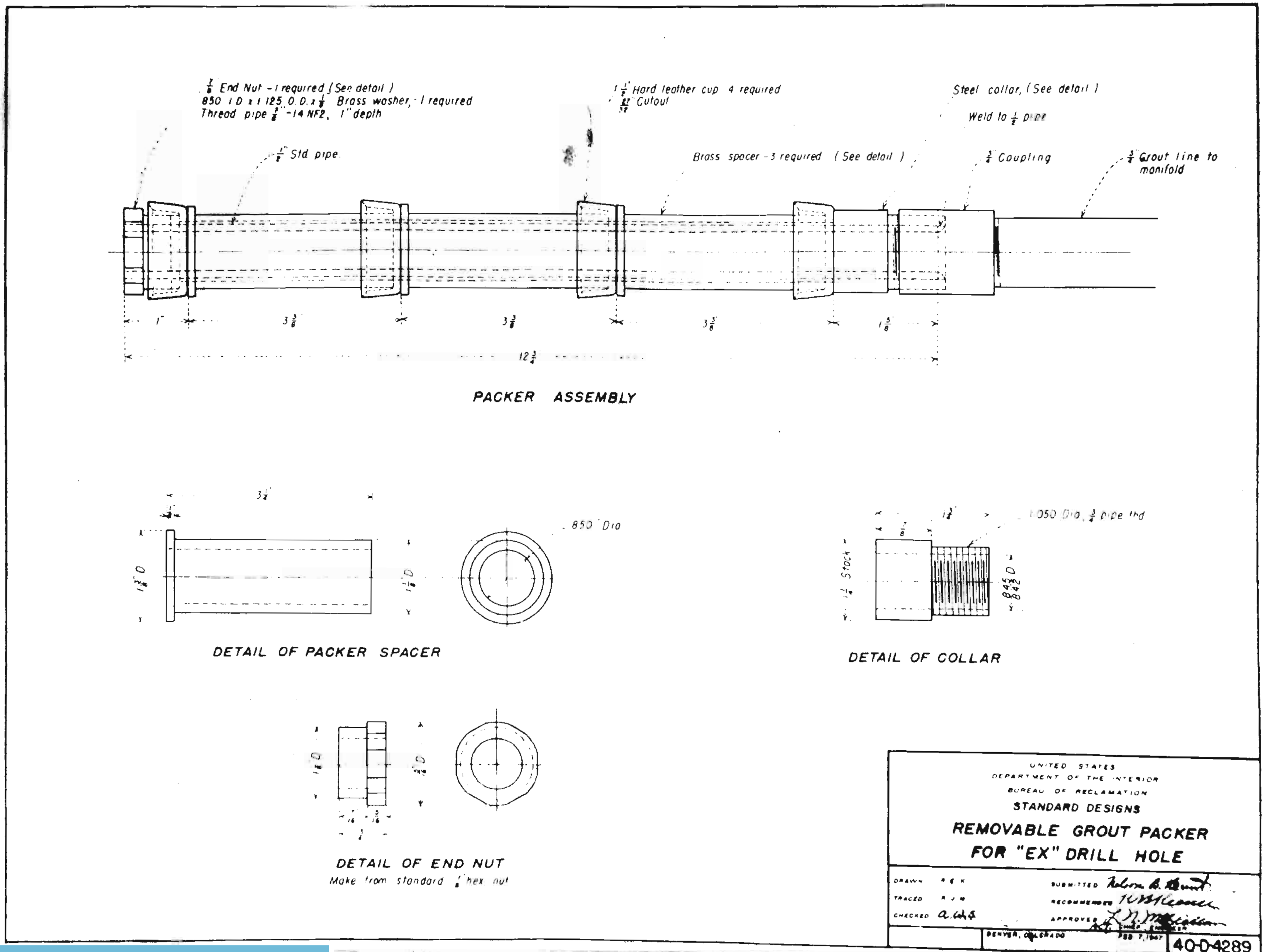
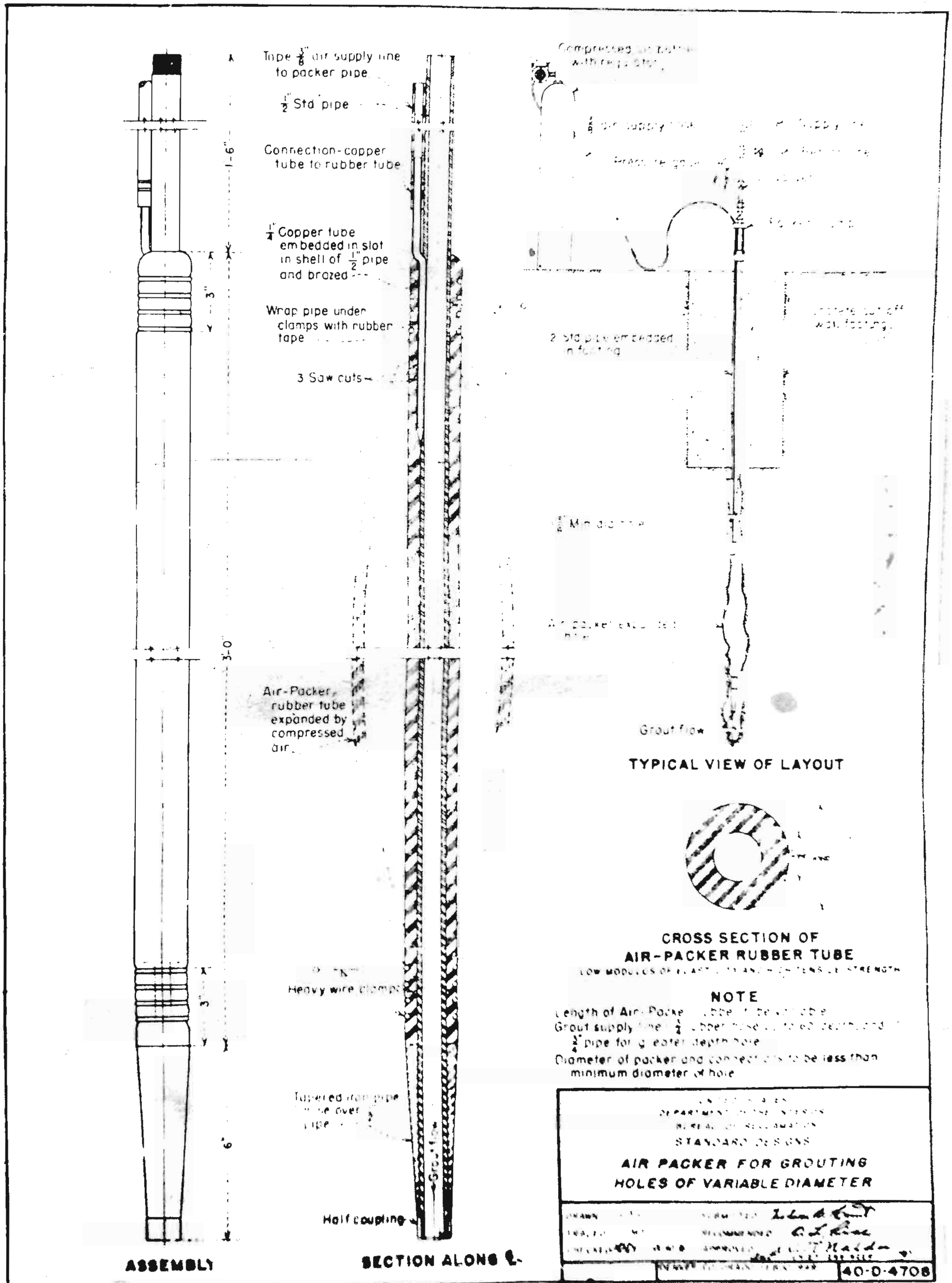

End Nut - 1 required (See detail)
.850 I.D. x 1.125 O.D. x 1/8 Brass washer, - 1 required
Thread pipe - 14 NF2, 1" depth
1/2" Std pipe
Hard leather cup 4 required
Cutout
Brass spacer - 3 required (See detail)
Steel collar, (See detail)
Weld to 1/2 pipe
3/4 Coupling
3/4 Grout line to manifold
PACKER ASSEMBLY
.850 Dia
DETAIL OF PACKER SPACER
1.050 Dia, 3/4 pipe thd
DETAIL OF COLLAR
DETAIL OF END NUT
Make from standard hex nut
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
STANDARD DESIGNS
REMOVABLE GROUT PACKER
FOR "EX" DRILL HOLE
DRAWN
TRACED
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO
40-D-4289

FIGURE 8



Tape 3/8" air supply line to packer pipe
1/2" Std pipe
Connection-copper tube to rubber tube
1/4" Copper tube embedded in slot in shell of 1/2" pipe and brazed
Wrap pipe under clamps with rubber tape
3 Saw cuts
Air-Packer, rubber tube expanded by compressed air
Heavy wire clamps
Half coupling
Grout flow
1'-6"
3"
3'-0"
6"
ASSEMBLY
SECTION ALONG ℄
Grout flow
TYPICAL VIEW OF LAYOUT
CROSS SECTION OF AIR-PACKER RUBBER TUBE
NOTE
Diameter of packer and connections to be less than minimum diameter of hole
STANDARD DESIGNS
AIR PACKER FOR GROUTING HOLES OF VARIABLE DIAMETER
40-D-4708

FIGURE 9

When a shaft is being sunk near a surface body of water, the pattern is altered slightly. Figure 10 shows this pattern. In this example, holes are closer together on the side nearest the water to prevent seepage into the excavation. A second series of holes may be drilled as indicated on Figure 6.

When a shaft is being sunk in stages, the grouting pattern most applicable is shown in Figure 11. It consists of drilling a ring of holes around the circumference of the shaft at an angle giving a radial pattern. A second ring of holes is drilled vertically downward. The horizontal displacement of the radial pattern at the bottom of the hole may be as much as ten feet. Since the water bearing strata may be characterized by vertical, inclined, and horizontal fissures, drilling in this manner makes it possible to intersect these openings. This allows the grout to enter these cavities to insure a complete grouting operation. This type pattern may be applied to the square or rectangular shafts as shown in Figure 12.

It should be noted that in the above examples, a drill hole is always placed in the center of the proposed excavation. This hole, besides being a grout hole, serves as a guide during sinking operations to help keep the shaft vertical. The areas of influence shown on the diagrams are circular when a homogeneous mass is grouted. As this area of influence for each hole will be determined by the types of material being treated, the pattern should be drilled so that the entire shaft area will be completely encircled by a curtain of grout. Various examples indicate that the area of influence may vary from a few inches up to several hundred feet. It becomes necessary to determine, by borings, the types of strata beneath the surface. The most suitable

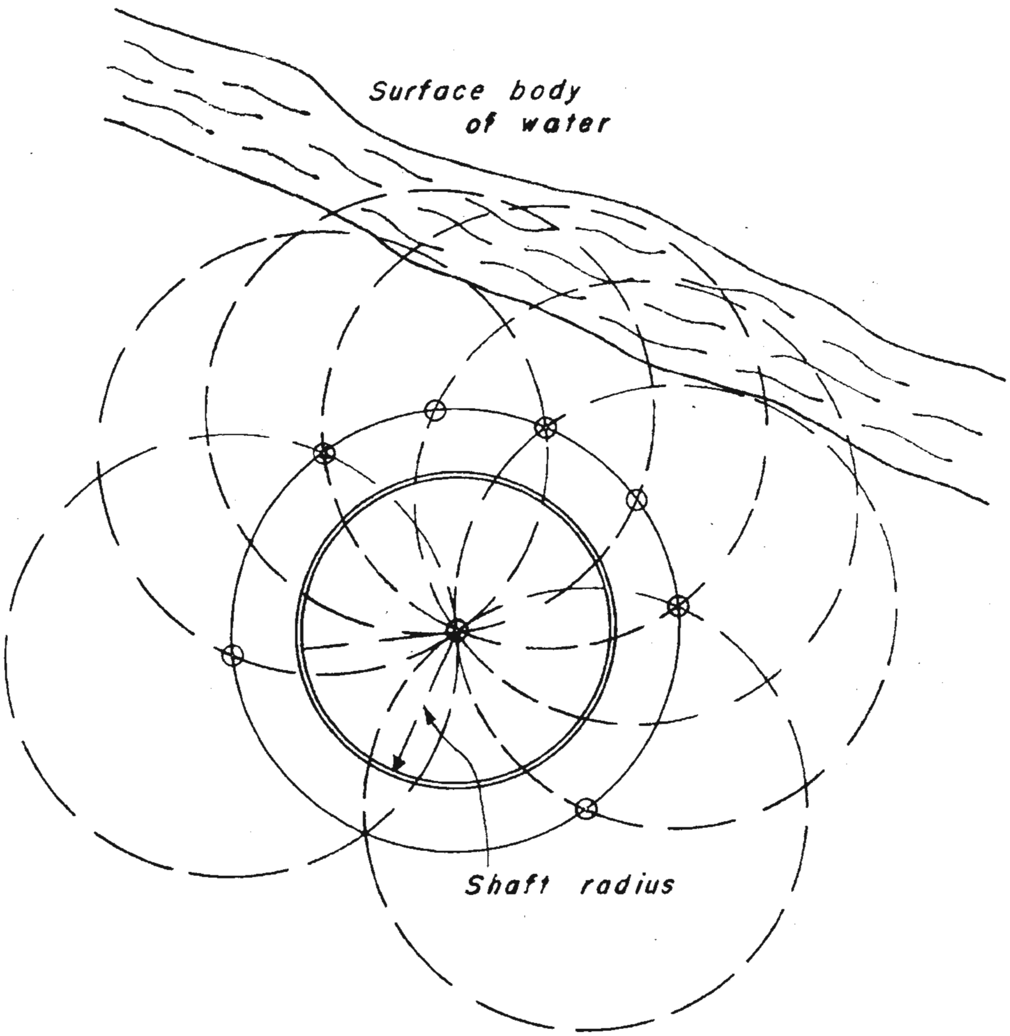
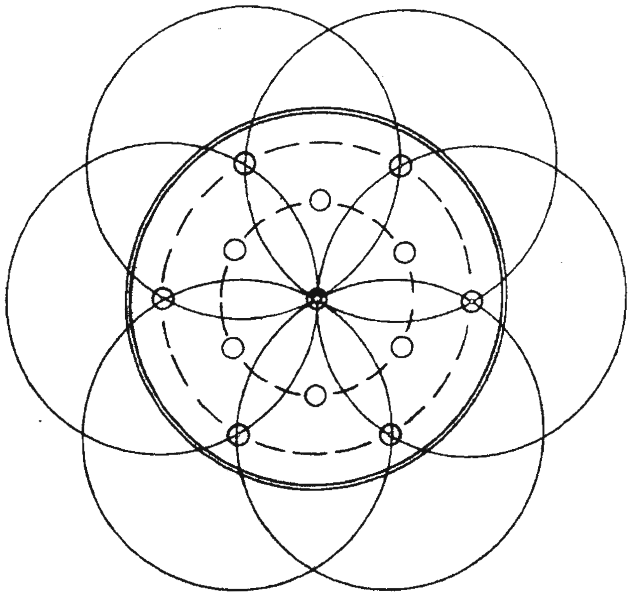
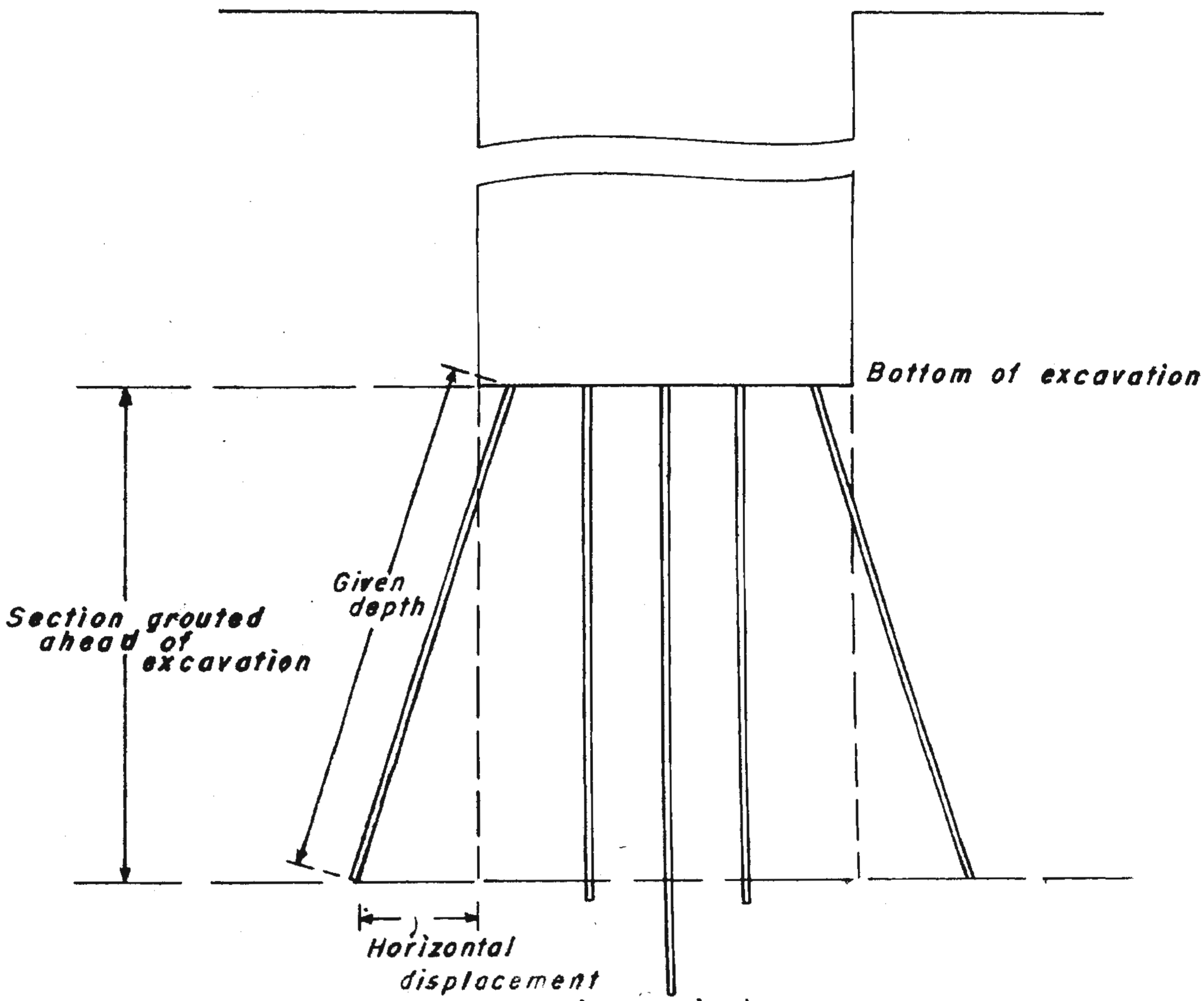


Figure 10. Drilling pattern for circular shaft near surface body of water.



