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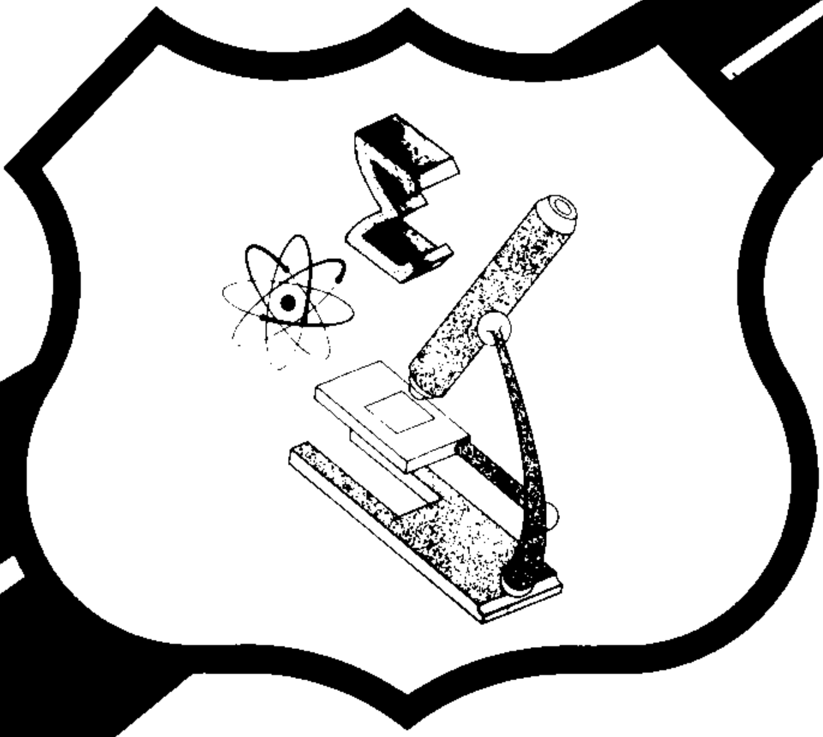
TREMIE CONCRETE FOR BRIDGE PIERS AND OTHER MASSIVE UNDERWATER PLACEMENTS

September 1981
Final Report



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Sea Grant College Program
University of California
La Jolla, CA 92093

FOREWORD

This report describes a laboratory and field investigation of concrete that is placed underwater by tremie. It will be of interest to bridge engineers and to other engineers concerned with hydraulic structures placed in rivers and along the coast. Technically, it presents recommended guidelines and specifications to cover all aspects of a field construction project, such as mixture design, placement procedures, flow patterns, and temperature development.

The report presents the results of the study partially funded by the Federal Highway Administration, Office of Research, Washington, D.C., under Contract DOT-FH-11-9402. This final report covers the entire study, which was initially sponsored and funded by NOAA, National Sea Grant College Program, Department of Commerce, under a grant to the California Sea Grant College Program, #04-7-158-44121, and by the California State Resource Agency, Project Number R/E-14.

Sufficient copies of the report are being distributed to provide a minumum of one copy to each FHWA regional office, one copy to each FHWA division office, and one copy to each State highway agency. Direct distribution is being made to the division offices. Additional copies of the report for the public are available from the National Technical Information Service (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Charles F. Scheffey
Director, Office of Research
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16. Abstract

This study reviewed the placement of mass concrete under water using a tremie. Areas investigated included (a) Mixture design of tremie concrete including the use of pozzolanic replacement of portions of the cement; (b) Flow patterns and flow related characteristics of tremie-placed concrete; (c) Heat development and associated cracking problems for tremie concrete; (d) Prediction of temperatures in massive tremie concrete placements; and (e) Quality of tremie-placed concrete. Additionally, the tremie placement of a massive cofferdam seal for a pier of a major bridge and the tremie placement of a deep cutoff wall through an existing earthfill dam are examined.

A recommended practice and a guide specification for massive tremie placements are provided. These items cover basic principles of tremie placement, concrete materials and mixture design, temperature considerations, placement equipment, preplacement planning, placement procedures, and postplacement evaluation.

Item #12 (continued)

This work is a result of research sponsored, in part, by NOAA, National Sea Grant College Program, Department of Commerce; under a grant to the California Sea Grant College Program, #04-7-158-44121, and by the California State Resources Agency, Project Number R/E-14.

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Introduction

When major structures are built in a river, harbor, or coastal area, the underwater portions of the structure usually require placement of underwater concrete. In some cases placement of underwater concrete is the only practicable means of construction, while in other cases, it may be the most economical or expeditious means.

In recent years, the device most frequently used for placing underwater concrete has been the tremie. A tremie is simply a pipe long enough to reach from above water to the location of concrete deposition. A hopper is usually attached to the top of the tremie to receive concrete being supplied by bucket, pump, or conveyor. In most cases, the lower end of the tremie is initially capped to exclude water. Once the tremie is filled with concrete, it is raised slightly, the end seal is broken, and the concrete flows out embedding the end of the tremie in a mound of concrete. In theory, subsequent concrete flows into this mound and is never exposed directly to the water. (See Chapter 2 regarding this flow theory.)

One critical element of a successful tremie placement is maintaining the embedment of the mouth of the tremie at all times in the fresh concrete. If this embedment is lost, water will enter the pipe and any concrete added at the hopper will fall through water resulting in severe segregation of aggregates and the washing out of cement and other fine particles. Such a segregated material is unfit for either a structural or nonstructural application.*

In bridge construction tremie concrete has long been used to seal cofferdams so that they may be dewatered and the piers constructed in the dry. In such cases, the tremie concrete serves as a temporary seal and as a mass concrete base. Tremie concrete has also been used to plug the bottom of caissons to insure full bearing over the surface area.

More recently, tremie concrete has been used for the structure itself rather than just as a seal. In this application, the tremie concrete is reinforced with pre-placed reinforcing steel. This structural use has been applied to dry docks, pump houses, and especially to the piers of major over-water bridges, including the several Chesapeake Bay Bridges, several Columbia River Bridges, and major crossings over San Francisco Bay.

Among the largest tremie concrete placements are the east anchorages of the two Delaware Memorial Bridges (quantities approached 30,000 yd^3 (23,000 m^3) each) and the repair and reconstruction of the stilling basin for Tarbela Dam in Pakistan (total placement of almost 57,000 yd^3 (43,000 m^3)

Among the deepest tremie placements are those of the Verrazano-Narrows Bridge (170 ft) (52 m) and the Wolf Creek Dam cutoff wall (280 ft) (85 m) which is described in Chapter 4. Even deeper placements have been made in mine shafts.

Although tremie concrete has proven itself on many projects, there have been a significant number of unsatisfactory placements which necessitated removal and reconstruction. Serious delays, large cost over-runs, and major claims have resulted.

In light of the problems which have occurred during tremie placements, the Construction Engineering and Management Group at the University of California, Berkeley, has undertaken a major study of the tremie placement process. This study has two main objectives. The first is to establish criteria for mixture design and placement procedures which will minimize the number of unsatisfactory events. The second objective is to facilitate and encourage the wider use of structural tremie concrete by insuring greater reliability. Achieving these two objectives will permit significant savings in costs and time on major underwater construction projects.

The work covered by this report consists of three interrelated areas of investigation The first area considers tremie concrete mixture design and tremie concrete flow after leaving the tremie pipe. The second area considers temperature development in massive tremie placements. The third area of investigation involved a project which, although not a mass underwater placement, offered a unique opportunity to examine a tremie placement at extreme depths (280 ft (85 m)) and which used a mixture suitable for mass placements. The work performed in each of these three areas of investigation is described in Chapters 1 through 6. Chapter 7 contains conclusions and recommendations relating to all areas and identifies areas requiring additional study. Additionally, Chapter 7 contains a recommended practice and a guide specification for massive tremie placements.

The work described in this report was jointly financed by the Federal Highway Administration (FHWA) and the University of California Sea Grant Program. This diversity of funding represents the diversity of applications for the results of the work. The recommendations presented apply to all massive underwater concrete placements whether for a bridge pier for a major highway or for a footing for an offshore terminal.

Much of the work described in this report was connected with the construction of the tremie

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* For more information on the tremie technique see references 1 through 5.

concrete seal for Pier 12 of the I-205 Bridge over the Columbia River near Portland, Oregon. An additional task covered by the FHWA grant for this research project was to provide logistical support, through the State of Oregon Highway Department, to three other groups of investigators working at the Pier 12 site. These investigations were aimed at determining the quality of the concrete in the seal by nondestructive methods. The specific investigations were as follows:

a. Lawrence Livermore Laboratory: Cross-Borehole Electromagnetic Examination; FHWA Purchase Order #7-3-0069, Task F.

b. Ensco, Inc.: Short Pulse Radar Investigation and High Energy Sparker System Investigation; DOT contracts DOT-FH-11-9120 and DOT-FH-11-9422.

c. Holosonics, Inc.: Through Transmission Acoustic Surveys for Evaluation of Tremie Concrete: DOT contract DOT-FH-11-9268, Task D.

The support received from Mr. Allan Harwood, Project Engineer for the State of Oregon, I-205 Bridge Project, and from Mr. Joe Turner, Resident Engineer, Corps of Engineers, Wolf Creek Dam Remedial Work, is gratefully acknowledged.

CHAPTER 1

SMALL-SCALE LABORATORY COMPARISONS OF SELECTED TREMIE CONCRETE MIXTURES

1.1 Objectives. The objectives of this portion of the project were to define the characteristics of a concrete mixture necessary for successful placement by tremie and to evaluate several non-traditional concrete mixtures which appeared to have potential for use in tremie placements. To accomplish these objectives, a variety of concrete mixtures meeting general guidelines for placement by tremie was compared to a reference tremie mixture using a series of standard and non-standard laboratory tests.

1.2 Background.

1.2.1 Workability of tremie concrete. There are two concrete characteristics generally regarded as critical for a successful tremie placement. The concrete must flow readily and it must be cohesive. In this case, cohesion is thought of as that property which prevents the concrete from segregating as well as prevents the cement from being washed out of the concrete due to contact with water. In practice, flowability and cohesiveness are usually achieved by adding extra cement, maintaining a low water-cement ratio and a high percentage of fine aggregate, and by having a high slump.

Unfortunately for the concrete technologist, these two desired characteristics are neither easily defined nor easily measured. These two terms may be replaced by the more general term "workability" which is commonly used to describe essentially the same characteristics for concrete which is placed in the dry. Although it will be shown that workability is no easier to measure than flowability or cohesiveness, there is certainly a great deal of previous work to draw upon.

An excellent definition for workability, which includes the characteristics required for tremie placement, was presented by Powers (ref. 6), "Workability is that property of a plastic concrete mixture which determines the ease with which it can be placed, and the degree to which it resists segregation. It embodies the combined effect of mobility and cohesiveness."

This definition is certainly not controversial. The difficulty arises in determining what properties of a fresh concrete determine its workability. Following is a brief sampling from the literature.

1. Powers (ref. 6) listed three factors as defining workability:

(a) The quantity of cement-water paste (including admixtures, if any) per unit volume of concrete.

(b) The consistency of the paste - which is dependent on the relative proportions and the kinds of material of which it is composed.

(c) The gradation and type of the aggregate.

2. Herschel (ref. 7) listed four characteristics which he thought defined the workability of a concrete mixture. These were "harshness, segregation, shear resistance and stickiness." His paper included tests for each of these items as well as examples of the use of the tests to evaluate a variety of concrete mixtures.

3. Tattersall (ref. 8) in an exhaustive study lists five factors affecting the workability of concrete:

(a) the time elapsed since mixing:

(b) the properties of the aggregate, in particular, particle shape and size distribution, porosity, and surface texture;

(c) the properties of the cement, to an extent that is less important in practice than the properties of the aggregate;

(d) the presence of admixtures;

(e) the relative proportions of the mix constituents.

Tattersall takes a rheological approach to measuring workability and argues that any of the commonly used tests for workability measure only one aspect while measurement of more than one is required. He writes that "at least two constants are needed to characterize the workability of fresh concrete, and the two constants are dimensionally different."

Tattersall concedes that development of a practical test to determine these two constants is some time away.

Presentation of theories of the factors comprising workability could go on for some length. Tattersall alone lists 143 references. A sufficient sample has been presented to establish that there is a wide variety of concepts concerning workability for which an equally large variety of tests have been proposed.

Based upon the work of the authors discussed above (and others), the following conclusions were drawn for the present work:

1. There is no single test which will provide definitive data on the workability of a concrete mixture. Any attempt to develop a single test for use with tremie concrete would probably be futile.

2. The most beneficial approach would be to apply a series of standard tests (each measuring some characteristic of potential tremie concretes) and non-standard tests (designed specially to relate to tremie placement) to a reference concrete mixture and the other mixtures of interest. Behavior of the various mixtures in relation to the reference mixture could then be assessed.

3. The objective of the testing would be to determine the significant characteristics required of tremie concrete, while simultaneously evaluating the selected mixtures, rather than to develop a single recommended concrete mixture.

With these conclusions in mind, a number of standard tests were reviewed to determine their suitability for use in this project. Several of the more common tests (i.e., Powers' Remolding Test) were eliminated prior to beginning actual laboratory work due to their incompatibility with concretes in the desired slump range. The tests which were selected are described in the next section.

1.2.2. Description of tests performed. A summary of the test program is presented in Table 1. The basic test plan was to subject each of the concrete mixtures to the selected tests three times. To insure objectivity, no mixture was tested more than once on a given day.

Due to capacity limitations in the laboratory mixing equipment, each day's test of a particular concrete mixture required that multiple batches of concrete be produced. Initially, four batches (1.8 ft^3 each (0.05 m^3)) were required. Later, after two tests had been dropped from the test program, the number of batches required was reduced to three. Table 1 also shows which tests were performed on each batch of concrete.

For each of the batches of concrete produced, the sump, unit weight, air content (two of every three batches), and temperature of the concrete were determined immediately after completion of mixing. If these variables were within the correct range for the mixture being tested, the batch was accepted as being representative of that mixture.

All concrete was batched and mixed in accordance with ASTM C 192* (CRD-C 10)**. As far as was possible, all tests throughout the test program were performed by the same individual to eliminate any operator induced variations.

A description of each of the tests in the program follows:

1. Slump test.

Standard: ASTM C-143 (CRD-C 5)
Frequency: One test per batch.
Data reported: Slump, in. (cm).

2. Unit weight.

Standard: ASTM C-138 (CRD-C 7).
Frequency: One test per batch.
Data Reported: Unit weight, lb/ft^3 (kg/m^3).

3. Air content (pressure method).

Standard: ASTM C-231 (CRD-C 41).
Frequency: Initially, two tests per four batches. Later, two tests per three batches.
Data Reported: Air content, percent.

4. Bleeding.

Standard: ASTM C-232 (CRD-C 9).

Frequency: One test per day.
Data reported: Total bleed water accumulation at 160 minutes (± 10 min) after completion of mixing, ml; bleed water as percentage of available mixing water.

5. Compressive Strength.

Standard: ASTM C-39 (CRD-C 4).
Frequency: Three cylinders (6 x 12 in. (15.2 x 30.5 cm)) were prepared from each batch.
Remarks: Specimens were cured in accordance with ASTM C-192 (CRD-C 10) and capped in accordance with ASTM C-617 (CRD-C 29) using a sulfur mortar. Testing was accomplished at 7, 28, and 90 days. Of the three cylinders made from a particular batch, one was tested at each age.
Data Reported: Compressive strength, $lb/in.^2$ (MPa).

6. Splitting Tensile Strength.

Standard: ASTM C-496 (CRD-C 77).
Frequency: One cylinder (3 x 6 in. (7.6 x 15.2 cm)) was prepared from each batch.
Remarks: Specimens were cured in accordance with ASTM C-192 (CRD-C 10). Testing was done at 28 days.
Data Reported: Splitting tensile strength, $lb/in.^2$ (MPa).

7. Time of Setting.

Standard: ASTM C-403 (CRD-C 86).
Frequency: One test per day.
Data Reported: Time of initial and final setting, minutes.

8. Relative Temperature Development.

Standard: None
Frequency: Two cylinders (6 x 12 in. (15.2 x 30.5 cm)) per day.
Remarks: Disposable metal cylinder molds were filled with concrete using the same procedures as the compressive strength cylinders. Each mold contained a thermocouple tied at the midpoint. Care was taken during the concrete placement to insure that the thermocouple was not disturbed. Each cylinder was wrapped in a fiberglass insulation blanket and placed in a constant temperature room. Concrete temperatures were recorded using a strip chart recorder and a digial thermometer.

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* ASTM test designations are from the Annual Book of ASTM Standards (ref. 9).

** CRD-C test designations are from the Corps of Engineers Handbook for Concrete and Cement (ref. 10).

TABLE 1 - SUMMARY OF TEST PROGRAM*

Test and Standard	Frequency	Batch 1**	Batch 2**	Batch 3**
Slump ASTM C-143† CRD-C 5††	1 per batch	Yes	Yes	Yes
Unit Weight ASTM C-138 CRD-C 7	1 per batch	Yes	Yes	Yes
Air Content ASTM C-231 CRD-C 41	2 per day	Yes	No	Yes
Bleeding ASTM C-232 CRD-C 9	1 per day	No	Yes	No
Compressive Strength ASTM C-39 CRD-C 4	9 cylinders per day (6 × 12 in. (15.2 × 30.5 cm))	3 cylinders	3 cylinders	3 cylinders
Splitting Tensile Strength ASTM C-496 CRD-C 77	3 cylinders per day (3 × 6 in. (7.6 × 15.2 cm))	1 cylinder	1 cylinder	1 cylinder
Time of Setting ASTM C-403 CRD-C 86	1 per day	Yes	No	No
Temperature Development Nonstandard	2 cylinders per day (6 × 12 in. (15.2 × 30.5 cm))	Yes	No	Yes
Slump Loss Nonstandard	1 series per day	Yes	No	No
Compacting Factor British Standard	2 per day (Abandoned - no data reported)	NA	NA	NA
Segregation Susceptibility Nonstandard	2 per day	No	Yes	Yes
Tremie Flow Nonstandard	2 per day	No	Yes	Yes
Flow Trough Nonstandard	2 per day (Abandoned - no data reported)	NA	NA	NA

*3 batches = 1 day's test of a particular mixture
3 days' tests = complete test of a mixture

**1.8 ft^3 (0.05 m^3)

†ASTM test designations from Reference 9
††CRD-C test designations from Reference 10

Data Reported: Maximum temperature increase above mixing temperature, degrees F (degrees C); time to achieve maximum temperature increase, hours.

9. Slump Loss.

Standard: none.
Frequency: One series of tests per day.
Remarks: Approximately 0.5 ft^3 (0.01 m^3) of concrete was set aside from the first batch. At specified times after mixing, a slump test in accordance with ASTM C-143 (CRD-C 7) was performed. Concrete used in the test was returned to the storage pan. The concrete in the pan was remixed by hand prior to each test.
Data Reported: Slump, inches (cm); slump as a percentage of initial slump at T = 15, 30, 60, 90, and 120 minutes after completion of mixing.

10. Compacting Factor.

Standard: British Standard 1881:1952 (ref. 11). This is not a standard test in the United States.
Frequency: Two tests per day.
Remarks: Figure 1 shows the basic apparatus. Concrete is placed into the top hopper and the flap is released allowing the concrete to drop into the lower hopper. The lower flap is then released allowing the concrete to drop into the cylinder. The concrete in the cylinder is then struck off and the cylinder is weighed. The cylinder is then refilled and thoroughly compacted. The ratio of the weight of the partially compacted (dropped) cylinder to the weight of the thoroughly compacted cylinder is termed the compacting factor. More information on this test may be found in the report of ACI Committee 211 (ref. 11) or in the work of Mather (ref. 12).
Data Reported: None, this test was abandoned after initial experimentation showed that it does not discriminate well among high slump concretes of the nature of the mixtures being tested.

11. Segregation Susceptibility

Standard: None.
Frequency: Two tests per day.
Remarks: This test was a modification of that presented by Hughes (ref. 13) and later revised by Ritchie (ref. 14). In the present case, the compacting factor apparatus was modified to be used on this test by fabricating a cone and two wooden discs. The modified apparatus is shown in Figure 2. The test begins similarly to the compacting factor test by dropping concrete into the bottom hopper. Then the concrete is dropped onto the cone which caused it to scatter onto two discs. The cohesion of the concrete controls the degree of scatter. Figure 3 shows a sample of concrete after being dropped on the cone.

The weight of concrete on the small and large discs was determined. Then the concrete on each disc was wet sieved on a 1/4 in. (0.64 cm) screen to obtain the coarse aggregate which was oven dried and weighed. Thus the following four weights were known:

Weight of concrete, large disc: B
Weight of coarse aggregate, large disc: Ba
Weight of concrete, small disc: A
Weight of coarse aggregate, small disc: Aa

Hughes used the above data to define the Stability Factor as follows:

$$SF = (Aa/A)/(Ba/B)$$

Ritchie used the same data to define the Cohesion Index as follows:

$$CI = B/A$$

Data Reported: Stability Factor; Cohesion Index.

12. Tremie Flow.

Standard: None.
Frequency: Two tests per day.
Remarks: This test was designed to simulate concrete flow through a tremie pipe. The apparatus is shown in Figures 4 and 5. Approximately 0.20 ft^3 (0.006 m^3) of concrete was placed into the tube in three layers. Each layer was rodded 25 times to produce a uniform density from test to test. After the concrete was in place, the tube was lifted until the mouth of the tube was 4.5 in. (11.4 cm) above the bottom of the pail allowing the concrete in the tube to flow into the pail (Figure 6).

After the flow stopped, the distance from the top of the tube to the top of the concrete in the tube was determined.
Data Reported: Flow of concrete, in. (cm).

13. Flow Trough.

Standard: None.
Frequency: Two tests per day.
Remarks: This test was intended to provide a qualitative measure of the ability of a concrete to resist washing out of the cement when flowing into water. The apparatus is shown in Figure 7. Approximately 0.1 ft^3 (0.003 m^3) of concrete was placed into the trough above the slide gate. When the gate was lifted, the concrete was intended to flow into the water and a qualitative estimate of cement washout was to have been made.
Data Reported: None, this test was abandoned after initial testing showed that no useful data was being obtained.

1.2.3. Description of concrete mixtures evaluated. The first step in the selection of mixtures to test was the development of the standard or reference mixture. The mixture selected was based upon recommendations from the literature and upon the senior author's personal experience on a number of major tremie placements. The basic elements of the reference mixture were:

Cement: 7 1/2 sacks/yd^3 (705 lb/yd^3) (418 kg/m^3) Water-cement ratio: ≤ 0.45.
Fine aggregate: 45% by weight of total aggregate.

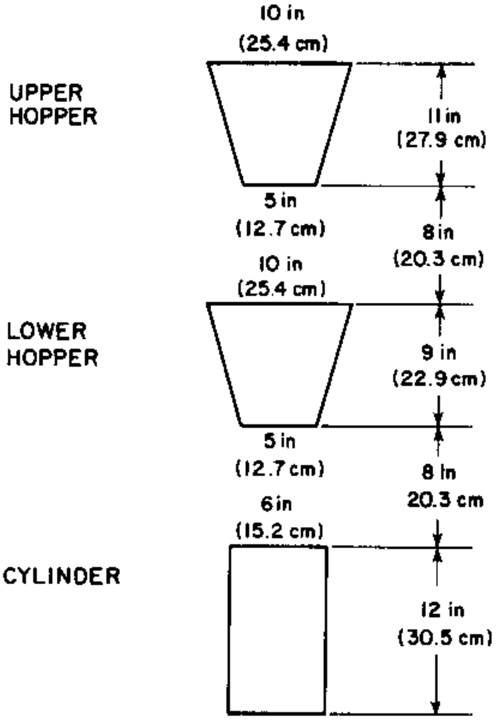

Figure 1. Schematic of compacting factor apparatus.

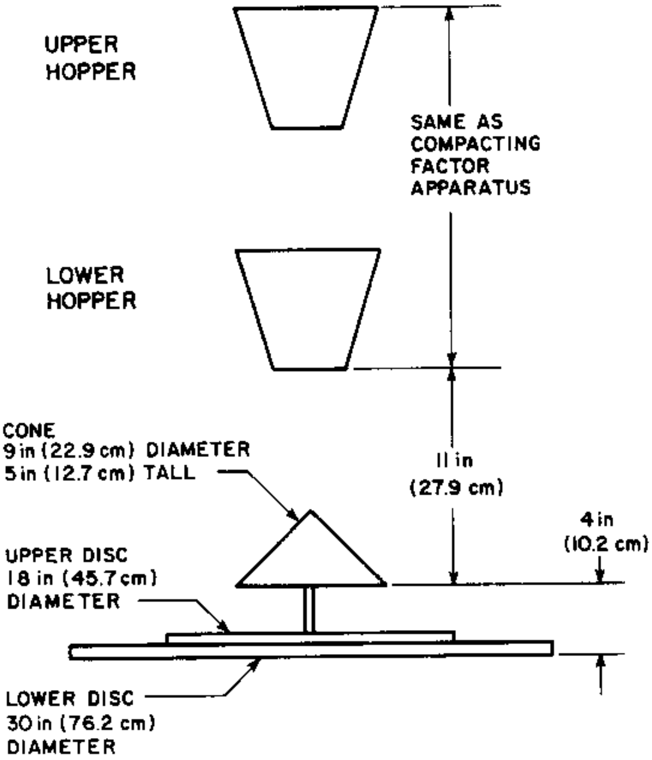

Figure 2. Schematic of segregation susceptibility apparatus.

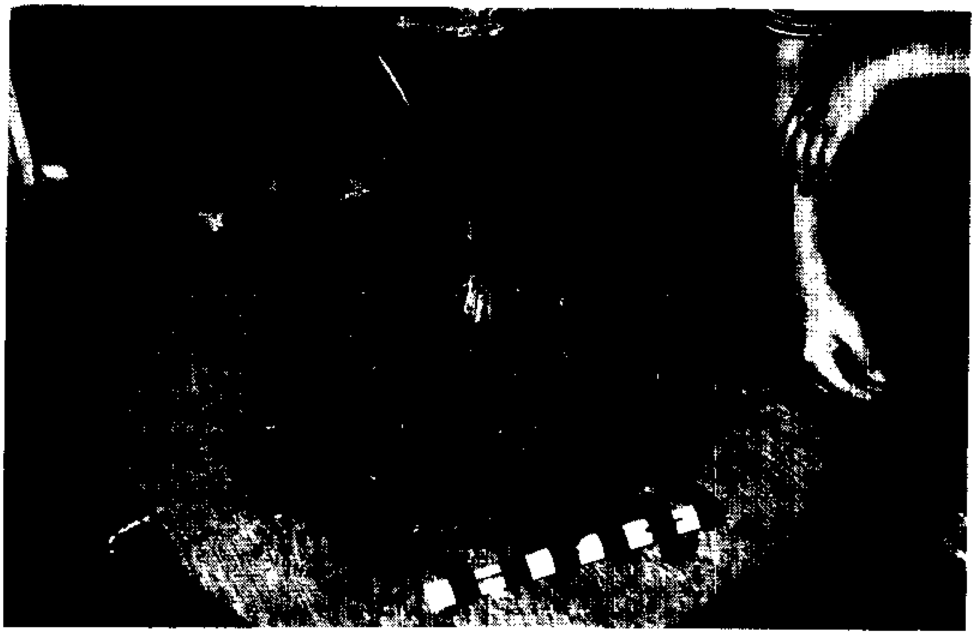

Figure 3. Concrete sample after performance of segregation susceptability test.

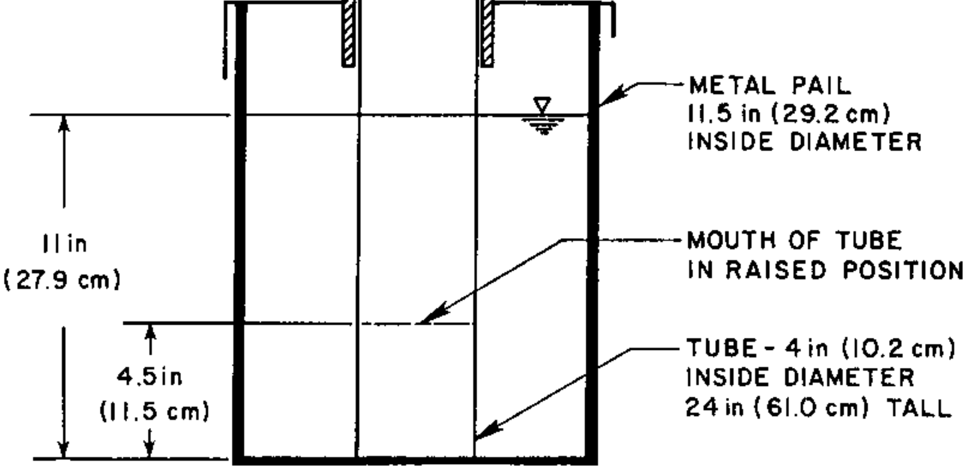

Figure 4. Schematic of tremie flow test apparatus.

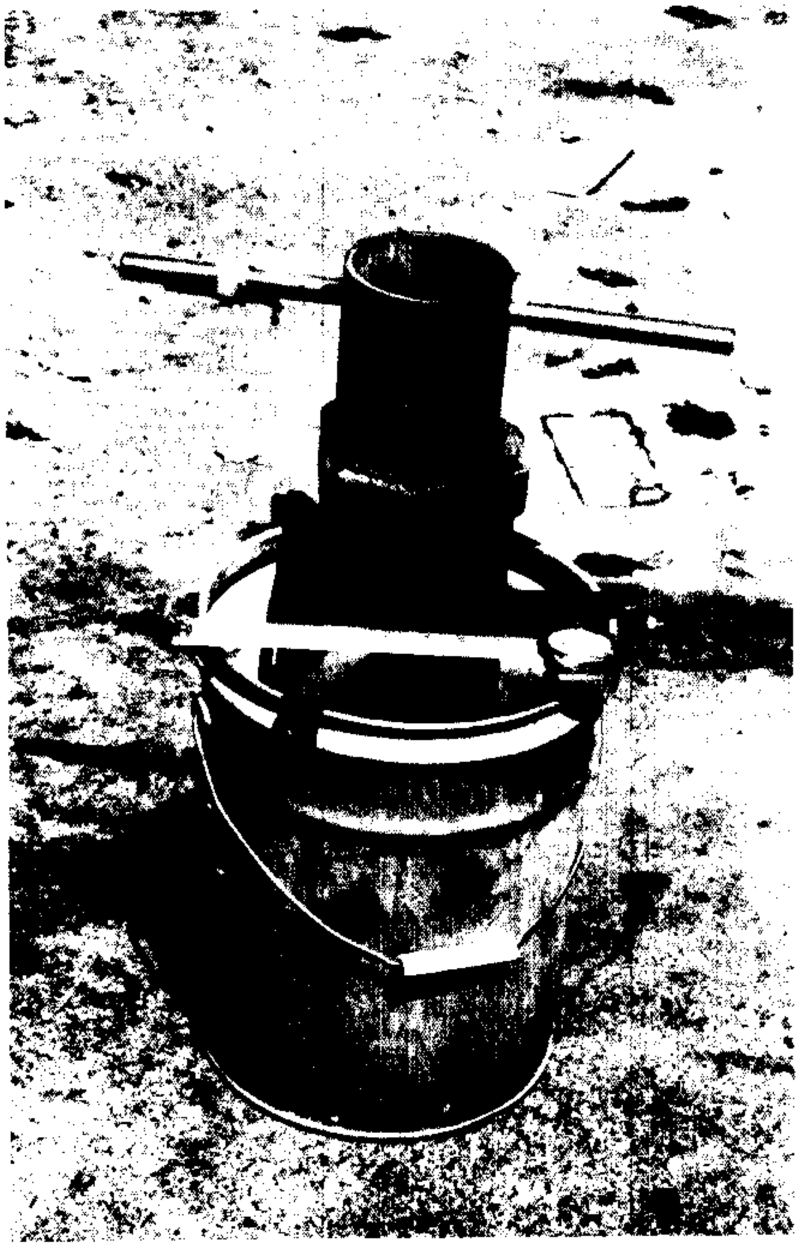

Figure 5. Tremie flow test apparatus.

Figure 6. Tremie flow test being performed. Tube is being lifted off of bottom of pail.

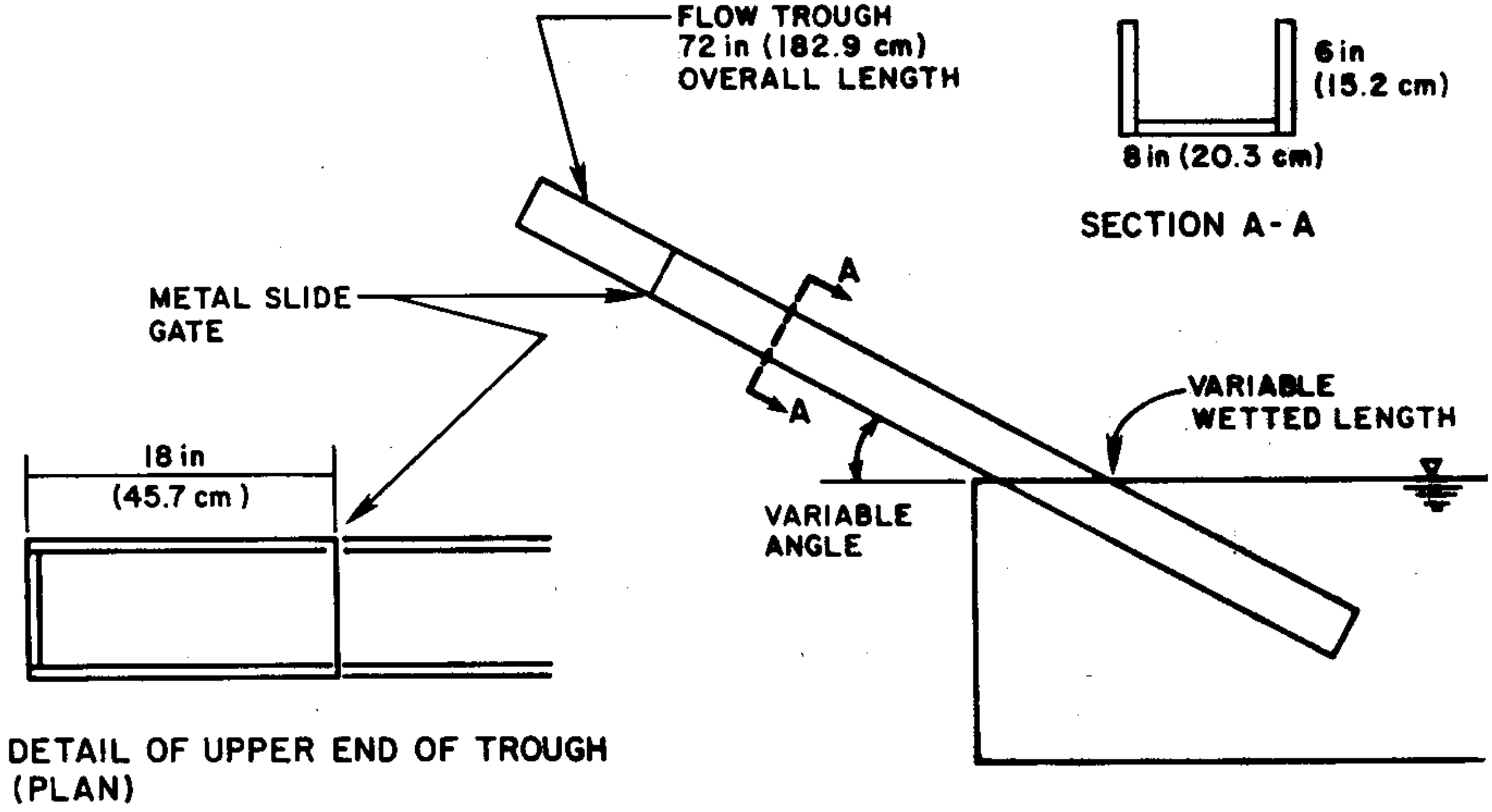

Figure 7. Schematic of flow trough apparatus.

Coarse aggregate: 3/4 in. (19.0 mm) maximum.
Admixture: Water reducer/retarder, in accordance with manufacturers recommendations.
Slump: 6 1/2 in. ± 3/4 in. (16.5 cm ± 1.9 cm).

It is interesting to note that the characteristics of this reference mixture, which was derived from the experience of many engineers on a variety of tremie concrete placements, meet very closely the several requirements listed above (section 1.2.1) as indicating good workability for a concrete mixture.

It must be noted that two of the items describing the reference mixture, high slump and a low water-cement ratio, could not be achieved in all of the mixtures evaluated. In those cases where there was a conflict, achievement of a slump in the desired range was used as the determining factor.

Once the reference mixture was established, the remainder of the mixtures in the program were developed. Table 2 presents a summary of all of the mixtures evaluated. Details of each mixture design may be found in Appendix A.

The first group of mixtures (Mixtures 2 and 3) were direct variations of the reference mixture which require no description.

The next group of mixtures was developed in response to the authors' concrern that little, if any, consideration was being given to problems of heat generation in massive tremie placements. While much work has been done concerning temperature development in massive placements done in the dry, as of the time of this testing, no such effort had been put forward for underwater placements.

The authors felt that one of the techniques frequently used for reducing temperature problems of mass concrete placed in the dry - pozzolanic replacement of a percentage of the cement - would also be suitable for use in underwater placements. However, unlike mass placements in the dry where total cement plus pozzolan contents are very low, the pozzolanic replacements for the candidate tremie mixtures were based upon the original 705 lb/yd^3 (418 kg/m^3) cement content since a harsh, no slump concrete would not have been acceptable. Mixtures 4, 5, and 6 were developed to evaluate pozzolanic replacements.

The next group of mixtures was based upon work published by The Netherlands Committee for Concrete Research (ref. 3) describing research on admixtures to improve the quality of tremie-placed concrete: "The Committee was on the look-out for admixtures which, as a result of exercising a 'glue-like' effect, would give the fresh concrete better cohesion so that it would be less severely attacked by water."

A variety of admixtures were evaluated primarily on the basis of two factors: the compressive strength of cubes manufactured above and below water; and, the washing out of cement from the concrete when dropped through water. Their findings were:

a. The addition of a small amount of bentonite (0.5% by weight of cement) gave the greatest ratio of underwater to dry strength for the cubes.

b. Larger amounts of bentonite (up to 5%) showed improvements in cement wash-out at the expense of compressive strength for cubes manufactured both above and below water.

Thus it appeared that bentonite additon or replacement would be beneficial. Mixtures 7, 8, and 9 were developed to examine a wide range of concentrations of bentonite.

The final group of mixtures was developed based upon experience in grouting where a thixotropic agent may be added to thicken grouts. It was believed that such an agent could help a tremie-placed concrete resist washing out of cement. A proprietary agent was selected and used to develop Mixtures 10 and 11. Due to the extreme thixotropic behavior of these mixtures as noted during trial batch preparations, the cement in Mixture 11 was reduced to 611 lb/yd^3 (362.5 kg/m^3) in an effort to develop a more economical mixture.

Due to problems with the behavior of Mixtures 10 and 11 which raised doubts about their suitability for use in a gravity feed tremie situation, testing of these two mixtures was limited to one repetition only. The problems which developed are described below.

Description of the materials used in the test mixtures may be found in Appendix B.

<u>1.3 Observations and discussion.</u> Table 3 presents a summary of the results of the tests for all of the mixtures. Summaries for each mixture are in Appendix C while data from each of the individual tests performed are in Appendix D. Discussion of the results of the specific tests is presented in the following sections. This data should be reviewed with the thought in mind that there were two basic types of tests in the test program - those in which a high ranking is believed to be indicative of improved performance as tremie-placed concrete and those in which the ranking is not particularly significant. The latter type of test was included to insure that no anomolies in performance had been caused by the various admixtures and additives.

<u>1.3.1 Slump, unit weight, air content, and temperature tests.</u> The data for all of the mixtures were within acceptable ranges. The following minor discrepancies were noted:

1. The slump for Mixture 9 was slightly below the stated range. However, this was tolerated to prevent increasing the water-cement ratio any higher than 0.67 which was necessary to achieve the 5.3 in. (13.5 cm) slump.

2. The slump for Mixture 11 was slightly above the stated range. This was attributed to the

TABLE 2 - SUMMARY OF CONCRETE MIXTURES TESTED

No.	Description*	Water-cement Ratio**
1	Standard Mixture (reference)	0.45
2	Standard Mixture without Water Reducing/Retarding Admixture	0.46
3	Standard Mixture without Water Reducing/Retarding Admixture with Air-Entraining Admixture	0.44
4	Standard Mixture with 20 Percent Replacement of Cement by Pozzolan	0.51
5	Standard Mixture without Water Reducing/Retarding Admixture with 20 Percent Replacement of Cement by Pozzolan	0.53
6	Standard Mixture with 50 Percent Replacement of Cement by Pozzolan	0.62
7	Standard Mixture with 1 Percent (by Weight of Cement) Addition of Bentonite	0.45
8	Standard Mixture with 10 Percent Replacement of Cement by Bentonite	0.58
9	Standard Mixture with 20 Percent Replacement of Cement by Bentonite	0.67
10	Standard Mixture with 1 Percent (by Weight of Cement) Thixotropic Additive	0.48
11	Standard Mixture less 94 lbs/yd^3 (55.8 kg/m^3) Cement with 1 Percent (by Weight of Cement) Thixotropic Additive without Water Reducing/Retarding Admixture	0.54

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*Replacements of cement by pozzolan or bentonite are given in terms of weight of cement. See Appendix A for mixture details.

**Water-cement ratio is based on weight of cement plus any replacement material.

TABLE 3 - SUMMARY OF MIXTURE EVALUATION TEST DATA

Test Item	Mixture										
	1	2	3	4	5	6	7	8	9	10*	11*
Slump, in. (cm)	7.2 (18.3)	6.7 (17.0)	6.5 (16.5)	6.6 (16.8)	6.3 (16.0)	6.0 (15.2)	6.6 (16.8)	6.7 (17.0)	5.3 (13.5)	6.8 (17.3)	7.5 (19.1)
Unit Weight, lb/ft^3 (kg/m^3)	150.6 (2413)	150.5 (2411)	142.4 (2281)	147.1 (2357)	146.4 (2345)	140.6 (2252)	150.3 (2408)	145.2 (2326)	140.4 (2249)	145.6 (2333)	147.6 (2365)
Air Content, Percent	1.6	1.2	6.9	1.4	1.2	1.3	1.3	0.9	1.3	4.6	2.5
Temperature, °F (°C)	71 (22)	74 (23)	73 (23)	72 (22)	73 (23)	74 (23)	72 (22)	73 (23)	74 (23)	73 (23)	72 (22)
Tremie Flow, in. (cm)	11.4 (29.0)	10.4 (26.4)	12.5 (31.8)	12.5 (31.8)	11.5 (29.2)	12.4 (31.5)	9.4 (23.9)	11.1 (28.2)	11.7 (29.7)	9.2 (23.4)	11.7 (29.7)
Time of Setting, min											
- initial	383	268	305	350	266	368	347	363	346	**	387
- final	497	366	439	485	409	593	461	489	535	**	583
Bleeding, Percent of Available Water	2.4	2.1	1.7	1.6	0.9	0.6	2.4	1.2	0.3	0.0	0.0
Cohesion Index	0.07	0.08	0.01	0.04	0.05	0.00	0.06	0.03	0.00	0.10	0.16
Stability Factor	0.79	0.68	0.93	0.82	0.88	1.00	0.83	0.86	1.00	0.88	0.84
Temperature Development											
- max. increase °F (°C)	34 (19)	31 (17)	34 (19)	29 (16)	29 (16)	19 (11)	33 (18)	34 (19)	34 (19)	31 (17)	NA
- time to max., hours	19.0	15.1	15.9	17.6	15.8	16.5	16.9	16.6	14.4	21.6	NA
Compressive Strength, lb/in.^{2} (MPa)											
- 7 days	4330 (29.9)	3750 (25.9)	2930 (20.2)	2790 (19.2)	2600 (17.9)	930 (6.4)	3990 (27.5)	2150 (14.8)	1420 (9.8)	3600 (24.8)	2600 (17.9)
- 28 days	6140 (42.3)	5630 (38.8)	4320 (29.8)	5340 (36.8)	4950 (34.1)	2860 (19.7)	5640 (38.9)	3770 (26.0)	2520 (17.4)	5570 (38.4)	4680 (32.3)
- 90 days	7300 (50.3)	6960 (48.0)	5390 (37.2)	6250 (43.1)	5850 (40.3)	4660 (32.1)	7040 (48.5)	4730 (32.6)	3180 (21.9)	NA	NA
Splitting Tensile Strength, lb/10^2 (MPa)	745 (5.1)	720 (5.0)	630 (4.3)	675 (4.7)	660 (4.6)	435 (3.0)	720 (5.0)	535 (3.7)	395 (2.7)	NA	NA
Slump Loss, Percent of Original Slump Remaining											
T = 15 min	79	91	87	84	91	100	61	88	92	96	91
= 30 min	78	83	87	80	82	92	64	78	86	96	94
= 60 min	55	72	82	69	76	78	57	67	60	100	63
= 90 min	50	62	77	66	64	64	55	54	42	76	47
= 120 min	42	58	68	53	59	50	42	43	29	80	38
MIXTURE INFORMATION											
Cement and Replacement Materials, lb/yd^3 (kg/m^3)											
- Cement	705 (418)	705 (418)	705 (418)	564 (335)	564 (335)	353 (209)	705 (418)	635 (377)	564 (335)	705 (418)	611 (363)
- Pozzolan	-	-	-	141 (84)	141 (84)	353 (209)	-	-	-	-	-
- Bentonite	-	-	-	-	-	-	8 (5)	71 (42)	141 (84)	-	-
Water-Cement (+ pozzolan or + bentonite ratio)	0.45	0.46	0.44	0.51	0.53	0.62	0.45	0.58	0.67	0.48	0.54
Admixture A ≡ Air entraining P ≡ Water reducer/retarder T ≡ Thixotropic	P	None	A	P	None	P	P	P	P	P, T	T

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*Data for mixtures 10 and 11 based on one day's test only.

**Did not set within observation period; achieved only 150 lb/in.^{2} (1.0 MPa) penetration resistance at 523 min.

difficulty of determining a slump versus mixing water relationship for an extremely thixotropic mixture. This difficulty in controlling the mixture by slump was one of the factors which eliminated this mixture from the complete test program.

3. The air content of Mixture 3 was slightly above the planned level. The discrepancy was accepted since it was not large enough to be detrimental to the test program.

1.3.2. Tremie flow test. Table 4 presents a ranking of the mixtures based upon this test. The greatest flow was given the highest ranking. Six of the mixtures ranked higher than the reference mixture in this test. The tremie flow value does not appear to be directly related to slump, as might be expected. The best performances were from the air-entrained concrete (Mixture 3) and the two concretes with the water reducer/retarder (Mixtures 4 and 6).

1.3.3 Time of setting test. Table 5 presents rankings of the mixtures based upon both initial and final setting times. The greatest time to achieve the defined penetration resistance (setting) was given the highest ranking in each case. This ranking scheme should not be interpreted to mean that greater times to achieve setting indicate more suitable tremie concrete mixtures. If time of setting is determined to be significant for a particular tremie placement, it can be easily controlled by use of appropriate admixtures.

With the exception of Mixture 10, none of the mixtures exhibited unsatisfactory setting characteristics. Mixture 10 showed an extreme retardation due to the combined action of the water reducer/retarder and the thixotropic additive. This occurrence points out the necessity for insuring that all admixtures are compatible.

1.3.4 Bleeding test. Table 6 presents a ranking for the mixtures based upon the percentage of available water lost through bleeding. The highest ranking has been given to the smallest amount of bleeding. Based upon this criteria, all of the mixtures bettered or equalled (one mixture) the performance of the reference mixture. Again, this ranking should not be interpreted to mean that no bleeding is necessarily better for a tremie concrete mixture. Rather, it may be stated that none of the mixtures evaluated would be expected to perform adversely based on this one factor.

It should be noted that for certain applications other than massive bridge piers or similar structures, large amounts of bleeding may be detrimental. One such case would be tremie-placed concrete used to fill a void beneath the base of an existing structure.

1.3.5 Segregation susceptibility tests. Table 7 presents rankings for the mixtures based upon the Cohesion Index and Stability Factor as determined in the segregation susceptibility tests. The basis for each of the rankings is explained below:

1. Cohesion Index. The Cohesion Index was defined earlier as

$$CI = B/A$$

where B = weight of concrete on the large disc
A = weight of concrete on the small disc

Thus the Cohesion Index is actually a measure of how well the mass of concrete holds together. For a very cohesive mixture no concrete would be found on the large disc and B would be zero. Therefore, a Cohesion Index of 0.0 would be the best case; and, the mixtures are ranked with the smallest Cohesion Index at the top of the rankings.

2. Stability Factor. Hughes (ref. 13) defined the stability of a concrete as its "ability to resist segregation of the coarse aggregate from the finer constituents while in an unconsolidated condition" His Stability Factor was defined earlier as:

$$SF = (Aa/A)/(Ba/B)$$

where A and B = as above
Aa = weight of coarse aggregate, small disc.
Ba = weight of coarse aggregate, large disc.

Each of the terms in the right side of the equation (Aa/A and Ba/B) define the ratio of the weight of the coarse aggregate in the sample to the total weight of that sample. If there is no segregation of coarse aggregate during the test, the Stability Factor will be 1.0, the best case. The mixtures are ranked in order of decreasing Stability Factor.

The preferred performance of a tremie concrete would be the highest ranking in either factor. For the Cohesion Index all but three of the mixtures ranked above the reference mixture. For the Stability Factor, all but one mixture out performed the reference. Considering both tests, the best results were seen for the 50% pozzolan replacement (Mixture 6), the 20% bentonite replacement (Mixture 9), and the air-entrained concrete (Mixture 3).

The poor ranking based on Cohesion Index for the two mixtures (10 and 11) containing the thixotropic additive was surprising and not readily explainable. Perhaps the energy developed by the concrete falling onto the cone was sufficient to overcome the thixotropic nature of the mixtures thus allowing a portion of the mass to flow onto the large disc.

1.3.6 Temperature development test. Table 8 presents rankings of the mixtures based upon increase in temperature after mixing. The smallest increase in temperature was given the highest ranking.

The mixtures are ranked essentially as would be expected on the basis of cementitious material content. However, the two mixtures containing the significant amounts of bentonite (Mixtures 8 and 9) show surprisingly large

TABLE 4 - RANKINGS, TREMIE FLOW TESTS

Flow, in. (cm)	Mixture	Slump, in. (cm)
12.5 (31.8)	3 4	6.5 (16.5) 6.6 (16.8)
12.4 (31.5)	6	6.0 (15.2)
11.7 (29.7)	9 11	5.3 (13.5) 7.5 (19.1)
11.5 (29.2)	5	6.3 (16.0)
11.4 (29.0)	1	7.2 (18.3)
11.1 (28.2)	8	6.7 (17.0)
10.4 (26.4)	2	6.7 (17.0)
9.4 (23.9)	7	6.6 (16.8)
9.2 (23.4)	10	6.8 (17.3)

TABLE 5 - RANKINGS, TIME OF SETTING TESTS*

Initial Setting		Final Setting	
Minutes	Mixture	Minutes	Mixture
387	11**	593	6
383	1	583	11**
368	6	535	9
363	8	497	1
350	4	489	8
347	7	485	4
346	9	461	7
305	3**	439	3**
268	2**	409	5**
266	5**	366	2**

*Mixture 10 had not achieved initial set after 523 min.

**Denotes mixtures which did not contain the water reducer/retarder.

TABLE 6 - RANKINGS, BLEEDING TESTS

Bleeding, Percent Available Water	Mixture	Water-Cement Ratio
0.0	10	0.48
	11*	0.54
0.3	9	0.67
0.6	6	0.62
0.9	5*	0.53
1.2	8	0.58
1.6	4	0.51
1.7	3*	0.44
2.1	2*	0.46
2.4	1	0.45
	7	0.45

*Denotes mixtures which did not contain the water reducer/retarder which promotes bleeding.

TABLE 7 - RANKINGS, SEGREGATION SUSCEPTIBILITY TESTS

Cohesion Index*		Stability Factor**	
C. I.	Mixture	S. F.	Mixture
0.00	6 9	1.00	6 9
0.01	3	0.93	3
0.03	8	0.88	5 10
0.04	4	0.86	8
0.05	5	0.84	11
0.06	7	0.83	7
0.07	1	0.82	4
0.08	2	0.79	1
0.10	10	0.68	2
0.16	11		

*For C. I., best ranking is 0.00.
**For S. F., best ranking is 1.00.

TABLE 8 - RANKINGS, TEMPERATURE DEVELOPMENT TESTS

Temperature Increase °F (°C)	Mixture*
19 (11)	6
29 (16)	4 5
31 (17)	2 10**
33 (18)	7
34 (19)	1 3 8 9

*Insufficient data were available for mixture 11

**Based on two cylinders only.

TABLE 9 - RANKINGS, COMPRESSIVE STRENGTH TESTS

	7 Days		28 Days			90 Days*	
Ranking	Comp. Str., lb/in.^{2} (MPa)	Mix	Comp. Str., lb/in.^{2} (MPa)	Mix	Water-Cement Ratio	Comp. Str., lb/in.^{2} (MPa)	Mix
I	4330 (29.9)	1	6140 (42.3)	1	0.45	7300 (50.3)	1
II	3990 (27.5)	7	5640 (38.9)	7	0.45	7040 (48.5)	7
III	3750 (25.9)	2	5630 (38.8)	2	0.46	6960 (48.0)	2
IV	3600 (24.8)	10	5570 (38.4)	10	0.48	6250 (43.1)	4
V	2930 (20.2)	3	5340 (36.8)	4	0.51	5850 (40.3)	5
VI	2790 (19.2)	4	4950 (34.1)	5	0.53	5390 (37.2)	3
VII	2600 (17.9)	11	4680 (32.3)	11	0.54	4730 (32.6)	8
VIII	2600 (17.9)	5	4320 (29.8)	3	0.44	4660 (32.1)	6
IX	2150 (14.8)	8	3770 (26.0)	8	0.58	3180 (21.9)	9
X	1420 (9.8)	9	2860 (19.7)	6	0.62		
XI	930 (6.4)	6	2520 (17.4)	9	0.67		

*Mixtures 10 and 11 not tested at 90 days.

temperature increases considering the reduced amounts of cement in them. These two mixtures also showed shorter than typical times to develop the maximum temperatures recorded (see Table 3). The cause of these anomalies is unknown. Additional temperature investigations should be conducted prior to use of a high bentonite content mixture.

A caution concerning this temperature data must be raised. These tests were intended to provide relative comparisons of the various mixtures only. The tests were not adiabatic and the data should not be interpreted as temperature increases to expect in actual placements. See Chapters 3 and 5 concerning temperatures in actual placements.

1.3.7 Compressive strength tests. Table 9 presents rankings of the mixtures based upon the compressive strength data. The highest ranking was given to the highest compressive strength. This data shows no surprises - the mixtures are ranked as would be expected based upon water-cement ratios and cementitious material contents. None of the mixtures appears to have been adversely affected by the various chemical and mineral admixtures.

As with several of the other tests, a high ranking in compressive strength does not necessarily imply that a concrete mixture is better suited for tremie placement. The strength required of the concrete should be a function of the particular placement (structural or nonstructural).

1.3.8 Splitting tensile strength test. Table 10 presents a ranking of the mixtures based upon splitting tensile strength. As for compressive strength, the mixtures are listed in order of decreasing strength. This data shows no adverse readings; all of the mixtures achieved an appropriate percentage of the compressive strength.

1.3.9 Slump loss test. Table 11 presents rankings of the mixtures based upon slump loss characteristics. The highest rankings were given to the mixtures retaining the greatest percentage of initial slump at each time increment. A slow loss of slump indicating that the concrete is stiffening slowly would be beneficial in a tremie placement - particularly in a large placement with long flow distances.

Nearly all of the mixtures performed better than the reference concrete on this test - none was ranked lower than the reference mixture at all time intervals.

An overall ranking for slump loss performance may be obtained by adding the rankings of each mixture at each of the five time intervals. If the summations are then ranked, the following listing of slump loss performance (best to worst) is obtained: Mixture 10, 3, 6, 5, 2, 4, 11, 8, 9, and 7 and 1 (tie).

While the mixtures are somewhat scattered in slump loss performance, the following general points may be made:

1. The best performer, Mixture 10 (thixotropic additive and water reducer/retarder) showed extremely long set times due to an apparent incompatibility of the two admixtures. The slow setting characteristics are apparently being seen in the slump loss performance.

2. The mixtures containing bentonite (7, 8, 9) are all grouped near the bottom end of the rankings.

3. The mixtures containing pozzolan (4, 5, 6,) are near the upper end of the rankings. Mixture 4, lowest ranked of the three, showed improving slump loss characteristics in the later time intervals (90 and 120 min).

1.3.10 Overall performance. Of the various tests performed, three are believed to be directly indicative of performance as tremie-placed concrete: tremie flow, segregation susceptibility, and slump loss. A fourth test, temperature development, may also be significant, depending upon the placement situation. Table 12 presents a summary of the performance of the various mixtures on these four tests. This table shows the ordinal rankings of the mixtures on each of the four tests. The overall rankings were determined by summing the individual ranks. The lowest total in the summation was given the highest overall ranking. All four of the tests were weighted equally to develop the overall ranking.

Based on this approach, the mixtures may be listed from best to worst performers as follows: Mixture 6, 3, 4, 5, 9 10, 8, 2, and 1 and 7 (tie). Mixture 11, for which there was no temperature data, would rank no lower than fifth overall, and it would probably be somewhat higher. Following are comments on the performance of the top five mixtures.

1. Mixture 6 (50% pozzolan replacement with the water reducer/retarder). Although this concrete out did all others, it may not be practical for use due to its slow strength gain characteristics.

2. Mixture 3 (air-entrained). Although performing well, this mixture developed higher temperatures than did the mixtures containing pozzolan. Therefore, it may not be suited to all placements.

3. Mixture 4 (20% pozzolan replacement with the water reducer/retarder). Notes below with Mixture 5.

4. Mixture 5 (20% pozzolan replacement without the water reducer/retarder). Mixtures 4 and 5 showed quite favorable performances. There were however, minor inconsistencies in each: Mixture 5 failed to rank highly in the tremie flow test while Mixture 4 was somewhat low in the segregation susceptibility test due to a low ranking in the stability factor portion of that test.

5. Mixture 9 (20% bentonite replacement with the water reducer/retarder). Although this mixture

TABLE 10 - RANKINGS, SPLITTING TENSILE STRENGTH TESTS*

Splitting Tensile Strength lb/in.^{2} (MPa)	Mixture	Percent of 28-day Compressive Strength
745 (5.1)	1	12.1
720 (5.0)	2	12.8
	7	
675 (4.7)	4	12.6
660 (4.6)	5	13.3
630 (4.3)	3	14.6
535 (3.7)	8	14.2
435 (3.0)	6	15.2
395 (2.7)	9	15.7

[*] Mixtures 10 and 11 not evaluated in this test.

TABLE 11 - RANKINGS, SLUMP LOSS TESTS

T = 15 min.*		T = 30 min.*		T = 60 min.*		T = 90 min.*		T = 120 min.*	
Percent**	Mixture	Percent**	Mixture	Percent**	Mixture	Percent**	Mixture	Percent**	Mixture
100	6	96	10	100	10	77	3†	80	10
96	10	94	11†	82	3†	76	10	68	3
92	9	92	6	78	6	66	4	59	5†
91	2†	87	3†	76	5†	64	5†	58	2
	11†	86	9	72	2†		6	53	4
	5†	83	2†	69	4	62	2†	50	6
88	8	82	5†	67	8	55	7	43	8
87	3	80	4	63	11†	54	8	42	1
84	4	78	8	60	9	50	1		7
79	1		1	57	7	47	11†	38	11†
61	7	64	7	55	1	42	9	29	9

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[*] Time since completion of mixing.

[**] Percentage remaining of initial (T = 0) slump.

[†] Denotes those mixtures not containing the water reducer/retarder.

TABLE 12 - OVERALL CONCRETE PERFORMANCE

Mixture	Rankings*					Overall Ranking††
	Tremie Flow	Segregation Susceptibility**	Slump Loss†	Temperature Development	Summation	
1	7	9	10	7	33	9
2	9	11	5	4	29	8
3	1	3	2	7	13	2
4	1	6	6	2	15	3
5	6	4	4	2	16	4
6	3	1	3	1	8	1
7	10	7	10	6	33	9
8	8	4	8	7	27	7
9	4	1	9	7	21	5
10	11	7	1	4	23	6
11	4	9	7	NA	20+	≥ 5

*Ordinal rankings on each test.

**Combined ranking for stability factor and cohesion index.

†Combined ranking for all five slump loss tests.

††Based on summation of individual tests.

was ranked fifth overall, its potential for use appears limited due to poor performance on the slump loss test. Additionally, this mixture was consistently ranked near the bottom in the compressive and splitting tensile strength evaluations.

In general, the mixtures containing pozzolan seem to offer the greatest potential for use in a massive tremie placement. The appropriate replacement rate (between 20 and 50%) should be determined to meet the strength requirements of the in-place concrete.

In regard to the remaining mixtures, the following points may be made:

1. The reference mixture (1) did not perform particularly well. Neither did the mixtures which most closely resembled the reference, Mixtures 2 and 7. It therefore appears that it is practical and feasible to improve upon the traditional tremie mixture design.

2. The addition of varying amounts of bentonite seems to have done little to improve the performance of the three concretes. Mixture 7 (1% bentonite addition) was ranked ninth. Mixture 8 (10% bentonite replacement) was ranked seventh. Mixture 9 (20% bentonie replacement) while ranked fifth had low strength and poor slump loss behavior as discussed above. It is noted that mixtures similar to these performed best in the Dutch tests (ref. 3).

3. The addition of the thixotropic agent did not seem to offer any particular advantages. Mixture 11 would have certainly ranked out of the top performers had temperature data been available. If only the three tests for which complete data are available for Mixture 11 are considered, it would rank seventh overall. Although Mixture 10 ranked sixth overall, its usefulness would be impaired by the long set time.

Additionally, based upon these small-scale tests and the large-scale tests described in Chapter 2, it appears that the use of any thixotropic agent (bentonite or admixture) may not be appropriate for mass concrete placed by tremie. This conclusion is based on two considerations. First, if a thixotropic concrete stops flowing due to a break in placement (production, transportation, etc.), the material will stiffen due to its thixotropic nature. Depending upon the geometry of the placement, to restart the concrete flow may require significant energy inputs. The weight of the concrete in the tremie pipe may not be sufficient to provide the required shearing action to restart flow. The second consideration relates to the practical problem of controlling a thixotropic mixture. The temptation to add additional water to a "stiff" mix should be obvious. A practical means of controlling the concrete other than slump would certainly be necessary.

1.4 Summary.

The following items summarize these tests:

1. Eleven different concrete mixtures were evaluated for use in massive tremie placements. These concretes included a reference mixture, an air-entrained concrete, several mixtures with pozzolanic or bentonite replacements of varying amounts of cement, and two mixtures containing a thixotropic admixture.

2. The concretes were evaluated using a series of standard and non-standard tests which allowed comparison with the reference mixture to be made.

3. The mixtures containing the pozzolanic replacements and the air-entrained concrete were the best overall performers. These mixtures out performed the reference mixture.

4. The thixotropic mixtures (achieved through addition of bentonite or thixotropic admixture) did not perform well and do not seem to be well suited for massive tremie placements.

CHAPTER 2

LARGE-SCALE LABORATORY TESTS OF TREMIE CONCRETE PLACEMENT

2.1 Objective. The objective of this portion of the project was to conduct large-scale tremie concrete placements in the laboratory using several different concrete mixtures. The following areas were of particular interest:

a. Determination of flow patterns of the concrete after exit from the tremie pipe;

b. Examination of tremie concrete mixtures containing pozzolanic replacement of varying percentages of the cement; and,

c. Evaluation of the effect of various admixtures on the flow pattern and surface slope of tremie-placed concrete.

2.2 Background.

2.2.1 Description of the test procedure. There are several reports in the literature of tremie concrete placements done on a model scale.* While these research programs have unquestionably added to our understanding of tremie concrete performance, they have generally been conducted with mortar rather than concrete and hence failed to model the heterogeneous character of concrete. It was believed that large-scale tests using a true concrete mixture would more accurately model underwater placements of concrete in the field.

Therefore, a series of laboratory placements was conducted using 6 yd^3 (4.6 m^3) of concrete for each test. A total of five such tests were performed.

A placement box was constructed with a size of 4 by 4 by 20 ft (1.2 by 1.2 x 6.1 m). This box was built of framing lumber and plywood sheets. Figures 8 and 9 show the placement box.

A variety of techniques were used to seal joints of the box to allow filling with water to a depth of 3.5 ft (1.1 m). An overflow spillway was used to maintain a constant water level once a placement was begun.

A length of 10-in. (25.4 cm) diameter steel pipe was used for the tremie pipe. A hopper was fabricated out of plywood to facilitate transferring concrete into the tremie pipe. Figure 10 shows details of the tremie and hopper in use during a placement. Figure 11 shows a schematic of the entire placement setup.

A concrete pump was used to transfer the concrete from the transit-mix truck to the tremie hopper for the first test. A concrete bucket mounted on a fork lift was used during the remainder of the tests.

The tests were begun with the tremie pipe dewatered - the bottom was sealed with a plate. The plate (and tremie) were initially resting on the bottom of the placement box. Once enough concrete was placed into the pipe to fill it, the tremie was slowly raised 7 in. (18 cm) using a fork lift, allowing concrete flow to begin. The pipe was blocked in its raised position and held there until the placement was completed. Figure 12 shows an overall view of the placement process.

In order to be able to identify the concrete during the subsequent coring operations, colors were added to various portions of the concrete during placement. The first third was placed without added color. The next third was colored red, and the final third was colored black. The coloring agents used were inorganic mineral additivies. These colors proved easy to trace, and the technique worked well.

During the placement, the fresh concrete was sampled and tested for slump, air content, and unit weight. Additionally, cylinders were taken for 28-day compressive strength tests. The results of these tests are presented below.

Also during the placement, soundings were taken at the conclusion of placing each color segment. These soundings were used to describe flow and to correlate data obtained in the coring program. Figure 13 shows soundings being taken.

Once a placement was completed, the concrete was allowed to cure for several days, and then the box was dewatered. The surface of the concrete was examined and photographed. Measurements were made to establish concrete thicknesses over the entire sample.

Once the surface examination and photography were completed, the coring program was begun. Cores were drilled using both 3 and 6 in. (7.6 and 15.2 cm) diameter bits. The coring pattern used is shown in Figure 14. Figure 15 shows the surface of the concrete of one test after coring was completed.

The cores obtained were examined, logged, photographed, and weighed to establish unit weights. The results of these tests are described below. The different colors of the various concrete segments were readily visible on the cores.

After the coring was complete, the concrete was broken into pieces which could be handled by the available equipment. A number of concrete pieces were taken to a local plant for cutting with a wire saw in order to provide a more readily visible indication of the flow patterns. Photographs of these sections are included and discussed below.

Once the concrete sections were removed, the forms were cleaned, reassembled, resealed and the next test was conducted.

2.2.2 Description of concrete mixtures evaluated. The small-scale evaluations of concrete mixtures conducted earlier (Chapter 1) had shown that

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* See references 3, 15, and 16.

Figure 8. Partially assembled
tremie placement box.

Figure 9. Tremie placement box
completely assembled
and ready for placement.

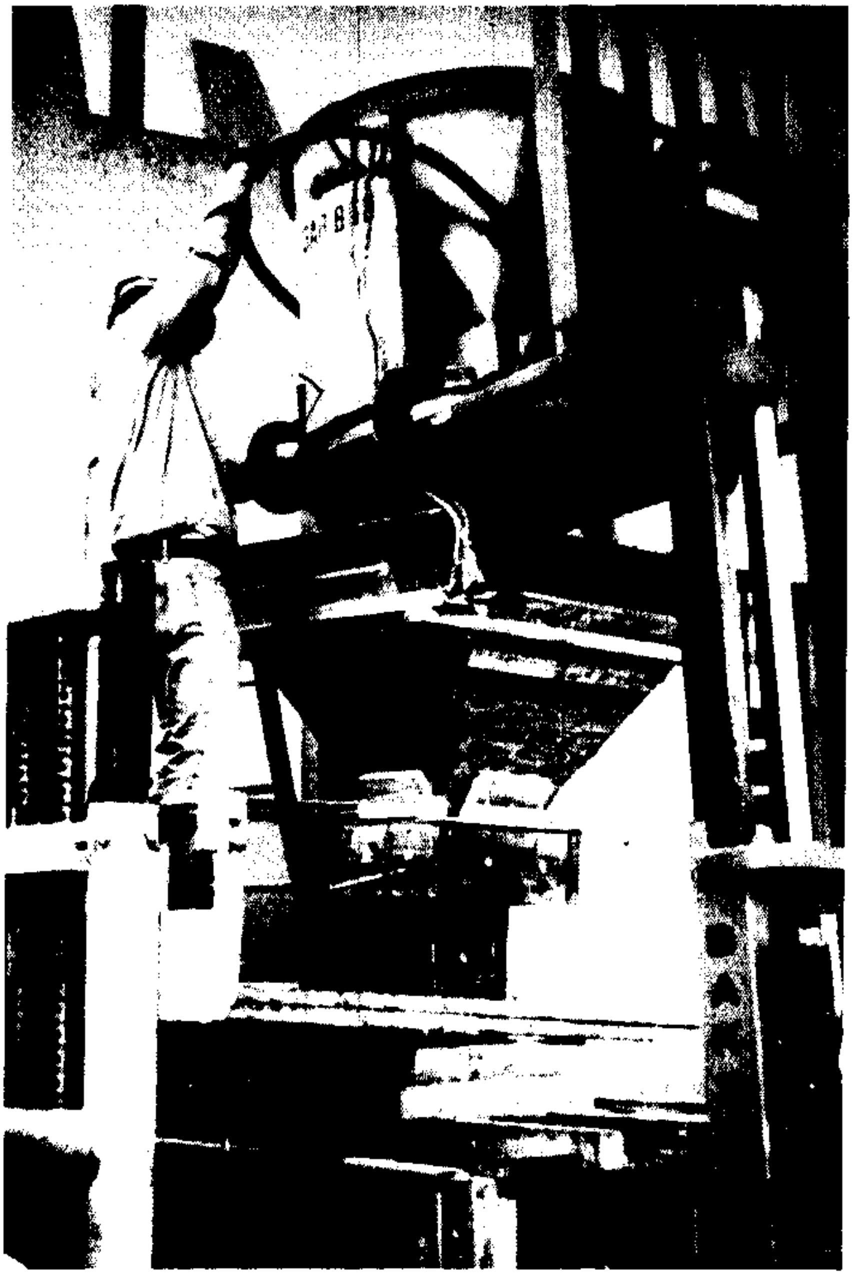


Figure 10. Details of tremie hopper and pipe during a placement. The tremie has been raised by the fork-lift on the left and is blocked with the mouth 7 in. (18 cm) above the bottom of the box.