(Plan)



(Elevation)

Figure 11. Drilling pattern for shaft sinking in stages.

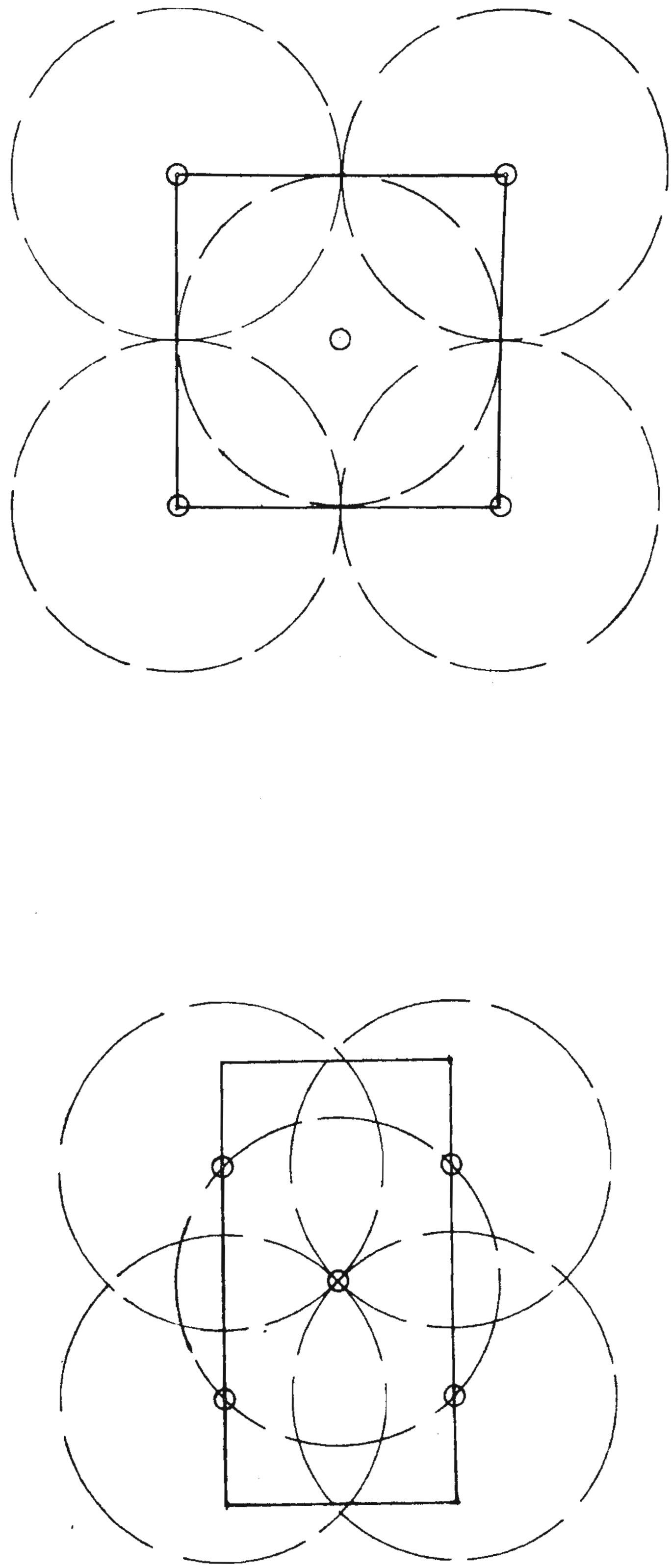


Figure 12. Drilling patterns for grouting square and rectangular shafts.

drill for this type of work generally is the core drill.

Figure 13 illustrates a method of sinking a slope through water-bearing strata. The slope is excavated in stages after each section is grouted. The shaded areas indicate the materials solidified by each hole. As already pointed out, sinking a slope is more difficult than sinking a vertical shaft in that a greater quantity of a water-bearing rock and soil must be penetrated. A thick bed of this material would delay operations considerable because it is necessary to wait after each injection for solidification before advancing. Chemical grouting offers the distinct advantage over cement in that chemicals can be made to solidify almost immediately.

In grouting behind a shaft lining, access holes must be drilled if they have not been left when the lining was placed. This is shown in Figure 14. As already stated, low pressure must be used so as not to crack or lift the liner.

Figure 15 illustrates the method of drilling for grouting a water-bearing stratum above a drift or entry. The grouting operation in openings of this type is usually carried out ahead of the excavation. When the water is found beneath the drift or entry, holes are drilled ahead at a downward angle with the floor. If water is found on the same level as the heading, horizontal holes are used for grouting ahead of the excavation. The angle indicated in this diagram is plus or minus 15 degrees and is determined by the condition found at the place of excavation, that is, when the stratum is thick, a greater angle should be used and when the stratum is thin, a lesser angle is used.

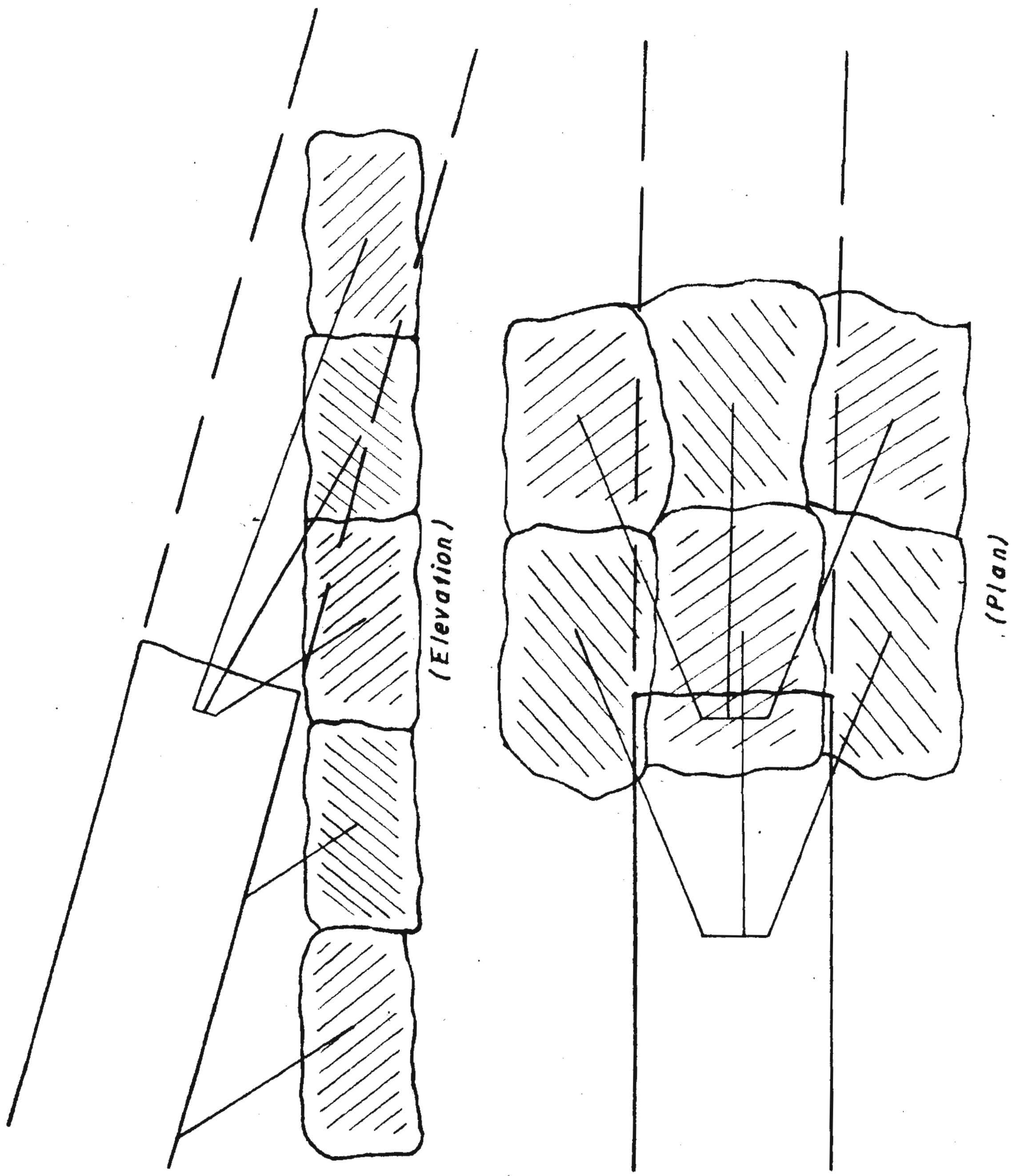


Figure 13. Diagram of grouting in slope sinking.

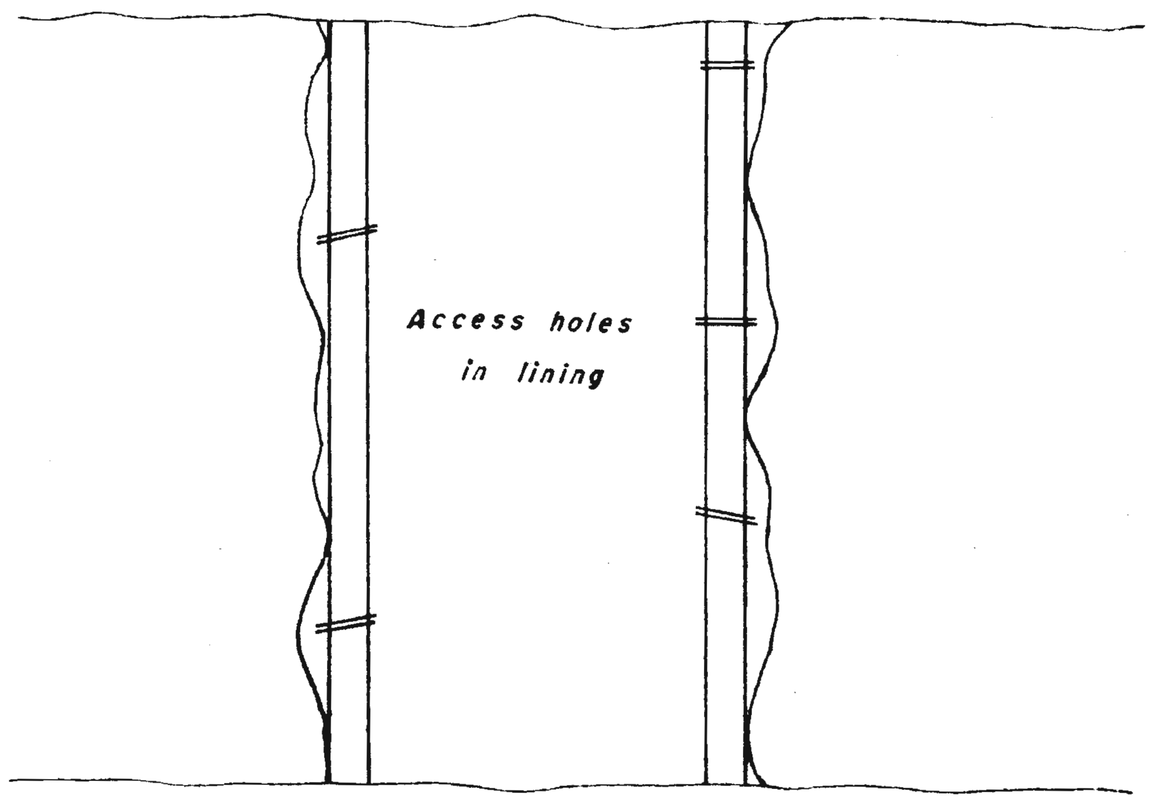


Figure 14. Grouting behind lining of a shaft.

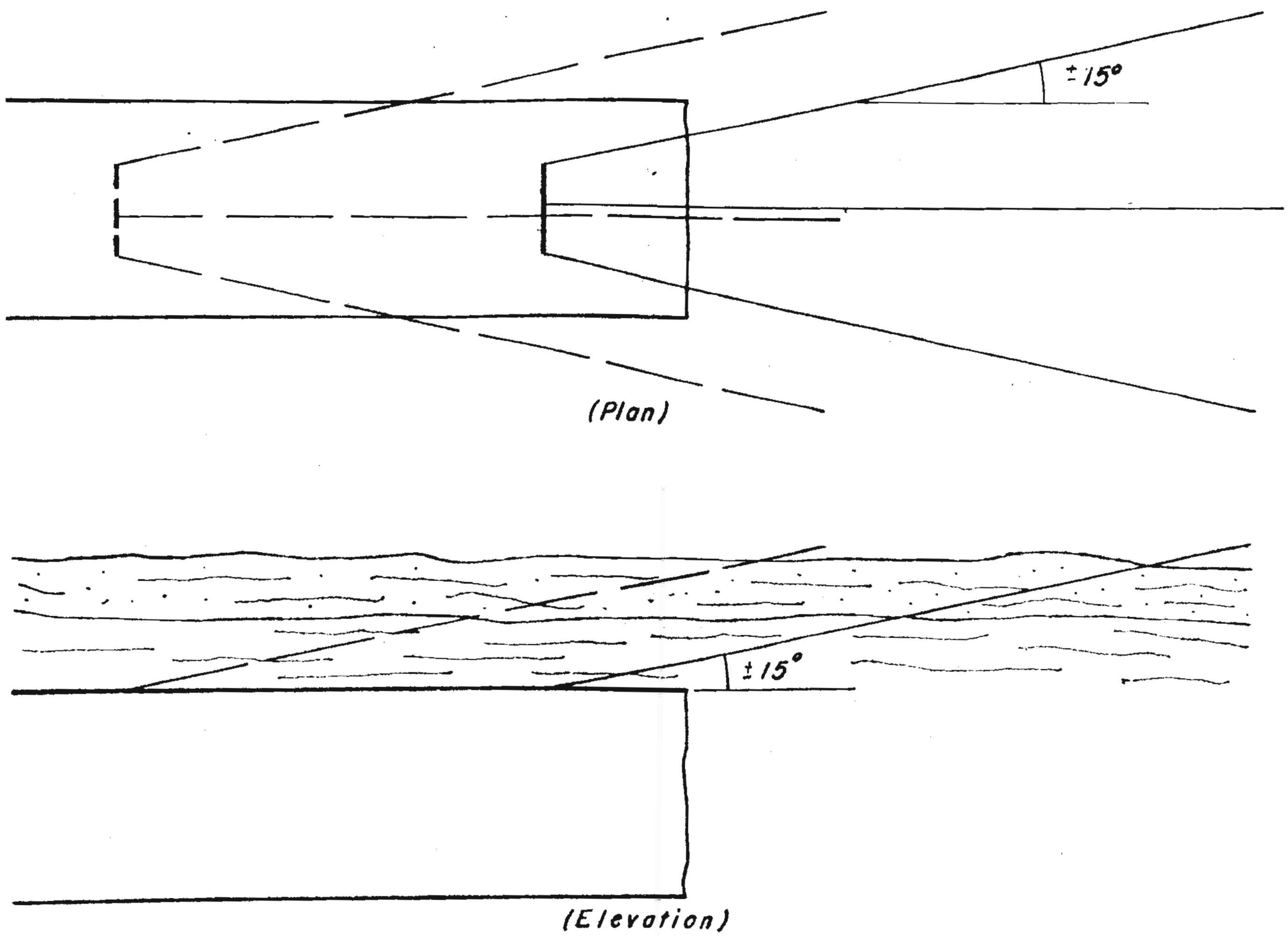


Figure 15. Drilling pattern for grouting a water-bearing stratum above a drift

Number of Holes Required

As stated previously, the spacing and number of bore holes needed for any grouting operation depends on the type or material being treated. Blandford (32) writes:

---

(32) Blandford, T., The process of cementation, The Iron and Coal Trades Review, Vol. 136, March 18, 1938. p. 477.

> The number of boreholes required to complete shaft cementation in advance of sinking varies considerably, and is controlled entirely by the nature and disposition of the fissures in the ground together with the diameter of the shaft concerned. For example, in a five foot diameter shaft, certain non-porous stratum may be efficiently treated by means of six to eight holes, whereas for the same shaft under different conditions it may be necessary to have 12 to 14 holes, and again, in porous rock it may be necessary to have 35 to 40 holes for efficient treatment in an 18 foot shaft.

Methods

Three methods are used to inject grout. These are listed as follows:

1. Retreating method
2. Advancing method
3. Entire hole method

The retreating method was discussed when considering Figures 6, 7, and 10 on pages 34, 36, and 40. The advancing method was discussed when considering Figure 11 on page 41.