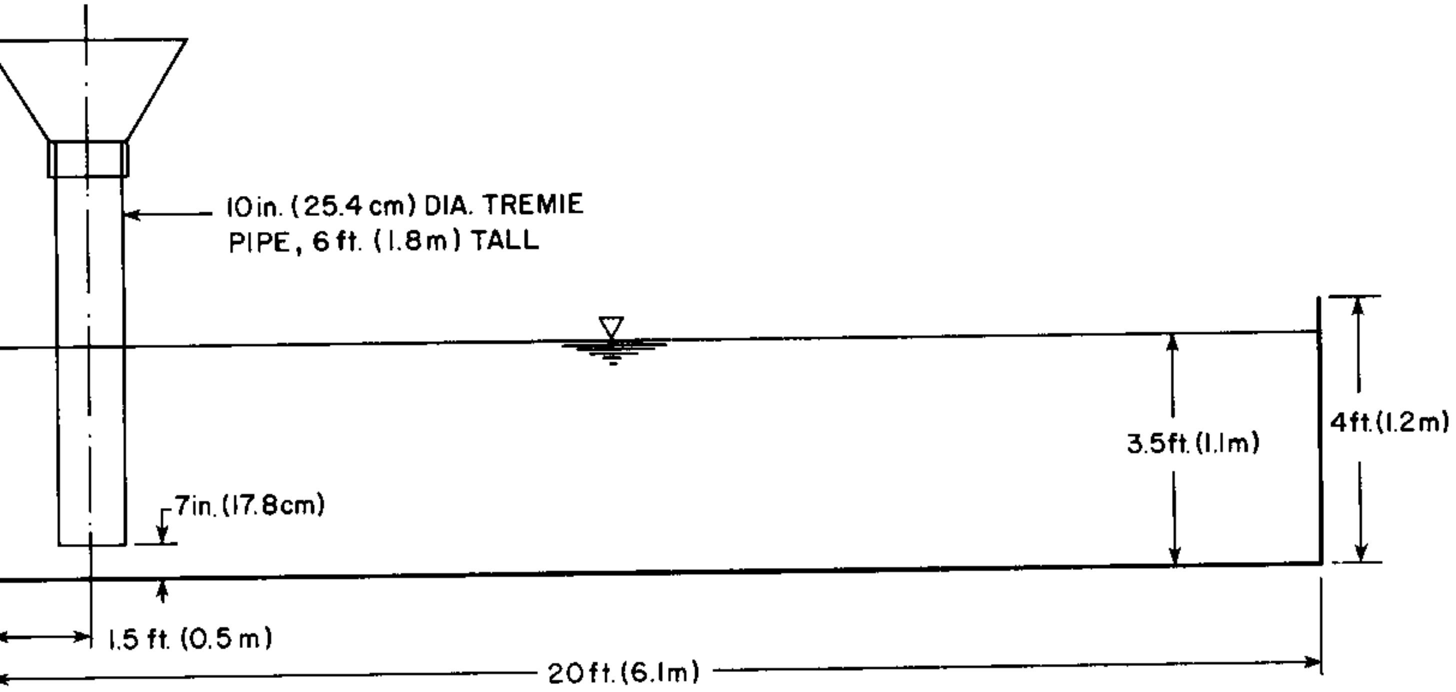


Figure 11. Schematic of tremie placement box. Tremie pipe is shown in the raised position. (Elevation view.)

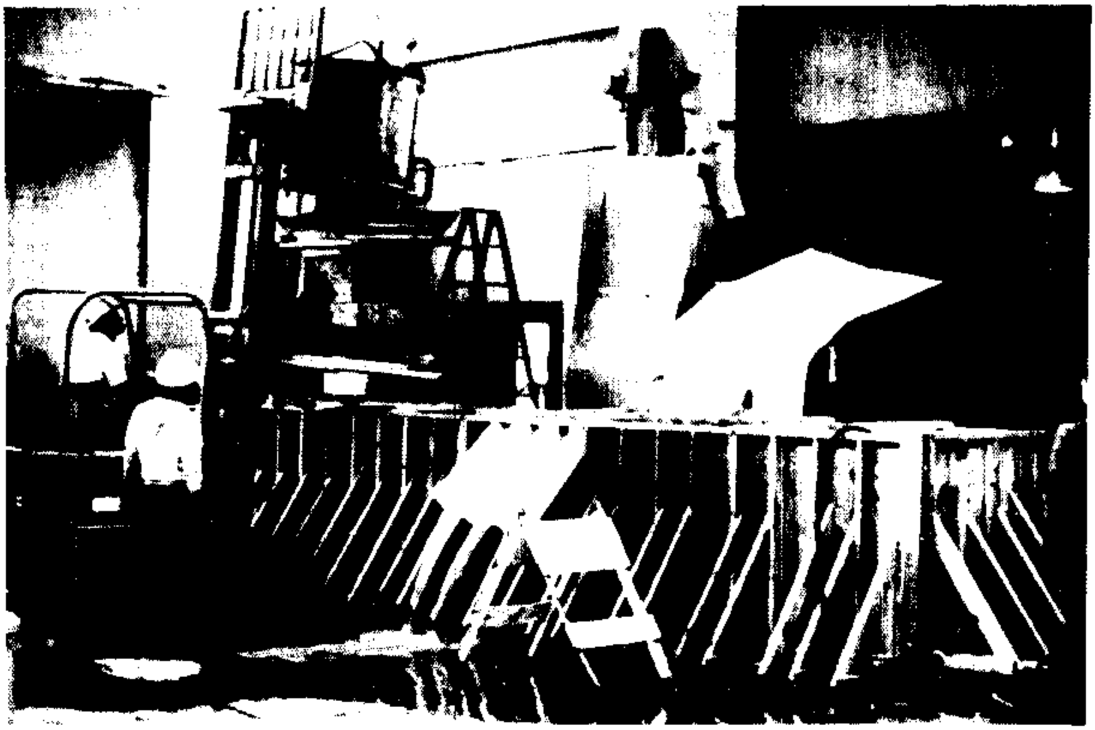


Figure 12. Overall view of placement operation. Note the overflow water from the placement box.

Figure 13. Taking soundings during break in concrete placement.

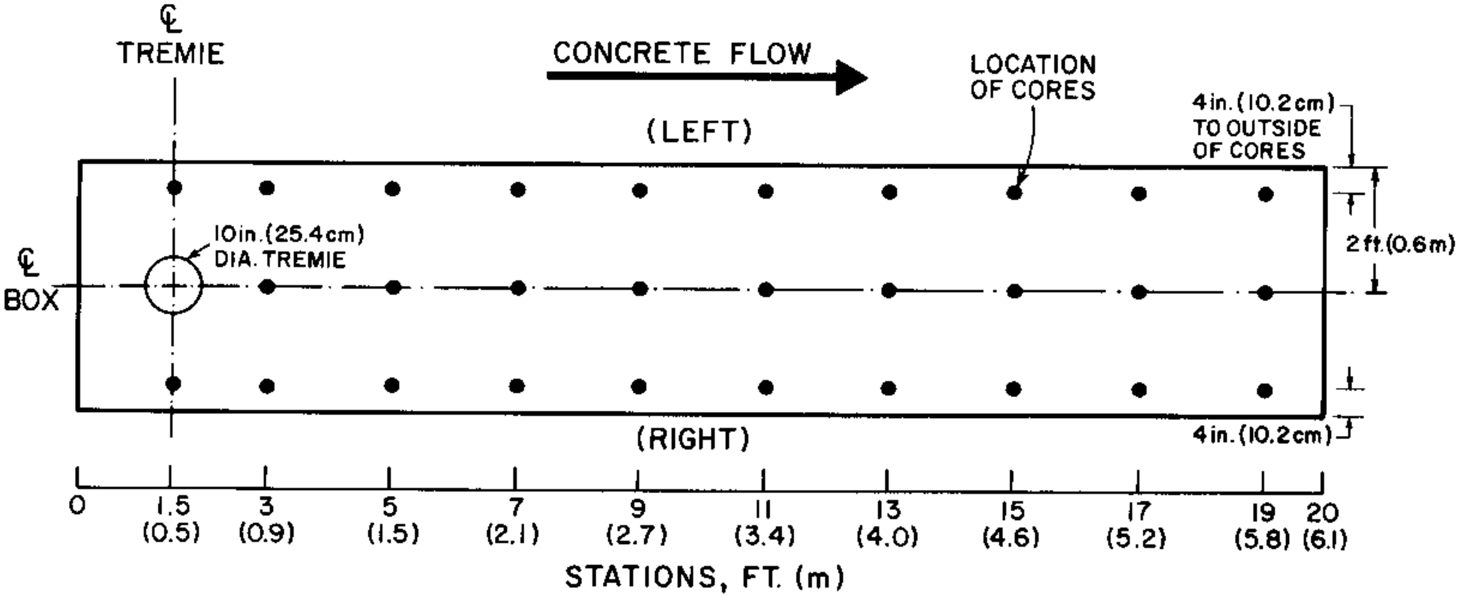


Figure 14. Coring pattern for large-scale laboratory placements. (Plan view.)

Figure 15. Tremie-placed concrete at completion of coring program. This sample is Test 1. Note core holes.

mixtures containing pozzolans could be expected to perform well as tremie-placed concrete. The results of those small scale tests and the decisions to use pozzolanic replacements in the concrete mixtures to be used for tremie placements in a major cofferdam seal (Chapter 3) and a deep cutoff wall (Chapter 4) led to the selection of a group of mixtures containing varying amounts of pozzolan for the laboratory large-scale placements.

In addition to the differing amounts of pozzolan, two different water reducing, retarding admixtures were used in the mixtures to determine the differences, if any, in the performance of the resulting concretes.

The mixtures which were tested were not selected to model a mixture from a particular project. Instead, as was done in the small-scale laboratory tests, a reference mixture and several variations were developed. The reference mixture was the same as that used in the small-scale tests. Materials (cement, aggregate, natural pozzolan) were from the same sources as for the small-scale tests. Table 13 shows the properties of the mixtures used in the large-scale tests.

2.2.3 Flow of tremie concrete. The subject of tremie concrete flow patterns has attracted many researchers, probably due to the relationship between concrete flow and laitance formation (which is a measure of the quality of tremie concrete). A wide variety of reports and proposed flow schemes may be found in the literature. A summary of several of these reports follows:

The initial concrete which flows out of the tremie builds up a small mound at the mouth of the pipe. It is this mound which seals the tremie for subsequent concrete flow. This initial concrete is in direct contact with water and is the most susceptible to washing and segregation; therefore, it contributes the most to the formation of laitance. Subsequent concrete has been assumed to flow into the concrete mass and therefore not be subjected to direct contact with the water. In some manner (usually unexplained in the reports) the initial concrete mass expands so that all of the later concrete flows into concrete and is not exposed to the water. This theory implies that the first concrete placed should be found above some or all of the concrete which is placed subsequently. Clearly, there must be some limit to this concept since the initial concrete (volume undefined) can only be stretched so far. Further, this initial concrete would ultimately set making additional expansion impossible.

Several representative reports from the literature follow:

1. The American Concrete Institute in its Recommended practice for Measuring, Mixing, Transporting and Placing Concrete (Ref. 1) states: "Tremie concrete flows outward from the bottom of the pipe pushing the existing surface of the concrete outward and upward." This statement clearly implies that newer concrete should be found under earlier concrete - at least until the tremie pipe is raised to start the process over.

2. Halloran and Talbot writing in the Journal of the American Concrete Institute (ref. 17) state: "As soon as the bottom of the pipe tremie was covered with concrete, the flow became an extrusion from within and through the mass of concrete and not a flow over the top of the already placed concrete."

A figure in this paper shows that the concrete will be found in essentially vertical layers parallel to the tremie pipe. The newer concrete will be found in the layers closest to the pipe with successively older concrete being found at greater distances from the pipe.

3. Strunge, in a paper prepared for the Offshore Technology Conference in 1970, (ref. 15) wrote: "The principle of the method is to bring the concrete through a pipe to the interior of the concrete being poured, thus preventing contact with the surrounding water."

Figures in this paper, based upon small-scale flow tests, show bulbs of concrete surrounding a tremie pipe. Successive concrete forms new bulbs which force the older concrete away from the pipe. Again, the end result is concrete which is layered vertically.

4. Williams, also writing in the Journal of the American Concrete Institute (ref. 18), described model tests in which seven batches of 0.75 ft^3 (0.02 m^3) each were placed at 20-minute intervals. Figures in this paper show definite horizontal layering. Williams reports for one mix, "Part of the mix 'rolled' down the steep slope.."

The intervals between the batches apparently necessitated raising the tremie pipe which could have contributed to the layering noted.

Additional examples could be cited, but these should be sufficient to establish that a degree of uncertainty exists concerning tremie concrete flow patterns. It was felt that the large-scale tests would be beneficial in providing additional information on this subject.

2.3 Observations and discussion

2.3.1 Direct observations of concrete flow. This section is based upon visual observations made during the five placements. This information is intended to describe only a portion of the flow phenomenon. Following sections will add additional information.

Two significant items were observed during the placements: 1. As was expected, there was an immediate flow which occurred as soon as the tremie pipe was lifted. This flow was made up of two components. First, there was a flow of concrete which quickly established a mound around the mouth of the pipe. Second, there was a flow layer of a colloidal suspension of

TABLE 13 - CHARACTERISTICS OF CONCRETE MIXTURES USED IN LABORATORY PLACEMENTS

Concrete Mixture [Note 1]	Cement Content lb/yd^3 (kg/m^3) [Note 2]	Pozzolan Content lb/yd^3 (kg/m^3) [Note 3]	Pozzolan Content Percent By Weight	Admixtures [Note 4]	Slump, in. (cm) [Note 6]	Air Content	Unit Weight lb/ft^3 (kg/m^3)	28-day Compressive Strength lb/in.^{2} (MPa) [Note 6]	
								Standard Cured	Test Site Cured [Note 7]
1 (Standard)	705 (418)	0	0	a	7.3 (18.5)	0.8%	154 (2,470)	5,390 (37.2)	5,190 (35.8)
2	353 (209)	353 (209)	50	a	6.8 (17.3)	2.3%	142 (2,270)	3,560 (24.5)	3,030 (20.9)
3	528 (313)	176 (104)	25	a	7.3 (18.5)	1.2%	142 (2,270)	2,910 (20.1)	2,510 (17.3)
4	705 (418)	0	0	b	7.5 (19.1)	0.4%	147 (2,360)	5,270 (36.3)	4,960 (34.2)
5	528 (313)	176 (104)	25	a and b [Note 5]	9.4 (23.9)	0.4%	147 (2,360)	5,470 (37.7)	5,020 (34.6)

NOTES:

1. For all mixtures:
   - Fine aggregate 45 percent of total aggregate by weight
   - Maximum water-cementitious material ratio: 0.45
   - Design slump: 7 inches (18 cm)
   - Maximum aggregate: 3/4 inch (19.0 mm)
2. Cement was Type II manufactured by Kaiser.
3. Pozzolan was a natural material meeting requirements of ASTM C618, Type N.
4. Admixtures:
   a. Water reducer/retarder: Master Builders Pozzolith 300R.
   b. Water reducer/retarder: Sika Plastiment.
5. Both admixtures inadvervently added to this mixture.
6. Average of three samples.
7. Cylinders sealed and stored next to placement box until capped and tested.

fine particles which traveled very rapidly to the far end of the placement box. These particles were apparently cement grains which were washed out of the concrete that initially flowed out of the tremie. The presence of the flow layer was unanticipated, and the speed of the flow was surprising - the layer was seen at the far end of the box (17.5 ft (5.3 m)) within several seconds.

Due to the colloidally suspended particles, the density of this flow layer was such that it remained as a cloudy layer on the bottom of the box. As the placement progressed, additional particles went into suspension, and the identity of the original layer was visually obscured.

The speed at which the colloidal layer traveled proved to be directly related to the speed at which the tremie pipe was raised to begin the placement. The faster the pipe was raised, the faster the layer flowed to the far end of the placement box.

These observations of the flow from the tremie pipe indicate an initial radial flow of substantial force which affects a much larger area than was anticipated. The actual volume of material in this colloidal suspension is very small indeed. This phenomenon reemphasizes the necessity for care in beginning a tremie placement. Not only could the seal be lost, but excessive laitance may be formed if the pipe is raised too rapidly or is agitated.

Equally important, if a tremie were being restarted in fresh concrete (as would happen when tremies are relocated during a large placement), the rapid flow observed could contribute to washing the surface of the existing concrete and thus increase laitance.

2. The second observation concerns flow of the concrete after a mound of concrete has built up around the mouth of the tremie pipe. During the first three tests, concrete was seen to be flowing vertically up alongside the tremie pipe. Once a sufficient amount of fresh concrete had built up around the tremie, the concrete appeared to slough off (similar to a soil slope failure). In these instances, the concrete may have pushed the earlier concrete away from the tremie pipe, or it may have simply flowed over the earlier concrete (Figure 16). Due to the turbidity of the water from the colloidal suspension, the exact mechanisms of flow could not be accurately determined.

It should be noted that these tests were essentially continuous placements. They were conducted quickly enough to prevent excessive stiffening of the first concrete placed before the test was completed.

These visual observations indicated a complex flow mechanism which may be a combination of some or all of these noted above. The observations do not seem to support a purely vertically layered theory, nor do they support the concept of continuous flow underneath the older concrete.

2.3.2 Flow during placement as determined by soundings. As described earlier in the test procedure, each test of 6 yd^3 (4.6 m^3) was broken into three approximately equal segments (by volume) which were colored differently. Between placing each of the segments and also following the final segment, soundings were taken at 20 points within the test box to determine concrete flow patterns. The soundings points were located as is shown in Figure 17. Concrete thicknesses as determined by the soundings are in Appendix E.

The sounding data have been used to draw centerline profiles for each of the tests (Figures 18 through 22). Plotting of these data showed very little lateral variation in the surface of the concrete during the placements; therefore, no cross sections are presented.

It must be noted that concrete for these tests was purchased from a ready-mix supplier. Therefore, the quantity of concrete placed may have varied slightly from test to test. Also, the first test was conducted using a concrete pump to transfer the mix to the tremie hopper, resulting in a certain amount of concrete loss in the pump and lines. Based on these considerations, the plots should not be superimposed for direct comparison. Rather, the plots are intended to show relative flow characteristics.

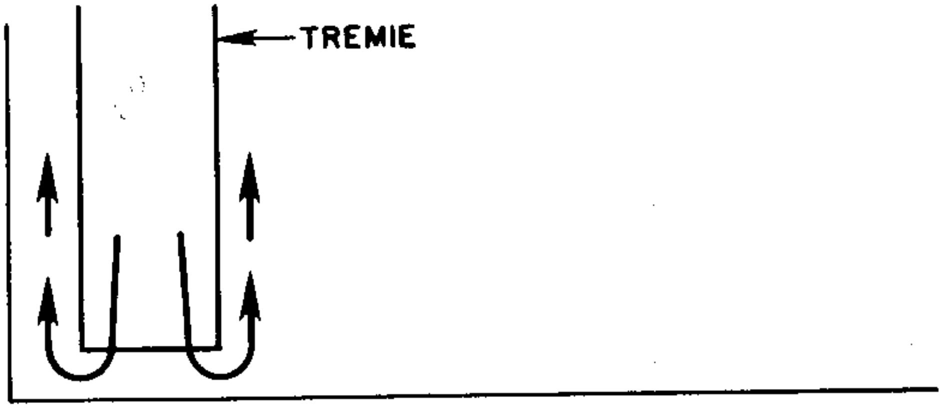
The following points may be made from the soundings.

1. This evaluation of soundings does not show which concrete is in which layer - only the relative thicknesses during the placement. Identification of specific concrete can only be accomplished from the cores. The profiles must not be interpreted as successive layers of differently colored concretes.

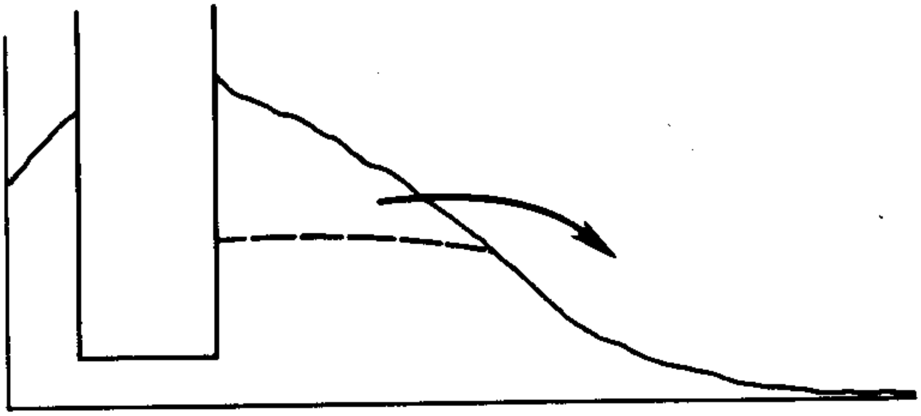
2. All of the mixtures showed the same basic flow pattern. The differences were in the degree of mounding at the tremie location, the over-all slope of the concrete, the amount of concrete which reached the far end of the box, and the rate at which concrete reached the far end. The soundings do not indicate whether the concrete was flowing into or over the existing concrete..

3. The first three tests produced results which were quite similar. For all three there was significant mounding near the tremie location (Figures 18, 19, 20). As a result of this mounding, very little concrete reached the far end of the placement. None of the three mixes appears to have a distinct advantage over either of the other two.

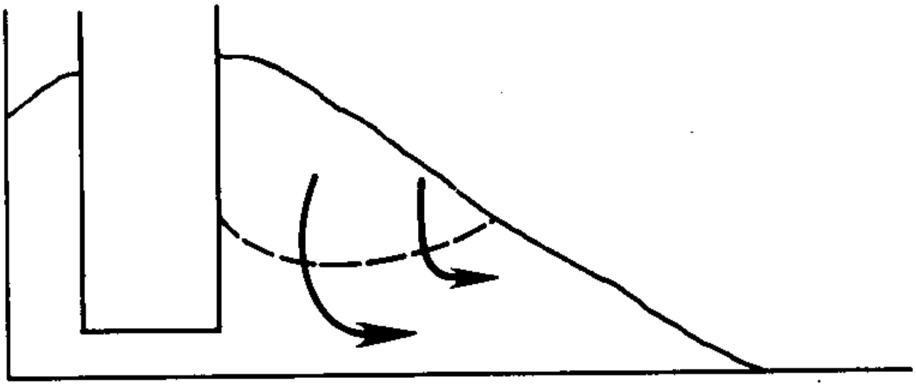
4. The final two tests were quite similar and showed a drastic difference from the first three tests (Figures 21 and 22). The mounding was essentially eliminated, the overall surface slopes were much flatter, and a much greater amount of concrete reached the far end of the placement. There is no clear advantage to either of these last two mixes, both would be quite satisfactory in an actual placement (based upon flow considerations).



a. Observed flow parallel to tremie pipe.



b. Postulated flow over base concrete after build-up in "a", above.



c. Postulated flow into base concrete pushing older concrete away from tremie after build-up in "a", above.

Figure 16. Observed and postulated flow of concrete near tremie pipe.

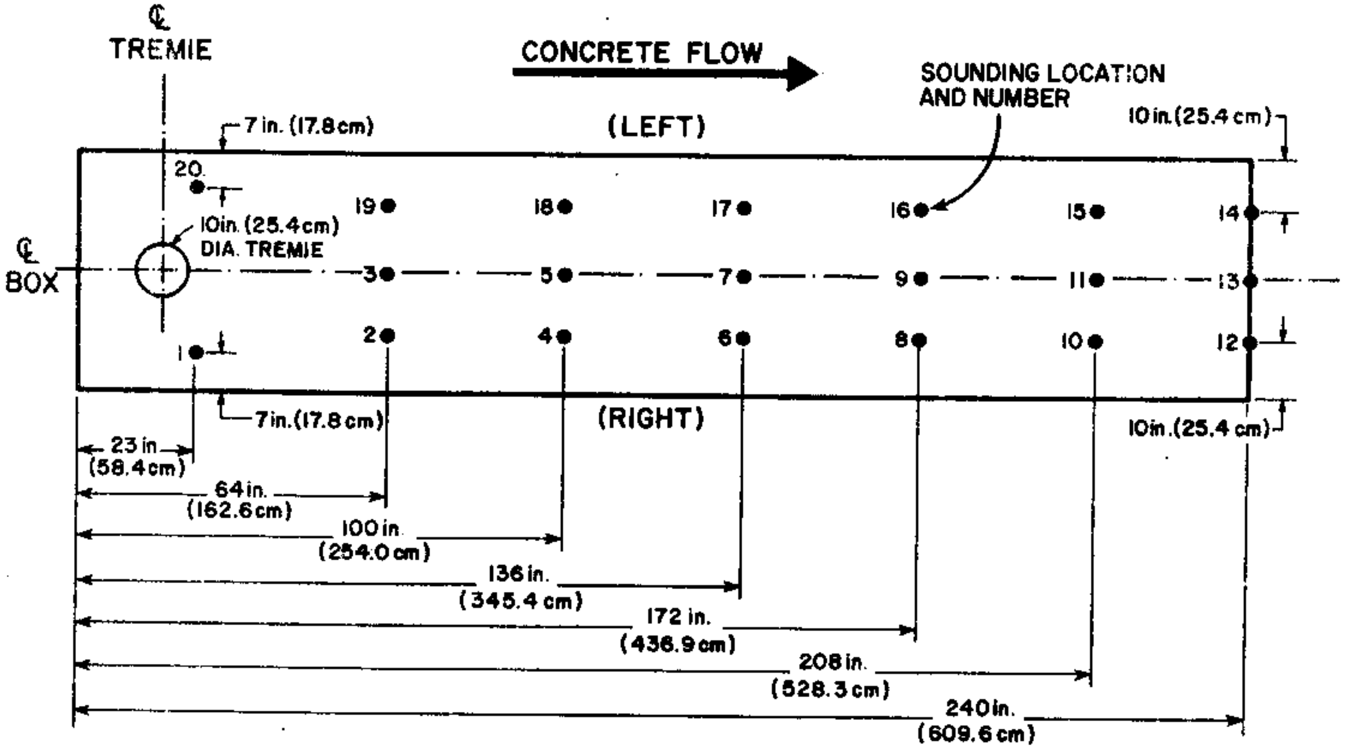


Figure 17. Sounding locations in tremie placement box. (Plan view.)

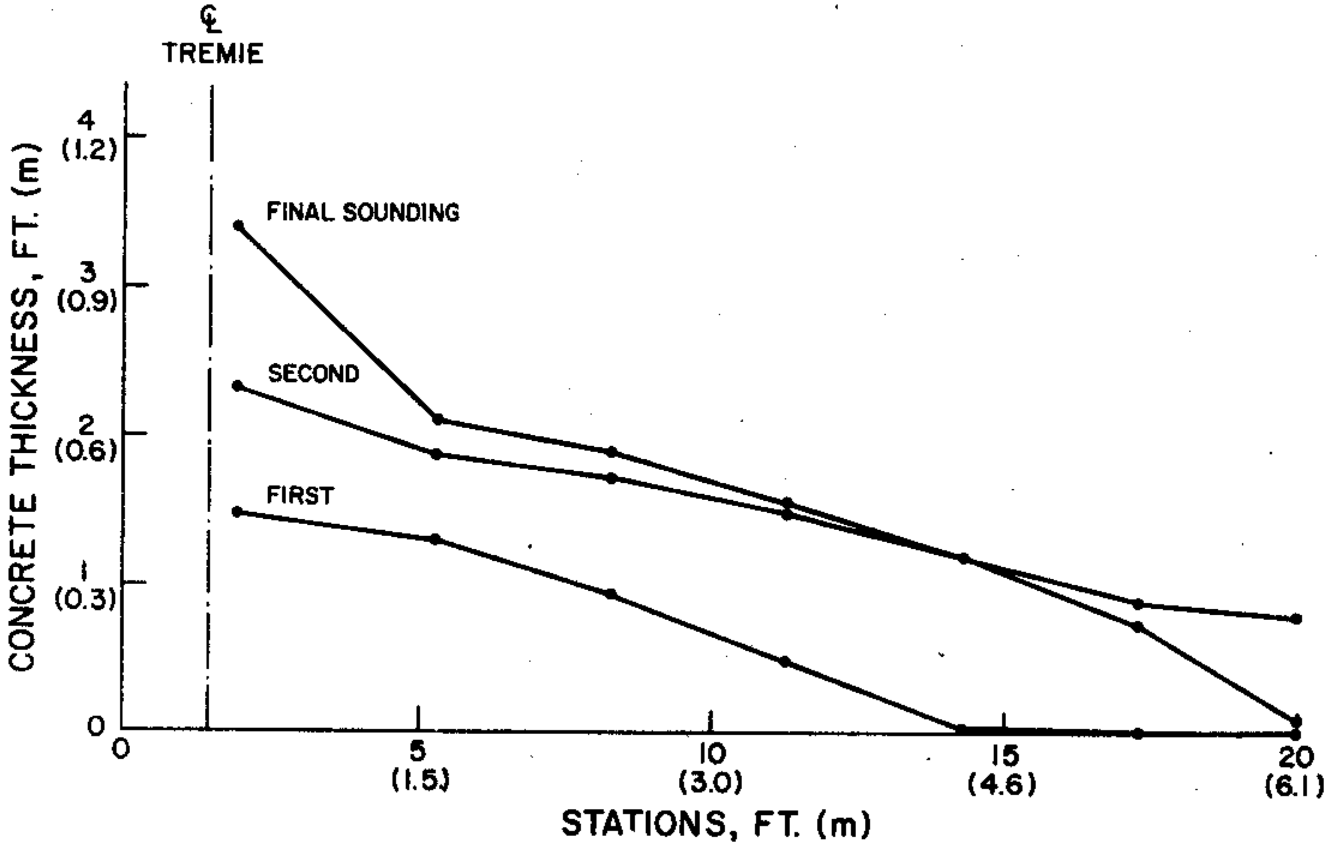


Figure 18. Tremie concrete profiles during placement, along centerline of box, Test 1.

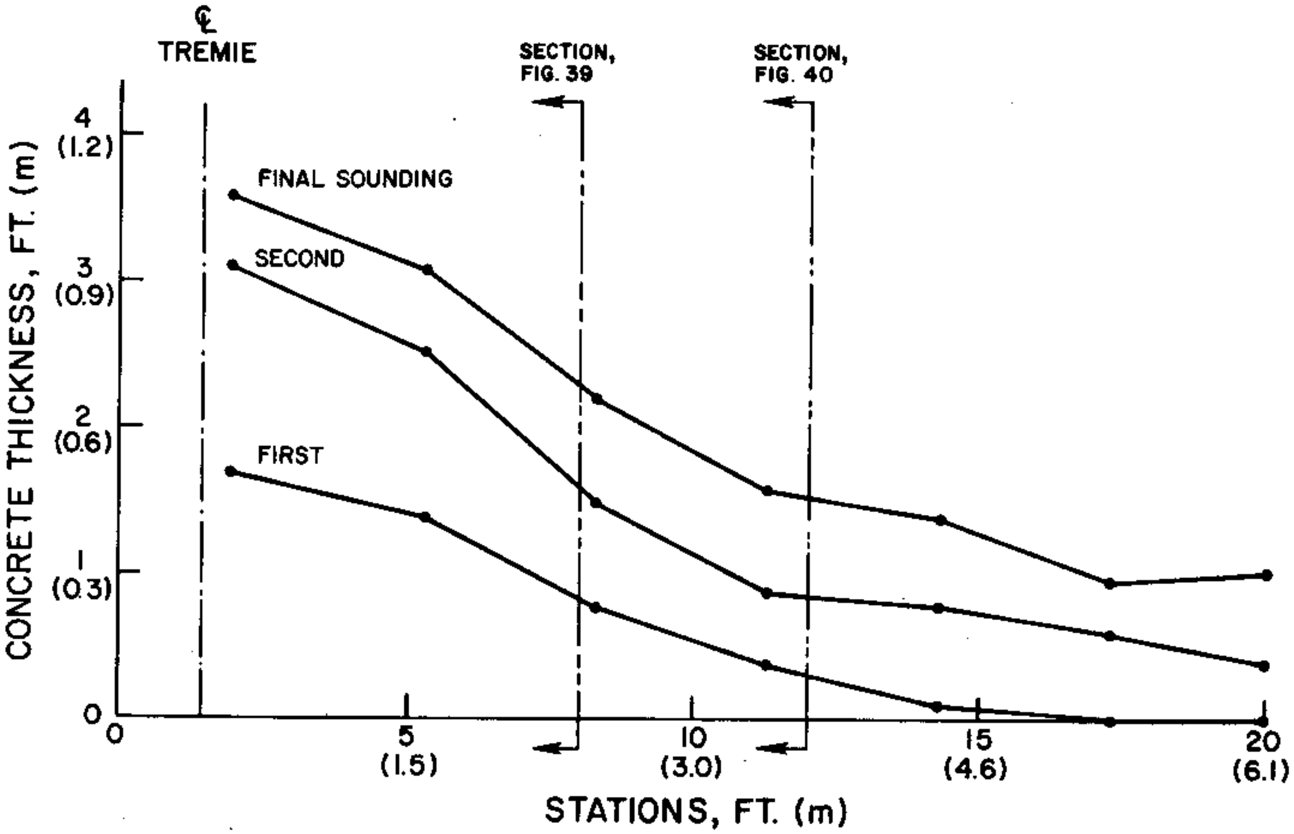


Figure 19. Tremie concrete profiles during placement, along centerline of box, Test 2.

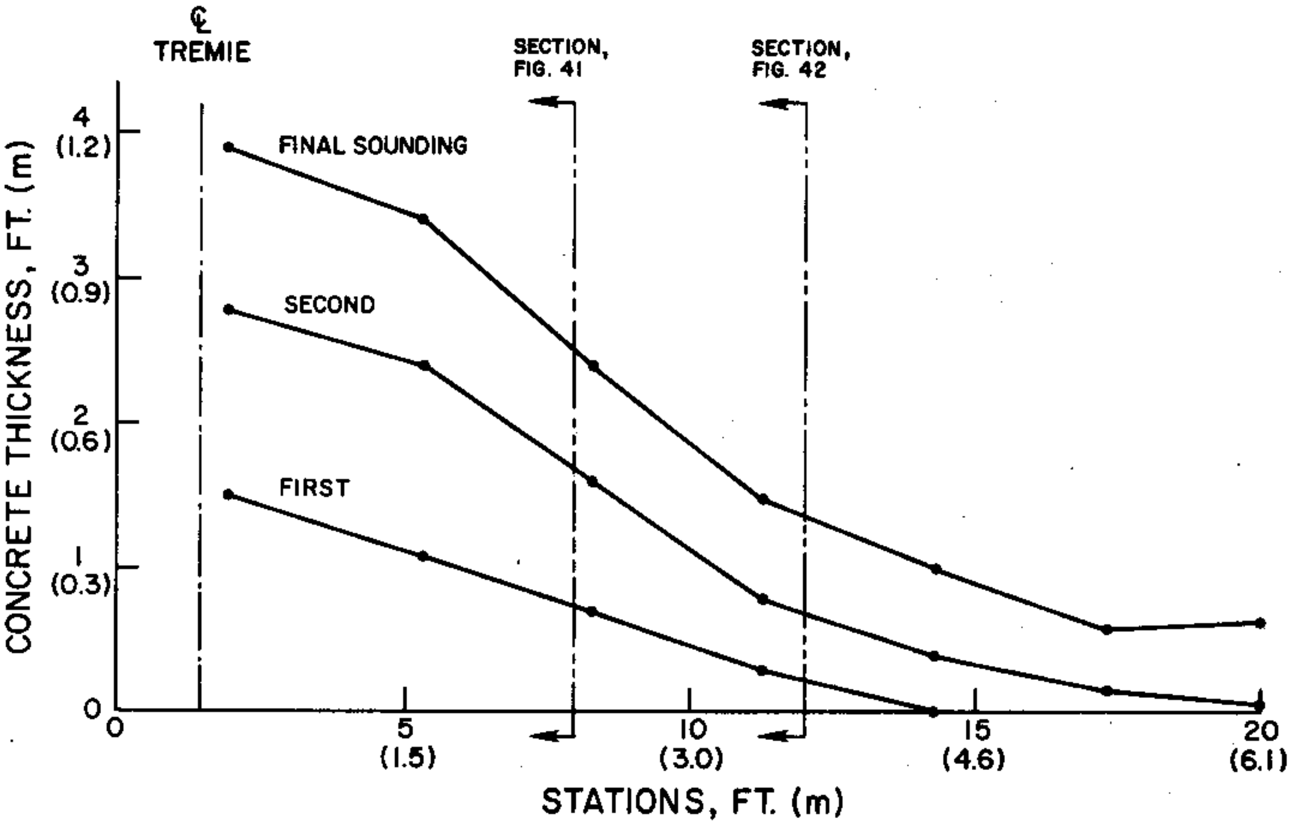


Figure 20. Tremie concrete profiles during placement, along centerline of box, Test 3.

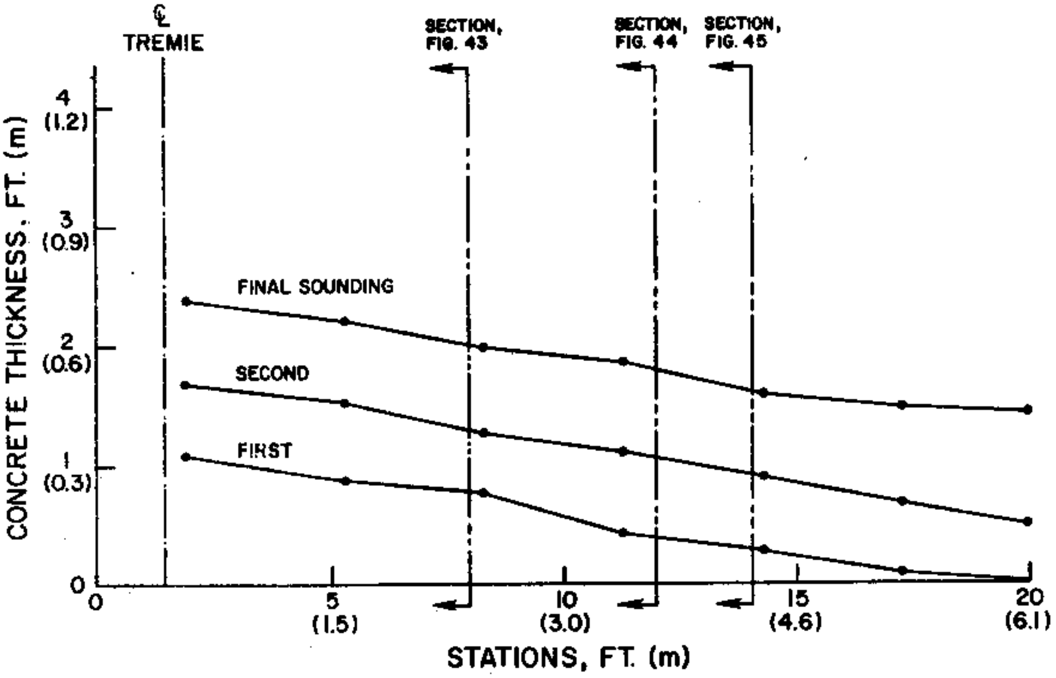


Figure 21. Tremie concrete profiles during placement, along centerline of box, Test 4.

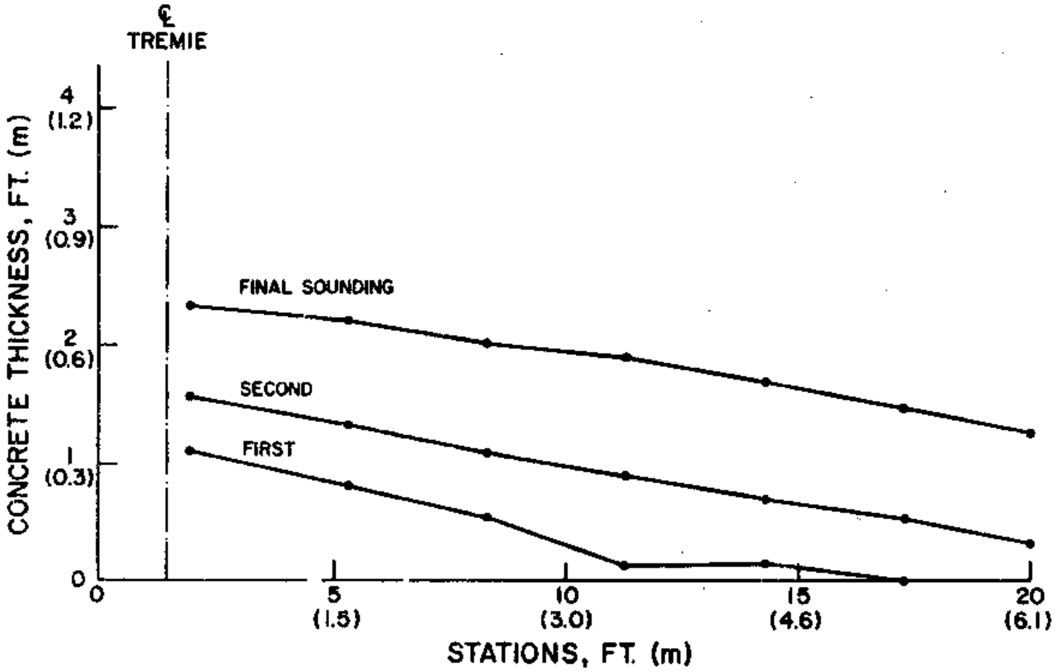


Figure 22. Tremie concrete profiles during placement, along centerline of box, Test 5.

5. On the basis of the flow during placement, the governing factor appears to be the addition of the second type of water reducer/retarder, regardless of whether pozzolan was incorporated into the concrete. When the mixtures are categorized as containing or not containing the second type of water reducer/retarder, the mixture with pozzolan performed as well as the reference mixture in each category.

2.3.3 Surface profiles and surface appearance. In addition to the soundings described above, a detailed mapping was conducted over the surface of the concrete samples after the box was dewatered (120 data points versus 20 for the soundings). Measurements were made to determine the concrete thickness at five locations laterally (outside edges, 12 in. (30.5 cm) from outside edges, and centerline) and at every 1 ft (30.5 cm) interval along the long axis of the box. The data obtained from these measurements are in Appendix F. Profiles showing the concrete thickness along the centerline and one edge are given in Figures 23 through 27. These profiles are included since they show a much more detailed view of the concrete surface than do the soundings. Since there is very little lateral variation, no cross sections are presented.

Photographs of the surfaces of the five tests are in Figures 28 through 33. A close-up of the surface of Test 1 is shown in Figure 29.

The following points may be made from the surface measurement data:

1. The profiles reinforce what was noted from the soundings concerning mounding and concrete flow to the far end. Additionally, the surface measurements show that the most severe mounding occurred directly under the thremie pipe for Tests 1, 2, and 3. Obviously, some of the mounding was caused by the withdrawal of the pipe.

2. The photographs show the surface appearance to be very similar for the first three tests. In these tests, the concrete surface was extremely rough, with Test 1 being the roughest. Figure 29 shows the development of ridges perpendicular to the flow direction in Test 1. These ridges were not seen in any of the other tests. The appearance of the ridges seems to indicate that the mass of concrete was being pushed away from the tremie as additional concrete was being added.

3. The surface profiles of the concrete for Tests 4 and 5 were also very similar and showed a significant improvement over the first three tests. Both tests showed much smoother and more uniform surfaces than the earlier tests.

4. As was true with the soundings data, the surface profiles and surface appearance appear to be a function of the admixtures used. The presence of the pozzolan does not appear to have a significant influence. (However, in the first three tests the two mixes containing pozzolan did provide slightly smoother surfaces). Based upon the surface profiles and textures obtained, the mixes containing the second type of water reducer/retarder would have been perferable in an actual placement.

5. The mounds at the tremie location in the first three tests were very similar to the mounds seen on the tremie seal discussed in Chapter 3.

2.3.4 Distribution of concrete colors. As is described above in the test procedure, extensive coring of the tremie-placed concrete was accomplished to determine the final distribution of concrete by its colors. The coring pattern used was presented earlier in Figure 14.

The information obtained from the cores was correlated with the overall profile data to produce approximate profiles of the color distribution along the centerline and right edge of the placement box. These profiles are presented in Figures 34 through 38. The data upon which these profiles are based are given in Appendix G.

The following considerations apply to these profiles:

1. In several instances less than complete recovery of cores was obtained. (These cases were believed to be due to coring problems rather than sand layers.) In these cases thicknesses of colors were approximated from the portions of cores recovered and from total sample thickness data at the point of coring.

2. The quantities of concrete of a given color may have varied slightly from test to test. However, the sequence of colors was always the same: gray/brown (depending upon pozzolan content), red, and black.

3. Except for minor variations caused by flow around reinforcing steel (described below in section 2.3.6), the color distributions were quite symmetrical across the short dimension of the placement box. Therefore, only one edge profile is shown.

Several blocks of concrete from these tests were cut with a wire saw to provide a more graphic representation of the color distribution. Photographs of these cross sections are presented in Figures 39 through 45.

The following points may be made concerning the concrete flow pattern as determined by the color distributions:

1. No single flow pattern was seen which would establish one of the theories described above (section 2.2.3) as the characteristic tremie flow mechanism. Several mechanisms appear to be involved.

2. The color distributions do not substantiate flow descriptions of the type which hold that the initial concrete is pushed upward by concrete placed subsequently. Concrete of an earlier color was found above later concrete in only a few minor instances. These in-

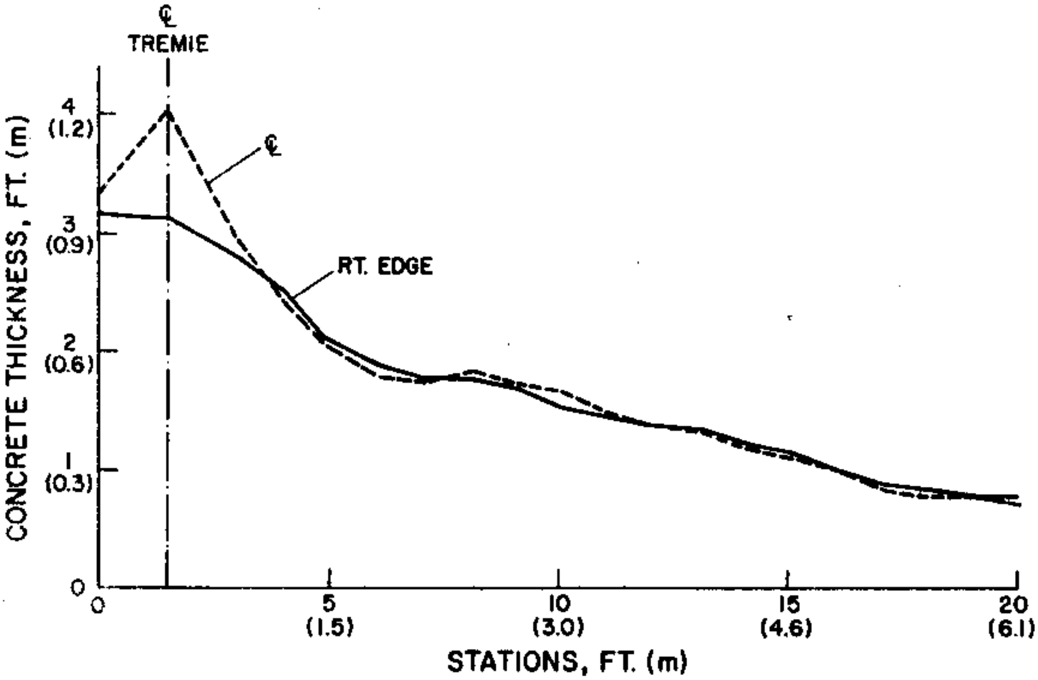


Figure 23. Centerline and right edge surface profiles, Test 1.

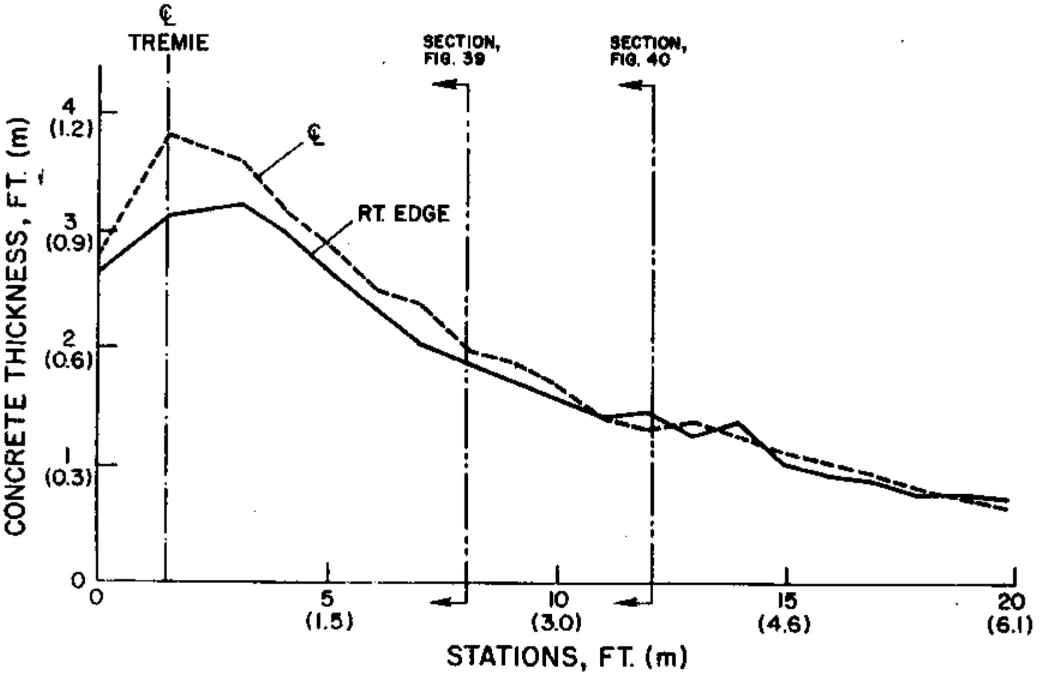


Figure 24. Centerline and right edge surface profiles, Test 2.

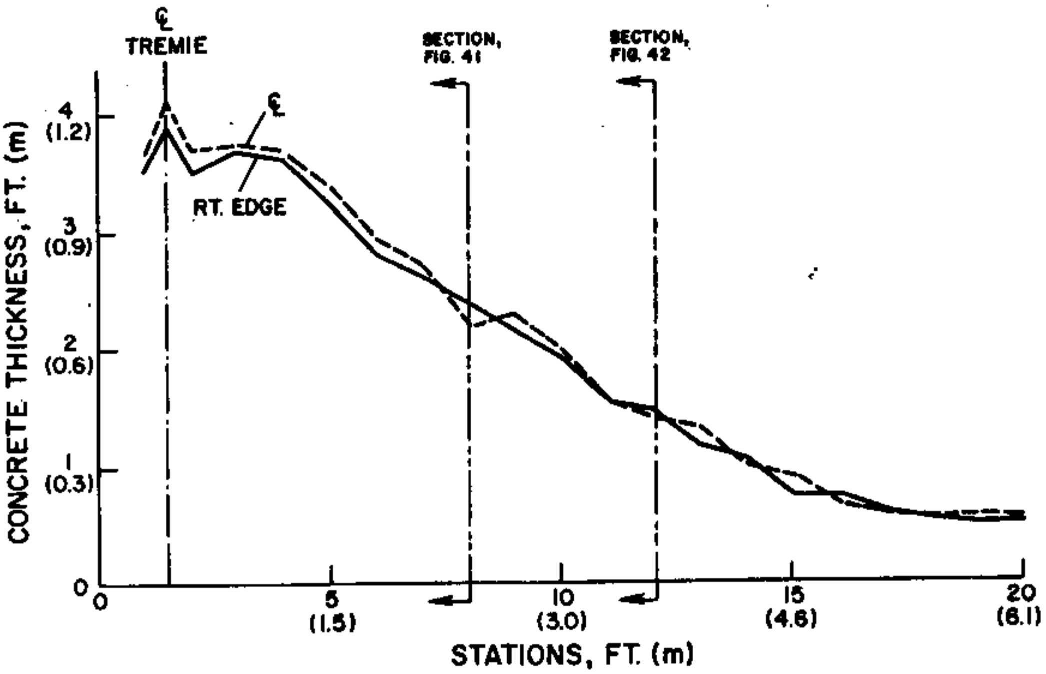


Figure 25. Centerline and right edge surface profiles, Test 3.

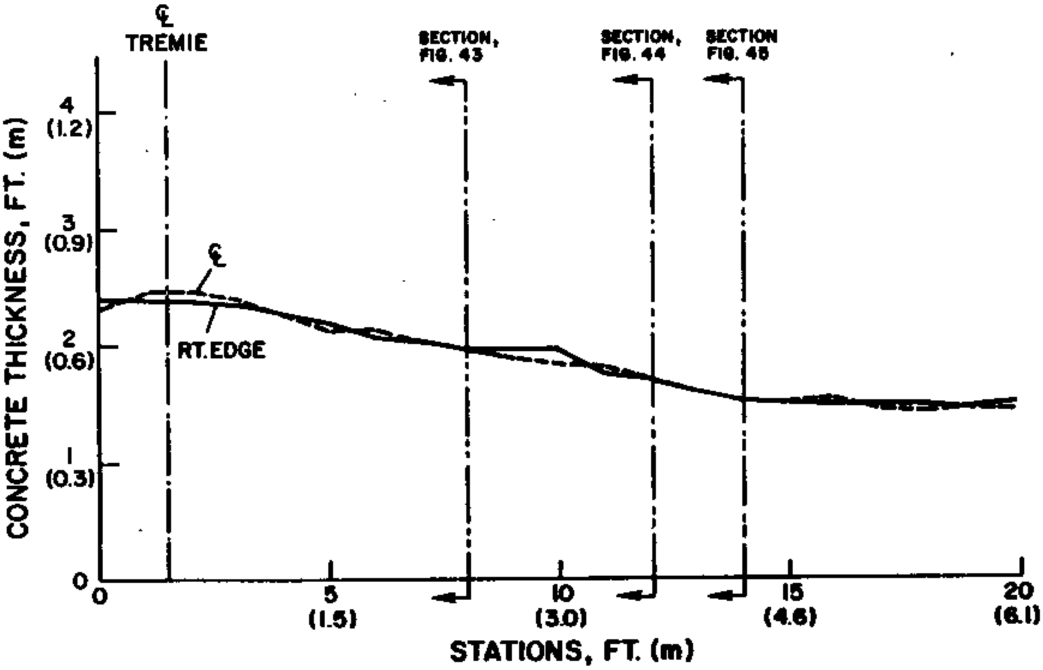


Figure 26. Centerline and right edge surface profiles, Test 4.

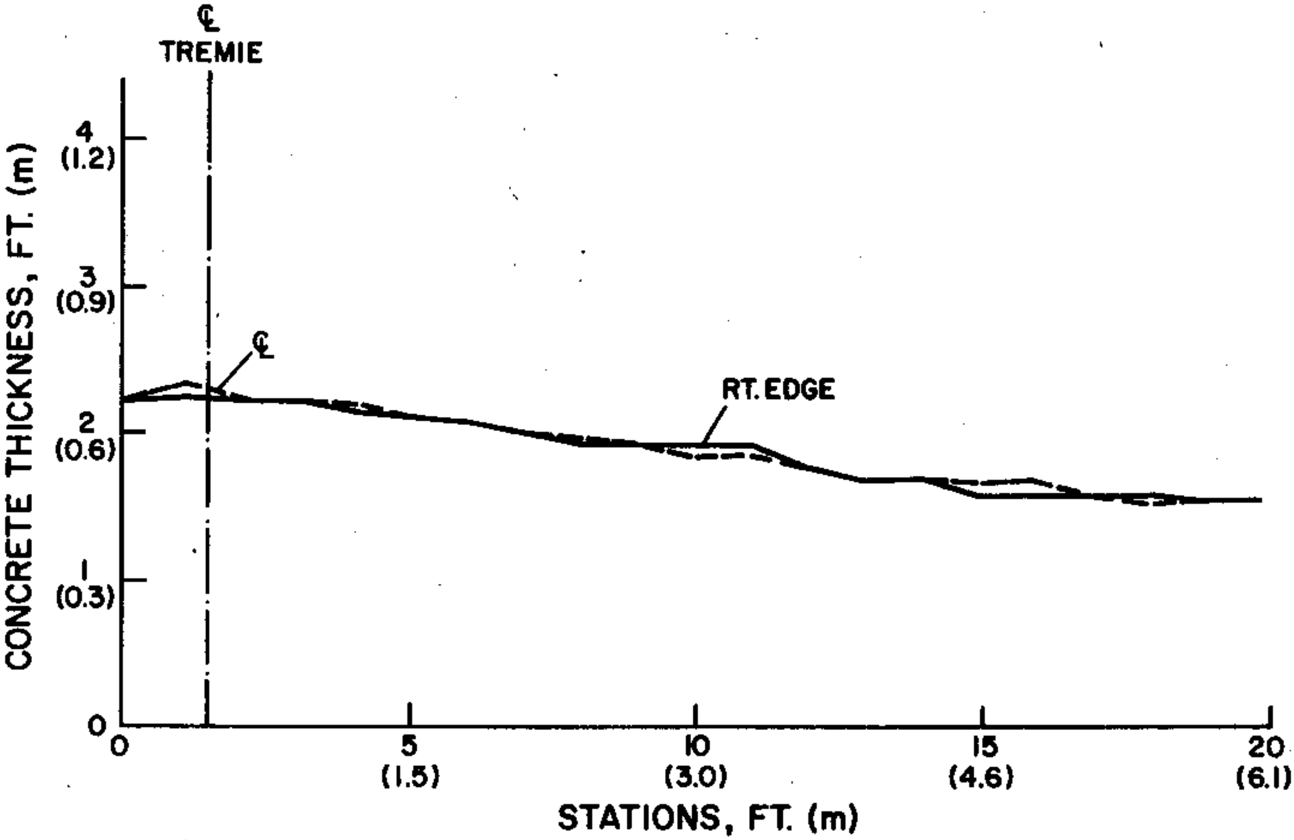


Figure 27. Centerline and right edge surface profile, Test 5.

Figure 28. Concrete surface,
Test 1.

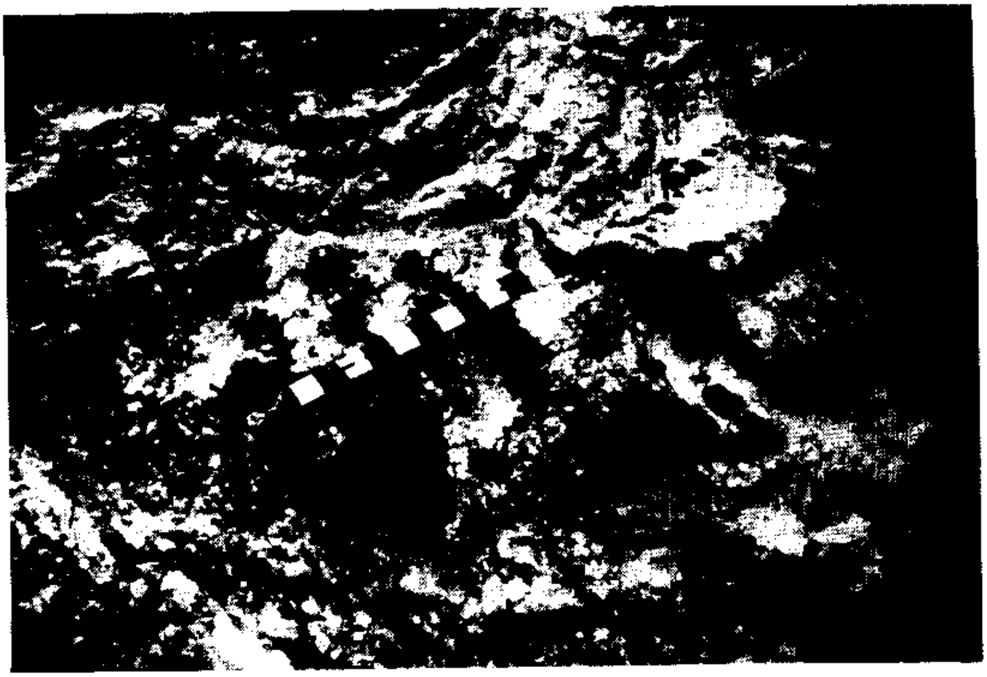


Figure 29. Close-up of concrete surface, Test 1.

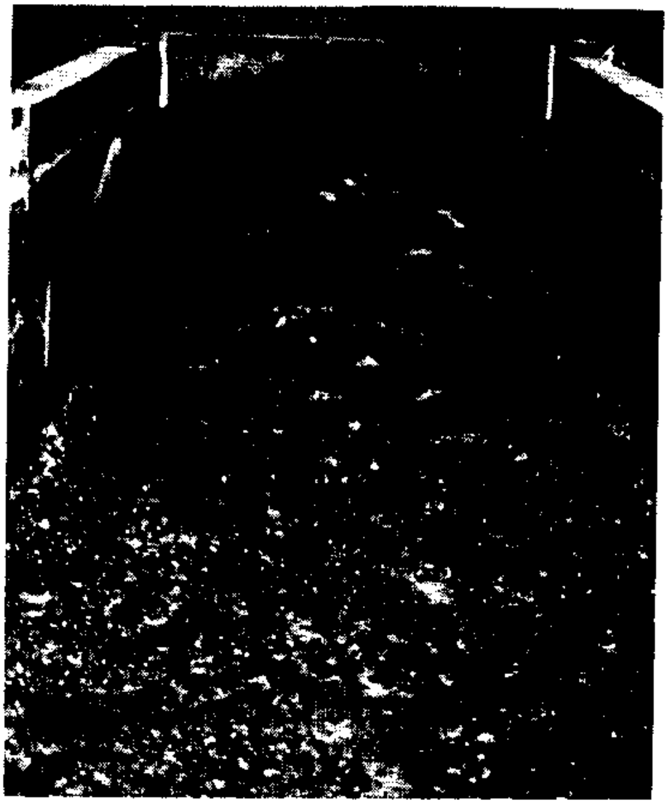


Figure 30. Concrete surface, Test 2.

Figure 31. Concrete surface, Test 3.

Figure 32. Concrete surface,
Test 4.

Figure 33. Concrete surface,
Test 5.

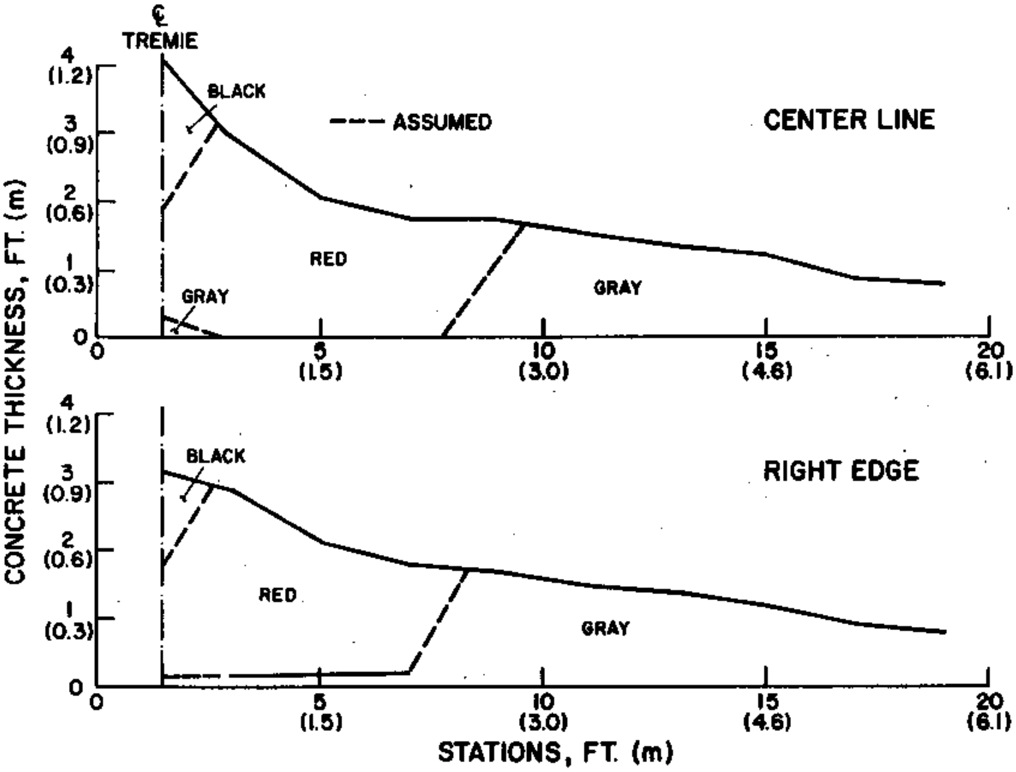


Figure 34. Color distribution, Test 1.

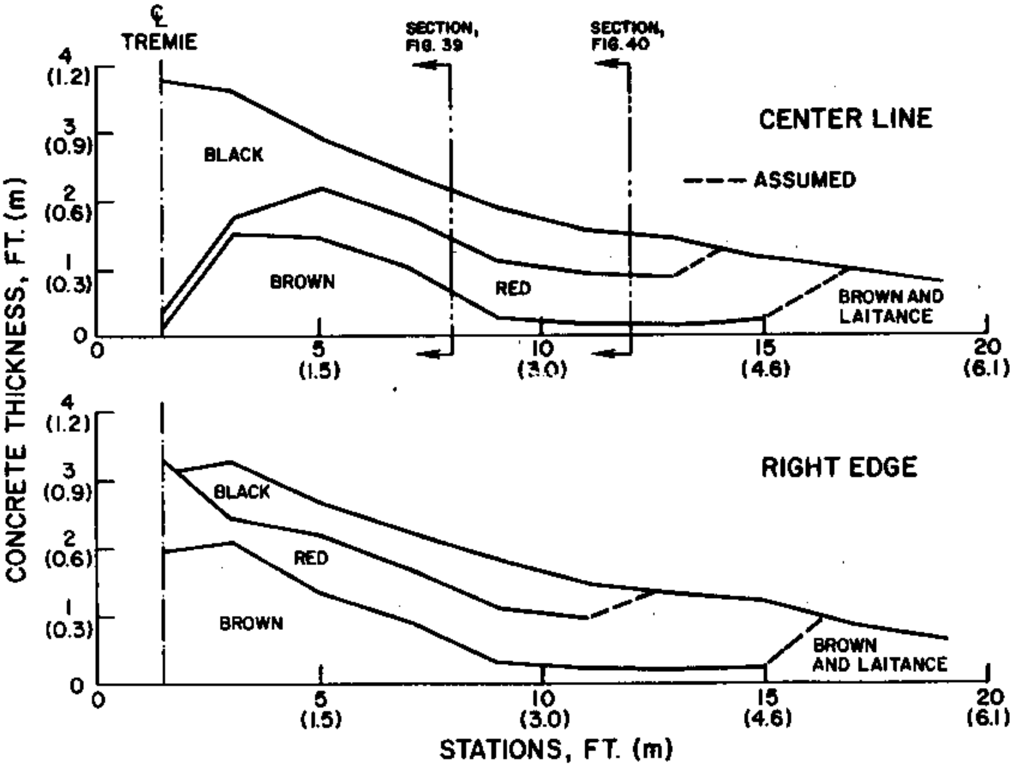


Figure 35. Color distribution, Test 2.

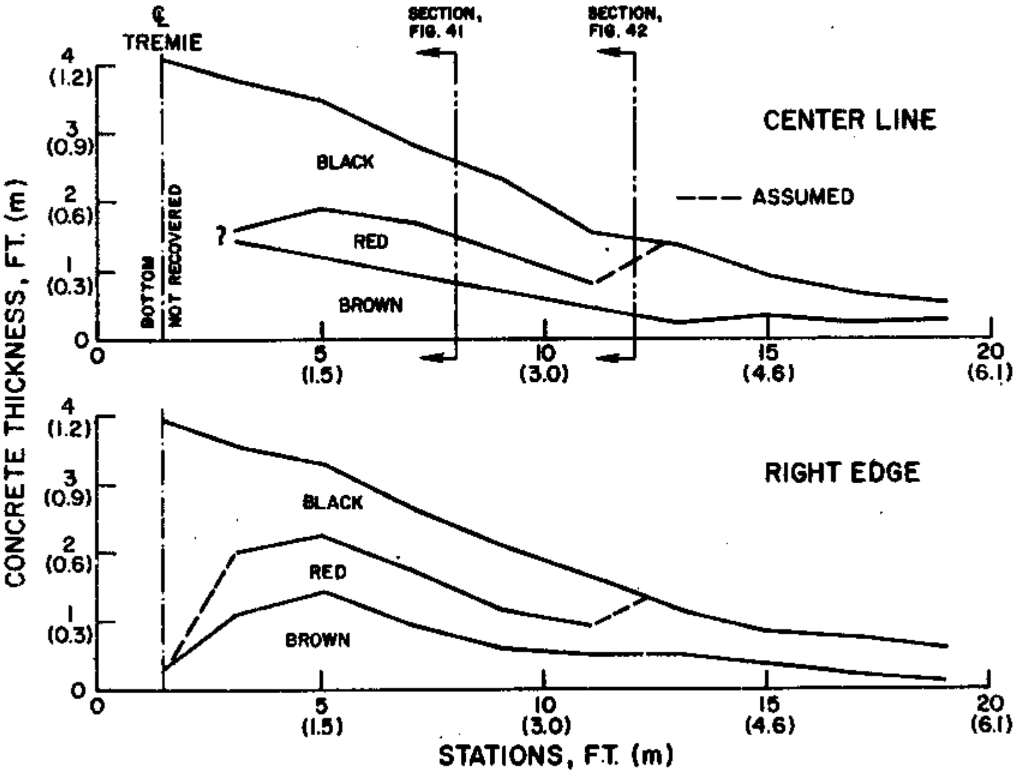


Figure 36. Color distribution, Test 3.