When grouting large openings, the entire hole is sometimes grouted, and, in such practices, the hole is drilled to full depth and a standpipe is caulked into place. Grout is injected through the full depth of the hole to refusal. This method is not as effective as the other methods because of loss of pressure due to friction in the hole. As a consequence, the reduced pressure deeper in the hole results in lesser penetration of the grout into the surrounding rock.

PRESSURES

Amounts Required

The determination of the correct or efficient grouting pressure is a difficult problem. Ordinarily, grouting pressures vary from 30 to 500 pounds per square inch, but pressures of several thousand pounds per square inch have been used. The maximum pressure is dependent on the character of the material to be grouted. The pressure should not be great enough to lift or disturb the natural formation, but greater penetration can be obtained by increasing pressure. Thus the deeper the hole, the greater the pressure. The minimum pressure should be limited to that necessary to maintain even flow of grout and prevent plugging of holes. It should be great enough to overcome the water head against which grout must be injected. The hole should be filled in the shortest possible time. Alternate drilling and grouting permits higher ultimate pressure than one injection at the full depth of the hole.

There are no definite rules which can be used to determine the effective grouting pressures. The highest possible pressure consistent with safety should be used. Low pressures are limited to thin beds. In grouting thinner beds, high pressures will rupture and displace the stratum. High pressures can be used in thicker beds. Denholm [33]

---

[33] Denholm, E. W. Pressure grouting: Some notes on standard practice The Surveyer, Vol. 103, No. 2724, April 7, 1944. p. 165.

offers the following rule which may be used for pressure cement grouting:

> As a rough rule in normal rock, pressure in pounds per square inch is equal to $1\frac{1}{4}$ to $1\frac{1}{2}$ times the depth in feet would generally be considered safe, which in rock lying in massive layers or at depths over 100 feet, this figure could in most cases be increased by from 25 per cent to 50 per cent.

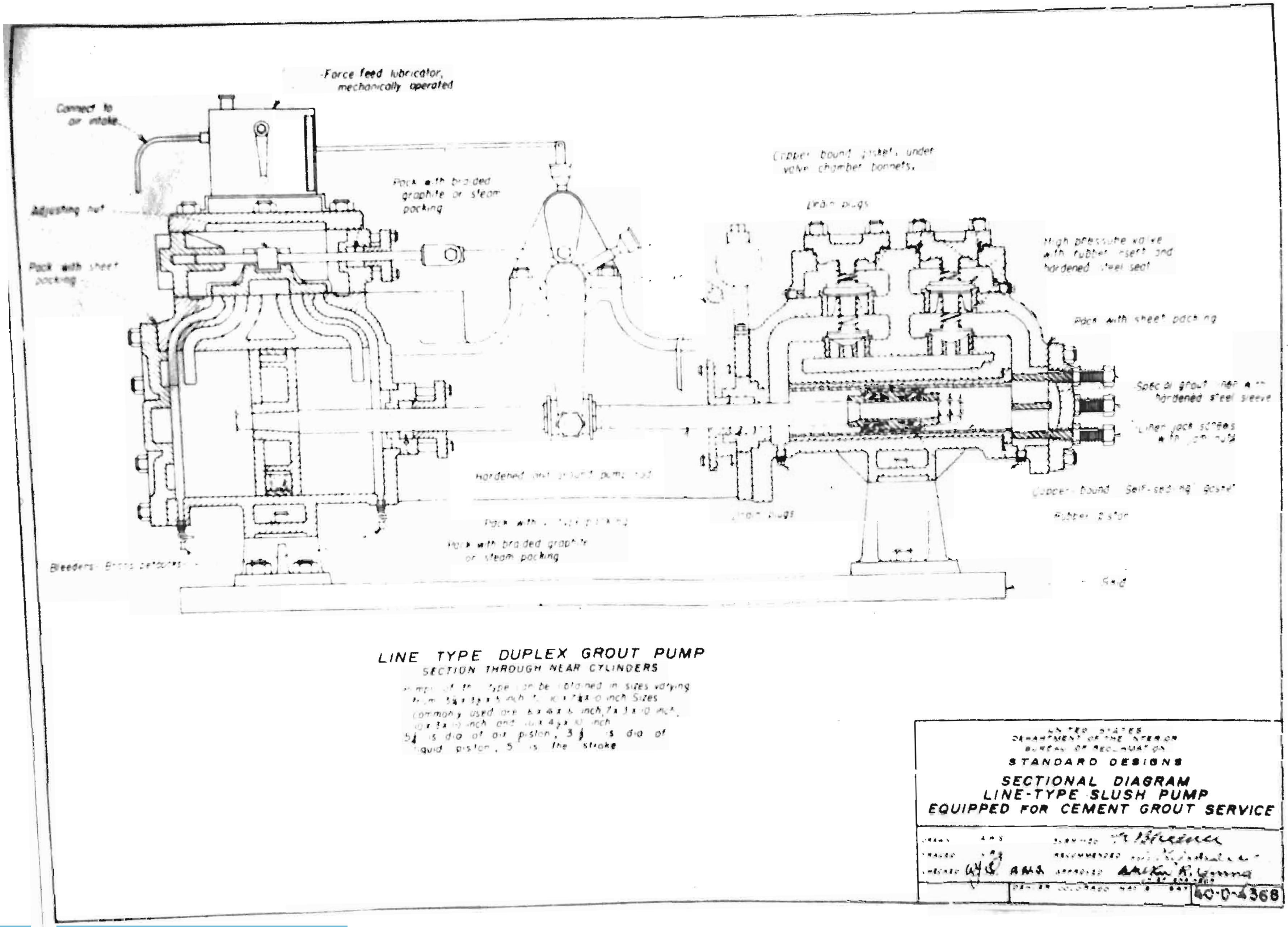
This rule, as stated, is approximate and may not always apply. It may be used if there are no other criteria for determining what pressure to use.

Pressure is an important consideration of grouting. Experience and judgement of the personnel on the job are two factors which will help make grouting a success.

Methods of Applying Pressure

The pressures used in grouting are obtained by pumps, pneumatic pressure injectors, and gravity. The most common type of pump employed in grouting is the double-acting slush pump, which is shown in Figure 16. This pump is made in a number of sizes and with capacities which vary from 20 to 100 gallons per minute and capable of pumping against pressures from 200 to 500 pounds per square inch. The driving power of these pumps may be supplied by steam, air, gasoline, or electricity. Pumps of this type are used for cement, chemical, asphalt, and clay grouting operations.

Pneumatic pressure injectors are essentially pressure chambers fitted with valves for admission of compressed air and discharge of grout. These machines are usually designed to operate against at pressures less than 100 pounds per square inch. Where greater pressures are needed, some other injector is used.



Force feed lubricator, mechanically operated
Connect to air intake
Adjusting nut
Pack with sheet packing
Pack with braided graphite or steam packing
Copper bound gaskets under valve chamber bonnets.
Drain plugs
High pressure valve with rubber insert and hardened steel seat
Pack with sheet packing
Special grout liner with hardened steel sleeve
Liner jack screws with jam nuts
Copper bound "Self-sealing" gasket
Rubber piston
Skid
Hardened and ground pump rod
Pack with braided graphite or steam packing
Drain plugs
Bleeders - Brass petcocks
LINE TYPE DUPLEX GROUT PUMP
SECTION THROUGH NEAR CYLINDERS
STANDARD DESIGNS
SECTIONAL DIAGRAM
LINE-TYPE SLUSH PUMP
EQUIPPED FOR CEMENT GROUT SERVICE
40-D-4368

FIGURE 16

Gravity is sometimes used to inject grout, particularly a cement grout. This type of injection relies on the weight of a column of grout to apply pressure to the grout. Table 3 shows the weight of a column of cement grout one inch square and one foot high. From this table the effective head can be computed.

Pumps are the most common means of applying pressure on grouts. Lewis (35) says:

---

(35) Lewis, J. S., Jr., op. cit. p. 701.

> The value of a pump for handling grout, as compared with compressed air chamber, is great. The pumps affords additional mixing of the fluid and makes possible a flexibility of control and continnity of flow that is not obtainable with the pneumatic machine. However, the pneumatic machine is superior for handling grout containing sand or sawdust or other coarse materials which are sometimes injected into large openings.

Hayes (36) says:

---

(36) Hayes, J. B. op. cit. p. 311.

> Unless extreme care is used, the air-pressure method is apt to force air into the seams if the grout flows faster than expected. Moreover, in some types of air-injection tanks the cement in a thin mix will settle to the bottom and plug the outlet, the pipe line, or the hole, before the job is really complete.

OTHER EQUIPMENT USED IN GROUTING

Cement Grouting Equipment

Pressure cement grouting is used on large jobs taking many thousand of sacks of cement or on small jobs using only a few sacks. In the above example, the equipment required would be quite different. The following list would be used on both large and small jobs:

TABLE 3 [34]

UNIT WEIGHT OF VARIOUS MIXES

WATER-CEMENT RATIO (By Volume)	UNIT WEIGHT (In Pounds)
0.75	0.798
1.00	0.736
1.25	0.692
1.50	0.660
1.75	0.634
2.00	0.614
2.25	0.598
2.50	0.584
2.75	0.572
3.00	0.562

---

(34) Minear, V. L., Use and Technique of Pressure Grouting in the Construction Industry, Symposium on Grouting, A. I. M. E. Technical Publication No. 3427, 1948. p. 4.

1. Water meter
2. Agitator sump
3. Air supply
4. Water supply
5. Pressure gages
6. Conduits or pipe and fittings
7. Valves
8. Hose

The consistancy of the grout used on any grouting job is very important. By use of a water meter, close control can be obtained in mixing the grout. A water meter that has proved highly satisfactory is a 1 to 1½ inch single disc type threaded for a pipe connection. This type has a six inch vertical register with two hands, a long hand which makes one revolution per cubic foot and a short hand which indicates 10 cubic feet per revolution. If sand and rock particles are present, it is necessary to provide some filtering device to remove them before they enter the meter. A water meter reading may be converted using Table 4.

After the grout has been mixed, it should be agitated continuously to prevent settlement while it is being pumped. This is accomplished with the use of an agitator similar to that shown in Figure 17. For smaller jobs, a simple arrangement of a barrel and a sump pump can be used to provide this agitation. The sump pump is connected in a closed circuit with the barrel. The grout is kept agitated by operating the pump. In any case, the agitator should have a capacity at least as large as the mixer.

An adequate air supply is necessary to complete a successful

TABLE 4 [37]

WATER-CEMENT RATIOS OF VOLUMETRIC
GROUT MIXES

WATER-CEMENT RATIO (WEIGHT)	Gallons of water per sack of cement	Cubic feet of water per sack of cement
0.27	3.0	
0.33		0.5
0.36	4.0	
0.44	5.0	
0.45		0.67
0.49	5.5	
0.50		0.75
0.51	5.75	
0.53	6.0	
0.62	7.0	
0.66		1.00
0.71	8.0	
0.83		1.25
0.89	10.0	
0.99		1.50
1.11	12.5	
1.16		1.75
1.32		2.00
1.33	15.0	
1.66		2.50
1.78	20.0	
1.99		3.00
2.22	25.0	
2.65		4.00
2.66	30.0	
3.32		5.00
3.55	40.00	
3.98		6.00
4.44	50.00	
4.65		7.00
6.64		10.00
13.28		20.00

(37) U. S. Bureau of Reclamation, Technical Memorandum 638, "Pressure Grouting Equipment", by A. W. Simonds. Page 38.

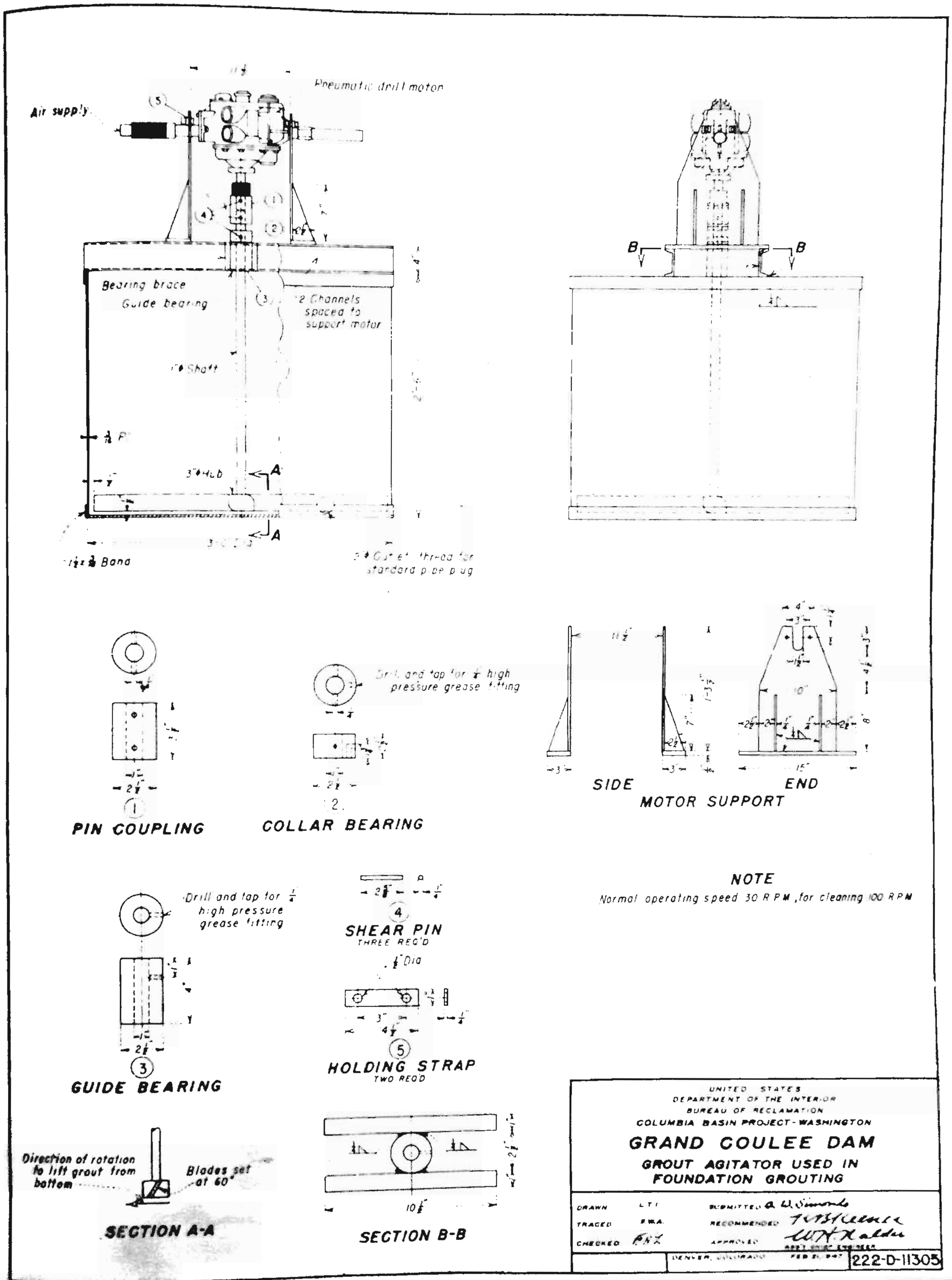

Pneumatic drill motor
Air supply
Bearing brace
Guide bearing
2 Channels spaced to support motor
1" Shaft
3" Hub
Band
Cut 6" thread for standard pipe plug
PIN COUPLING
Drill and tap for ¼" high pressure grease fitting
COLLAR BEARING
SIDE
END
MOTOR SUPPORT
NOTE
Normal operating speed 30 R.P.M., for cleaning 100 R.P.M.
Drill and tap for ¼" high pressure grease fitting
GUIDE BEARING
SHEAR PIN
THREE REQ'D
HOLDING STRAP
TWO REQ'D
Direction of rotation to lift grout from bottom
Blades set at 60°
SECTION A-A
SECTION B-B
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT - WASHINGTON
GRAND COULEE DAM
GROUT AGITATOR USED IN
FOUNDATION GROUTING
DRAWN
TRACED
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO
222-D-11305

FIGURE 17

grouting operation. The actual requirement will depend on the type equipment to be used. The following quantities of air at 100 pounds per square inch should be considered as maxima for ordinary grouting when air-driven equipment is used: (38)

---

(38) Simonds, A. W., Pressure grouting equipment, U. S. Bureau of Reclamation Technical Memorandum 638, p. 14.

---

1. One 6 x $2\frac{1}{2}$ x 6 inch pump, one 7 cubic foot mixer, one 7 cubic foot agitator will require 200 cubic feet of air per minute.

2. One 10 x 3 x 10 inch pump, one 17 cubic foot mixer, one 17 cubic foot agitator will require 300 cubic feet of air per minute for an average hole. For a fast hole at low pressure, the consumption may reach 600 to 800 cubic feet of air per minute.

3. One 10 x 3 x 10 inch pump, one 27 cubic foot mixer, one 27 cubic foot agitator will require 300 cubic feet per minute for an average hole. A fast hole at low pressure may require 800 to 1000 cubic feet per minute.

An adequate water supply is necessary in all grouting operations. If the water contains trash or sand, some filtering device should be installed. Large amounts of these materials have a harmful affect on the strength properties of the cement after hardening.

Reliable pressure gages are essential in pressure grouting. A pressure gage is the best indicator to the case of penetration of the grout and the stresses which may be set up in the structure being grouted.

For ordinary grouting, 1 to $1\frac{1}{2}$ inch pipe and fitting are satisfactory. Grout can be pumped long distances through supply lines of this size. Larger sizes than $1\frac{1}{2}$ inch pipe allow more grout to be pumped but this advantage is offset by additional cost. Larger sizes of pipe are also proportionally harder to handle.

Brass globe valves should be used for pump throttles. All other valves should be quick-acting, lubricated plug valves. These valves are made in different weights. They are designed to withstand the different pressures at which they might be used.