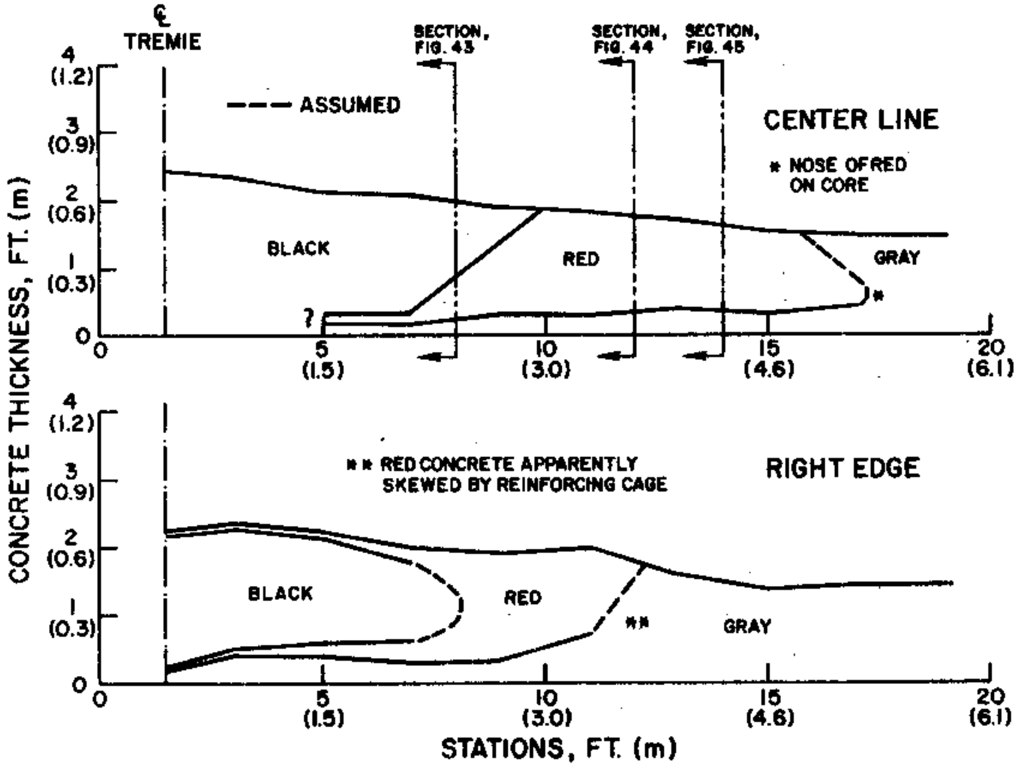


Figure 37. Color distribution, Test 4.

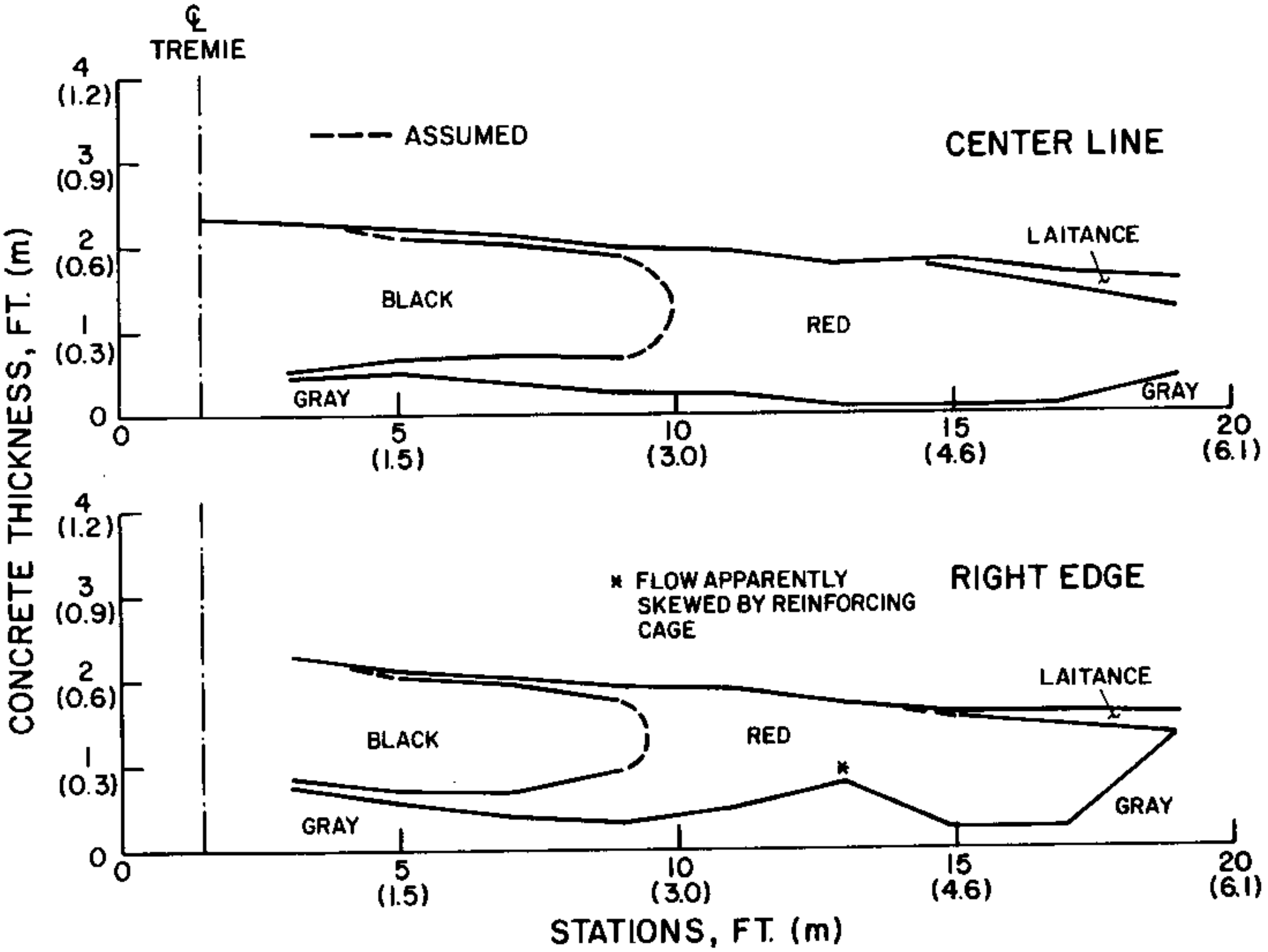
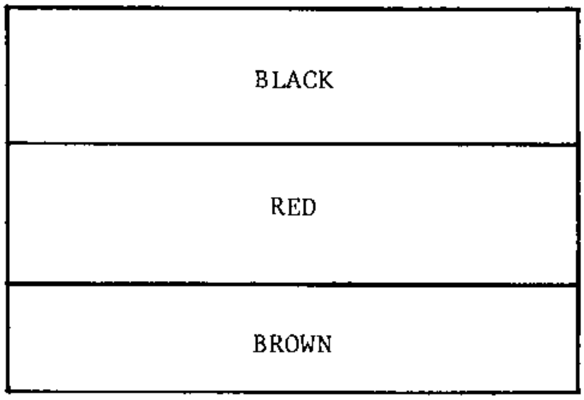


Figure 38. Color distribution, Test 5.

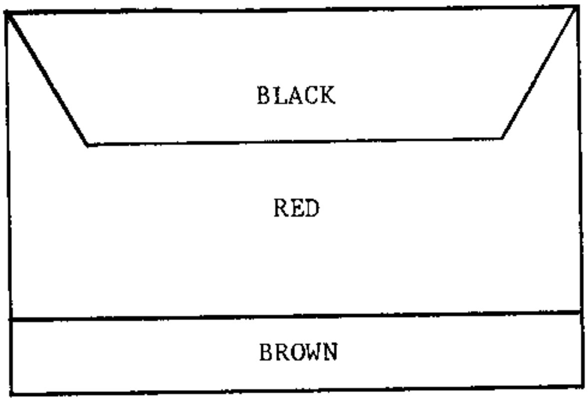
a. Photograph with boundaries between colors enhanced.



b. Schematic.

Figure 39. Cross section, Test 2, 8 ft (2.4 m) line.

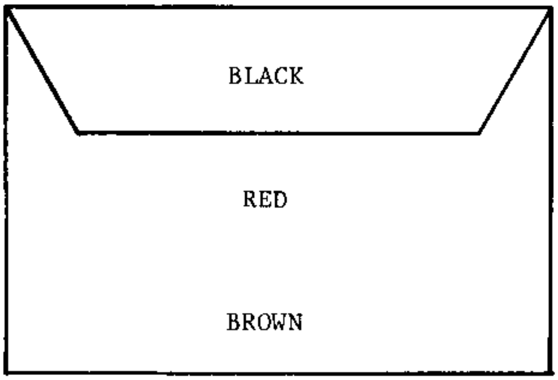
a. Photograph with boundaries between colors enhanced.



b. Schematic.

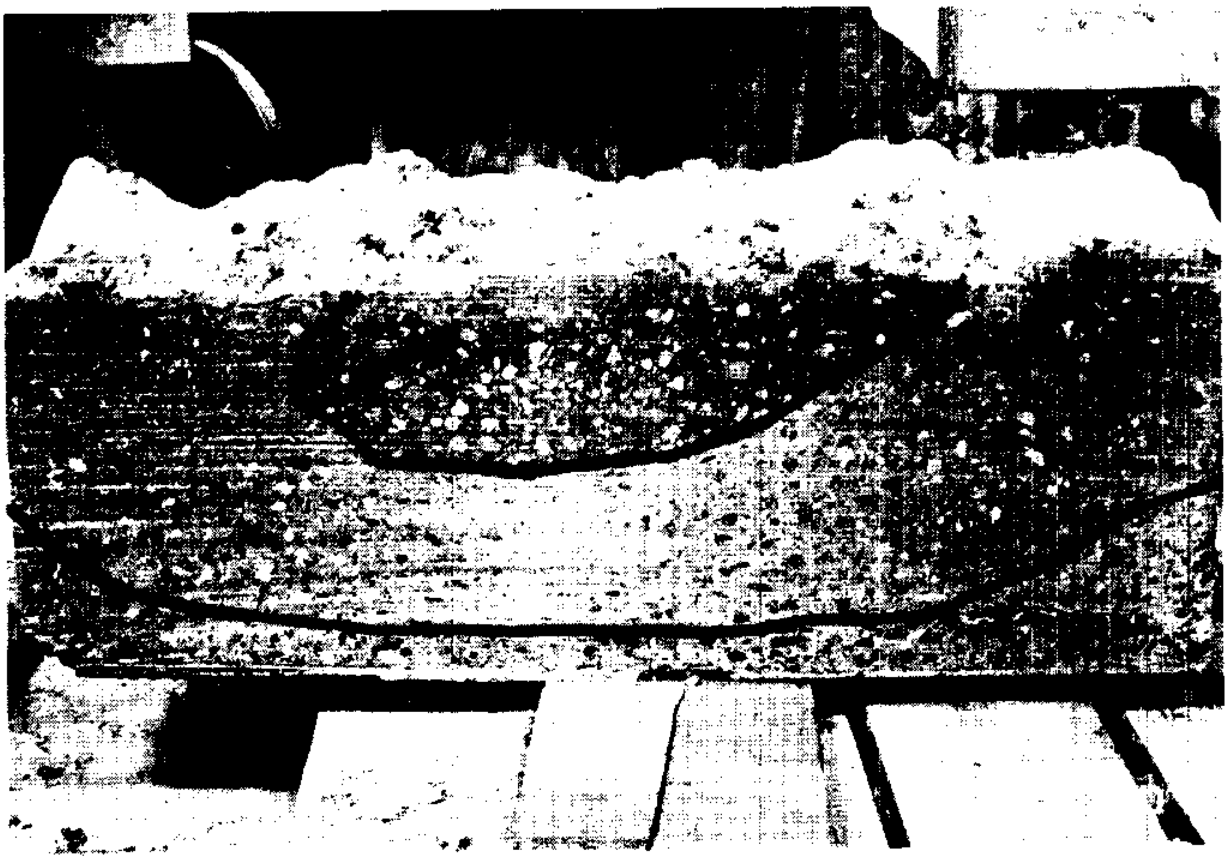
Figure 40. Cross section, Test 2, 12 ft (3.7 m) line.

a. Photograph with boundaries between colors enhanced. Exact division between red and brown not visible on this photograph.

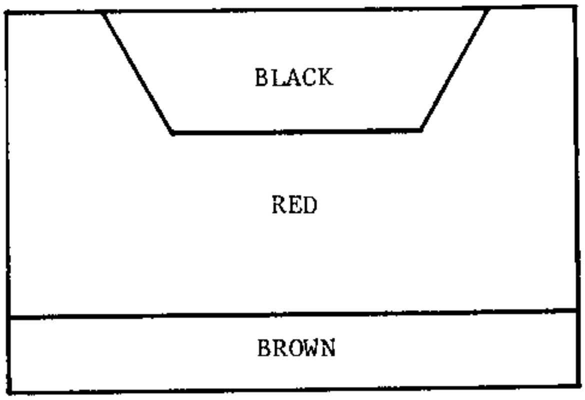


b. Schematic.

Figure 41. Cross section, Test 3, 8 ft (2.4 m) line.

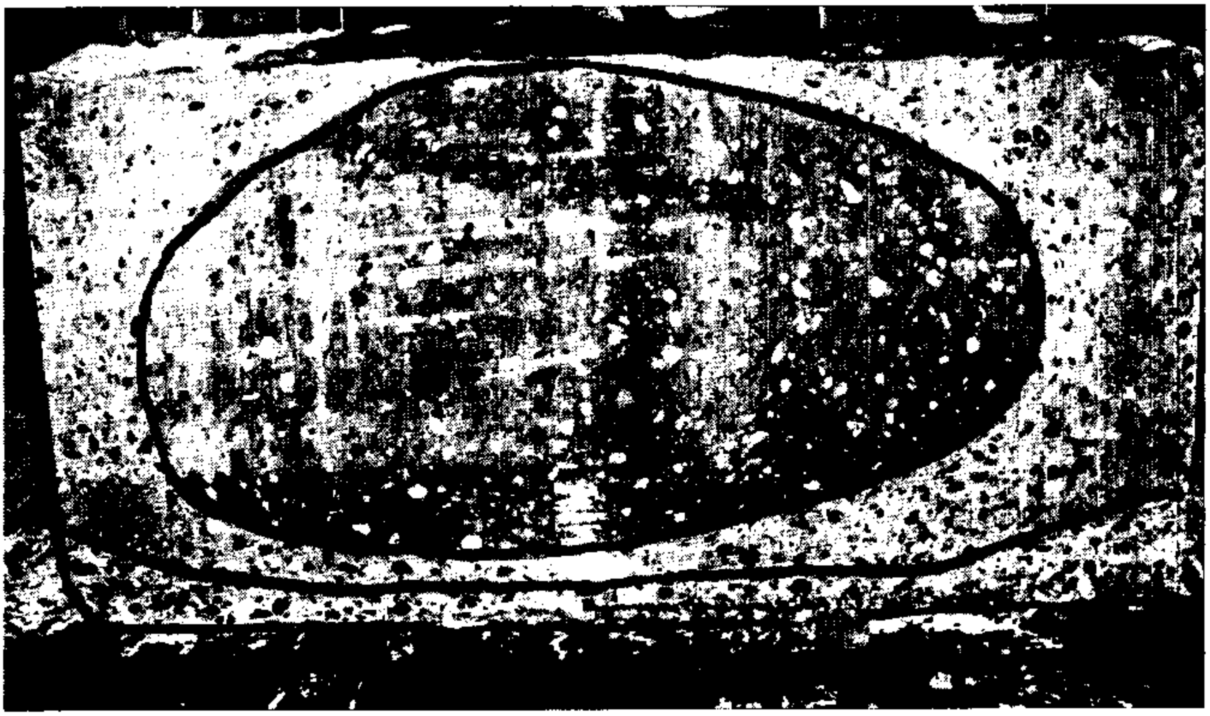


a. Photograph with boundaries between colors enhanced.

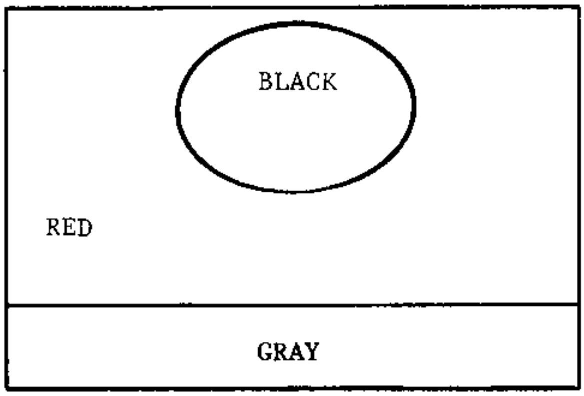


b. Schematic.

Figure 42. Cross section, Test 3, 12 ft (3.7 m) line.

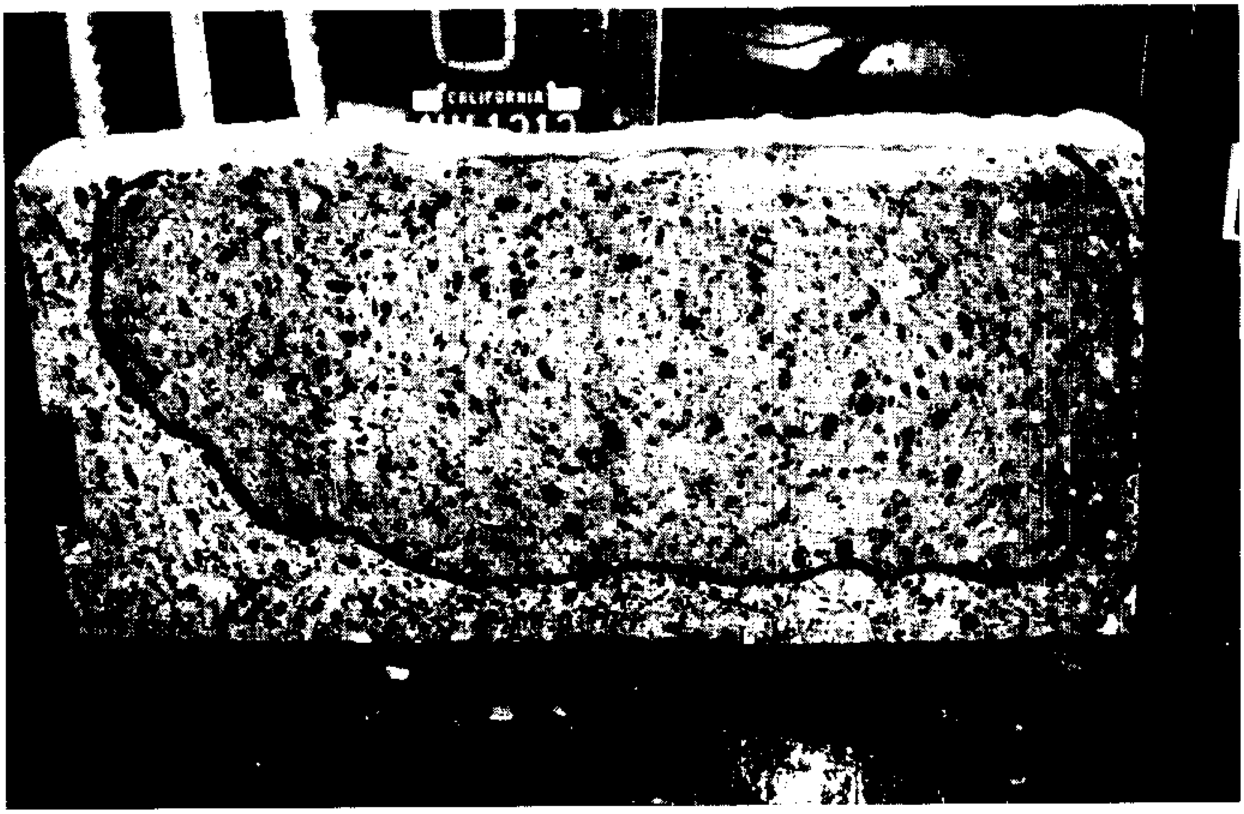


a. Photograph with boundaries between colors enhanced.

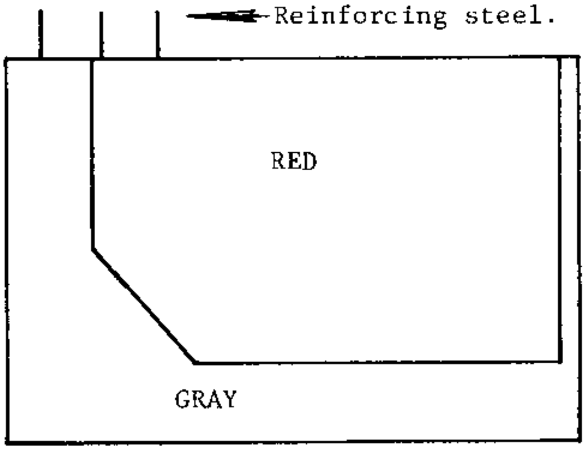


b. Schematic.

Figure 43. Cross section, Test 4, 8 ft (2.4 m) line.



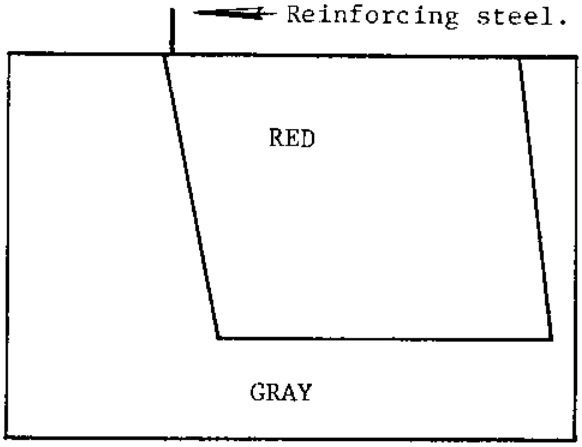
a. Photograph with boundaries between colors enhanced.



b. Schematic.

Figure 44. Cross section, Test 4, 12 ft (3.7 m) line. Note reinforcing steel.

a. Photograph with boundaries between colors enhanced.



b. Schematic.

Figure 45. Cross section, Test 4, 14 ft (4.3 m) line. Red colored concrete is offset due to flow around reinforcing steel.

stances were of the nature of that shown in Figure 43. It appears that these instances are "noses" of concrete pushing into earlier concrete. They are probably the result of the formation of bulbs of concrete around the mouth of the tremie. The sides of the placement box also may have had a role in the formation of these areas by reducing lateral flow.

3. Two basic flow mechanisms seem to be present in these tests. (With the exception of Test 1, the mixtures can again be categorized by the presence of the second type of water reducer/retarder.) In Tests 2 and 3, the pattern seems to be horizontal layers with the later concrete flowing over earlier concrete. In Tests 1, 4, and 5, the pattern appears to indicate that later concrete was pushing earlier concrete away from the tremie rather than flowing over it.

4. The color distributions of Tests 2 and 3 support the earlier comments (section 2.3.1) describing flow back-up alongside the tremie pipe, before lateral flow took place. For these tests, the concrete could have flowed upward first and then down and over the earlier concrete creating the horizontal layers noted.

5. The data from Tests 4 and 5 could also support the concept of flow back-up alongside and parallel to the tremie pipe. However, if this were the case, the flow after the upward rise was probably essentially a shear failure which caused a movement of the entire mass away from the tremie pipe. Since mixtures 4 and 5 contained the second type of water reducer/retarder, there may have been less shear resistance in the fresh concrete.

6. Perhaps a better theory for Tests 4 and 5 is the formation of a bulb of concrete around the tremie pipe. Rather than flowing upward, new concrete would simply push earlier concrete away from the tremie. Again, this theory would depend upon the lowered shear capacity of the concrete in these tests. This theory would also account for the small amounts of red concrete found over black concrete.

7. The data for Test 1 seem to fit the bulb pattern described above, except that upward flow alongside the tremie was detected during this test. This mixture did not contain the second type of water reducer/retarder. It must be noted that Test 1 was conducted by pumping the concrete from the truck to the tremie hopper. The incremental volumes of concrete placed (and thus the changes in color) were determined in a much more approximate and inaccurate manner than during the other tests. These inaccuracies may make close comparisons with the other tests somewhat inappropriate.

8. It is interesting to note that ridges were seen on the surface of Test 1 at approximately the 9 and 11 ft (2.7 and 3.4 m) lines. The ridges can be interpreted, on the basis of the color distribution, as being formed by the red concrete pushing the gray concrete away from the tremie.

9. Item 2, above, indicates that the general notion of concrete flowing into an existing mound and thus being protected from contact with the water may not always be correct. In the layer type of flow, there is a significant chance that most of the tremie concrete will be exposed directly to water during the placement.

10. It was pointed out earlier not to equate sounding data with color layers. The need for that warning can be seen by comparing the figures showing sounding data with those showing color distributions. Concrete from the first color placed continued to move as additional concrete was added. Apparently, tremie concrete may be expected to be moving for a long period of time after it exits from the tremie pipe.

11. Although the coring program did provide valuable data, it was extremely time-consuming, difficult, and expensive. Development of an alternative approach, if investigations of this nature are undertaken in the future, is highly recommended.

2.3.5 Concrete density. The cores obtained from the last four placements were also used to evaluate the density of the in-place tremie concrete. Density and unit weight were determined according to the following formula:

$$\text{Unit weight} = \frac{w_a}{w_a - w_w} \gamma w$$

where w_a = weight in air

w_w = weight in water

γ_w = unit weight of water

Selected data from these calculations are presented in Table 14. Unit weights of fresh concrete calculated in accordance with ASTM C-138 are also presented in this table for comparison.

The following points may be made concerning the concrete densities:

1. In-place unit weights for concrete at the location of the tremie were very close to those determined for the fresh concrete by the standard ASTM test. Differences for the four tests ranged from 0.1 to 2.2 percent with the in-place concrete being heavier in all cases. Thus, the process of flowing through the tremie does produce a dense concrete near the tremie pipe.

2. There is a general decrease in concrete unit weight as distance from the tremie increases. When the effects of laitance accumulation on the surface are neglected by using cores not affected by the laitance, this decrease is not significant, as is shown below (amounts of laitance accumulation are discussed in section 2.3.7, below):

TABLE 14 - REPRESENTATIVE CONCRETE UNIT WEIGHTS
SEE FIGURE 14 FOR CORE LOCATIONS

Test	Station	Depth**	Unit Weight	
			lb/ft^3	(kg/m^3)
2	ASTM C 138		142.0	2,275
2	Tremie, center	Top	141.3	2,263
	Tremie, left	Bottom	137.8	2,207
	5, left	Bottom	138.1	2,212
	7, center	Bottom	138.1	2,212
	15, center*	Top	137.0	2,195
3	ASTM C 138		142.0	2,275
3	Tremie, center	Top	143.1	2,292
	Tremie, left	Top	139.4	2,233
	Tremie, left	Bottom	140.9	2,257
	5, left	Bottom	140.2	2,246
	9, right	Center	140.6	2,252
	15, center	--	138.1	2,212
	17, right	--	136.9	2,193
	19, left*	--	127.9	2,049
4	ASTM C 138		147.0	2,355
4	Tremie, center	Center	145.5	2,331
	Tremie, left	Top	143.6	2,300
	5, right	Top	144.7	2,318
	5, left	Top	145.3	2,327
	11, center	Bottom	147.3	2,360
	17, right	Bottom	145.0	2,323
	17, center*	Top	139.7	2,238
	19, left	Top	142.1	2,275
5	ASTM C 138		147.0	2,355
5	Tremie, center	Top	145.2	2,326
	Tremie, left	Top	145.9	2,337
	7, center	Top	144.7	2,318
	7, right	Top	146.7	2,350
	15, left	Top	145.0	2,323
	15, left	Bottom	146.4	2,345
	17, center	Top	144.9	2,321
	19, center*	Top	134.5	2,154
	19, center	Bottom	145.9	2,337
	19, right	Top	134.6	2,156
	19, right	Bottom	145.8	2,335

*Indicates cores which included surface laitance.

**No entry indicates core was recovered full depth in one piece.

Test	At Tremie
2	141.3 lb/ft^3(2263 kg/m^3)
3	143.1 lb/ft^3(2292 kg/m^3)
4	145.5 lb/ft^3(2331 kg/m^3)
5	145.2 lb/ft^3(2326 kg/m^3)

Test	Station	At Station
2	15	137.0 lb/ft^3(2195 kg/m^3)
3	15	138.1 lb/ft^3(2212 kg/m^3)
4	19	142.1 lb/ft^3(2275 kg/m^3)
5	19	145.8 lb/ft^3(2335 kg/m^3)

3. When laitance is included in the calcalculations, the decrease becomes much greater. The data below are for cores which had a surface layer of laitance.

Test 3, Core 19L ($\sim$1.5 in. (3.8 cm) laitance): 127.9 lb/ft^3(2049 kg/m^3)

Test 5, Core 19R ($\sim$3.0 in. (7.6 cm) laitance): 134.6 lb/ft^3(2156 kg/m^3)

It may be argued that some of the laitance resulted from an "end-effects" phenomenon as the concrete reached the end of the placement box. However, the same effects will occur in actual placements as the concrete reaches the boundaries of the placement. Therefore, these data reemphasize the requirement for removal of washed material at the far end of a placement to insure that such material does not become trapped in or part of the final concrete product.

4. As is described below, flow of tremie concrete around reinforcing steel was also examined during these tests. Flow around the bars seems to have little effect on the concrete density as is shown below:

Test 4

Core 9R, bottom, 146.8 lb/ft^3 (2352 kg/m^3)

Core 11R, top, 144.5 lb/ft^3 (2315 kg/m^3)

Bars

Core 13R, bottom, 147.1 lb/ft^3 (2357 kg/m^3)

Bars

Core 15R, top, 136.8 lb/ft^3 (2192 kg/m^3)
(includes surface laitance, 3.0 in. (7.6 cm))

Test 5

Core 9R, bottom, 149.0 lb/ft^3 (2387 kg/m^3)

Core 11R, bottom, 147.7 lb/ft^3 (2366 kg/m^3)

Bars

Core 13R, bottom, 147.2 lb/ft^3 (2358 kg/m^3)

Bars

Core 15R, bottom, 148.2 lb/ft^3 (2374 kg/m^3)

The change in density caused by the reinforcing steel does not appear to be significant, as long as laitance is not trapped near the steel.

2.3.6. Flow around reinforcing steel. Reinforcing steel was placed in four of the tests to simulate reinforced tremie placements. Observations were made of the flow of the concrete around these bars.

For Tests 1 and 2, the bars were placed in a row across the end of the placement box. For Tests 4 and 5, the bars were assembled into a cage along the side of the box. Details of the bar placement are in Figure 46.

The material reaching the end of the box in the first two tests was largely laitance. This material did flow well around the bars but it would not have provided satisfactory bond had these been actual placements. Figure 47 shows flow around bars in Test 1.

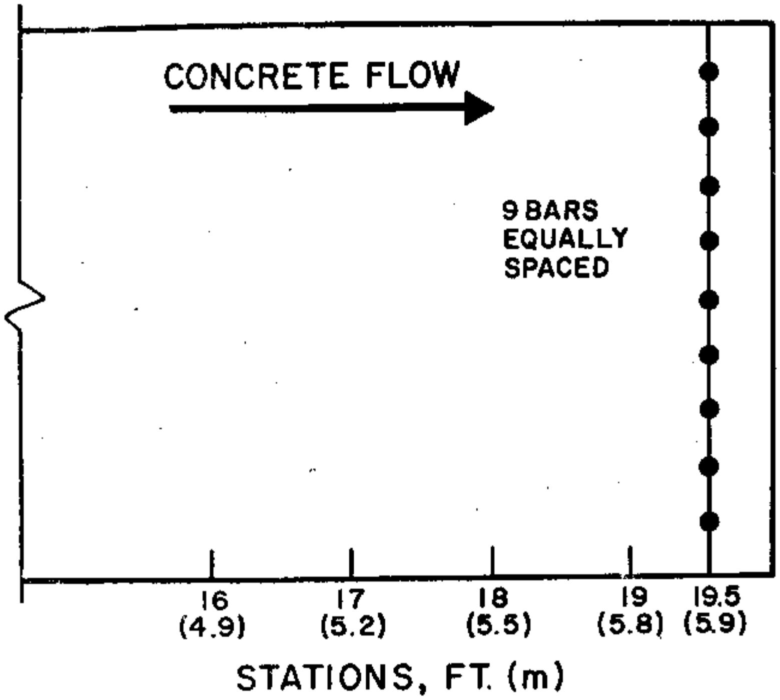
Moving the bars closer to the tremie pipe resolved the laitance problems and allowed more valid observations of concrete flow around the steel. The results were extremely good, as shown in Figure 48. While the bars had very little influence on the concrete, there were two noticeable effects.

1. There was a minor buildup of concrete upstream of the bars, as can be seen in the profiles along the right edge given earlier. This buildup was on the order of a few inches and would cause no problem in an actual placement.

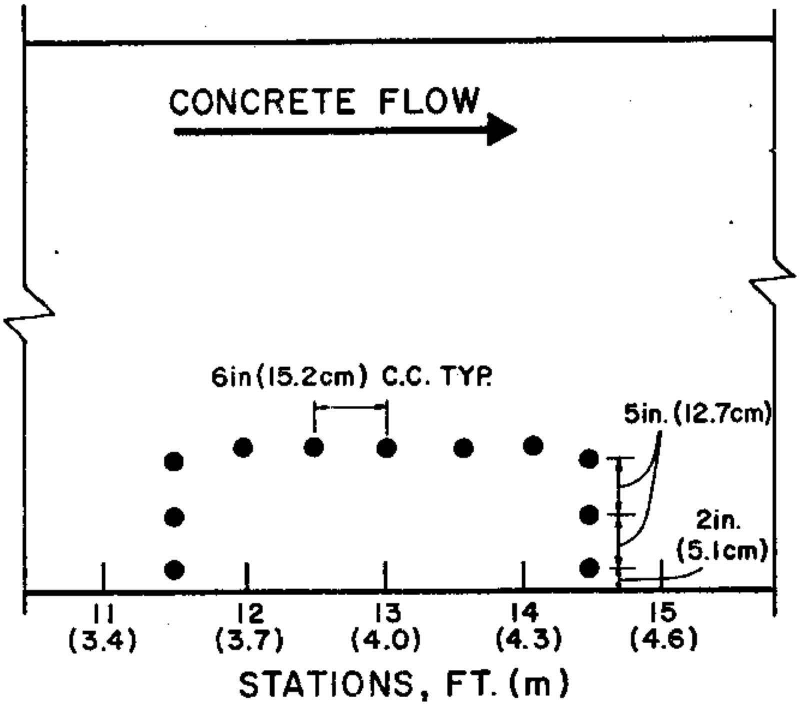
2. The bars did cause concrete flow to skew away from the steel. This is clearly seen in Figure 45. Although interesting, this phenomenon would not affect the quality of the concrete.

Overall, concrete (Tests 4 and 5) flowed well and embedded the bars satisfactorily. The slight buildup behind the bars reemphasizes the necessity for careful detailing of reinforcing steel for tremie applications to insure wide enough spaces for the concrete to flow through. There was no difference detected in the flow and bar embedment between the concretes with and without the pozzolan.

2.3.7. Laitance formation. One area which is always of concern during a tremie placement is the washing out of some of the cement paste from the concrete and the subsequent formation of laitance. The fear of this occurrence is one of the two reasons (the



a. End of placement box, Tests 1 and 2. (Also see Figure 47.)



b. Side of placement box, Tests 4 and 5. (Also see Figure 48.)

Figure 46. Reinforcing steel placement. (Plan view.) Steel used was No. 11 bars.

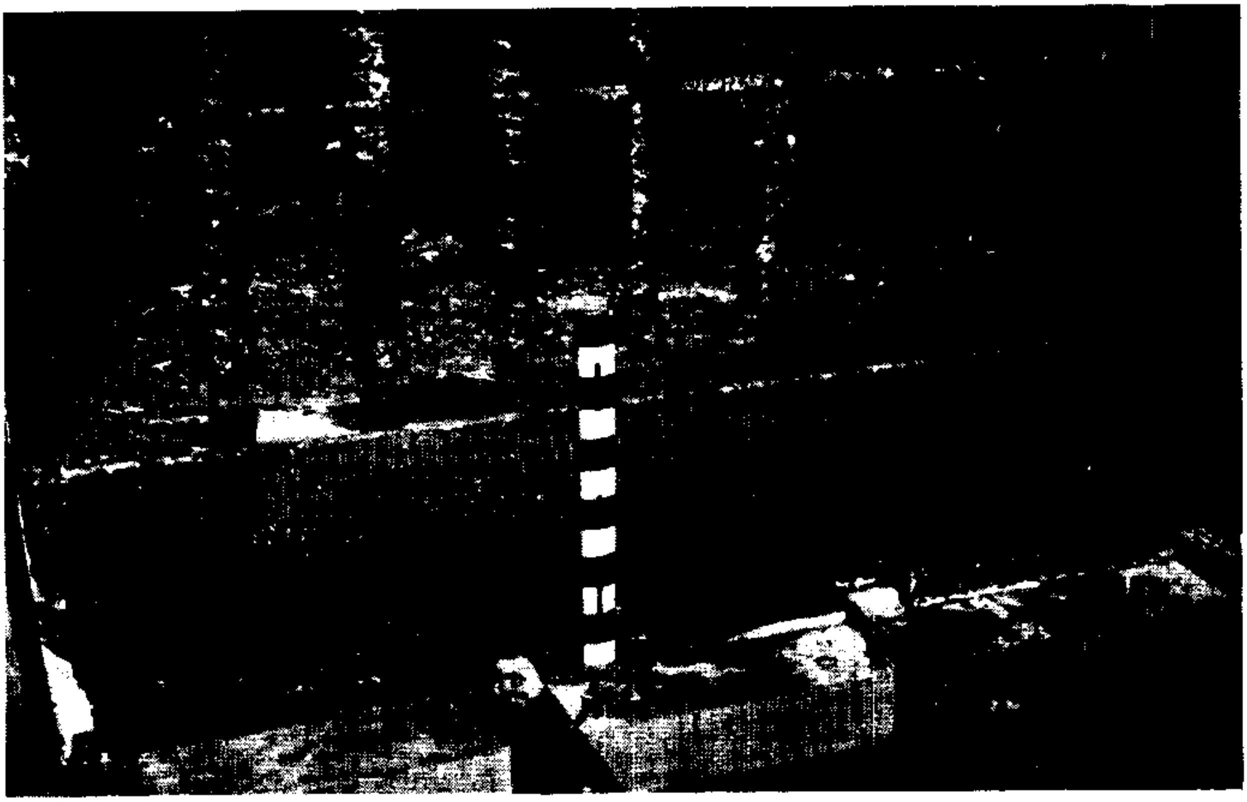


Figure 47. Concrete (laitance) flow around reinforcing steel, Test 1.

Figure 48. Concrete flow around reinforcing steel, Test 5.

other being improved workability and flow) traditionally given for increasing the cement content for tremie placements.

The results of these placements show that cement loss/laitance formation is indeed a problem which must be considered.

For the first two tests, the material which reached the far end of the placement was almost entirely laitance. Test 3 did show concrete at the end of the box, but there was also a significant amount of laitance. The quality of the concrete near the end of the box in these tests was unsatisfactory for the first two tests and marginal for the third.

The concrete at the far end of the box for the last two tests showed a much smaller amount of laitance - only a few inches, with this laitance being on top of sound concrete.

The change in the amount of laitance may be the result of the following:

1. The second type of water reducing/retarding admixture may have increased the bond of the cement into the concrete.

2. The type of flow observed for Tests 4 and 5 may have exposed less of the concrete to contact with the water; and therefore, there was less opportunity for cement to be washed out. The flow seen in Tests 2 and 3, horizontal layers, would have exposed more concrete to washing.

When washing out does occur, little of the cement seems to go into suspension in the water. The majority appears to stay near the surface of the concrete and to flow toward the low end of the placement. In all of the tests, there was a minimal layer (1/4 to 1/2 in. (0.6-1.3 cm)) of laitance which was deposited over the entire sample by cement precipitating out of suspension after the placement was completed.

No difference was detected in laitance formation for the concretes with and without pozzolan. However, the laitance in Test 2 which contained significant proportions of pozzolan which had washed out was soft and did not set, as did the other accumulations of laitance.

2.4 Summary. The following items summarize these tests:

1. Five concrete mixtures of approximately 6 yd^3 each (4.6 m^3) were placed by tremie under water in a laboratory placement box. The mixtures differed in pozzolan content and in, the types of admixtures used.

2. The concrete placements were divided into three equal segments which were colored differently to allow for later identification of the concrete.

3. Data were collected during and after the concrete placements covering concrete flow patterns, final color distribution, density, flow around reinforcing steel, and laitance formation.

4. No single flow mechanism for tremie placed concrete was identified. Instead, two basic flow patterns were seen. The first of these was horizontally layered while the second was vertically layered. The latter produced much flatter concrete slopes, provided better quality concrete at the far end of the placement, and produced much less laitance, making it the preferred flow pattern for actual placements.

5. The type of flow mechanism which develops appears to be a function of the concrete being placed. The tests with the vertically layered flow used concrete containing the second type of water reducer/retarder. Apparently, this admixture reduced the shear resistance of the fresh concrete allowing the vertically layered type of flow to take place.

6. The results of these flow tests lead to the conclusion that determination of the shear resistance of a potential tremie concrete mixture is a critical step in the mixture design and evaluation process. Additional effort to develop a usable shear test for fresh concrete appears to be justified.

7. The concrete mixtures containing the pozzolanic replacements performed very well indicating that the recommendations of the small-scale tests (Chapter 1) were correct.

8. These large-scale flow tests have led to a better understanding of the tremie placement process. By designing concrete mixtures to give a particular type of flow, the engineer will have a greater degree of control over underwater placements which should lead to improved results on future projects.

CHAPTER 3

TREMIE CONCRETE PLACEMENT, I-205 COLUMBIA RIVER BRIDGE

3.1 Objective. The objective of this portion of the project was to observe tremie concrete placement of a nonstructural seal for a pier of a major bridge. The following areas were of particular interest:

a. Behavior of a tremie concrete mixture containing a fly ash replacement of a portion of the cement;

b. Prediction and measurement of temperatures developed within the seal concrete; and,

c. Examination of flow patterns of the tremie concrete.

3.2 Background.

3.2.1 Description of the bridge. This bridge, when completed, will cross the Columbia River east of Portland, Oregon. The bridge will provide a bypass around the downtown Portland area for I-5 users as well as carry local commuter traffic.

The total project length is 11,750 ft (3,580 m). Included in this total are major bridges over the north and south channels of the Columbia River and a 1,100 ft (335 m) fill section across an island. The North Channel crossing is two entirely separate structures which share a common foundation at Piers 12 and 13 only. The South Channel crossing is two separate structures for all of its length. The South Channel Bridges will be 3,120 ft (951 m) long and will be constructed using a cast-in-place technique. The North Channel Bridges will be constructed using a segmented box girder technique. These structures will have a total length of 7,460 ft (2,274 m) with main spans of 480; 600; and 480 ft (146; 183; 146 m). When complete, the North Channel structures will be the longest segmented box girder bridges in North America.

The contractor who was awarded the substructure contract for the North Channel Bridges is a joint venture of Willamette-Western Corp, Alaska Constructors, Inc., and General Construction Co. He is using both structural and nonstructural tremie concrete on the project. Reusable steel forms are being used to cast 26 double bell piers incorporating reinforced tremie concrete. Two additional piers are being constructed using cofferdams with tremie-placed seals. Except where specifically noted, the work covered in this report deals with nonstructural tremie-placed concrete seal of Pier 12 of the North Channel Crossing.

3.2.2 Geometry of Pier 12. This pier is the northernmost river pier in the project. The main 600 ft (183 m) span of the two bridges will be between Pier 12 and Pier 13, the next pier to the south. Pier 12 was constructed using a cofferdam made up of ARBED interlocked H-piles. Two levels of internal bracing were used to strengthen the cofferdam. The nominal inside dimensions of the cofferdam were 54 x 140 ft (16.5 x 42.6 m). The base of the seal was designed to be at a depth of 78 ft (23.8 m) with the top of the seal at a depth of 45 ft (13.7 m). These nominal dimensions lead to a volume of concrete required of 9,240 yd^3 (7,065 m^3).

The actual dimensions of the cofferdam varied slightly as did the top and bottom elevations of the seal. A total of 9,750 yd^3 (7,455 m^3) of concrete were actually placed by tremie.*

3.2.3 Temperature predictions. Early in the planning process, the State of Oregon and the contractor raised the question of problems associated with temperature development in such a large placement. At their request, several analyses were performed using a computer program based upon a one-dimensional heat flow evaluation technique usually referred to as the Carlson Method after its developer, Roy Carlson (ref. 24).

The following assumptions were made while applying the Carlson Method:

a. Heat flow is considered in one direction only. For the tremie placement of Pier 12, heat low in the vertical direction was evaluated.

b. Heat generation within the concrete is adiabatic.

c. The adiabatic temperature increase for a mix being evaluated is directly proportional to the adiabatic temperature increase of a reference mix whose adiabatic curve is known. The proportional constant is the cement content of the trial mix divided by the cement content of the reference mix.

d. Heat generation for a given amount of pozzolanic material is one-half that of the same weight of cement.

e. The thermal diffusivity of the concrete and the underlying rock is 1.00 ft^2/day (1.08 x $10^{-6} m^2/s$).

f. The initial temperature of the underlying material is the same as the river water.

g. The continuous placement of the tremie may be modelled by an incremental technique.

Due to the assumptions noted and to uncertainties about the input data for actual materials to be used, the results of the predictions were viewed as only relative indications of the temperatures

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* For more information on the bridge itself and the construction techniques being used, see references 19 through 23.

which would be developed by the various mixtures. The temperature predictions are shown in Table 15.

These predictions indicated that high temperatures could be expected in the seal concrete and that replacement of a portion of the cement would be the most feasible way of meeting the State's desire for a 140°F (60°C) maximum temperature.

The desire to reduce temperature in the seal concrete was heightened by surface cracking of a large pier shaft on shore which occurred at about the time the calculations were being done. This cracking was attributed to thermal gradient problems.

It must be stressed that one of the most significant assumptions of the Carlson Method is that heat flux occurs only in the vertical direction. Thus, the predictions above are valid only for the center of the concrete mass. For those areas near the edges of the seal, where potentially significant temperature gradients may develop, another technique must be used. To overcome this problem, a program was written to allow use of an existing finite-element program for prediction of temperatures in tremie concrete as is described in Chapter 5.

3.2.4 Tremie concrete mixture. Based upon the predictions above, the concrete mixture described in Table 16 was selected for use. This mixture was developed as is outlined in the table. As is also shown in Table 16, this mixture has an equivalent cement content for heat generation purposes of 611 lb/yd^3 (361 kg/m^3).

3.2.5 Placement technique. Tremie concrete placement for Pier 12 began at 8 A.M. on 15 May 1978, and was essentially continuous for 72 hours. The majority of the concrete was batched in a floating plant moored at the site. Two pumps were used to transfer concrete from the plant to the tremies. Additional concrete was batched at a nearby ready-mix plant and was trucked to the site. This concrete was pumped along a causeway leading from shore to the cofferdam. Figures 49 and 50 show the site and the cofferdam during the placement process.

The tremies were manufactured from 10 in. (25.4 cm) pipe. Connections were flanged and gasketed. A hopper was bolted onto the top of each tremie and each tremie had its own frame and air-hoist to allow for vertical movement. The upper portions of the tremies were made up of 5 ft (1.5 m) sections which allowed for removal of sections as the placement progressed. Details of the tremies and the support frames are shown in Figures 51 and 52.

The tremies were started dry with the lower end sealed with a metal plate and rubber gasket (Figure 53). The plate was wired onto the end of the tremie. The concrete used to fill the the tremies initially was therefore dropped approximately 80 ft (24.4 m). Once full of concrete, the tremies were lifted breaking the wires which allowed the concrete flow to begin. The same sealing techniques were used when a tremie was moved and restarted.

Three tremies (two supplied by the floating plant and one supplied from shore) were normally in use at one time. Placement was started with all three tremies along the short centerline of the cofferdam. As the seal in this area was brought up to grade, the tremies were moved toward the ends of the cofferdam. The locations for restarting a tremie were established by soundings.

3.3 Observations and Discussion

3.3.1 Measured temperatures. The temperatures which developed in the tremie concrete were measured using 34 resistance thermometers placed in the northeast quadrant of the cofferdam. These instruments were located at various elevations in four planes (Rows 1-4) perpendicular to the long axis of the cofferdam as is shown in Figure 54. Exact instrument locations are given in Appendix H.

Readings were made manually using a variable resistance box nominally every two hours for the first 80 hours after the placement began (Figure 55). Readings were then taken two or three times daily for an additional 13 days until the contractor began preparing to place the next lift of concrete for the pier. Temperature data, a description of the data recording technique, and data reduction methods are given in Appendix I. The data obtained are discussed below:

a. Maximum temperatures. The maximum temperature recorded for each instrument and a brief desciption of instrument locations are given in Table 17. Note that the river temperature during and following placement was approximately 55° F (13°C). The concrete placement temperature ranged from 60 to 65°F (16 to 18° C). The maximum concrete temperature recorded therefore represents a 90 to 95° F (32 to 35° C) increase.

The temperatures recorded for instruments 5, 7, and 9 are less than anticipated. These instruments may have malfunctioned or the low readings may have been caused by a zone of incemented material (described below in section 3.3.4).

A summary of temperatures based upon instrument groupings is given in Table 18. As anticipated, the maximum temperatures developed in the center of the concrete mass.

The temperatures which developed near the outside edges of the seal and near the top surface represent potentially significant thermal gradients as is discussed below. The range of temperatures in the group of instruments near the top surface of the seal may be attributed to the varying depths of concrete cover which were actually achieved.

b. Temperature histories. The locations of four representative instruments are shown in Figure 56. Time versus temperature curves for these instruments are presented in Figures 57 through 60.

TABLE 15 - TEMPERATURES PREDICTED USING THE CARLSON METHOD

Cement Type	Cement Content Sacks/yd^3 lb/yd^3 (kg/m^3)	Percent Fly Ash Replacement	Seal Thickness ft (m)	Initial Concrete Temp., °F (°C)	Predicted Maximum Temp., °F (°C)
I	7.5 705 (418)	0	38 (11.6)	65 (18)	176 (80)
		20			164 (73)
	7.0 658 (390)	0			168 (76)
		20			158 (70)
II	7.5 705 (418)	0			160 (71)
		20			150 (66)
	7.0 658 (390)	0			154 (68)
		20			145 (63)
	7.0 658 (390)	0	33 (10.0)	60 (16)	150 (66)
		20			141 (61)

NOTES: (1) Predicted temperatures at 10 days after beginning of placement.

(2) All predictions assume river water temperatures of 45°F (7°C).

Figure 49. Overall view of site during placement of tremie concrete for Pier 12 of I-205 Bridge.

TABLE 16 - TREMIE CONCRETE MIXTURE, PIER 12, I-205 BRIDGE

Cement, Type II	526 lb/yd^3 (312 kg/m^3)
Fly Ash	165 lb/yd^3 (98 kg/m^3)
Coarse Aggregate 3/4 inch (19.0 mm) maximum	1,622 lb/yd^3 (962 kg/m^3)
Fine Aggregate	1,277 lb/yd^3 (758 kg/m^3)
Water	304 lb/yd^3 (180 kg/m^3)
Water Reducing Admixture	Per manufacturer's recommendations
Slump	6 - 9 inches (15 - 23 cm)
Design Strength (28 days)	3,300 lb/in.^{2} (22.8 MPa)
Actual Strengths (28 days) (approximate average)	5,000 lb/in.^{2} (34.5 MPa)
Water-cement+flyash Ratio	0.44

This mixture was developed as follows:

Cement: 7 sacks/yd^3 = 658 lb/yd^3 (390 kg/m^3)
Less 20 percent -132 (-78)
Net 526 lb/yd^3 (312 kg/m^3)

Fly Ash: 125 percent of cement reduction = 165 lb/yd^3 (98 kg/m^3)

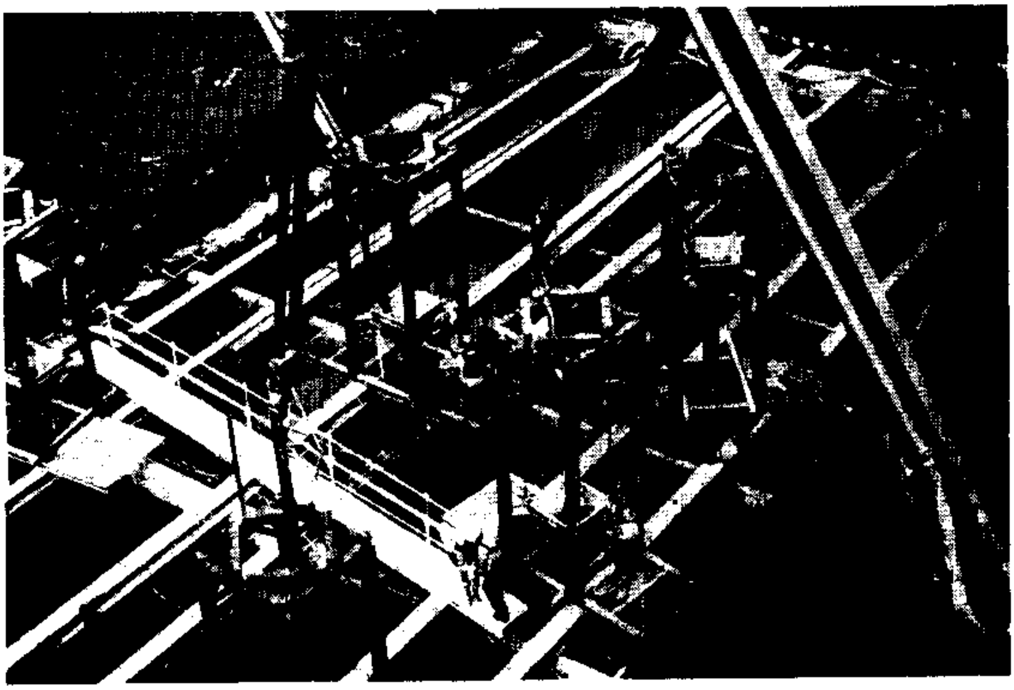


Figure 50. View inside cofferdam during tremie concrete placement.

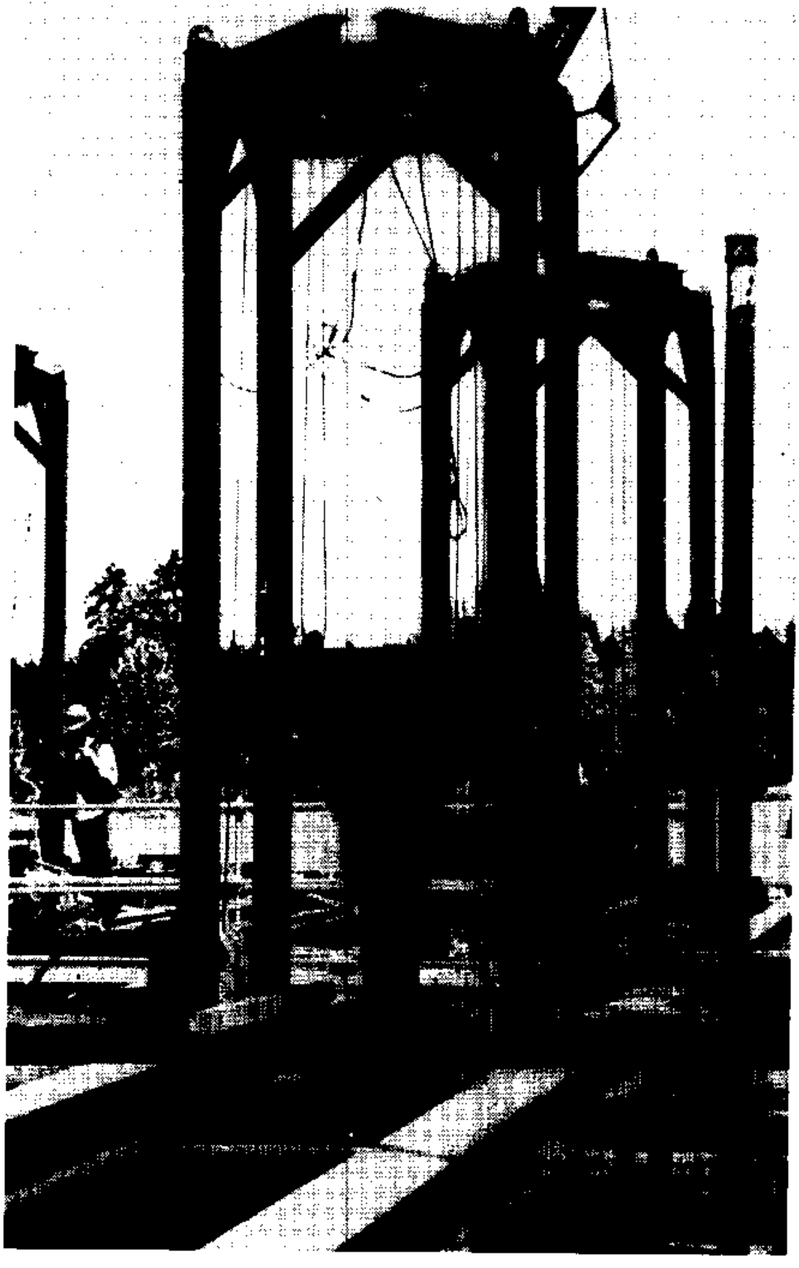


Figure 51. Details of tremie placement equipment - frame supporting hopper and pipe. Note air hoist which allowed vertical movement of pipe during placement.

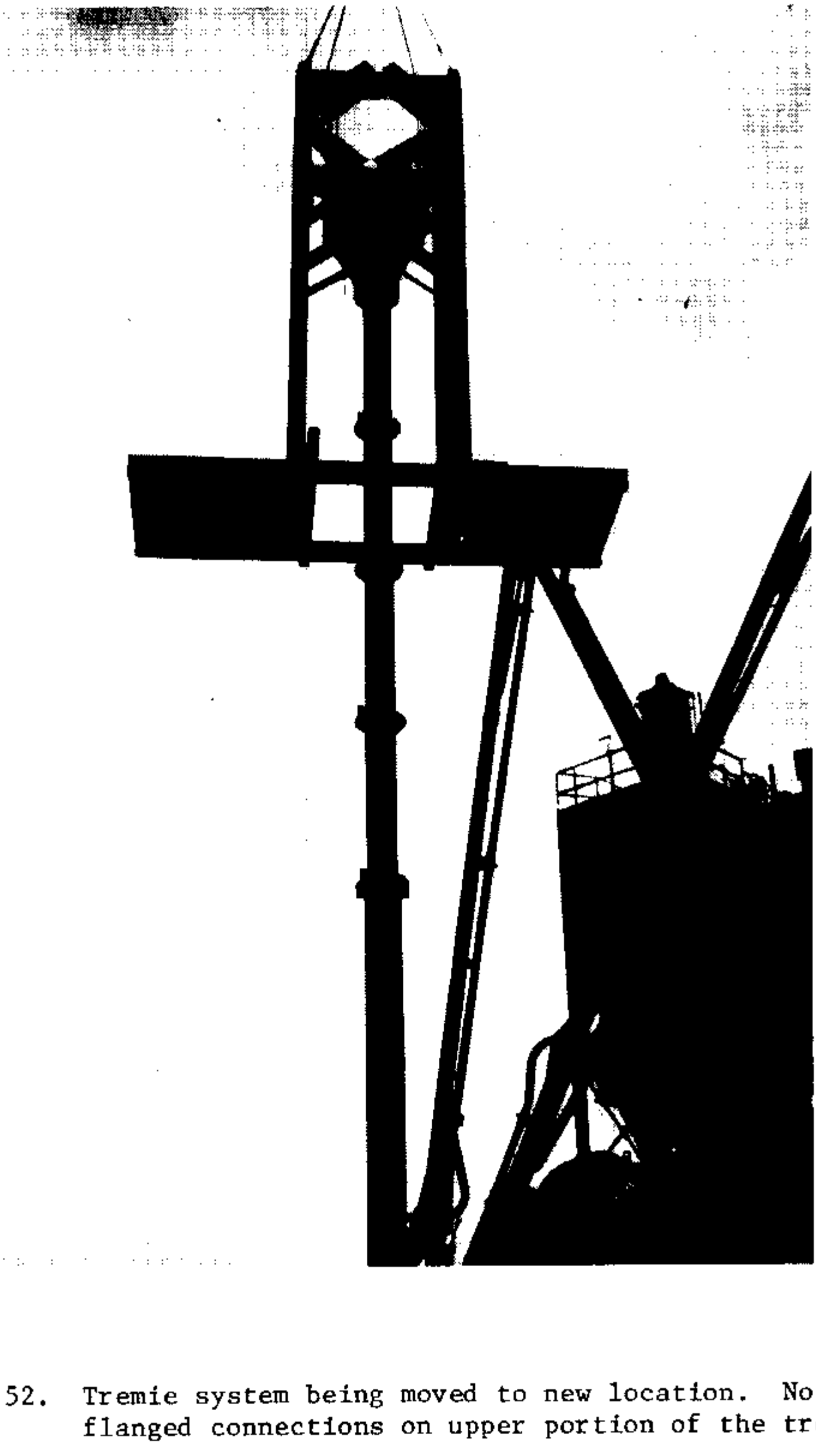


Figure 52. Tremie system being moved to new location. Note flanged connections on upper portion of the tremie pipe.

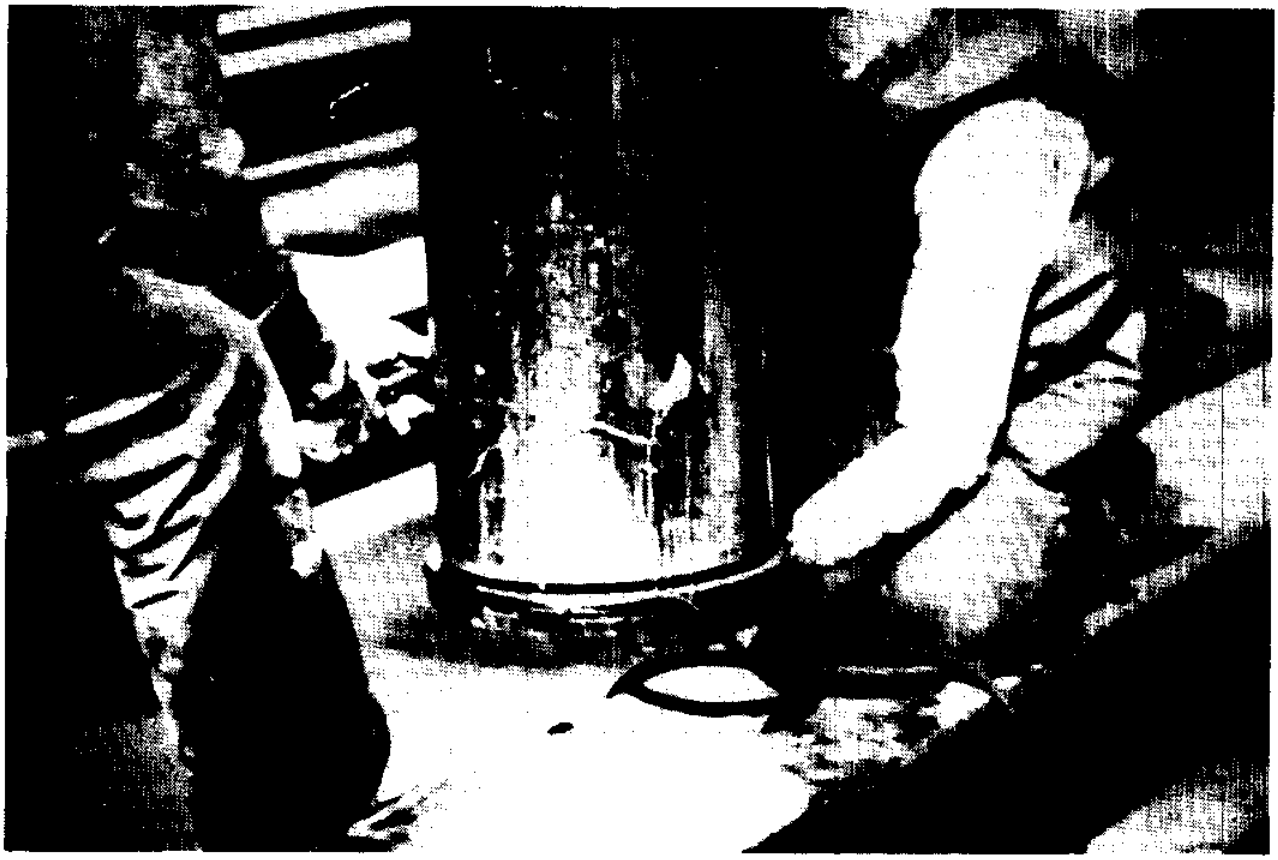
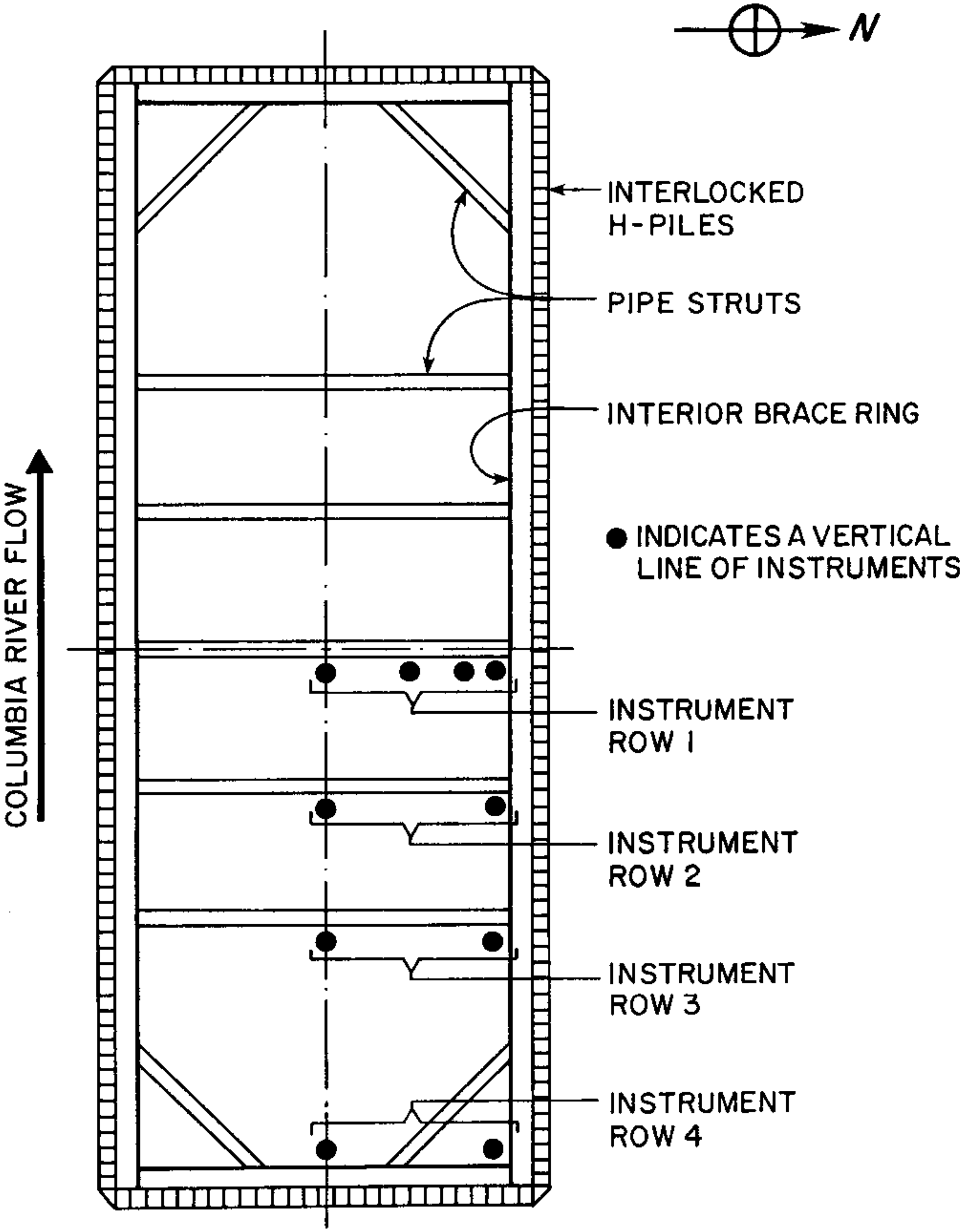


Figure 53. Steel end plate and rubber washer being tied to end of tremie pipe to seal pipe during a change of tremie location.



NOMINAL 54 x 140 ft. (16.5 x 42.7 m) INSIDE SHEET PILES

Figure 54. General instrumentation plan, Pier 12, I-205 Bridge.

Figure 55. Manual recording of temperatures in seal concrete.
Note interlocked ARBED H-pile system.

TABLE 17 - MAXIMUM TEMPERATURES RECORDED IN PIER 12 SEAL CONCRETE

Inst. No.	Row	Instrument Location		Max Temp, °F (°C)	Elapsed Time, Hrs.	Temp at 386 Hrs, °F (°C)	Temp at 29 Days, °F (°C)
		Horizontally	Vertically				
1*	1	Mid-Depth of Water in Cofferdam		57 (14)	140	57 (14)	NA
2*	1	Water, 1 Ft Above Design Seal Surface		58 (14)	340	57 (14)	NA
3*	1	C-L	Top of Seal	57 (14)	140	57 (14)	NA
4	1	C-L	Top of Seal	110 (43)	110	92 (33)	NA
5**	1	C-L	Mid-depth	129 (54)	180	129 (54)	NA
6	1	C-L	Bottom	122 (50)	130	119 (48)	NA
7**	1	Off C-L	Top Qtr Pt	95 (35)	250	79 (26)	NA
8	1	Off C-L	Bottom Qtr Pt	155 (68)	310	155 (68)	150 (66)
9**	1	Off C-L	Mid-depth	116 (47)	220	106 (41)	NA
10	1	Outside Edge	Top of Seal	82 (28)	90	60 (16)	NA
11	1	Outside Edge	Top of Seal	107 (42)	100	61 (16)	NA
12	1	Outside Edge	Mid-depth	92 (33)	66	74 (23)	NA
13	1	Outside Edge	Bottom	94 (34)	24	81 (27)	NA
14	1	Water Outside	Cofferdam	Instrument Lost			NA
15	2	C-L	Top of Seal	90 (32)	120	82 (28)	78 (26)
16	2	C-L	Mid-depth	150 (66)	380	150 (66)	154 (68)
17	2	C-L	Bottom	119 (48)	150	117 (47)	111 (44)
18	2	Outside Edge	Top of Seal	121 (49)	130	93 (34)	NA
19	2	Outside Edge	Mid-depth	105 (41)	210	81 (27)	NA
20	2	Outside Edge	Bottom	101 (38)	50	84 (29)	NA
21	3	C-L	Top of Seal	114 (46)	140	101 (38)	NA
22	3	C-L	Top of Seal	139 (59)	180	130 (54)	NA
23	3	C-L	Mid-depth	154 (68)	370	154 (68)	148 (64)
24	3	C-L	Bottom	118 (48)	180	116 (47)	NA
25	3	Outside Edge	Top of Seal	108 (42)	140	86 (30)	75 (24)
26	3	Outside Edge	Top of Seal	127 (53)	170	105 (41)	87 (31)
27	3	Outside Edge	Mid-depth	125 (52)	180	109 (43)	96 (36)
28	3	Outside Edge	Bottom	102 (39)	100	78 (26)	67 (19)
29	4	C-L	Top of Seal	94 (34)	130	70 (21)	NA
30	4	C-L	Mid-depth	142 (61)	170	121 (49)	NA
31	4	C-L	Bottom	100 (38)	70	90 (32)	NA
32	4	Outside Edge	Top of Seal	116 (47)	140	90 (32)	NA
33	4	Outside Edge	Mid-depth	143 (62)	150	112 (44)	NA
34	4	Outside Edge	Bottom	87 (31)	22	64 (18)	NA

*Instrument located in water, not in concrete. Instrument 3 was not embedded in concrete as planned.