The pump suction hose should be between 2½ and 4 inches in diameter and about five feet long. When grouting through a hose care should be taken not to exceed the safe working pressure. A hose may be reinforced somewhat by wrapping with telephone wire.

Chemical Grouting Equipment

The equipment used in the chemical grouting processes is dependent on the method employed. Schematically, Figure 18 illustrates the equipment used in the Joosten process. The pumps used in these processes are the same as those used in cement grouting. The Joosten, Jorgensen, and Francois processes require two mixing tanks, since the chemicals are injected separately. The K. L. M. process requires only one tank because the chemicals are mixed and injected at the same time. Barrels of 50 gallons capacity have been used as mixing tanks. The valves and holes used are the same as the type used in cement grouting. The injection pipe, often referred to as a needle, is between 15 and 30 feet long and made of strong one inch steel pipe. The lower 20 to 24 inches of the injection pipe is perforated with 0.08 inch holes. When chemicals are being used to treat loose, unconsolidated material, a steel point is attached to the end of the injection pipe to facilitate driving. The steel point is not used on the grout pipe when solidifying cracks and cavities in solid material.

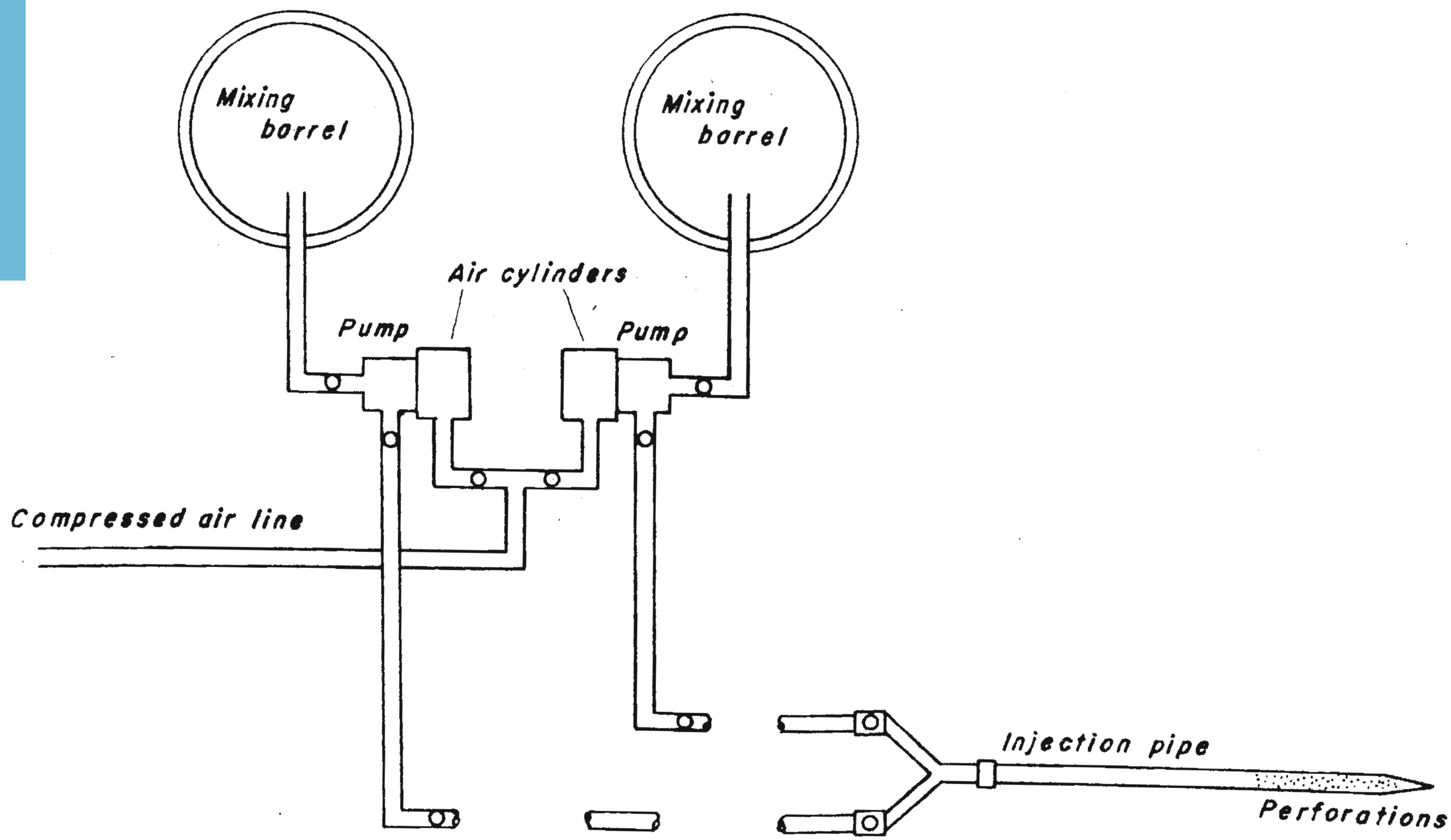


Figure 18 Schematic Diagram of Equipment Used in Joosten Process
(After Jorgensen)

Asphalt Grouting Equipment

The equipment required in the Christians process is relatively simple and inexpensive. Christians [39] says:

---

[39] Christians, G. W., op. cit. p. 801.

> A heating kettle for melting the asphalt, and a small adjustable-stroke piston pump driven by a one horsepower motor are all that is required for handling the asphalt to the pipe line. The pipe is usually $1\frac{1}{2}$ inch, extra heavy throughout the upper portion, while that in the crevice bearing rock is $1\frac{1}{2}$ inch standard-weight pipe perforated by 3/4 inch holes. It is heated by an iron resistance wire which enters through an insulated stuffing bar at the top and is held in the center of the pipe by suitable insulators at the pipe couplings and fastened electrically and mechanically to the pipe at the bottom. The electric circuit passes down the wire and back up the pipe. The wire is kept taut by tension springs at the bottom.

The steam-heating system equipment is much the same as that in the above process. The difference is in the heating method. In the Shellperm process, equipment similar to that employed for chemical grouting processes is used to place the asphalt-in-water emulsion.

Clay Grouting Equipment

The equipment used in reservoir grouting is determined by the scope of the project. The colloidal suspension must be pumped through a pipe line to the area to be grouted and discharged to the bottom of the reservoir. The pipe line used on the Chenery Reservoir [40] was

---

[40] Lee, C. H. Sealing Chenery Reservoir, Western Construction News, Vol. 5, December 15, 1930. p. 624.

---

four inches in diameter. In some instances when only a small area is to be treated, the clay is carried by boat to the area to be sealed and dumped into the water.

According to Randolph,[41] the equipment used on Madden Dam project

[41] Randolph, E. S., op. cit. p. 210-212.

consisted of:

1. Mixer
2. Screen
3. Pump
4. Air Compressor
5. Water Supply
6. Connections and fittings

The mixer used was built especially for this operation. It consisted of a stirring and chopping loops rotating in opposite directions to mix and stir the grout. This was done until the clay grout reached a uniform consistancy. The capacity was two cubic yards.

After mixing, the grout was discharged onto a ½ inch screen to remove the lumps which might be present. These lumps were saved and remixed with the next batch.

Three types of injectors were used on this operation. A compressed air chamber was used for low pressure grouting. This was operated at 100 pounds per square inch. Pressure up to 150 pounds per square inch was obtained with the use of an ordinary slush pump. For higher pressures up to 300 pounds per square inch, a specially designed, single-acting ram pump was used. This pump had a capacity of 1½ cubic yard per hour.

The compressor was a portable plant furnishing air at 100 pounds per square inch. It had a capacity of 220 cubic feet per minute. The water supply was obtained from a nearby stream. It was used both for mixing the grout and general washing and cleaning purposes.

The injection pipes were the same as in pressure cement grouting. The manifold hook-up was like that shown in Figure 4.

SPECIAL GROUTING METHODS

Carbon Dioxide Pressure Method

The Bureau of Mines used a new approach to pressure cement grouting by utilizing carbon dioxide gas under pressure to inject grout.[42]

---

(42) Tainter, S. L., Grouting diamond drill holes at the Christman mine, Gila county, Arizona, U. S. Bureau of Mines Reports of Investigations 4559.

Figure 19 illustrates the equipment used.

A thin mixture of cement was poured into the hole to be grouted. A mixture of drilling mud, weighing nine pounds per gallon, was poured on top of the cement. The carbon dioxide cylinder was connected to the standpipe as shown in Figure 19. Pressure was gradually applied. After the pressure reached a maximum, the valve was closed. The pressure gradually reduced to about 100 pounds. At this point, the remaining gas was bled off. The hole was immediately refilled with drilling mud. The pressure was applied. This pressure was equal to the maximum from the first run plus 20 pounds per square inch. This pressure was maintained until the cement hardened.

Bentonite-Petroleum Grouting Method

Investigation has pointed out that bentonite mixed with gasoline and other petroleum products does not swell. When a mixture of this type comes in contact with water the water displaces the petroleum and the bentonite begins to swell. The Bureau of Reclamation investigated

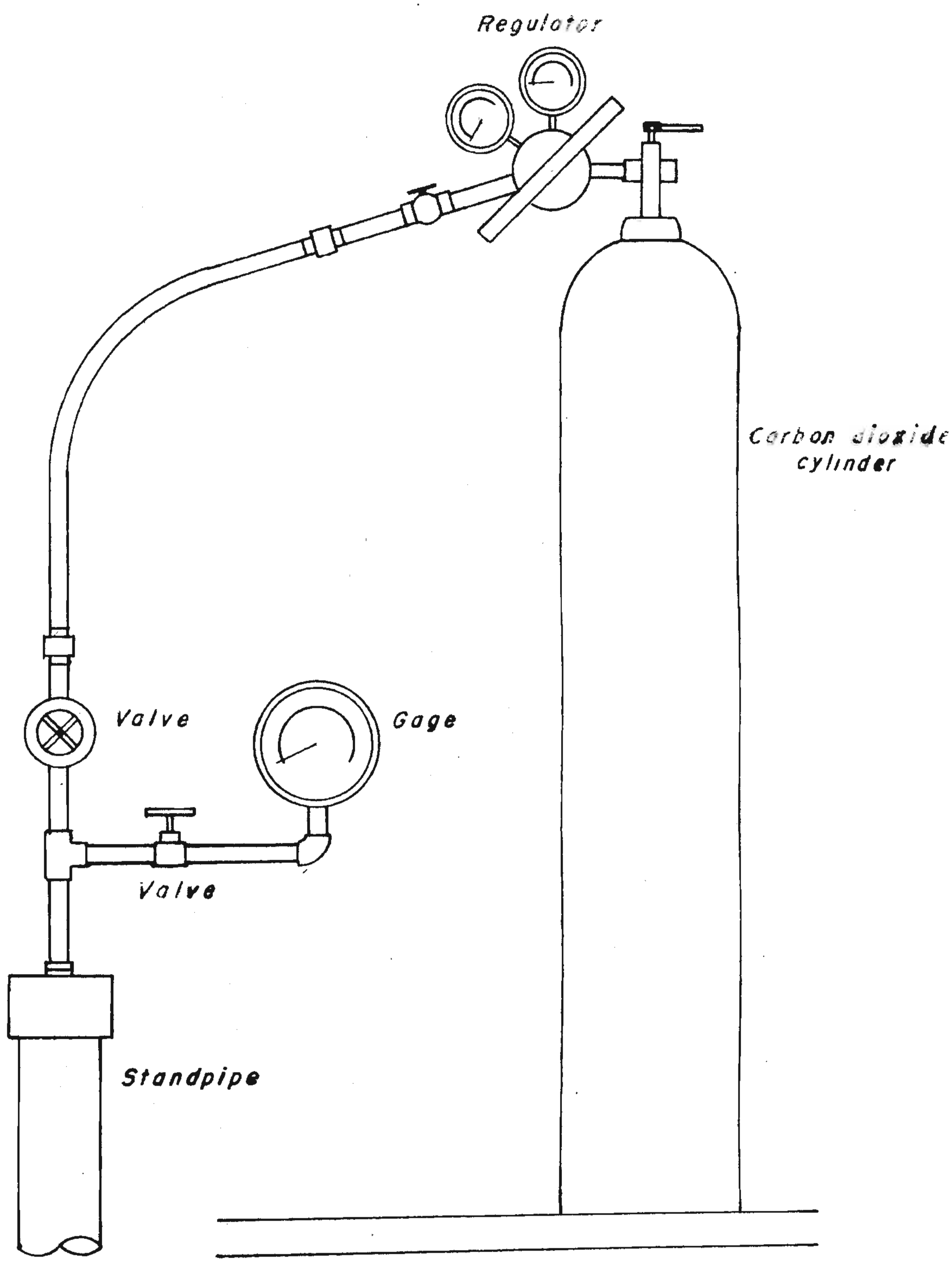


Figure 19. Carbon dioxide pressure equipment.

(After U. S. Bureau of Mines)

this subject and reported the following findings: (43)

---

(43) Grouting with bentonite mixed in products of petroleum, U. S. Bureau of Reclamations Laboratory Report No. C-229, January 27, 1944. p. 4.

---

1. A grout can be made from bentonite and any one of a number of petroleum oils. This grout will not swell until it comes in contact with water. Upon contact with water, the water displaces the oil and swelling takes place. The rate of swelling depends upon the thickness or viscosity of the oil.

2. The flow of underground water in certain porous formations can be sealed by proper application of bentonite-oil grout. Whether the use of bentonite-oil grout would be applicable to any given grouting problem in the field may only be ascertained by actual trial.

3. Bentonite-oil grout will not penetrate water-bearing sand for any appreciable distance. Twelve inches was the maximum depth obtained in laboratory test.

4. Oil in bentonite-oil grout attacks rubber sealings, pistons and other parts in a grout pump and will render such parts useless with prolonged usage.

5. The bentonite-oil grout should be placed as rapidly as possible so that the grout will be forced into the cavities before the oil is washed away from the bentonite. The equipment should be of sufficient capacity for rapid injection.

Table 5 summarizes the test conducted by the Bureau of Reclamation and it should be noted that oil-bentonite grout was effective on aggregate of plus 3/8 of an inch. The penetration of the grout in sand was ineffective. The void spaces in this material were too small and filtered the bentonite.

The proper proportions of oil to bentonite will depend upon the grouting conditions. It was found that the ratio of oil to bentonite could be as low as 0.60 to 1.0 by volume before the grout became too

TABLE 5 (44)

PETROLEUM-BENTONITE GROUT TESTS

Test Run Number	Size of Aggregate	Oil Used	Mix Oil to Bentonite	Grouting Method	Grouting Pressure (pounds)	Head of H_2O in Feet	Results
1	3/8"-3/4"	Fuel Oil	1 : 1	pump	20	115	Bentonite fails to stop flow of water.
2	3/8"-3/4"	Kerosene	1 : 1	pump	20	115	Flow of water was not stopped
3	#4-3/8"	Fuel Oil	1 : 1	pump	20	7	Flow was almost completely stopped
4	3/8"-3/4"	Kerosene	1 : 1	pump	20	7	Flow completely stopped
5	#16-#4	Fuel Oil	1.5 : 1	pump	30	7	Grout did not penetrate sand approximate penetration 8 inches
6	3/4"-1½"	Kerosene	0.7 : 1	Pressure tank	20	7	Bentonite stopped flow
7	#16-#4	No. 10 oil	0.8 : 1	Pressure tank	30	7	Did not stop flow Penetration approximately 12 inches

(44) Adapted from U. S. Bureau of Reclamation Laboratory Report No. C-229. p. 5.

thick to pump. Swelling begins immediately in the case of gasoline and fuel oil and is proportionally slower as the oils become thicker. This would indicate that gasoline or kerosene would be better in large open formations and the heavier oils would be better in tighter formations and where it was desired to pump the grout for some distance through water.

SUMMARY

Cement grout is the most widely used material in grouting. This grout is applicable to fissured or faulted rock or solid strata where void spaces are large enough to permit the cement particals to enter. Cement grouted soils and structures offer high strength after hardening. This type of grout is not as applicable as asphalt is in flowing water. Considerable cement grout is washed away before the voids can be plugged.

Chemical grouting is most applicable in loose unconsolidated soils with a permeability of not more than 0.1 or less than 0.0001 centimeters per second. The soil to be solidified by this method should not contain more than 20 per cent clay.

Asphalt grouts are applicable to large openings especially where water is flowing at a high velocity. The smallest opening which can be sealed effectively is ½ inch. The most suitable grout stiffens rather than hardens to brittleness.

Clay grouting is used where a material is needed to fill seams in which water is not flowing. Clay offers little resistance to erosion by water. It has been used in place of other materials, when clay was close at hand and thus considerably cheaper to place.

FREEZING

Introduction

The freezing method is essentially a process used to solidify water-bearing soils and rock by solidifying the water contained in these materials. The greatest use of freezing is in hardening water-bearing materials to permit the sinking of shafts. This method has been used also for stabilizing landslide areas and loose earth around excavations. The use of freezing in the construction industry has been small, but its use appears to be increasing.

The freezing method has been used infrequently in the United States, but has been widely used in England and on the Continent of Europe. Recently, freezing was used in England to penetrate heavy flows of water overlying coal formations. Using this method, previously inaccessible coal has been developed into minable coal. (45)

---

(45)Refrigeration permits mine shaft sinking, Refrigerating Engineering, April 1949. p. 335.

In writing about the Gilbertsville Dam of the Tennessee Valley Authority, Gough (46) states:

---

(46)Gough, H. B. A wet shaft frozen tight, Engineering News-Record Vol. 122, No. 19, May 11, 1939. p. 74.

> Seepage troubles, considered impossible to meet by other methods that permitted the purposes of the shaft to be served, were completely overcome by freezing.