** Readings for these instruments appear to be questionable. See text.

TABLE 18 - MAXIMUM TEMPERATURES GROUPED BY INSTRUMENT LOCATION

	Instruments and Temperatures		
		°F	(°C)
At or near center-line of pier, mid-depth of seal. (Excluding Row 4)	# 5*	129	(54)
	# 7*	95	(35)
	# 8	155	(68)
	# 9*	116	(47)
	#16	150	(66)
	#23	154	(68)
At or near center-line of pier, bottom of seal (Excluding Row 4)	# 6	122	(50)
	#17	119	(48)
	#24	118	(48)
Outside edge of cofferdam, mid-depth of seal	#12	92	(33)
	#19	105	(41)
	#30	142	(61)
	#33	143	(62)
Outside edge of cofferdam, bottom of seal	#13	94	(34)
	#20	101	(38)
	#28	102	(39)
	#31	100	(38)
	#34	87	(31)
Near top surface, all locations	# 4	110	(43)
	#10	82	(28)
	#15	90	(32)
	#18	121	(49)
	#21	114	(46)
	#25	108	(42)
	#29	94	(34)
	#32	116	(47)

NOTE: *Readings for these instruments appear to be questionable. See text.

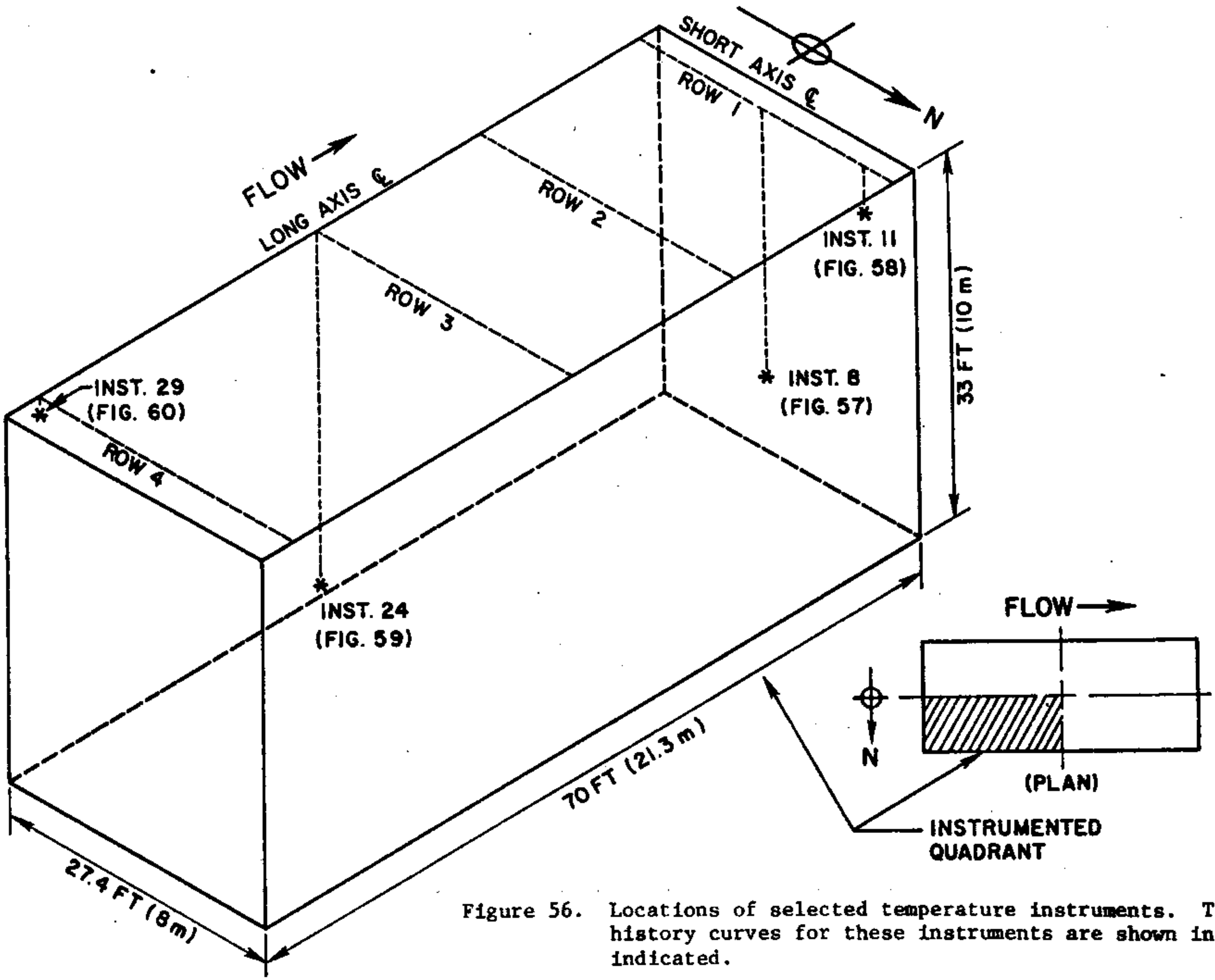


Figure 56. Locations of selected temperature instruments. Temperature history curves for these instruments are shown in the figures indicated.

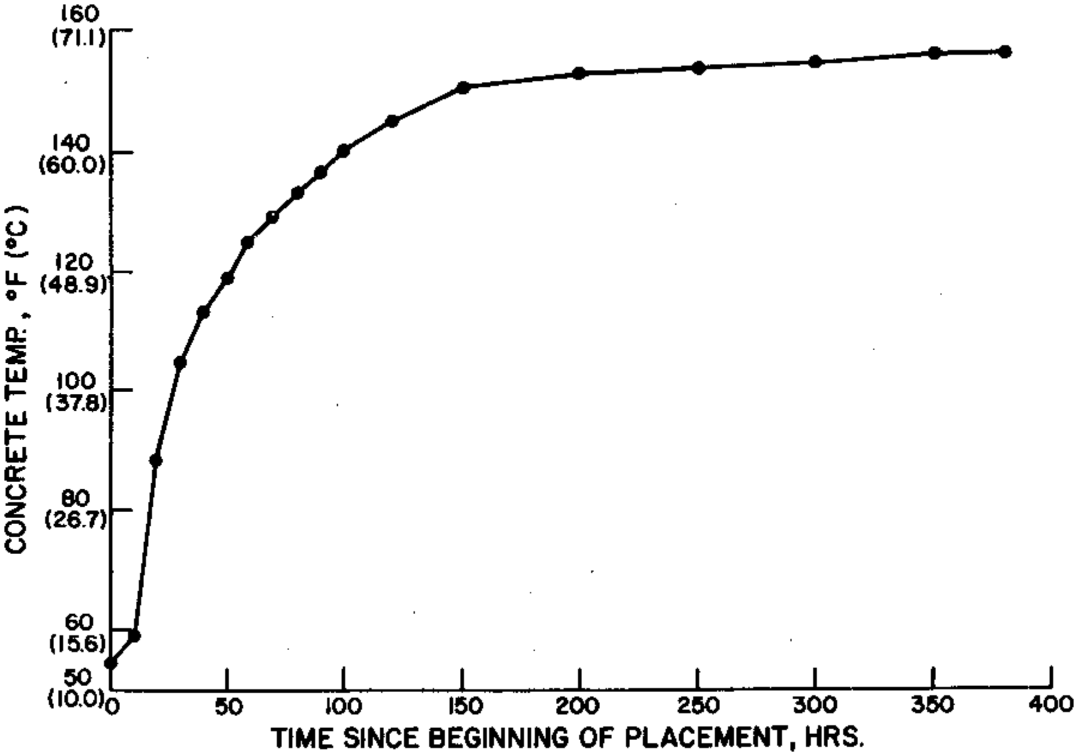


Figure 57. Temperature history, Inst. No. 8, near centerline, mid-depth of seal.

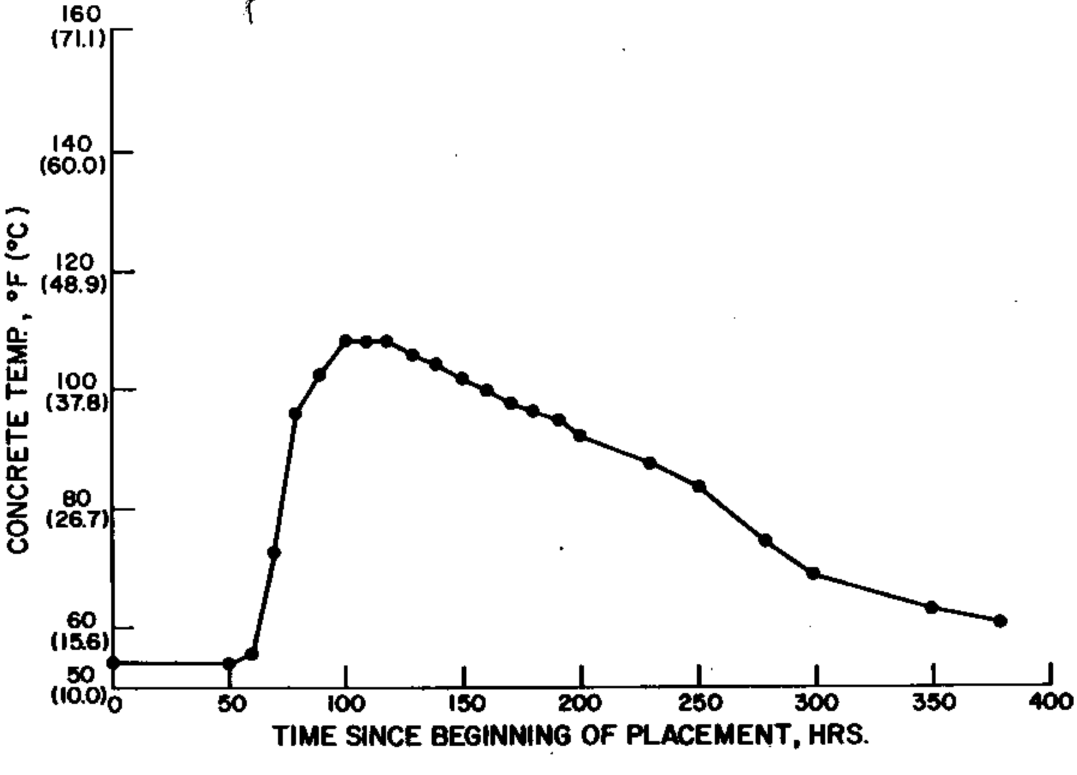


Figure 58. Temperature history, Inst. No. 11, outside edge, top of seal.

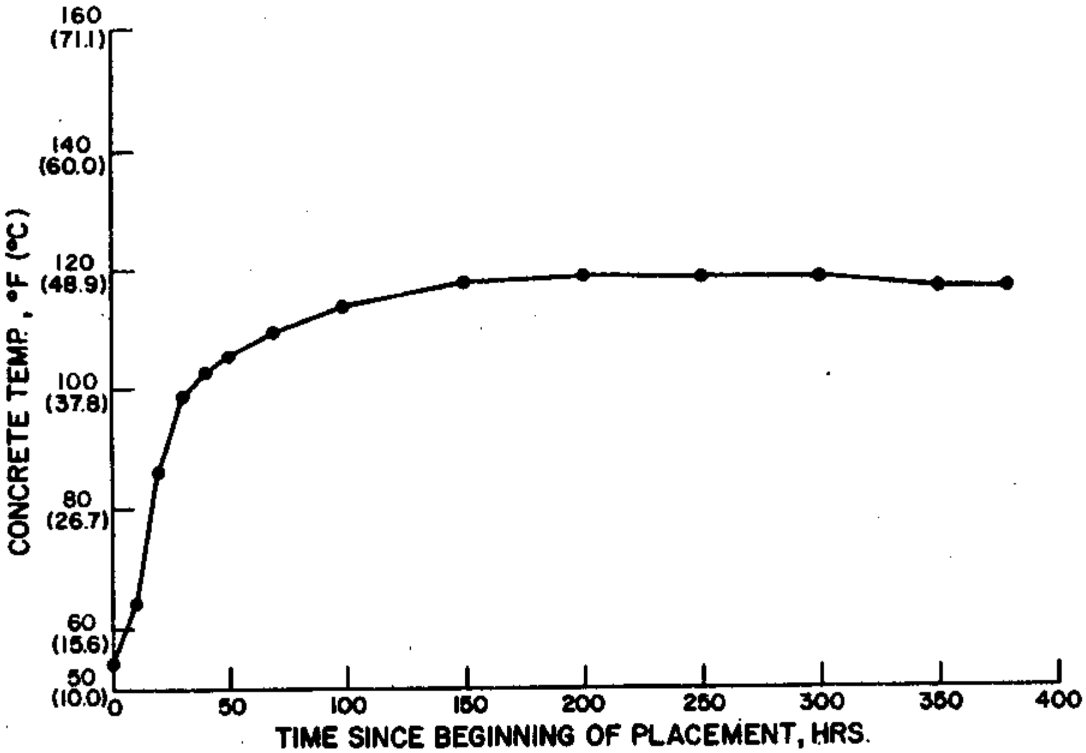


Figure 59. Temperature history, Inst. No. 24, centerline, bottom of seal.

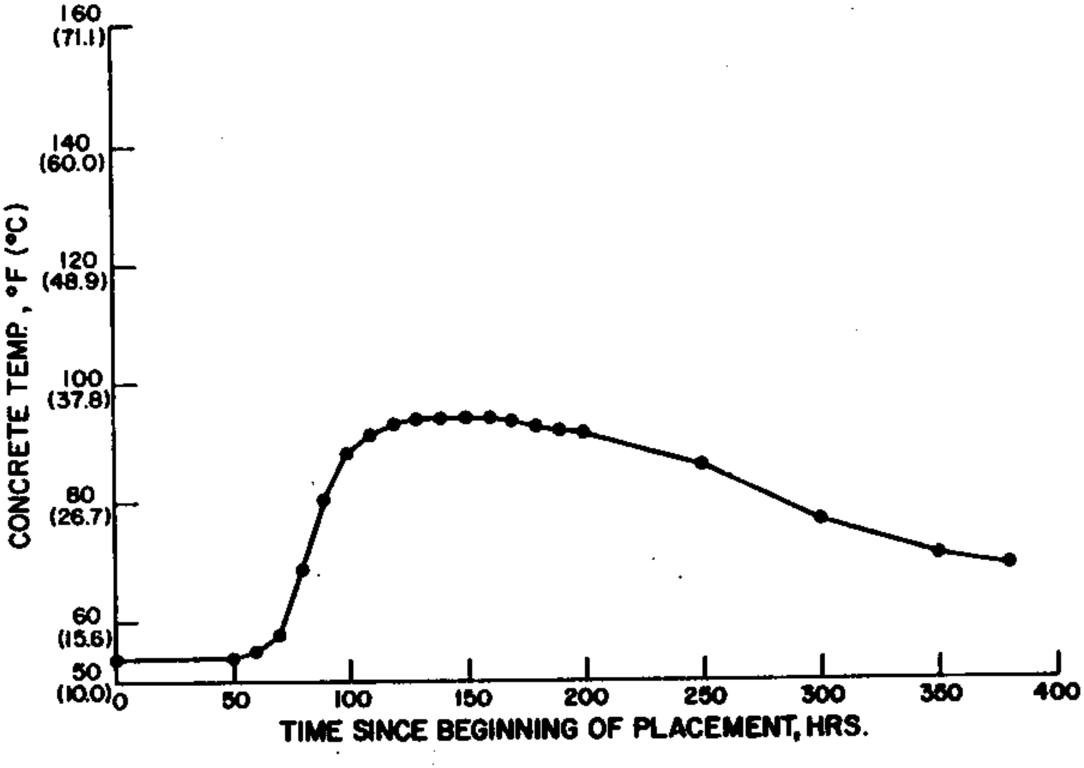


Figure 60. Temperature history, Inst. No. 29, centerline, top of seal.

Readings for several instruments were taken on 13 June 1978, 29 days after placement began. These temperatures are also shown in Table 17. A summary of temperatures 386 hours after placement began (the end of regular readings) is as follows:

60-85°F (16-29°C) 11 instruments
(exterior locations)

86-105°F (30-41°C) 7 instruments
(top of seal locations)

106-125°F (42-52°C) 7 instruments
(various locations)

126-155°F (53-68°C) 5 instruments
(interior locations)

Thus, after 386 hours, the interior of the concrete remained very close to its maximum temperature while the edges and surfaces were showing significant cooling.

c. Gradients. The data for those instruments near the edge or near the top of the seal were examined to determine the temperature gradients which developed in the extreme portions of the concrete. The outside surface of the concrete was assumed to be at the water temperature, 55°F (13° C). Table 19 summarizes these gradients by instrument location. The data in this table point out the following:

1. Large temperature differentials developed in the outside portions of the concrete - a maximum difference of 88°F (31°C) above the river temperature was recorded.

2. When the distances of the instruments from the face of the concrete are taken into account to develop a gradient in terms of temperature change per unit length, the various instruments may be compared. The gradients for the mid-depth and top instruments, taken to the outside of the seal, are both approximately 1.5° F/in. (0.4° C/cm). For the top instruments taken toward the top surface, the gradients were more varied and ranged up to 4.4° F/in. (1.0° C/cm).

3. The rate of gradient development was generally consistent at 0.4°F/hr (0.2° C/hr) when the bottom instruments are excluded. The bottom instruments developed their maximum values at a faster rate since the underlying material was not as efficient a heat sink as the river water.

d. Temperature induced stress. A detailed examination of temperature induced stress is beyond the scope of this report. However, the following calculations are presented based upon typical gradients described above to point out the significance of the temperatures which were developed in the seal concrete.

Consider a mid-depth location 40 in. (1 m) from the outside of the seal (typical temperature instrument location) at which the gradient is 1.5°F/in. (0.33°C/cm). Assuming complete constraint and neglecting creep the approximate change in stress across the concrete section may be calculated using the following equation:*

$$\Delta\sigma = (E\,\alpha\Delta T)R$$

where $\alpha = 5.5 \times 10^{-6}$ in./in./°F
$\Delta T = 1.5°$ F/in. x 40 in. = 60°F
R = 1.0 for complete constraint
For $E = 1.0 \times 10^6$ lb/in.^{2}, $\Delta\sigma = 330$ lb/in.^{2}
For $E = 3.0 \times 10^6$ lb/in.^{2}, $\Delta\sigma = 990$ lb/in.^{2}

Further, assume a rate of temperature development of 0.4°F/hr (0.22° C/hr). For the total differential of 60°F (33°C), the stress calculated above would be developed in 150 hours.

Since the exact properties of the concrete at early ages are unknown, it is impossible to say with certainty what effects the stresses calculated above would have on the seal. It appears that these stresses are large enough and develop rapidly enough to be of concern.

3.3.2 Measured versus predicted temperatures. After the placement was complete, the Carlson Method program described above was used to predict temperatures within the seal based upon the actual placement conditions (mixture design, water temperature and concrete temperature). The temperatures predicted by this run were compared with the measured temperatures to determine the reliability of the prediction technique. Overall, the prediction technique was accurate to within approximately ten percent of measured values when considering locations near the center of the concrete mass. A summary of predicted versus measured temperatures for various elevations within the seal is given in Table 20. Comparisons of the various instrument groups are given below. Tables of predicted versus measured temperatures are given in Appendix J.

A. Mid-depth instruments. The maximum temperature predicted at the end of 10 days after the beginning of placement was 144°F (62°C) at a station approximately 13 ft (4 m) above the base of the seal. From about 7 ft (2 m) to 28 ft (9 m) above the base of the seal, the predicted temperature was slightly above 140°F (60°C). A comparison of the mid-depth instruments along or near the center line of the seal at the end of 10 days shows:

Inst. No. 5: 129°F (54° C)
Inst. No. 7: 92°F (33° C)
Inst. No. 8: 153°F (67° C)
Inst. No. 16: 145°F (63° C)
Inst. No. 23: 150°F (66° C)

The readings for instruments 5 and 7 are not consistent with similarly placed instruments.

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* $\Delta\sigma = (E\,\alpha\Delta T)R$

Where $\alpha = 2.5 \times 10^{-5}$ cm/cm/° C
$\Delta T = 0.33°$ C/cm x 102 cm = 34°C
R = 1.0 for complete constraint
For E = 6895 MPa, $\Delta\sigma$ = 2.3 MPa
E = 20685 MPa, $\Delta\sigma$ = 6.9 MPa

TABLE 19 – TEMPERATURE GRADIENTS IN OUTER PORTIONS OF SEAL CONCRETE

Instrument Location	Ranges		Rate of Temperature Development
	Temperatures	Gradients	
Edge of Seal, Mid-Depth (5 Inst.)	37 - 88°F (21 - 49°C)	0.9 - 2.1° F/in. (0.2 - 0.5° C/cm)	0.2 - 0.6° F/hr (0.1 - 0.3° C/hr)
Edge of Seal, Bottom; Gradient to Outside Edge (5 Inst.)	32 - 47°F (18 - 26°C)	0.8 - 1.2° F/in. (0.2 - 0.3° C/cm)	0.5 - 1.6° F/hr (0.3 - 0.9° C/hr)
Top of Seal; Gradient to Outside Edge (9 Inst.)	27 - 84° F (15 - 47° C)	0.7 - 1.9° F/in. (0.2 - 0.4° C/cm)	0.3 - 0.5° F/hr (0.2 - 0.3° C/hr)
Top of Seal; Gradient to Top (4 Inst.)	35 - 53° F (19 - 29° C)	1.6 - 4.4° F/in. (0.3 - 1.0° C/cm)	0.3 - 0.4° F/hr. (= 0.2° C/hr)

TABLE 20 - PREDICTED VERSUS MEASURED TEMPERATURES AT VARIOUS ELEVATIONS, 240 HOURS AFTER BEGINNING OF PLACEMENT

Elevation Above Bottom of Seal, Ft. (m)	Predicted Temp., °F (°C)	Measured Temperature Inst #/°F(°C) (Multiple inst at same elevation are on same line)
35 (10.7)	55 (13)	
34	71 (22)	#3/56 (13); #15/86 (30)
32	110 (43)	#4/101 (38); #21/108 (42)
30 (9.1)	127 (53)	#22/137 (58)
28	138 (59)	
26	142 (61)	#7*/92 (33)
24 (7.3)	143 (62)	
22	143 (62)	
20	143 (62)	#16/145 (63)
18 (5.5)	143 (62)	#5*/129 (54); #9*/116 (47); #23/150 (66)
16	143 (62)	
14	144 (62)	
12 (3.7)	144 (62)	
10	143 (62)	#8/153 (67)
8	141 (61)	
6 (1.8)	137 (58)	
4	130 (54)	
2	118 (48)	
1	103 (39)	#6/122 (50); #17/119 (48); #24/118 (48)
0 (0)	100 (38)	

*Readings for these instruments appear to be questionable. See text.

TABLE 21 - SUMMARY OF CONCRETE PRODUCTION FOR PIER 12

Time, hours	Production, yd^3 (m^3)		Total
	Land Plant	Floating Plant	
0 - 10	477 (365)	1,074 (821)	1,551 (1,186)
10 - 20	450 (344)	984 (752)	1,434 (1,096)
20 - 30	405 (310)	990 (757)	1,395 (1,067)
30 - 40	482 (369)	558 (427)	1,040 (796)
40 - 50	578 (442)	636 (486)	1,214 (928)
50 - 60	544 (416)	1,194 (913)	1,738 (1,329)
60 - 72	528 (404)	834 (638)	1,362 (1,042)
TOTALS*	3,464 (2,648)	6,270 (4,794)	9,734 (7,442)

*NOTE: Totals for SI units differ due to rounding.

The remainder of the instruments are in good agreement with the predictions, with the predictions being about 10°F (5.5°C) below measured values.

b. Bottom instruments. A comparison of three instruments showed very good agreement with predicted values. The maximum predicted temperature was 110°F (43° C) at a station approximately 1 ft (0.3 m) above the base of the seal. Measured temperastures were as follows:

Inst No. 6: 123° F (51° C)
Inst No. 17: 119° F (48° C)
Inst No. 24: 119° F (48° C)

Again, the predictions are below the measured values by about the same difference as for the mid-depth instruments.

c. Top instruments. A comparison of four instruments near the top of the seal also showed very good agreement with predicted values. Due to the variable cover which was achieved over the instruments, the comparisons below are given in ranges of temperatures representing the top 5 ft (1.5 m) of the seal.

Time after placement started	Predicted temperatures °F	Predicted temperatures °C	Measured temperatures °F	Measured temperatures °C
5.0 days	80-120	(27-49)	90-125	(32-52)
10.0 days	71-132	(22-56)	86-138	(30-59)

As above, the measured values were above the predicted values by about the same difference.

d. Edge instruments. As noted earlier, the Carlson Method assumes heat flow in one direction only. For those instruments near the outside edges of the seal where significant lateral heat flow could be expected, the measured temperatures were well below predicted values. However, two instruments, 30 and 33, both located at mid-depth at the end of the cofferdam, developed maximum temperastures higher than anticipated for their outside positions. Both instruments did show significant temperature decreases by 380 hours showing the influence of the outside locations. The extra concrete thickness between these instruments and the cofferdam wall (when compared to other edge instruments) may account for the higher temperatures which developed.

3.3.3 Concrete flow patterns. Soundings were taken by State inspectors throughout the placement period to monitor progress and to provide data for examining the flow of the tremie concrete. After the placement, the soundings were also correlated with temperature readings in an attempt to discover why measured temperatures were not as high as anticipated for instruments 5, 7, and 9. The following items are based upon this sounding data and upon concrete production data.

a. Concrete production rate. Table 21 shows concrete production data for the placement period. Since there was little delay between concrete production and placement, this data may be viewed as essentially a record of concrete placement. The total production was 9,734 yd^3 (7,442 m^3) with an average of 135 yd^3/hr (103 m^3/hr) for the 72 hr placement period. This rate agrees well with that assumed for the temperature predictions of 150 yd^3/hr (115 m^3/hr).

Production showed the most noticeable drop during the 30 to 40 hour period due to difficulties of resupplying cement to the floating batch plant. This slow-down can be seen in the cross-sections presented below.

For the first 21.5 hrs while the tremies were along the short centerline of the cofferdam, the production rate translated into an average concrete rate of rise of 0.8 ft/hr (24 cm/hr) adjacent to the tremies and 0.4 ft/hr (12 cm/hr) at the far ends of the seal. These rates are both well below recommended rates found in the literature (refs. 1, 4, and 15).

b. Concrete flow distance. Concrete was detected both by temperature and by soundings at the ends of the cofferdam within about 5 hrs after placement began. This concrete was flowing in excess of 70 ft (21 m), again higher than normally recommended limits (refs. 1 and 4).

c. Placement cross-sections. Figures 61 through 64 show cross-sections of the seal during the placement for four different locations. The variations in production noted above are apparent in these figures. Two items are of special interest in these figures;

1. Temperature instrument locations were plotted on Figure 63 in an attempt to explain the low readings for instruments 5, 7, and 9. The figure does not indicate any abnormality in the rate at which these instruments were embedded in the concrete.

2. The location marked (*) in Figures 61 and 63 indicates an area in which a major zone of uncemented material was found after the placement was completed. The placement rate at this location appears to be higher than average, but would not normally draw attention during the placement. The unusually steep slope of the concrete at the 30 hour line of Figure 63 may have contributed to the formation of the poor quality zone by trapping laitance.

c. Concrete slopes. The sounding data was used to determine the surface slope of the tremie concrete during and after completion of the placement. The points made below may also be seen on Figures 61 through 64.

1. The slope of the concrete parallel to the short axis of the cofferdam was much flatter than that in the long direction. This short axis slope had an average value of 1:23 along the centerline and 1:47 at the ends of the cofferdam. These flat slopes probably resulted from the close lateral spacing of the tremies. While all three tremies were along the

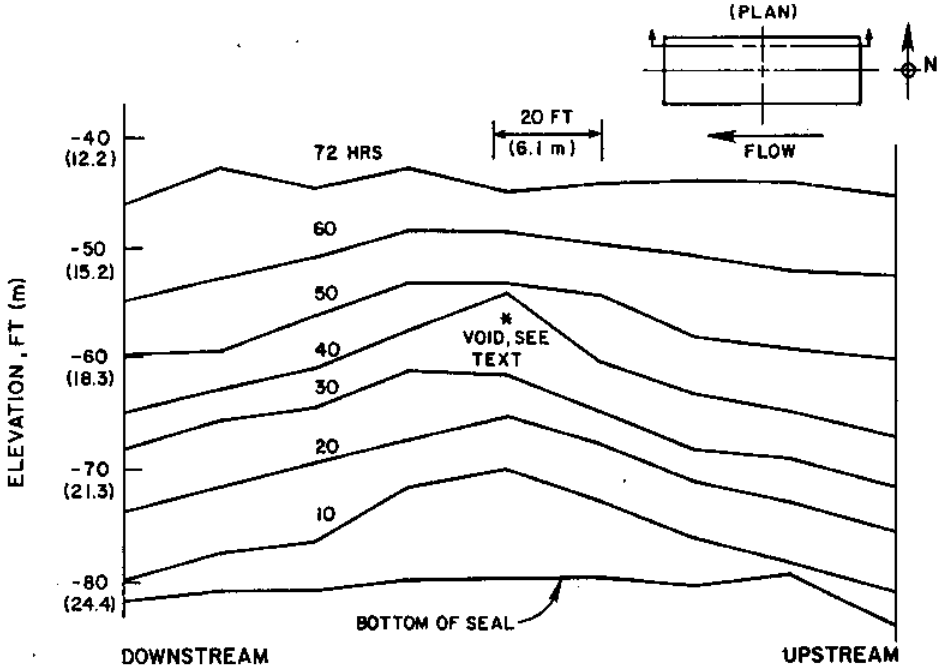

Figure 61. Tremie concrete profiles at various times after beginning of placement, long axis of seal, adjacent to north side of cofferdam.

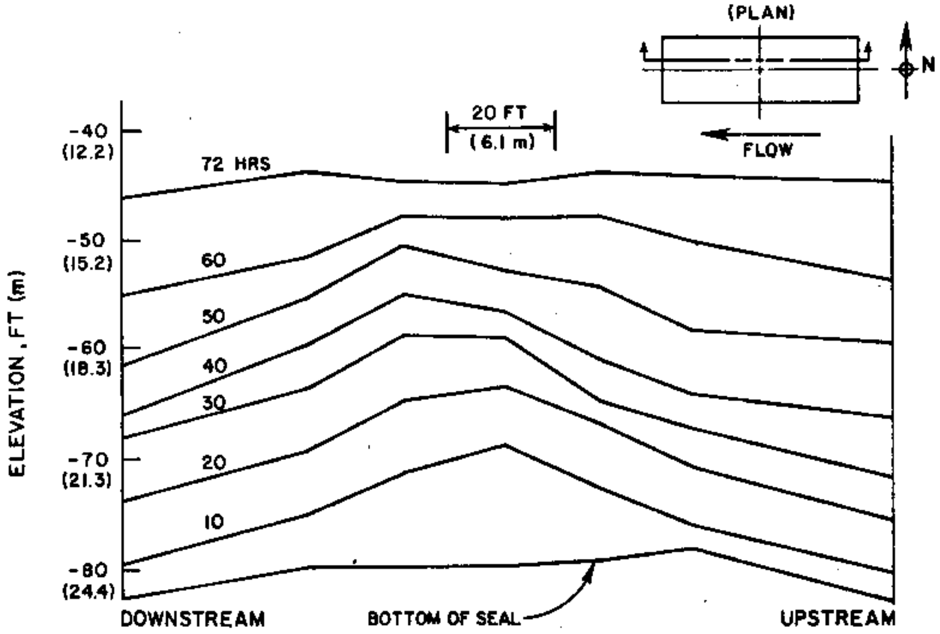

Figure 62. Tremie concrete profiles at various times after beginning of placement, long axis of seal, north of center line.

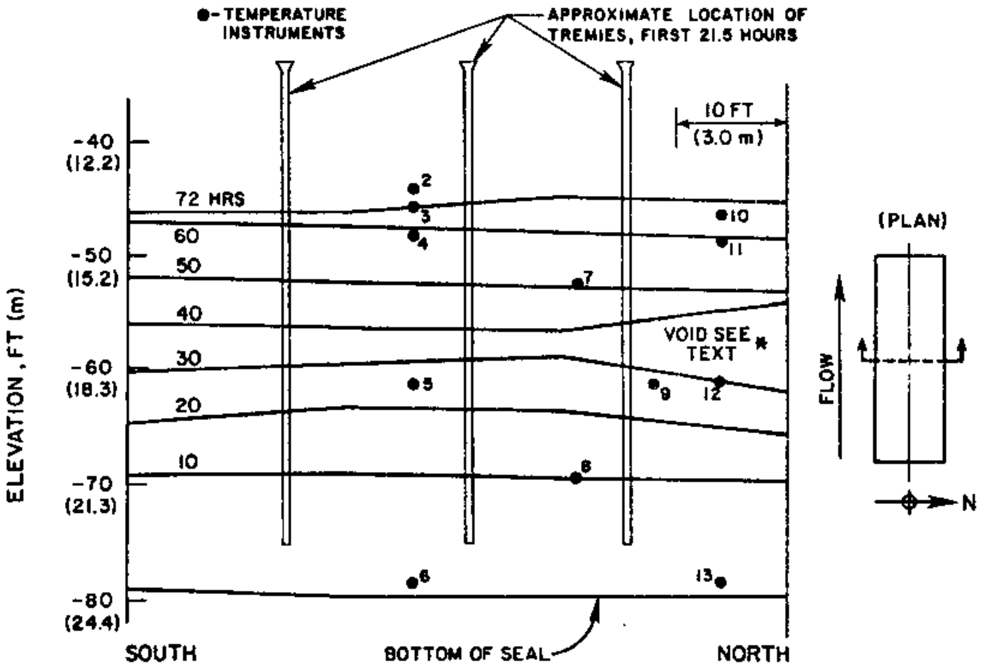

Figure 63. Tremie concrete profiles at various times after beginning of placement, short axis of seal, along centerline.

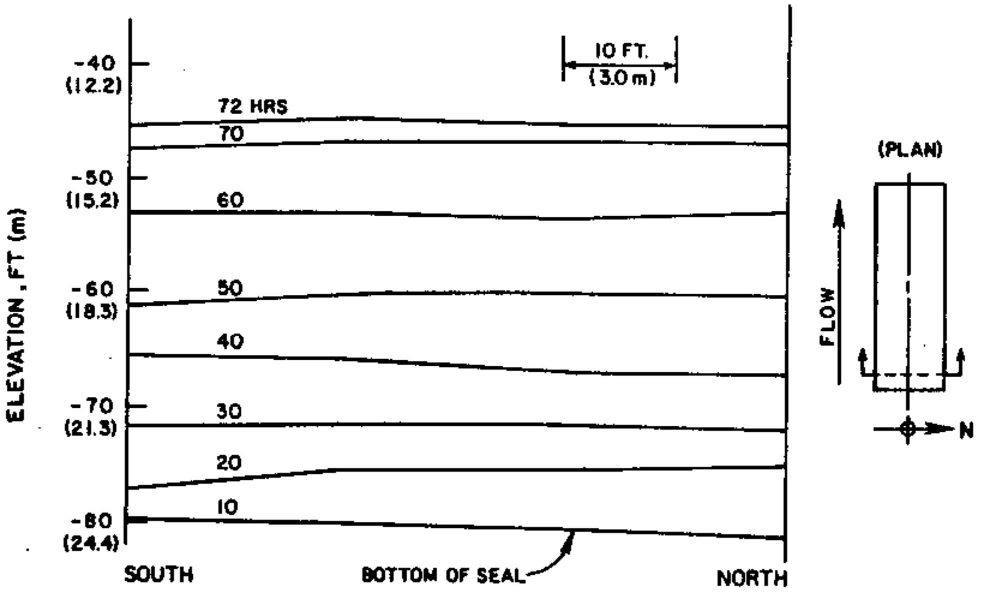

Figure 64. Tremie concrete profiles at various times after beginning of placement, short axis of seal, upstream end of cofferdam.

short centerline (approximately the first 21.5 hours), the spacing was less than 20 ft (6 m) from tremie to tremie.