The freezing method generally, consists of drilling holes through the material to be frozen. Into each hole are lowered two concentric pipes. The internal pipe carries the cooled liquid down to the bottom of the hole. The liquid is discharged into the larger pipe and is returned to the surface through the annular space between the pipes. By cooling the circulating liquid, heat is removed from the ground around the freezing pipe. The circulating liquid is cooled by a commercial refrigerating plant. The depths which have been frozen vary from 30 to over 2000 feet. The process becomes uneconomical if used to greater depths, because of the excessive cost and the long period of time required to freeze rock and soil.

Freezing Methods

Ackerman and Locher [47] in writing about the freezing method, as it was described in The Engineer, London, May 19, 1939, write:

> Two processes are now available for freezing ground. The Poetsch process and the Dehottay process. In the former, ammonia is generally used as the refrigerating fluid; this is confined to the primary circuit and is used to lower the temperature of a calcium chloride brine which circulates continuously through a refrigerating chamber and thence through pipes installed in four holes sunk at about 3 ft. intervals into the strata to be frozen. Although this process has long been used, it has several weak points. It is slow and consequently expensive; also the power consumption is high. Should a freezing pipe break and brine escape from it, a body of ground will be formed which it will be impossible to freeze, and to remedy this condition will be difficult. The more recently introduced Dehottay process claims to have overcome certain of these troubles. In it carbon dioxide is used as the refrigerating fluid, the brine circuit is done away with, and the carbon dioxide itself circulates through the freezing tubes in the four holes. In this way the power required for the circulation of the brine is saved, the exchange of heat between the ammonia circuit and brine circuit is eliminated, and dangers due to leakage of brine are avoided, escape of CO_2 having no ill effects on the ground.

---

[47] Ackerman, A. J. and Locher, C. J., Construction planning and plant. First Edition, McGraw-Hill, 1940. p. 220.

Equipment Used

The equipment necessary to freeze strata are listed as follows:

1. Refrigeration unit.
2. Refrigerant.
3. Freezing tubes.

Refrigeration Unit

Biquet, (48) writes:

---

(48) Biquet, M., Freezing process enables lessees to sink shafts in deep marsh land of North Belgium, Coal Age, Vol. 25, No. 23, June 5, 1924, p. 832.

> The refrigerating machines most commonly used are those that are based on the evaporation of a liquefiable gas, such as ammonia, carbon anhydride, sulphuric anhydride, or a methyl chloride, ammonia, and carbon dioxide being those most generally used.

The gases are compressed and liquified in the condenser. The heat of compression is removed by a continuous stream of water running over the condenser coils. The liquified gases are passed through the freezing coils and the refrigerant is circulated over these coils. The liquified gases are allowed to vaporize in the vacuum maintained by the gas compressor. As these liquified gases evaporate, they absorb heat from the refrigerant thus cooling the refrigerant to the required degree. The refrigerant absorbs the heat from the underground strata. These strata are gradually cooled until they reach the low temperature of the refrigerant.

The refrigerating plant may consist of a number of components to give it the desired capacity. As an example of a refrigerating unit with a given capacity, Skerret (49) writes:

(49)Skerret, R. G., How Antwerp is building two tunnels under the Scheldt, Compressed Air Magazine, Vol. 37, November 1932, p. 3965.

> The refrigerating plant for the western ventilating shaft consisted of two ammonia compressors, eight evaporators, one condenser, two brine pumps, and two circulating pumps. Its capacity was equivalent to 90 tons of ice per hour at a temperature of 4 deg. below zero Fahrenheit.

Refrigerant

The refrigerant, or brine, most commonly used is a 25 per cent solution of calcium chloride which solution freezes at approximately 30 degrees F. below zero. Magnesium chloride is sometimes used instead of calcium chloride, because it precipitates less at low temperature and, therefore, does not clog the circulating pipes. One of the prime requisites of the refrigerant is that it does not freeze at the low temperatures produced by the refrigeration unit.

The Dehottay process, as already indicated, combines the refrigerant and the refrigerating unit by circulating carbon dioxide through the freezing pipes. This eliminates the brine circuit and reduces the amount of equipment needed and the power consumption of the refrigeration unit.

Freezing Tubes

The freezing tubes are made up of two concentric pipes. The outer pipe is closed at the bottom. The inner pipe is open at the lower end which is about 8 inches above the closed end of the outer pipe. The diameters of the two pipes vary with different operations. The diameter of the outer pipe varies from two to eight inches. The smaller pipe is one inch or more in diameter. Figure 20 illustrates this arrangement in schematic diagram.

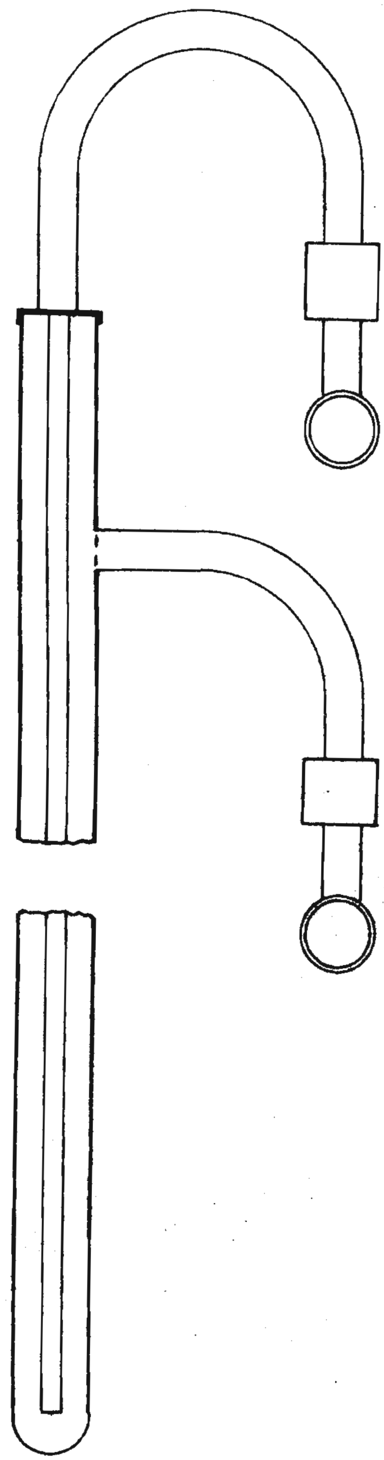


Figure 20. Schematic diagram of freezing tube.

The ratio of diameters of the pipes that make up the freezing tubes must be such that the circulating liquid flows down the center pipe rapidly and up through the annular space more slowly. There is no exact rule for determining the rate of flow in these pipes. The velocity down the smaller pipe is two or more feet per second. The return flow is usually between 0.9 and 1.5 feet per second. Gough (50)

---

(50) Gough, H. B., op. cit. p. 76.

---

writes:

> Another improvement would be to change the dimensions of the vertical freezing pipe assemblies themselves, substituting a smaller diameter pipe for the 1 in. intake and a larger diameter for the 2 in. outlet casing. This rearrangement would cause the incoming cold brine to travel with greater velocity and reach the bottom of the freezing pipe more quickly, with a consequent reduction in heat transfer from the warmer outgoing brine to the incoming brine through the pipe. Thus the incoming brine would be colder when it reached the bottom, and its effectiveness at the lower levels increased.

It may be found that using whatever pipes are available may save time and money. In discussing the construction of the Grand Coulee Dam, Froage (51) writes:

---

(51) Froage, L. V., Frozen earth dam at Grand Coulee, Mechanical Engineering, Vol. 63, No. 1, January 1941. p. 10.

> Pipe sizes of $1\frac{1}{2}$ and 3 inches were selected because they were used in large quantities throughout the project and would have maximum salvage value.

The pipes used in the freezing process should be made of a metal capable of resisting the changes of temperture to which they are subjected. It is necessary that all joints be tight. If brine leaks into the soil to be frozen, this soil will be difficult to freeze.

Operation

Initial Preparation

The initial step in a freezing process, for shaft sinking, is the investigation of the strata to be penetrated. Biquet [52] writes:

---

[52] Biquet, M., op. cit. p. 831

> Preliminary to the initiation of the freezing process, a careful study is made of the strata to be penetrated: (1) with regard to their nature because the freezing is transmitted differantly in different strata, (2) in respect to the water in the strata encountered, which may be standing or gushing, and either fresh or of varying degrees of salinity, and (3) with regard to the permeability of the surface layers.

From study (3) in the above quotation, it should be possible to determine if the excavation can be started before the freezing process is begun. Several advantages are realized if excavation of the shaft is carried out to the water-bearing strata before freezing is started. Biquet [53]

---

[53] Biquet, M., Ibid.

---

lists them as follows:

1. A reduction in drilling.
2. A diminution of the cold necessary for that part of the shaft that is driven without freezing.
3. A saving resulting from the greater facility of work at the surface, the distributing equipment for the brine being placed in this foreshaft.

If it is not possible to sink a foreshaft, it becomes necessary to drill the holes to full depth and freeze this depth before beginning the shaft excavation.

Drilling the Holes

The number of holes required for the process is dependent on several factors. The depth to be frozen will affect the size of the circle along the circumference on which the holes are to be drilled. The spacing of the holes depends on the ease with which the ground is frozen. All materials do not freeze at the same rate. According to Landgrauber [54]:

---

[54] Landgrauber, F. W., Freezing sands, Refrigerating Engineering, Vol. 13, No. 8, February 1927. p. 263.

> Quicksand freezes most readily, clay soils less so; brown coals set up a serious obstacle, being poor conductors. Soils containing sands also freezes into the most solid wall.

If the ground does not freeze readily, the distance between the holes must be decreased.

Shafts sunk by the freezing process are usually circular in shape. The radius of the circle on which these holes are drilled is equal to the radius of the shaft plus from 2 to 15 feet. Figure 21 shows a plan view of the drilling pattern for freezing.

It is very important that all holes be drilled vertical so that the frozen area will be a predetermined thickness; otherwise, there will be places where the shaft protection will be inadequate. If some of the holes are not vertical, it is the usual practice to redrill them so that the spacing underground will be the same as the surface spacing.

In drilling the holes, it is usually necessary to case them as the drill penetrates to the required depth. The hole should be large enough to permit the casing to be placed. The casing should be large enough to permit the freezing tubes to be placed. In other words, the size of

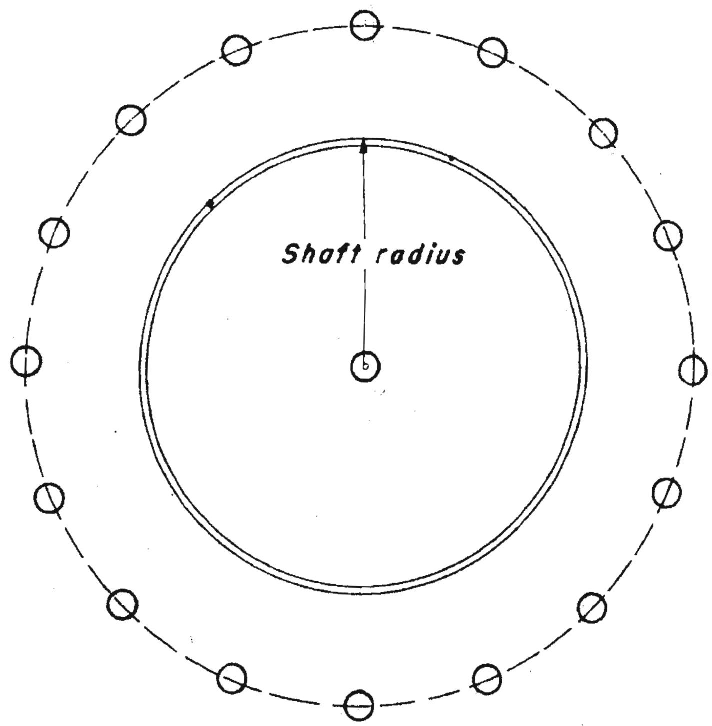


Figure 21. Plan view of drilling pattern for freezing.

the bit used in drilling will be dependent on the size of the freezing pipes used. In most cases, the holes are drilled 10 feet into the solid rock which underlies the material to be frozen. This insures freezing to the full depth of the hole.

Freezing the Strata

After the holes have been drilled and the freezing tubes have been placed, the refrigerating plant is connected to these tubes. As soon as all connections are completed, the plant is put in operation.

When the plant is started, the temperatures of the rock and soil fall rapidly. This is due to the large differential temperature between the refrigerant and the soil and rock which are being frozen. Months are often required to freeze this material. The freezing is not uniform along the freezing tubes. Biquet (55) states:

---

(55) Biquet, M., op. cit. p. 832.

> The theory of M. Lebreton proves that, other things being equal, the cross-section of the ice wall formed around the pipe will assume the shape of an erect cone, of a cylinder, or of an inverted cone, according as the depth to be frozen is equal to, less, or greater than the theoretical depth, which depends on the following elements; The thickness of the inner pipes, their diameter, the conductivity of the metal, the quantity of salt solution in circulation at any time, and finally, the specific heat of the brine. Inversely, the depth being given, the form of the ice wall will depend on the elements that have just been enumerated.
>
> With the aid of Lebreton's theory, the shape of the ice wall may be calculated. Consequently, knowing the quantity of water contained in the ground (or assuming it approximately) the number of necessary units of freezing for the formation of this ice wall can be deduced; but it is necessary to remember that all the cooling does not result in the formation of ice. At each level, the temperature decreases progressively from that of the natural ground to that of the brine returning in the freezing pipe.
>
> Taking into account, also, the losses due to radiation in the brine pipe, between the central refrigeration plant and the

shaft to be frozen, the total units of freezing that must be employed can easily de deduced. On ascertaining the length of time required to form the ice wall, we find the degree of refrigeration per hour that is required.

Froage [56] suggests a method of estimating the spacing of freezing

---

[56] Froage, L. V., op. cit. pp. 10-11.

---

tubes. He writes:

> Since the capacity of the refrigerating plant determined the time estimated for freezing the arch at 20 days, the spacing of the refrigerating points was calculated on this same basis. Although no data were available which applied directly to the time required for freezing of earth, the following formula for freezing of large sheets of plate ice was selected as being applicable because the thermal conductivity of the ice and of a wide variety of mineral matter is almost identical.
>
> $$\frac{21 X t X t}{32 - T} = \text{freezing time, hr.}$$
>
> where t equals thickness of frozen material, in.
> T equals temperature of brine, [57] deg. F.

---

[57] Motz, W. H., A lecture course on the principals of refrigeration, Nickerson and Collins Company, Chicago, Illinois, 1922. Lecture 11, p. 21.

By assuming the temperature of the brine and estimating the freezing time, it is possible to solve for the thickness of the frozen earth. The distance between the tubes would be twice the value of this thickness.

During the freezing process, it is necessary to determine when the area to be penetrated is enveloped by the ice wall. A bore hole is drilled in the center of the shaft site into which no freezing pipe is inserted. Variations in the temperature and level of the water in this hole indicate the progress of the freezing. When the ice wall has completely enveloped the shaft area, excavation is started or continued. Either light blasting or hand excavation should be used in excavating ground treated by the freezing process. Heavy blasts will rupture the ice wall and permit water to drain into the excavation.

Thawing

After the excavation has been completed and lined, it is necessary to thaw the frozen zone. The lining must be caulked to stop any leaks that show up as thawing progresses.

There are three general methods of thawing. They are:

1. Gradually increasing the temperature of the circulating brine. This is the reverse process of freezing.
2. Filling the excavation with water.
3. Aerating the excavation.

Another method was suggested by Froage [58] which was used on the Grand

---

[58] Froage, L. V., op. cit. p. 13.

Coulee Dam. He writes:

> Steam hoses were inserted in the $1\frac{1}{2}$ inch inner pipes and pushed to the bottom. The hoses were securely tied in place and steam at full boiler pressure was turned on. In the process of thawing, many of the pipes were fractured at the coupling, but they usually held together so that the entire point could be recovered. The breaking of pipes during thawing could be avoided by inserting the steam hose in the $1\frac{1}{2}$ inch pipe very slowly and thawing the pipe loose progressively from the top, but as speed was imperative and the breaking of pipe was not important so long as it could be recovered, this thawing procedure was not used.

Summary

The freezing process is used mostly in shaft sinking operations. The process is expensive and time consuming, but is applicable where other methods of stabilizing soils are not effective and cannot be used.

The method offers several advantages. It is not affected by moving water and it may be used in any water-bearing soil or rock regardless of physical composition and size of void spaces.

The two main disadvantages of the freezing process is the high cost and the long period of time required to freeze the formations; some operations have taken several years to complete. Saline water affects the efficiency and applicability. Lower temperatures over longer periods of time are required to complete the freezing of ground containing salt water.

DRY ICE-ISOPROPYL ALCOHOL FREEZING METHOD

Introduction

An original research was conducted by the author to test the applicability of freezing water-bearing sands with isopropyl alcohol as the refrigerant and dry ice as the cooling medium. This problem was suggested by Mr. M. P. Nackowski, Instructor in Geology, Missouri School of Mines and Metallurgy, Rolla, Missouri.

In conducting this experiment, it was the author's intention to find the rate at which sand saturated with water could be frozen and the temperatures that could be obtained in so doing. These objectives stemmed from the hope that low temperatures could be developed with this method. This would result in fast freezing.

Two tests were conducted. Each will be discussed separately, giving the equipment, procedure, and results.

Test I

Equipment

The research was started after the necessary equipment had been acquired and assembled. The items for the first experiment are listed as follows:

1. Insulated freezing chamber
2. Copper coil
3. Heat exchanger
4. Thermometers
5. Reservoir
6. Centrifugal pump
7. Isopropyl alcohol
8. Dry ice

9. Sand and container

The insulated freezing chamber was constructed of a carbide container, a wooden container, and sawdust insulation. A pressed fiber top provided a cover for the chamber. The outside wooden container was 17 inches wide, 17 inches long, and 18 inches high. The carbide container was 12 inches in diameter and 14 inches high. The insulation consisted of from 2.5 to 6 inches of sawdust. The bottom of the chest was insulated with four inches of sawdust. The pressed fiber cover provided three inches of insulation for the top.

The coil in the freezing chamber was made from a piece of copper tubing one-half inch in diameter and approximately 15.5 feet long. This tube was formed into a helical shape around a 4.5 inch piece of pipe.

The heat exchanger was made of one inch copper tubing 12 inches long. A copper tube three-eights of an inch in diameter and 15 inches long was placed in the center of the one inch tube. This exchanger is diagramatically illustrated in Figure 22. The exchanger was designed so that the ratio of the effective area of the large tube to the area of the small tube was 7 to 1. With this ratio the alcohol flowed 7 times as fast in the small tube as it did in the larger tube.

The temperature readings were obtained with the use of two low-reading thermometers placed in the circulating system. One was placed between the freezing chamber and the heat exchanger and the other was placed between the heat exchanger and the reservoir.

The reservoir was used to provide a means of filling the system with alcohol. It also provided an escape for air bubbles and vaporized alcohol which might have become trapped in the unit. A filtering

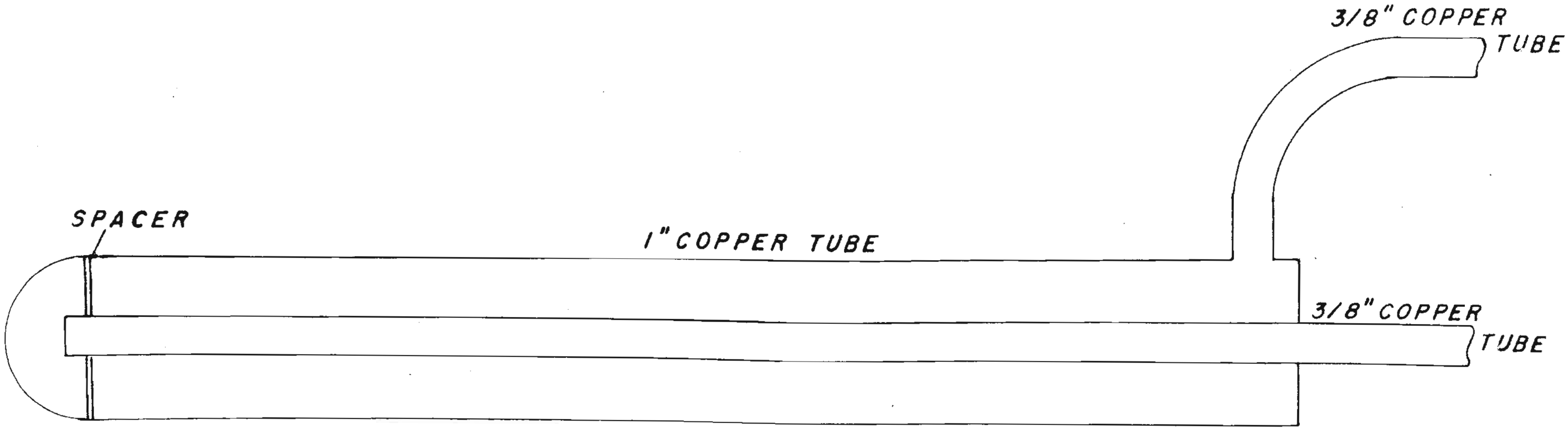


FIGURE 22. DIAGRAM OF HEAT EXCHANGER

flask was used as a reservoir in the first test.

An Eastern model A-1 centrifugal pump was used in the initial test to circulate the alcohol. This pump was powered by a 1/100 horsepower motor. The motor was connected to the impeller by a drive shaft.

Isopropyl alcohol was chosen because it is less toxic and also is cheaper than other low-freezing liquids. Solid carbon dioxide sublimes at minus 78.5 deg. C. and isopropyl alcohol freezes at minus 88.5 deg. C. The alcohol would, therefore, remain liquid at the subliming temperature of dry ice.

The sand used in this experiment was ordinary river sand screened to minus 28 mesh Tyler standard scale to remove large pieces of dirt and other impurities. The iron container which was used to hold the water-saturated sand was 10 inches in diameter and 11 inches deep.

Procedure

The equipment was assembled as follows: (1) A rubber hose with a low-reading thermometer placed near the heat exchanger was attached from the outlet of the freezing chamber to the heat exchanger; (2) another length of hose with a low-reading thermometer near the heat exchanger was used to connect the exchanger and the reservoir; (3) the reservoir was connected to the centrifugal pump with hose; and (4) the pump was connected with hose to the freezing chamber.

Fifty pounds of dry ice and one-half gallon of isopropyl alcohol were used in this test.

Results

Some freezing of the saturated sand and water mixture did occur in the four hours during which the unit was operated.

Several difficulties were met while conducting this test. As the dry ice sublimed it became necessary to tamp the remaining ice to maintain contact with the coil. An insufficient number of thermometers, which were difficult to read, were used during the test. No method was used to determine the velocity of the alcohol circulating in the unit.

Test II

Equipment

The second test was conducted with the following equipment:

1. Insulated freezing chamber
2. Kerosene
3. Copper coil
4. Heat exchanger
5. Orifice
6. Pressure gage
7. Globe valve
8. Chromel-alumel thermocouples
9. Potentiometer
10. Reservoir
11. Centrifugal pump
12. Sand and container
13. Isopropyl alcohol
14. Dry ice

The insulated freezing chamber used in this test was the same as the one used in test I. Because of the difficulty found in keeping the dry ice in contact with the coil during test I, it was decided to use some liquid to provide this contact. Kersosene was chosen as this liquid because it was relatively inexpensive and less volatile than some of the other liquids that could have been used. In order to reduce the volume of the chamber, the carbide container was lined with two inch by four inch pieces of wood. This lining reduced the diameter to eight inches.

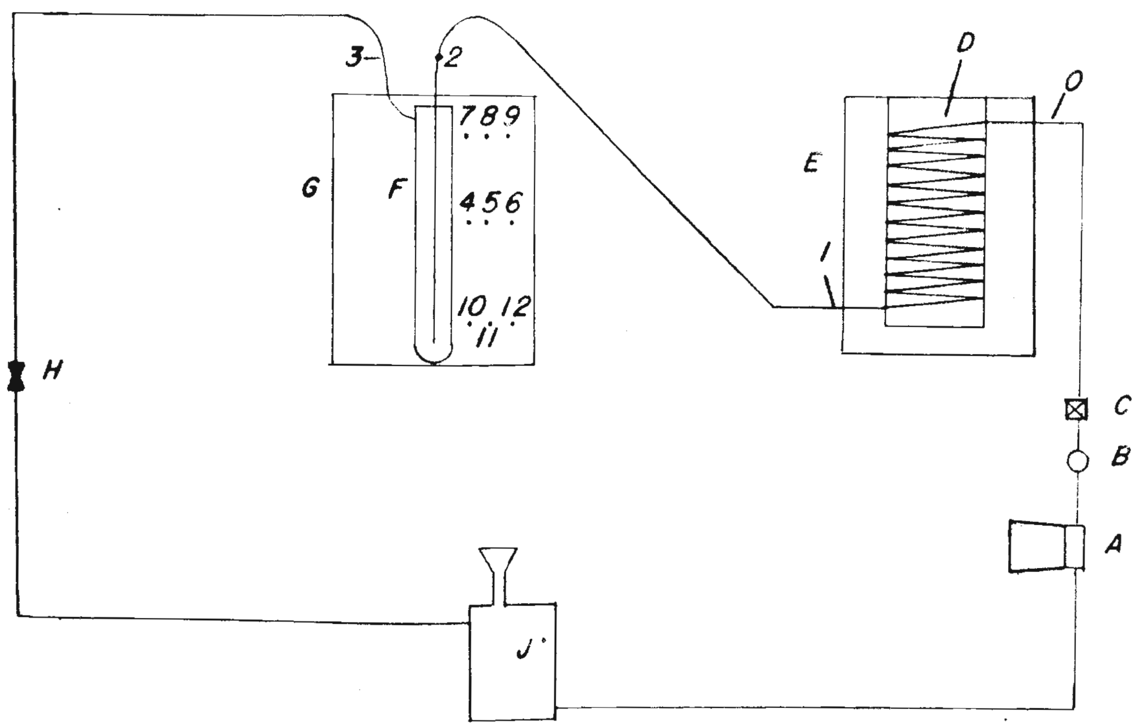
The copper coil and heat exchanger used in this test were the same as those used in test I. No changes were made in either of these pieces of equipment.

A globe valve and pressure gage were put into the circulating system to determine the velocity of the alcohol. The valve was used as a throttle for the pump. By regulating the pressure built up by the pump, the flow was kept at a constant velocity. As a check against this method, a three-sixteens inch orifice was used in the system. A manometer capable of indicating up to 30 inches differential pressure, was connected to the taps on either side of the orifice.

Thirteen chromel-alumel thermocouples were used to determine the temperatures of the water-saturated sand and of the circulating alcohol. The position of these thermocouples is indicated on Figure 23. In series with the thermocouples were a potentiometer, a thirteen pole switch which was numbered from zero to twelve, and a double-throw switch which was used to change the polarity of the potentiometer. When the temperatures were below zero degrees C., the double-throw switch enabled the operator to change the polarity of the potentiometer and read this temperature.

A quart oil can, tapped at the top and the bottom to provide an entrance and exit, respectively, was used as the reservoir in the second test. To provide insulation for the reservoir, it was placed in a box and packed with sawdust.

The pump in test I proved to be too small for this process. An



A-Centrifugal pump
B-Pressure gage
C-Valve
D-Copper coil
E-Freezing chamber
F-Heat exchanger
G-Container of sand
H-3/16" Orifice
J-Reservoir
Numbers indicate position of thermocouples

Figure 23. Schematic diagram of freezing unit.

Eastern model E-7 centrifugal pump was obtained and used in test II. This pump was capable of developing 30 p.s.i. at zero flow and zero p.s.i. at a flow of nine gallons per minute.

The sand, container, and alcohol were the same as those used in test I. A new supply of dry ice was obtained.

Procedure

The equipment used in test II was assembled as illustrated in Figure 23, the thermocouples numbered 0, 1, 2, and 3 in Figure 23 were difficult to seal into the circuit. After many attempts, this problem was solved by using dental stone around the thermocouples and covering this stone with a plastic which was dissolved in acetone. Several coats of plastic were applied and this effectively sealed the thermocouples.

Nine thermocouples were placed in the sand. The depth of thermocouples numbered 7, 8, and 9 shown in Figure 23 averaged three inches below the surface. The depth of these numbered 4, 5, and 6 was 5.5 inches and the depth of those numbered 10, 11, and 12 was nine inches.

The circulating system was filled with 0.62 gallons of alcohol, the initial temperatures were recorded, and then fifty pounds of dry ice were placed in the freezing chamber. The pump was started and the velocity was regulated to circulate a constant flow of 2.35 gallons of alcohol per minute. At the end of five minutes, another reading of all the thermocouples was recorded and readings were taken every 10 minutes to the end of the test.

Results

The water-saturated sand was frozen. The thickness of freezing ranged from one-quarter of an inch at the surface to more than one inch at the bottom. The shape of the frozen sand approximated that of an upright cone.

Table 6 shows the temperatures in degrees centigrade for ten minute intervals measured at each of the thermocouples. The temperatures of the water-saturated sand have been plotted on graphs. Figures 24, 25, and 26 show the relationship of temperature versus depth at given time intervals. In Figure 24, the water-saturated sand reached thermal equilibrium after 105 minutes.

Figures 27, 28, and 29 show the relationship of temperature versus distance from the heat exchanger for the various time intervals. These curves were approaching a straight line as the test progressed.

Figures 30 and 31 are the results of an attempt to construct a graph showing the isothermal lines in the water-saturated sand at the end of 105 minutes. As three points determined the curves and as thermal equilibrium was not reached at all points covered by these curves, the isothermal lines could not be plotted.

During the time interval between 85 and 105 minutes, an attempt was made to determine the effect of a reduced circulation on the heat transfer. The pump was throttled down so that 1.8 gallons of alcohol was being circulated per minute. Table 6 shows that the temperature began to rise. It is the author's opinion that the heat of friction generated by the pump caused the increase in temperature. The constant circulation of 2.35 gallons per minute was resumed and the temperature of the alcohol lowered.

As the temperature of the alcohol decreased, the differential head over the orifice also decreased. The author believes that this change was caused by a change in density of the isopropyl alcohol as it became colder.

TABLE 6

TEMPERATURES MEASURED WITH THERMOCOUPLES

TIME (MIN.)	ALCOHOL				SAND								
	0	1	2	3	4	5	6	7	8	9	10	11	12
0	32.75	33.5	33.8	33.25	29.0	28.75	28.9	28.4	28.4	28.0	29.5	29.5	29.4
5	23.5	18.8	18.0	17.5	29.5	29.6	29.1	28.4	29.1	28.8	29.4	29.4	29.4
15	3.0	0	-4.9	-4.25	23.5	29.6	29.3	22.4	27.4	28.2	22.4	27.5	28.2
25	-9.2	-14.9	-14.6	-13.5	18.5	26.3	29.6	16.3	23.8	26.6	16.0	25.0	27.75
35	-9.0	-14.5	-16.2	-14.7	-15.8	23.8	27.3	14.0	21.6	25.0	13.3	22.75	25.25
45	-10.25	-17.0	-15.75	-11.75	13.6	21.5	25.0	12.5	19.2	23.6	11.0	20.8	24.0
55	-13.5	-18.9	-18.4	-15.8	12.0	20.0	23.8	10.5	17.8	22.5	9.0	18.6	22.5
65	-14.0	-19.8	-19.6	-17.0	10.2	18.6	22.75	9.25	16.0	21.4	7.2	17.0	22.0
75	-15.0	-19.0	-20.5	-16.0	8.75	17.0	21.3	7.5	14.8	20.9	5.75	15.5	18.9
85	-14.0	-21.0	-21.1	-24.4	7.25	15.3	19.4	6.75	14.0	19.0	4.4	13.85	17.3
95	-12.7	-20.3	-19.7	-21.0	6.75	14.2	18.7	5.8	13.1	17.8	3.5	12.6	16.5
105	-11.3	-17.2	-17.2	-14.0	6.2	13.2	17.3	6.2	12.5	17.2	3.0	11.5	15.2
115	-14.0	-20.0	-19.1	-18.8	5.3	12.5	16.3	5.5	11.4	16.0	2.2	10.8	14.2
125	-15.75	-19.8	-19.8	-18.8	4.2	11.4	15.4	4.4	11.0	14.9	1.3	9.5	13.6
135	-17.0	-21.25	-21.75	-20.3	2.6	10.5	14.7	3.4	9.8	12.5	.25	8.8	12.8
145	-17.6	-23.0	-22.3	-20.5	2.0	10.0	14.0	2.6	8.9	12.4	0	8.2	12.4
155	-15.5	-19.5	-19.5	-19.0	1.5	8.7	13.3	2.0	7.5	11.0	-.75	7.4	11.5
165	-15.9	-19.0	-19.0	-18.7	.5	7.8	12.6	.8	6.3	9.75	-1.3	7.1	10.8
175	-19.0	-21.0	-21.0	-20.7	-.3	7.0	10.0	0	5.8	10.0	-2.0	6.35	9.75

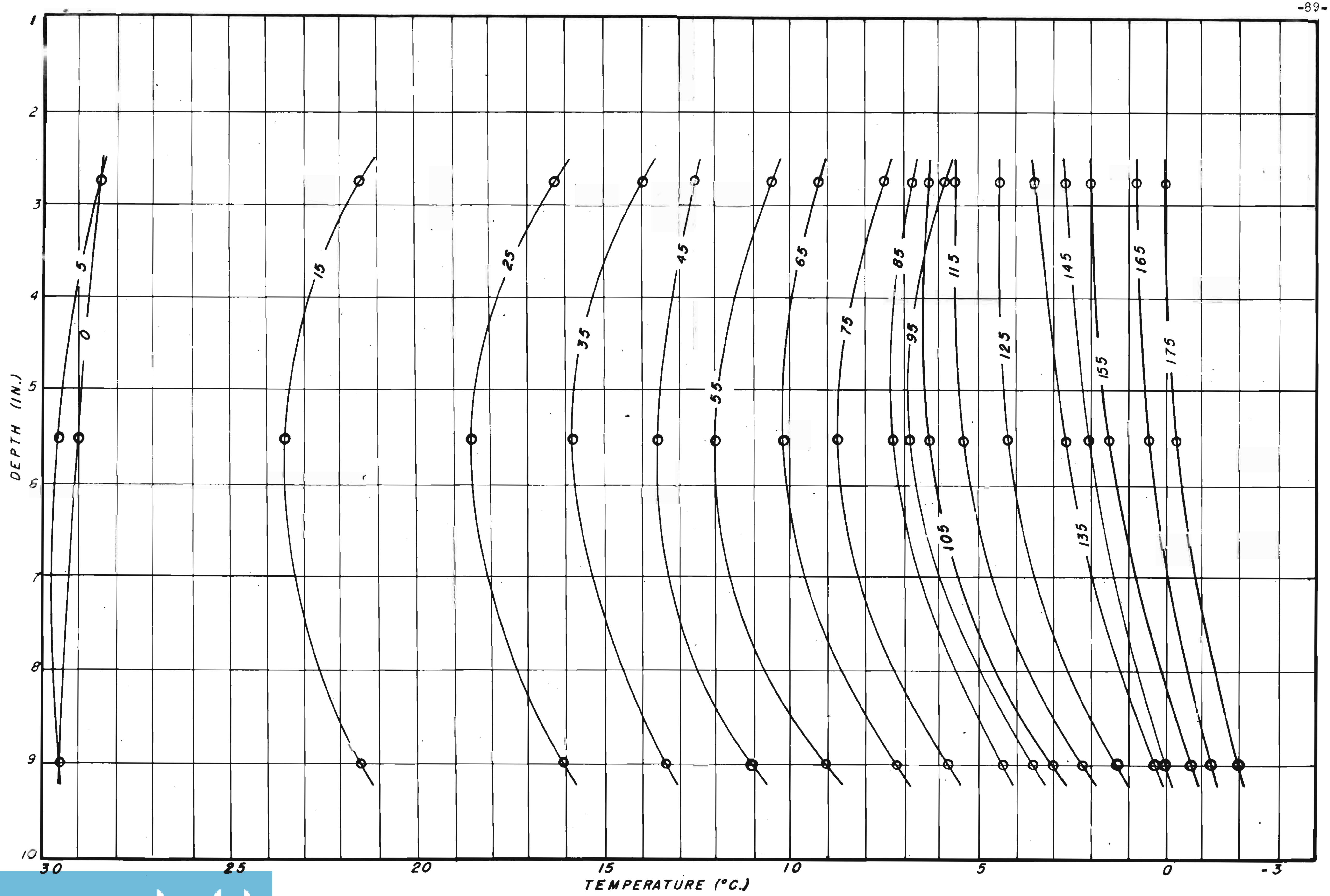


Figure 24. Temperature-depth-time curves 1" from heat exchanger.
(Numbers indicate time in minutes)

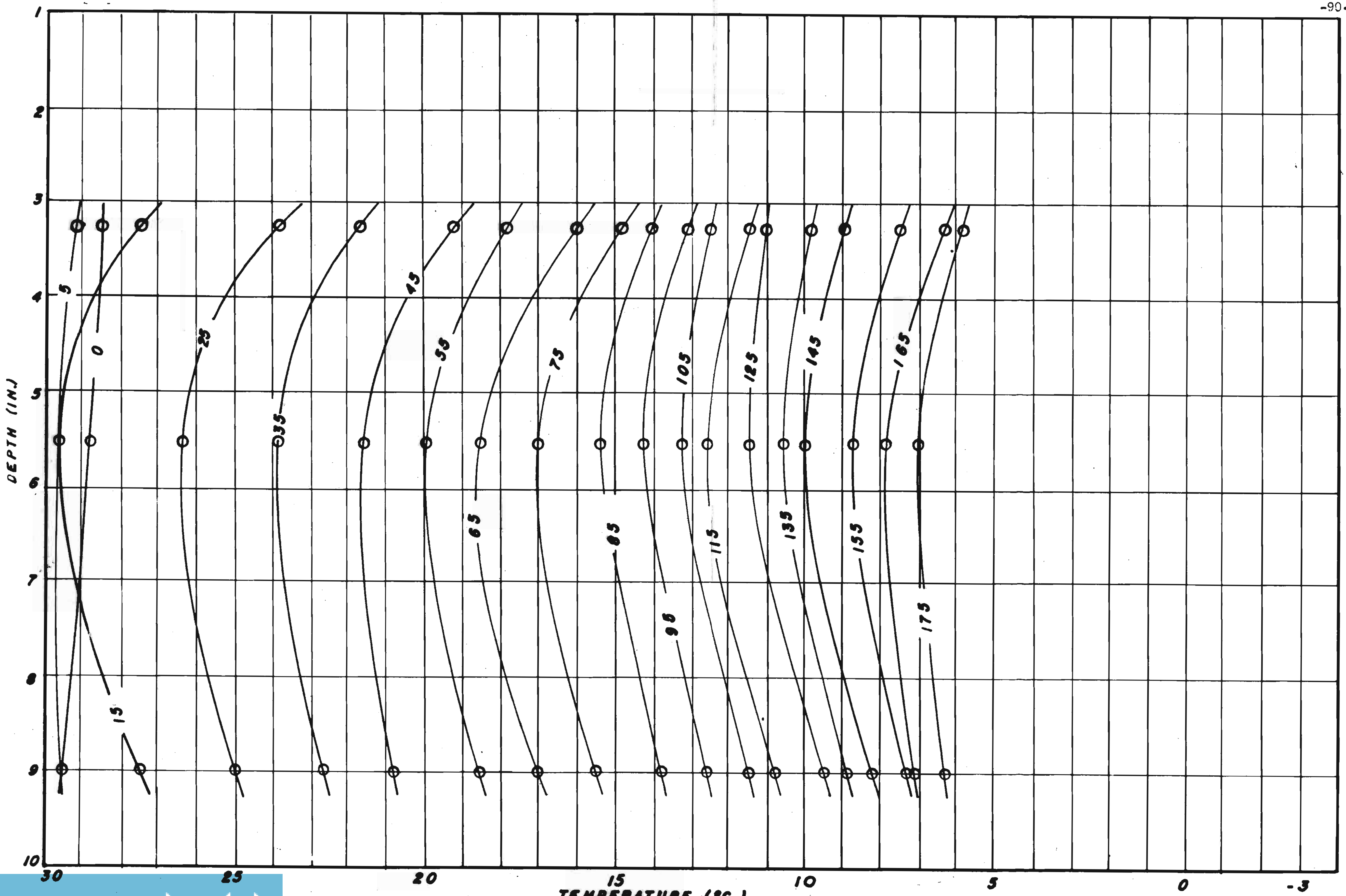


Figure 25. Temperature-depth-time curves 2" from heat exchanger.
(Numbers indicate time in minutes)

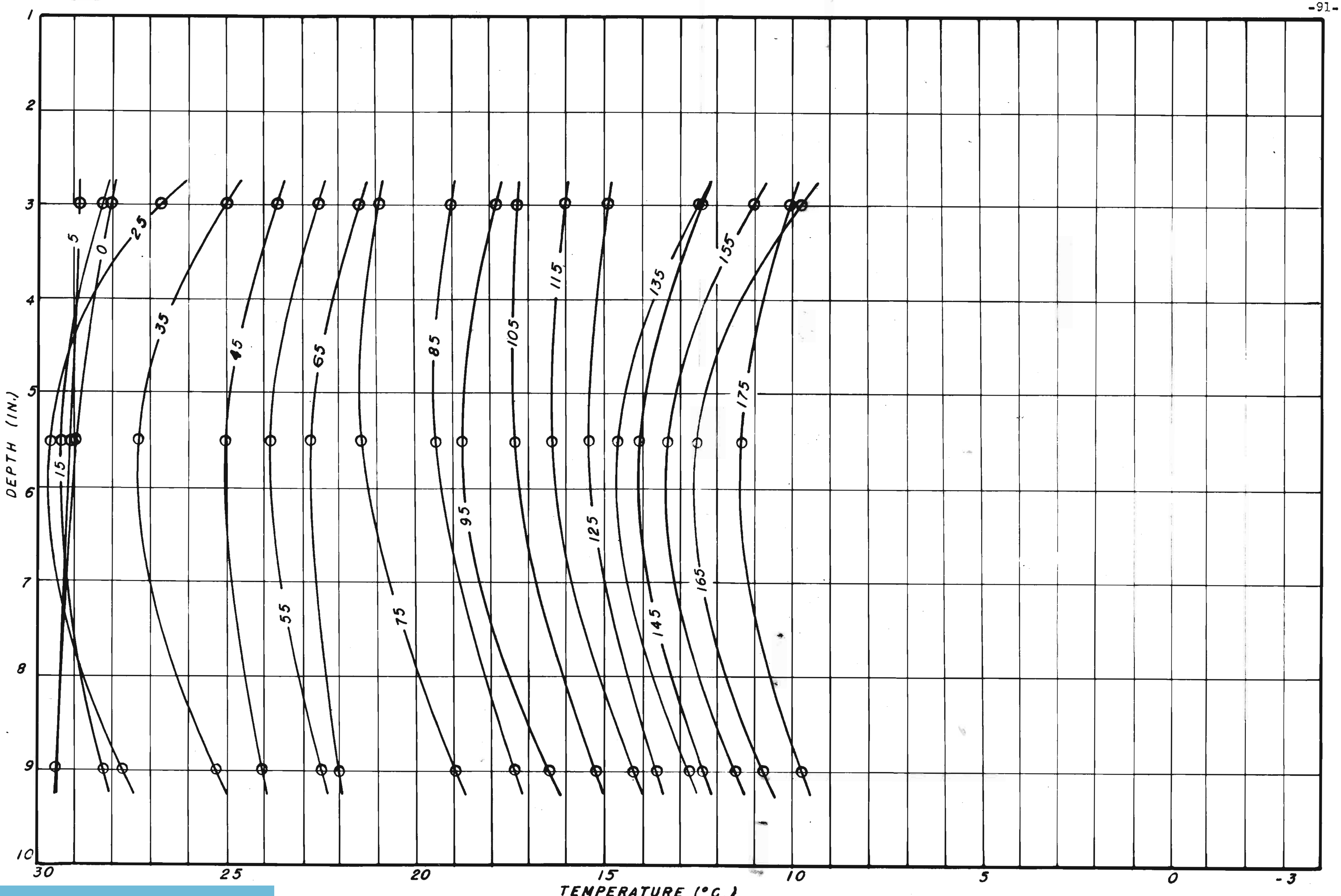


Figure 26. Temperature-depth-time curves 3" from heat exchanger.
(Numbers indicate time in minutes)

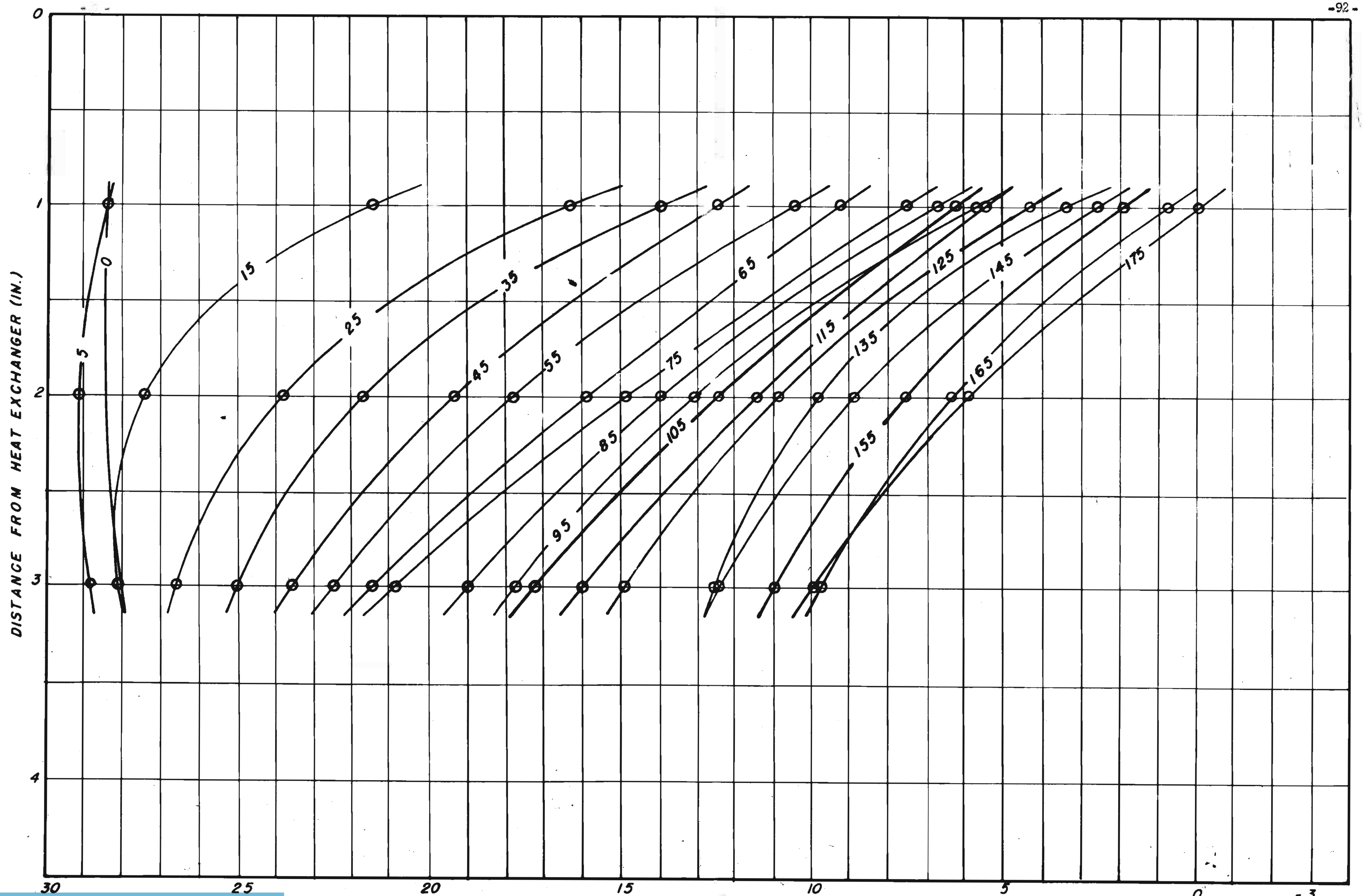


Figure 27. Temperature-distance from heat exchanger-time curves 3" below surface of sand.
(Numbers indicate time in minutes)

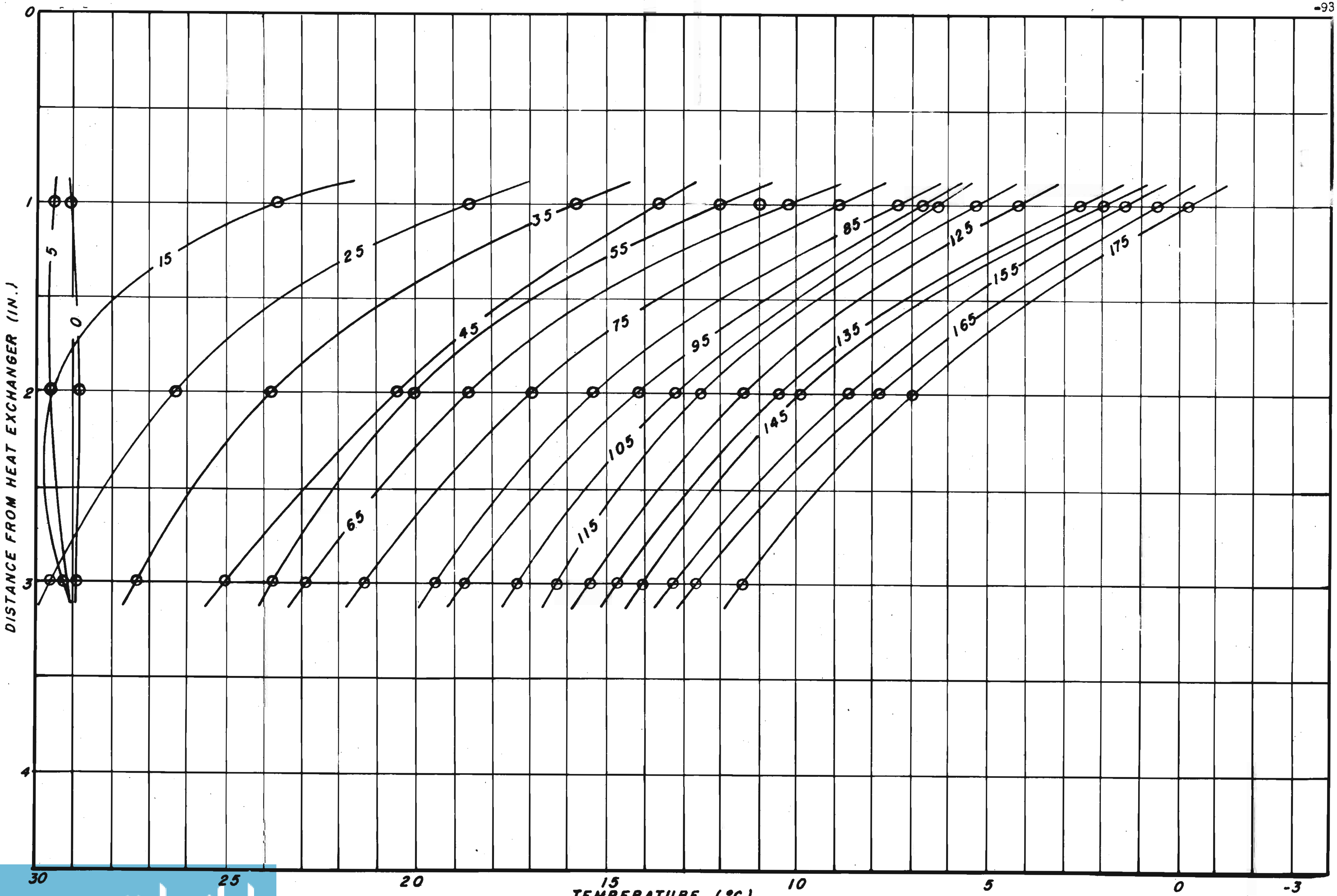


Figure 28. Temperature-distance from heat exchanger-time curves 5.5" below surface of sand. (Numbers indicate time in minutes)

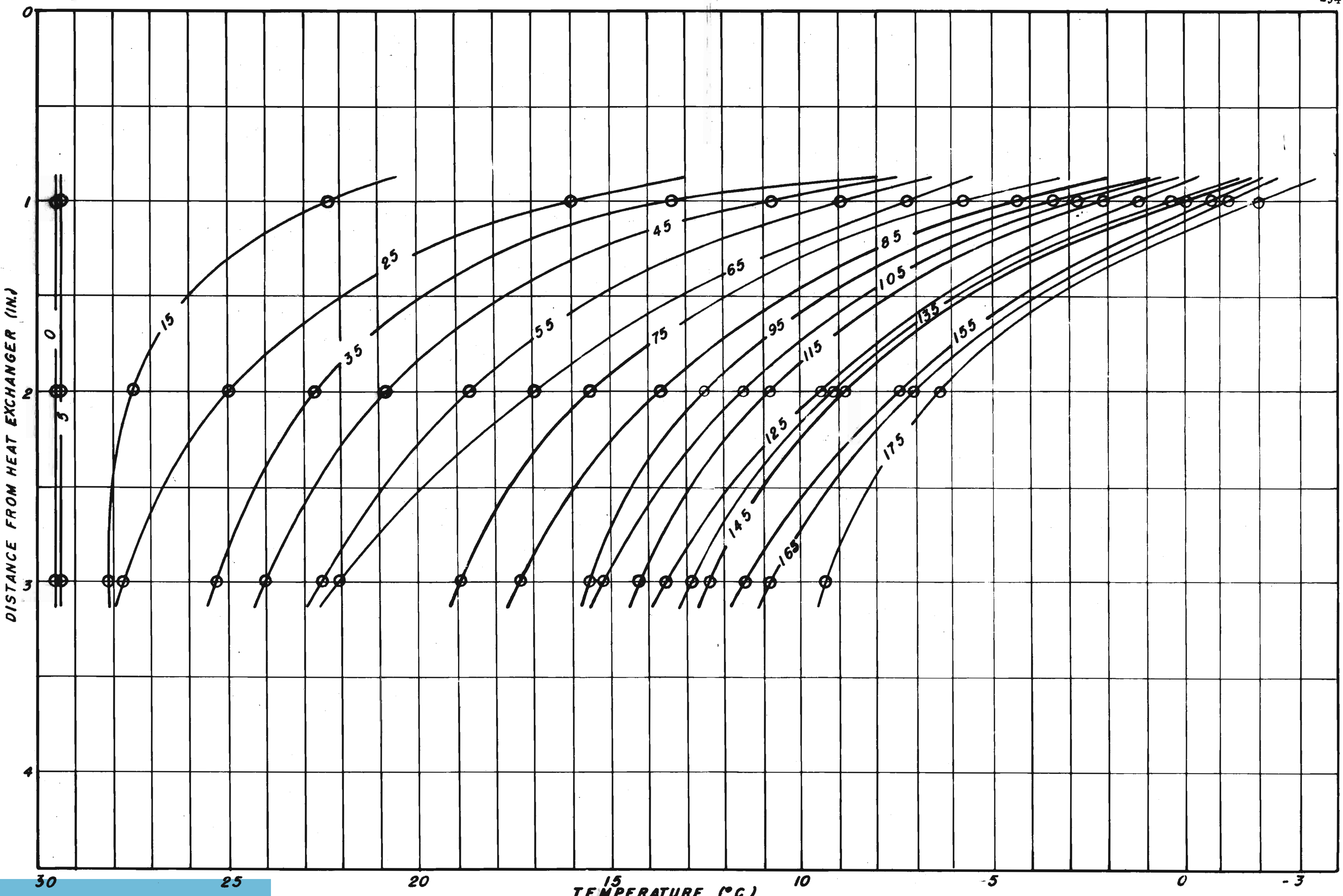


Figure 29. Temperature-distance from heat exchanger-time curves 9" below surface of sand.
(Numbers indicate time in minutes)

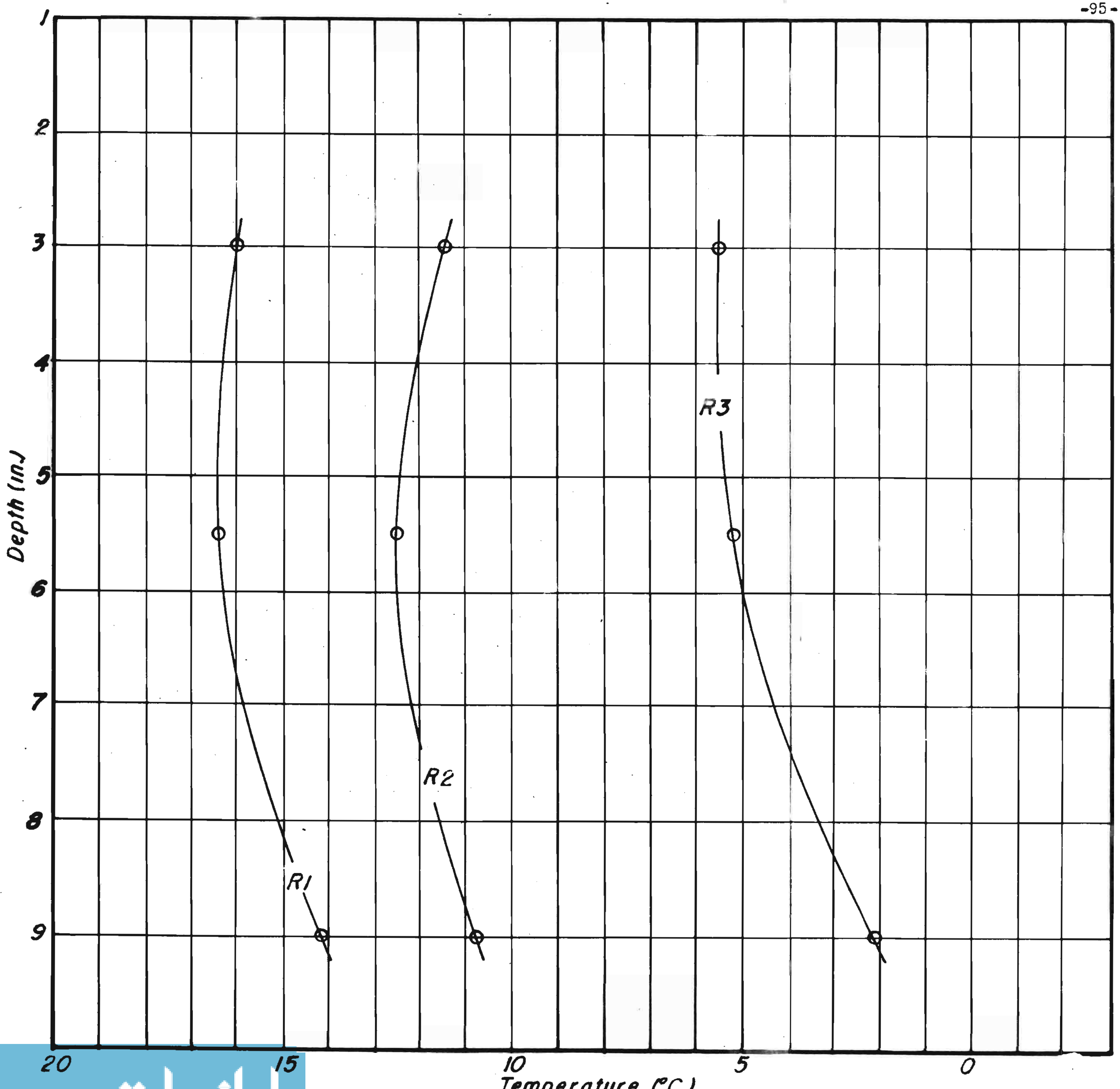


Figure30. Temperature-depth-time curves at 105 minutes.
(R = distance from heat exchanger in inches.)

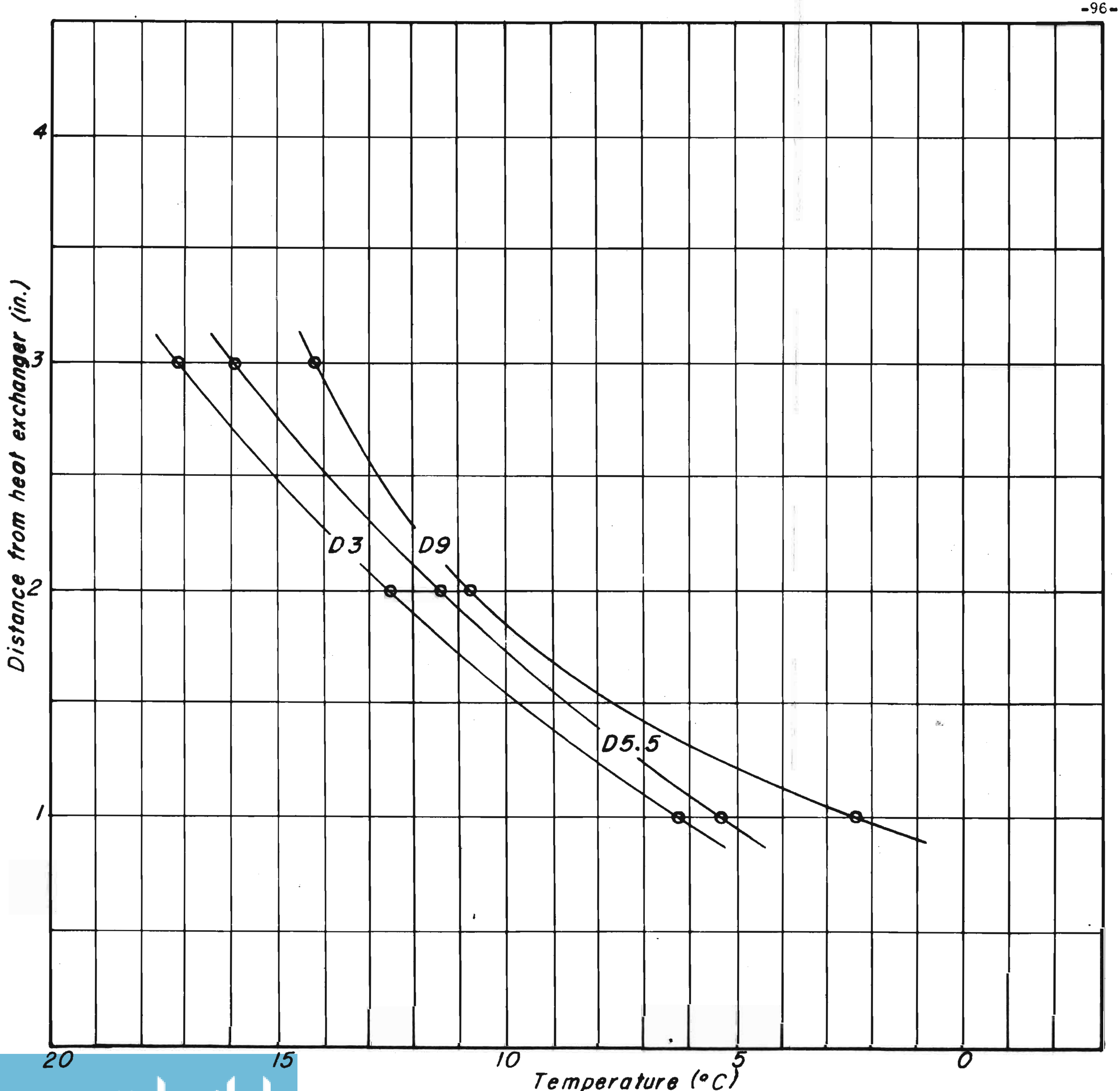


Figure 31. Temperature-distance from heat exchanger-time curves at 105 minutes.
(D = depth in inches)

Summary

The first test was a failure since not enough data were obtained. In attempting to correct this for the second test, additional equipment was obtained so that the shortcomings of the first test were not repeated. The results of both tests showed that a water-saturated sand could be frozen in laboratory experiment using this method of freezing.

Conclusions

1. Dry ice-isopropyl alcohol can be used to freeze quicksand in laboratory experiments.
2. More tests should be performed using more thermocouples to obtain detailed information concerning the temperature gradient in the quicksand.
3. Future tests should be carried through a longer period of time so that thermal equilibrium can be reached throughout all parts of the quicksand.
4. Future tests in which the temperature difference between the saturated sand-water mixture and the atmosphere is not as large as in these tests. Perhaps the experiments should be conducted in the experimental mine of the Missouri School of Mines.
5. Where necessary, the lines carrying the cooled alcohol should be insulated to improve efficiency.

BIBLIOGRAPHY

Grouting

Abrams, D. A., Test of impure waters for mixing concrete. American Concrete Institute. Proceedings of Twentieth Anniversary Convention. Vol. 20, 1924.

Beanfield, R. McC. Technique of grouting foundations. Western Construction News. Vol. 3, No. 19, October 10, 1928. pp. 634-638.

Blandford, T. The process of cementation. The Iron and Coal Trades Review. Vol. 136, March 18, 1938. pp. 477-479.

Christians, G. W. Asphalt grouting under Hales Bar Dam. Engineering News-Record. Vol. 96, No. 3, May 20, 1926. pp. 798-802.

Crawhall, J. S. Tunneling a water-bearing fault by cementation. Engineering News-Record. Vol. 102, May 30, 1929. p.874.

Denholm, E. W. Pressure grouting: some notes on standard practice. The Surveyor. Vol. 103, No. 2724, April 7, 1944. pp. 165-166.

Elgin, R. A. How Leadville Tunnel is driven through bad ground. Engineering and Mining Journal, Vol. 146, No. 3, March 1945, pp. 96-100.

Freeman, M. H. Discussion on the Astoria Tunnel, American Society of Civil Engineers Transactions. Vol. 80, 1916. p. 677.

Grouting with bentonite mixed in products of petroleum, U. S. Bureau of Reclamation. Laboratory report No. C-229, January 27, 1944. p. 4.

Gutmann, I. Algerian rockfill dam substructures. Engineering News-Record. Vol. 120, May 26, 1938. p. 749.

Hays, J. B. Foundation experiences, T. V. A. American Society of Civil Engineers Transactions. Vol. 106, 1941. p. 718.

Hays, J. B. Improving foundation rock for dams. Civil Engineering. Vol. 9, No. 5, May 1939. p. 309.

Jorgensen, L. R. Solidifying gravel, sand, and weak rock. Western Construction News. Vol. 6, November 10, 1931. pp 591-593.

Kellog, F. H. Clay grouting at Madden Reservoir. Engineering News-Record. Vol 109, No. 14, October 6, 1932. pp. 395-396.

Lee, C. H. Sealing Chenery Reservoir. Western Construction News. Vol. 5, December 25, 1930. p. 624.

Lewis, J. S., Jr. Foundation experiences, T. V. A. American Society of Civil Engineers Transactions. Vol. 106, 1941. p. 718.

Minear, V. L. The art of pressure grouting. The Reclamation Era. Vol. 27, March 1937. p. 59.

Randolph, E. S. Sealing reservoir lakes with clay grouting. The Military Engineer. Vol. 28, No. 159, May-June 1936. p. 209.

Riedel, C. M. Chemical joint sealing and soil solidification. Engineering News-Record. Vol. 127, August 14, 1941. p. 77.

Ritter, N. E. and Stroup, R. J. Sinking Eagle-Picher's New Garret shaft. Mining Congress Journal. Vol. 24, No. 9, September 1938. p. 14.

Simonds, A. W. Pressure grouting equipment. U. S. Bureau of Reclamation. Technical Memorandum 638. p. 14.

Soil Mechanics Bulletin No. 9. U. S. Waterways Experiment Station, Vicksburg, Mississippi. March 1939. p. 8.

Stiefel, F. W. Overcoming underground difficulties. Compressed Air Magazine. Vol. 46, No. 12, December 1941. p. 6613.

Sturges, F. C. Introduction - grouting in mines. A. I. M. E. Technical Publication 2427. Symposium on grouting. February 1948. pp. 1-3.

Symposium on grouting. A. I. M. E. Technical Publication 2427. February 1948. pp. 1-23.

Tainter, S. L. Grouting diamond-drill holes at the Christmas Mine, Gila County, Arizona. U. S. Bureau of Mines. Report of Investigations 4559.

Underground dam. Petroleum Refiner. Vol. 28, No. 3, March 1949. A Gulf Publishing Company Publication. p. 114.

U. S. Engineers, Final Laboratory Report. Tests for chemical consolidation of foundation materials at Lock and Dam No. 3, Mississippi River. U. S. Engineers Sub-Office Hydraulics Laboratory, Iowa City, Iowa. November 1937. 30 pp.

<u>Freezing</u>

Ackerman, A. J. and Locher, C. J. Construction planning and plant. First Edition, McGraw-Hill, 1940. pp. 219-220.

Biquet, M. Freezing process enables lessees to sink shafts in deep marsh land of North Belgium. Coal Age. Vol. 25, No. 23, June 5, 1924. pp. 831-834.

Froage, L. V. Frozen earth dam a t Grand Coulee. Mechanical Engineering, Vol. 63, No. 1, January 1941. pp. 9-15, 36.

Gough, H. B. A wet shaft frozen tight. Engineering News-Record. Vol. 122, No. 19, May 11, 1939. pp. 74-76.

Landgrauber, F. W. Freezing sands. Refrigerating Engineering Vol. 13, No. 8, February 1927. p. 263.

Motz, W. H. A lecture course on the principals of refrigeration. Nickerson and Collins Company. Chicago, Illinois, 1922. Lecture 11, p. 21.

Refrigeration permits shaft sinking. Refrigerating Engineering. April 1949. p. 335.

Shaft sinking at Calverton Colleriery. The Engineer. Vol. 188, No. 4887, September 23, 1949. pp. 355-356.

Skerret, R. G. How Antwerp is building tow tunnels under the scheldt. Compressed Air Magazine. Vol. 37, November 1932. pp. 3962-3966.

VITA

Robert Walter Heins was born June 10, 1924 at Edgerton, Wisconsin. Elementary schooling was received at Platteville, Wisconsin. He graduated from Platteville High School in May, 1942. He attended Wisconsin Institute of Technology from September 1942 to March 1943, at which time he left school to enter the Army. While in the Army he transferred to the Army Air Force. On May 20, 1944, he graduated from Navigation School at Ellington Field, Texas, and received a commission of Second Lieutenant. After his discharge, he re-entered the Wisconsin Institute of Technology in February, 1946, and was graduated in May 1948. He entered the Missouri School of Mines in September 1948 and was graduated with a degree of Bachelor of Science in Mining Engineering, May 1949.