2. The slope along the long axis was usually greater than that described above. It ranged from an average of 1:6 for the zone nearest the tremies to an average of 1:10 for the areas closest to the ends of the cofferdam.

3. The slopes based upon soundings taken after the placement was completed vary considerably between sounding points (approximately 18 ft (5.5 m) apart) ranging from 1:7 to flat. In general, the soundings showed that a reasonably flat surface was obtained.

3.3.4 Concrete quality. One author (Holland) vistied the site once the cofferdam was dewatered and inspected the concrete. The following is based upon his observations, the results of core sampling, and observations of the Project Engineer.

a. Visual inspection. The concrete which was visible (not under water in low areas) was sound and a minimum of laitance was present. The surface concrete which was tested with a heavy steel probe was resistant to penetration. No cracking was visible on the surface.

One noticeable problem was very evident, however. The surface of the concrete was extremely uneven -- much more so than was anticipated from the soundings which showed a maximum differential between adjacent soundings of 2.6 ft (0.8 m). A number of mounds 3 to 4 ft (0.9 to 1.2 m) tall were present as were several low areas. The maximum differential between the mounds and low areas was approximately 4 to 6 ft (1.2 to 1.8 m). The mounds were located at the positions of the tremie pipes near the end of the placement when attempts were being made to bring the top of the seal to grade. See Figures 65 and 66.

The mounding problem probably resulted from the typically low volumes of concrete placed through the tremies at the end of the placement and the steep slopes being achieved near the tremie pipes. Not enough concrete was being placed to overcome flow resistance and flatten out the slopes.

The mounds forced the contractor to remove concrete to allow for correct positioning of reinforcing steel for the next lift of concrete.

b. Cores. Initially, four cores were drilled into the seal as is shown in Figure 67. When inspected, these cores were very good and showed virtually no bad concrete. Two cores, #4 and #1, showed several inches of possibly trapped liatance (Figure 68).

Water was flowing from all core holes, with the greatest flow coming from hole #2, which went all the way through the seal. Since there was flow from the other cores which did not go through the seal, a system of small seams of permeable material is probably present. The flow may also be partially attributable to any cracking which was caused by the thermal gradients which were developed. Figure 69 shows this water flow from one core hole.

One of the investigators mentioned in the Introduction, Lawrence Livermore Laboratory, reported an anomoly in their readings in the southwest quadrant of the cofferdam. Core #5 (Figure 67) was drilled to determine the validity of the readings. This core turned out to be sound with no bad material found at any depth.

c. Major void. A major void area was discovered on the north side of the seal in the vicinity of the intersection of the noth edge and the short centerline. This area has been mentioned earlier and is shown on Figures 61 and 63. The void consisted of an area of uncemented aggregates. No explanation for the origin of this void area is readily available.

This void was actually two distinct areas. The first began about 4 ft (1.2 m) below the top of the seal and was 12 to 18 in. (30 to 46 cm) thick. This area extended 10 to 12 ft (3 to 3.7 m) in the long direction of the seal and was reported as reaching about 20 in. (51 cm) into the seal from the edge by a diver.

The second area began 8 to 10 ft (2.4 to 3 m) below the top of the seal and was approximately 3 ft (1 m) thick. The diver could measure a length of 15 ft (4.6 m) and estimated a total length of 20 to 25 ft (6.1 to 7.6 m). This area extended at least 6 ft (1.8 m) into the seal from the outside edge.

The lack of cemented material in the lower void is probably the cause of the low readings of instruments 7 and 9 and possibly instrument 5. No hydration was occurring and there was apparently water present to help carry heat to the outside of the cofferdam. Both of these factors could have contributed to the low readings.

d. Diver inspection. In addition to examining the voids described above, a diver inspected the vertical surfaces of the seal concrete after the piling was pulled. No cracks were found, but this does not necessarily rule out cracking caused by thermal expansion since the inspection was conducted under conditions of poor visibility. Also, the subsequent cooling of the concrete mass could have closed early cracks.

3.4 Summary. The following items summarize this placement:

1. A total of 9,734 yd^3 (7,442 m^3) of concrete were placed by tremie for a nonstructural seal for Pier 12 of the I-205 Columbia River Bridge. The placement was continuous for 72 hours with an average concrete placement rate of 135 yd^3/hr (102 m^3/hr).

Figure 65. Mounding on surface of seal. This mound was located at one of the final tremie locations.

Figure 66. Low area in surface of seal. This photo was taken during preparation of the next lift of concrete.

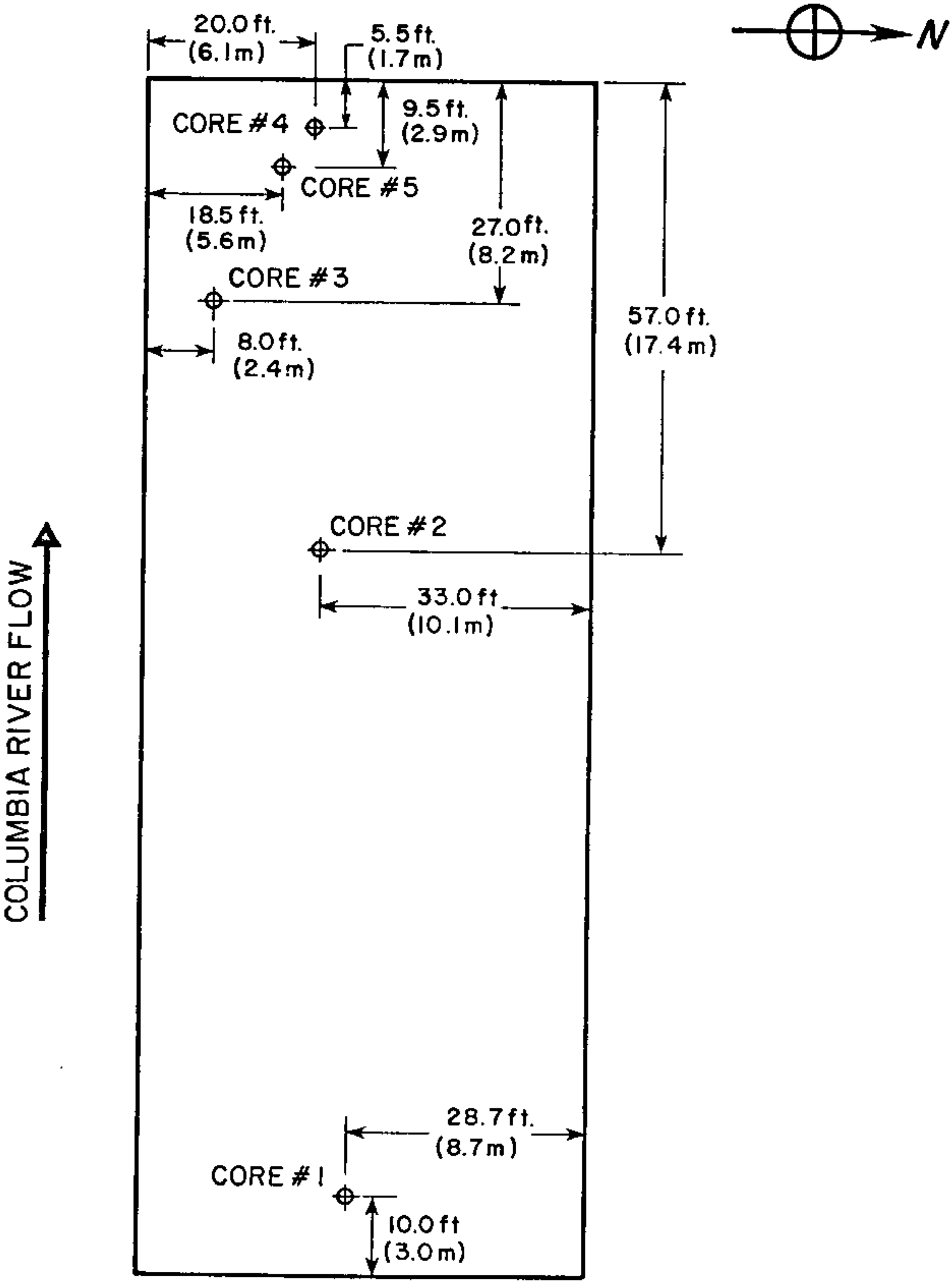

Figure 67. Core locations, Pier 12, Dimensions to inside of interlocked piles.

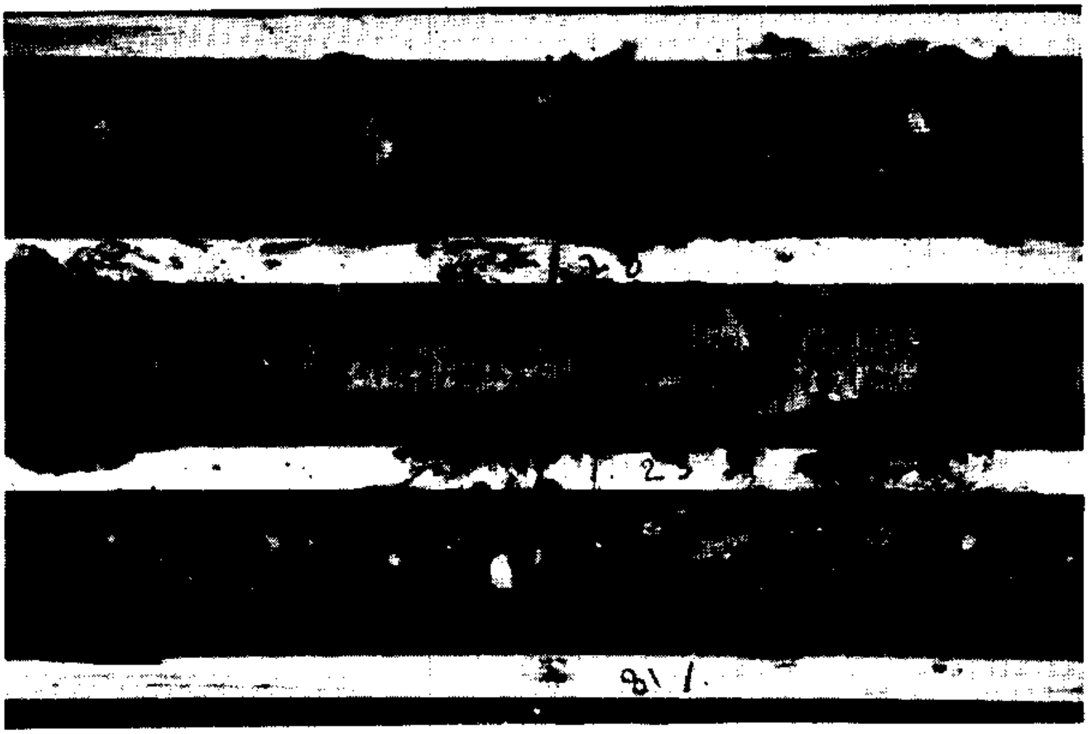

Figure 68. Section of core taken from tremie concrete. Note the area at the 23 ft (7.0 m) mark. This small zone of laitance was the worst concrete seen on the four cores.

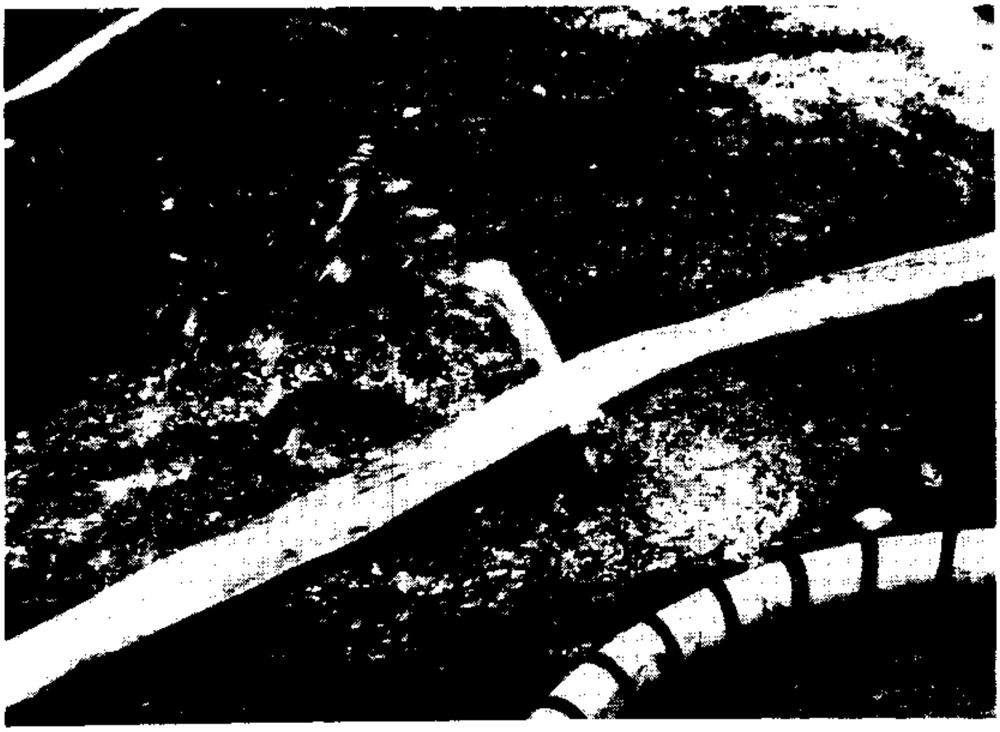

Figure 69. Water flowing from core hole in tremie seal.

2. The concrete mixture used included fly ash as approximately 24 percent by weight of the cementitious material. The fly ash was included to reduce the heat generated by the hydration process. This is, as far as is known, the first major underwater placement to include fly ash for the purpose of reducing heat.

3. Temperature predictions made for the seal concrete using the Carlson one-dimensional prediction technique proved to be accurate to within 10 percent of measured values. The predictions were, in this case, on the low side of the measured temperatures. The predictions were accurate for the entire vertical section of the seal at those locations where lateral heat flow to the outside of the mass could be neglected.

4. A maximum temperature of 155°F (68° C) developed in the center of the concrete mass. Concrete temperatures developed as expected for various instrument locations with the exception of one zone of low temperature which is believed to have been caused by an area later found to be largely uncemented aggregate.

5. Steep temperature gradients developed across relatively thin concrete sections between outermost temperature instruments and the exterior of the seal. These gradients developed rapidly and may have been high enough to generate stresses large enough to cause cracking in the concrete with consequent water entry into the mass.

6. Tremie concrete flowed a maximum distance of over 70 ft (21 m) without apparent detrimental effects. Cores taken near the extremes of the flow revealed sound concrete. Cross sections and calculations based on soundings showed rather steep slopes in the direction of flow nearest the tremies, 1:6, while near the ends of the cofferdam the slope had flattened to 1:10.

7. The concrete produced was generally very sound and capable of performing its intended function. Localized mounding necessitated extra work for the contractor in preparing for the next lift of concrete for the pier. Two areas of uncemented aggregates were found within the seal which required grouting.

8. Inspection of the seal concrete upper surface after dewatering revealed no cracking. Inspection of the vertical concrete surfaces by a diver after removal of the cofferdam piling also failed to reveal evidence of cracking.

9. Water flow was observed from core holes including holes which did not penetrate the full thickness of the seal. Thin seams of permeable material or cracks caused by thermally induced stress or a combination of both are postulated as the source of the flows.

CHAPTER 4
TREMIE CONCRETE CUTOFF WALL, WOLF CREEK DAM

4.1 Objective. The objective of this portion of the project was to observe and review placement of tremie concrete during construction of a cutoff wall through an existing earthfill dam. Three areas were of particular interest:

a. Behavior of a tremie concrete mixture containing a fly ash replacement of a portion of the cement;

b. Placement of tremie concrete at extreme depths; and

c. Identification of problems in mixture design or placement technique which resulted in zones of poor quality concrete.

4.2 Background

4.2.1 Description of the dam.* Wolf Creek Dam is a multi-purpose structure (power generation, flood control, recreation) located on the Cumberland River near Jamestown, KY. It lies in an area of karst topography approximately sixty miles (97 km) from Mammoth Cave. Lake Cumberland, impounded by the dam, is the largest man-made lake east of the Mississippi River.

Construction of the dam was begun in 1941, but work was discontinued for three years during World War II. The work accomplished prior to the war was mainly site preparation and construction of the cutoff trench under the earthfill portion of the dam. The project was completed for full beneficial use in 1952.

The dam consists of an earthfill section 3940 ft (1201 m) long and a concrete gravity section 1796 ft (547 m) long. The maximum height of the embankment section is 258 ft (79 m). The concrete section includes a gated spillway with ten radial gates having a rated discharge of 553,000 ft^3/sec (15,660 m^3/s). The power plant has an installed capacity of 270,000 kw in six units.

4.2.2 Description of problem. In October, 1967, a muddy flow appeared in the tailrace of the dam. In March, 1968, a sink hole appeared on the toe of the dam near the switchyard. An investigation of this hole showed it was connected to a solution cavity. In April, 1968, a second sink hole appeared near the first. Dye placed in this hole appeared in the tailrace where the muddy flow had originally been seen.

As a result of these occurrences, an emergency grouting program was undertaken. This program resulted in placement of 260,000 ft^3 (7,360 m^3) of grout but provided no assurance of completely resolving the problems. After extensive site investigations, the Corps of Engineers and its consultants theorized that the flow was either through the original cutoff trench or through a combination of the cutoff trench and a series of solution features. (It should be noted that the original cutoff trench is only about 10 ft (3 m) wide at its narrowest point. Photographs indicate that the rock in the walls of the trench is fractured and jointed and in many cases the walls are vertical or even overhang the excavated portion.) The repair procedure recommended was to construct a positive cutoff wall through the earthfill portion reaching into sound rock below the dam. Additionally, a cutoff wall was to be constructed to isolate the switchyard area.

4.2.3 Repair procedures. The construction procedure selected to install the cutoff walls was modification of the slurry wall procedure often used on foundation excavations.* The embankment cutoff wall is 2240 ft (683 m) long and has a maximum depth of 280 ft (85 m). Due to concern over the stability of the dam during construction, the wall was constructed of alternating primary (cased, 26 in. (66 cm) diameter on 4.5 ft (137 cm) centers) and secondary (uncased) elements rather than of panels as is frequently done on slurry wall foundation projects. Figure 70 shows a schematic of these elements.

A total of 1256 elements were placed to construct both of the walls for a total contract cost of $96.4 million. These elements were broken down as follows:

Over 250 ft (76 m) deep:	158
200 to 250 ft (61 to 76 m) deep:	666
150 to 200 ft (46 to 61 m) deep:	168
90 to 150 ft (27 to 46 m) deep:	174
less than 90 ft (27 m) deep:	90

The contractor awarded the project, ICOS Corporation of America, is a pioneer in the field of slurry wall construction. Following is a step-by-step description of the procedure used for the embankment wall.**

a. Site Preparation. Since the crest width of the dam is only 32 ft (10 m), the contractor constructed a work platform 170 ft (52 m) wide inside parallel walls of sheet piling. Actual excavation took place in a concrete lined starter trench which was constructed along the axis of the wall. Much of the excavation and casing handling equipment was especially designed by the contractor for this project (Figure 71).

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*For additional descriptions of this project see references 25, 26, 27, 28, 29, and 30.

*For a general description of the slurry wall technique see references 31 and 32.

**Since the switchyard wall was much shallower and since no problems were encountered during its construction, the remainder of the chapter deals only with the embankment wall.

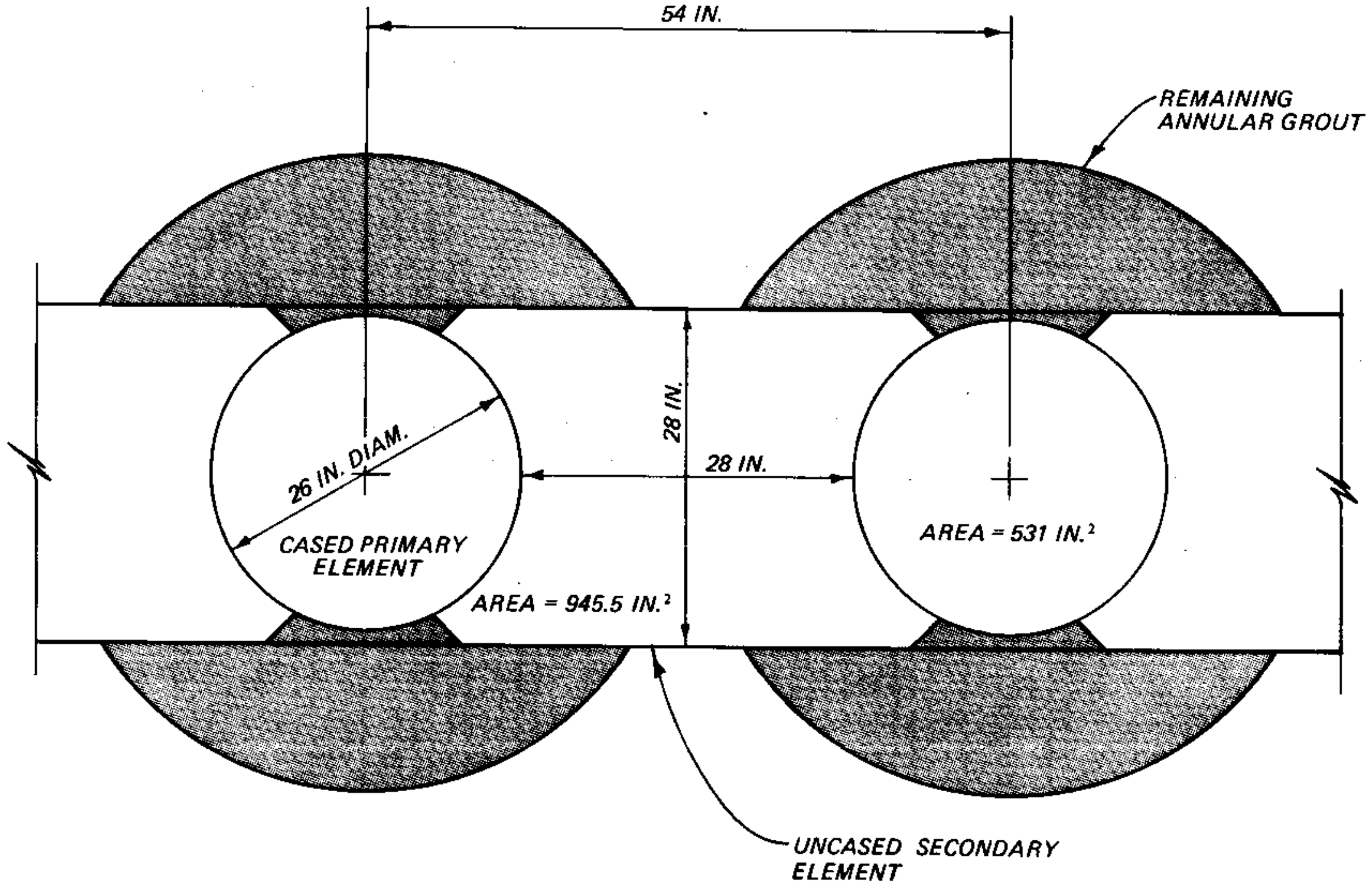


Figure 70. Schematic of tremie-placed cutoff wall. (1 in. = 2.54 cm, 1 in.^{2} = 6.45 cm^2).

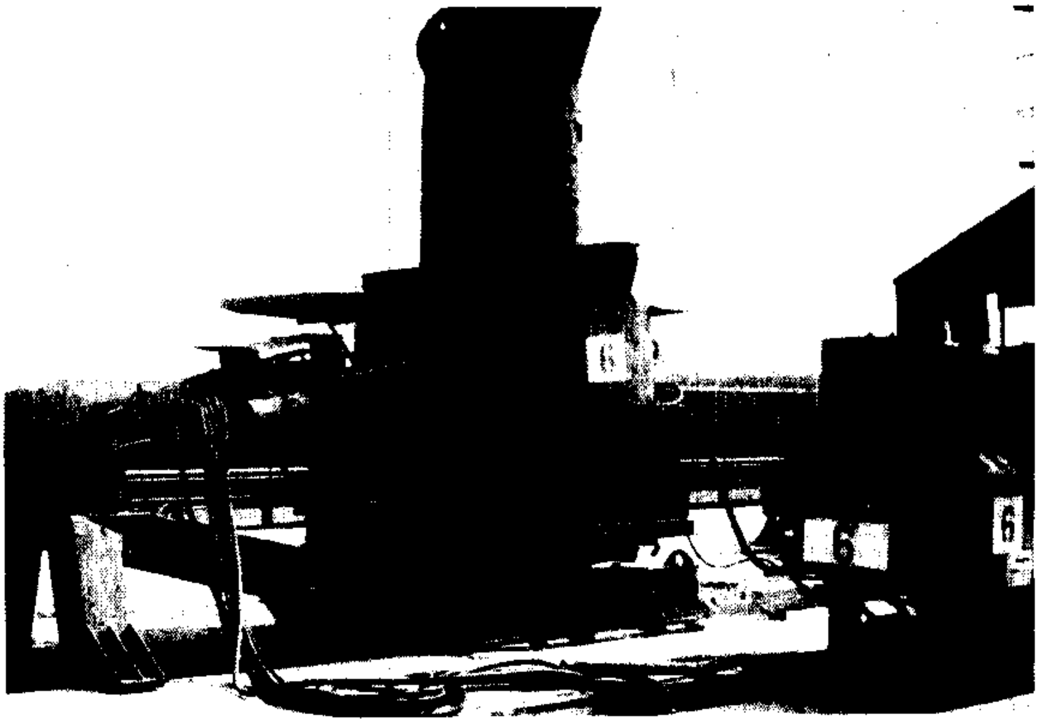


Figure 71. Casing handling machine which rotates casing and applies vertical force for casing installation or removal.

Figure 72. Breather tube in tremie hopper. The tube extends to the top of the hopper and allows air to escape during placement.

b. Primary elements. Initially, a 53 in. (135 cm) diameter hole was excavated with a clam shell to a depth of approximately 76 ft (23 m). At that point a 47 in. (119 cm) diameter casing was inserted and excavation was continued inside the casing. Additional sections of casing were added as necessary (with especially designed joints which were flush inside and outside) until the casing reached down 142 ft (43 m). From there to the top of the rock, a 41 in. (104 cm) diameter casing was used. Excavation below the 76 ft (23 m) point was done through bentonite slurry.

When rock was reached, a rock drill was used to drill a 36 in. (91 cm) diameter hole to the planned bottom of the wall. Then, a NX core hole was taken 25 ft (8 m) deeper into the rock. This hole was pressure tested and, if satisfactory, filled with grout. If the rock failed the pressure test, the 36 in. (91 cm) diameter hole was continued deeper.

Once the hole was founded in sound rock, the 26 in. (66 cm) diameter permanent casing was placed. This casing was filled with water to keep it in place. After the permanent casing was in place, the annular space between the permanent and excavation casings was filled with grout as the 41 and 47 in. (104 and 119 cm) diameter casings were removed. The annular space grout was allowed to set 10 days before an element was filled with tremie concrete.

To begin the filling process, enough bentonite slurry was placed into the casing to displace the lower 20 ft (6 m) of water. The purpose of this bentonite was to lubricate the inside walls of the casing during concrete placement. Concrete was batched and mixed at a plant near the dam and transported to the tremie site by trucks. Two unusual items concerning the tremie placement are worthy of noting here. First, the tremie hopper was equipped with a breathing tube which allowed air to escape during concreting (Figure 72). Almost no air was seen bubbling to the surface as is common on most tremie placements. Second, the contractor developed a novel technique for supporting the tremie pipe. Figure 73 shows how this technique worked.

c. Secondary Elements. Construction of a secondary element followed completion of two adjacent primary elements. The overall construction sequence was planned to allow an adequate curing period for the concrete in the primary elements before work was started on the intervening secondary element.

The construction process for secondary elements was identical to that described above with the following exceptions: First, the excavation was accomplished using a clam shell which followed the walls of the adjacent primary elements (Figure 74). This procedure removed the annular grout on one side of the primary elements and insured a concrete to casing bond once the secondary elements were concreted. Second, the secondary elements were excavated through bentonite slurry for their full depth since they were not cased. The secondary elements, once socketed into sound rock, were then filled with tremie concrete to displace the slurry.

4.3 Observations and discussion. The following comments are based upon site visits be Ben C. Gerwick, Jr., and T. C. Holland, and upon correspondence with the Resident Engineer at the site.

4.3.1 Quality of tremie concrete. One item in the construction procedure which is not mentioned above is the extensive drilling of cores which was done - approximately ten percent of the elements were cored. This coring program revealed minor but consistent problems in the quality of the concrete in the primary elements. These problems included minor areas of segregated sand and/or coarse aggregate, zones of trapped laitance, and zones of lightly to extremely honeycombed concrete. These bad areas are scattered vertically in the cores and do not appear to follow a discernable pattern. Figure 75 shows a portion of a core from one element showing the variations in concrete quality.

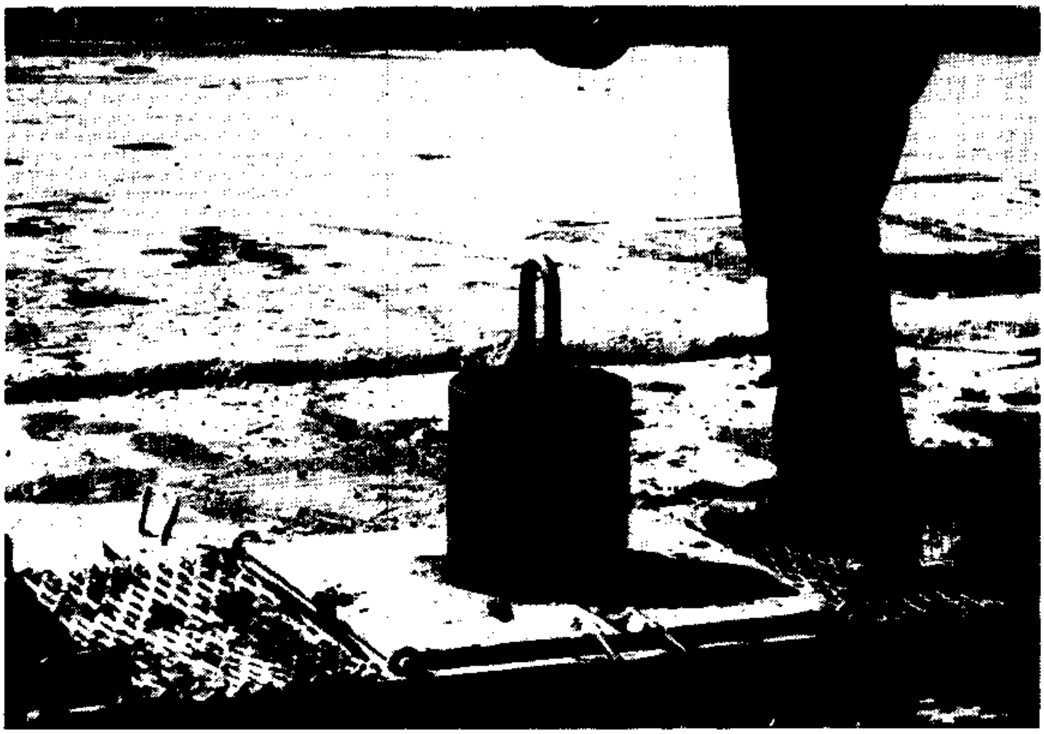
Multiple borings taken in the same element have shown that the zones of poor quality concrete vary horizontally as well as vertically. For example, in element P-465 the first boring showed a 41.5 ft (12.6 m) loss of core. A second boring showed was made which showed good concrete for its full depth.

It is important to note that these problems have been found in the primary elements only. Those anomalies which have shown up in the cores of the secondary elements have been explained by such factors as loss of drill vertically causing cores to cut into the annular grout near the primary elements or by drilling into a stepped portion of the foundation rock causing loss of a portion of the core. Professional staff at the site are satisfied that all anomalies which have appeared in the cores of the secondary elements can be explained. However, as will be shown below, there are not as readily available explanations for the problems discovered in the primary elements.

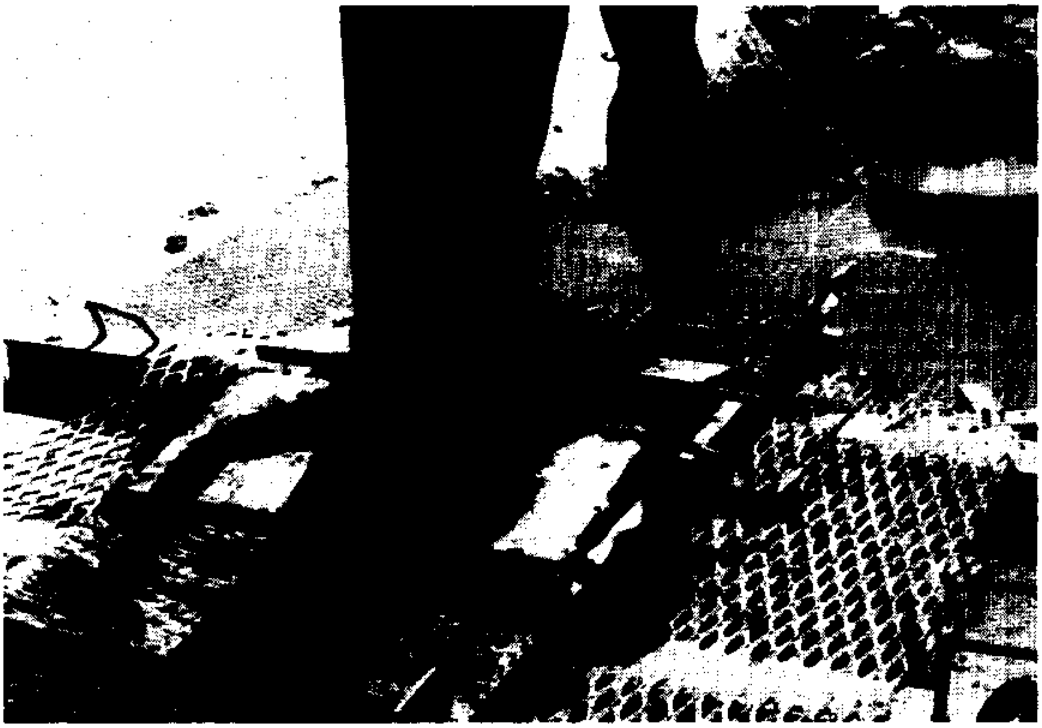
4.3.2 Tremie starting procedures. One of the areas suspected of contributing to the concrete problems was the procedure used initially to seal the tremie pipe. The placements were begun with the tremie pipe full of water.

Initially, a rubber basketball was used as a "go-devil" to start the tremie placements. The ball, initially floating inside the tremie, was forced down the pipe as concrete was introduced into the hopper. The ball separated the water and the fresh concrete and pushed the water ahead of itself out of the mouth of the tremie. This procedure was abandoned due to the realization that the hydrostatic head in the deep holes collapsed the ball causing a loss of seal in the tremie and a subsequent segregation and washing of the concrete.

The technique selected to replace the basketball was the use of a pine sphere produced at the site. While this did resolve the question



a. Loop is used to raise tremie as sections of pipe are removed. Tremie pipe is supported by coupling resting on plate.



b. Tremie pipe being raised. Note how plates open to allow passage of couplings.

Figure 73. Tremie support scheme.

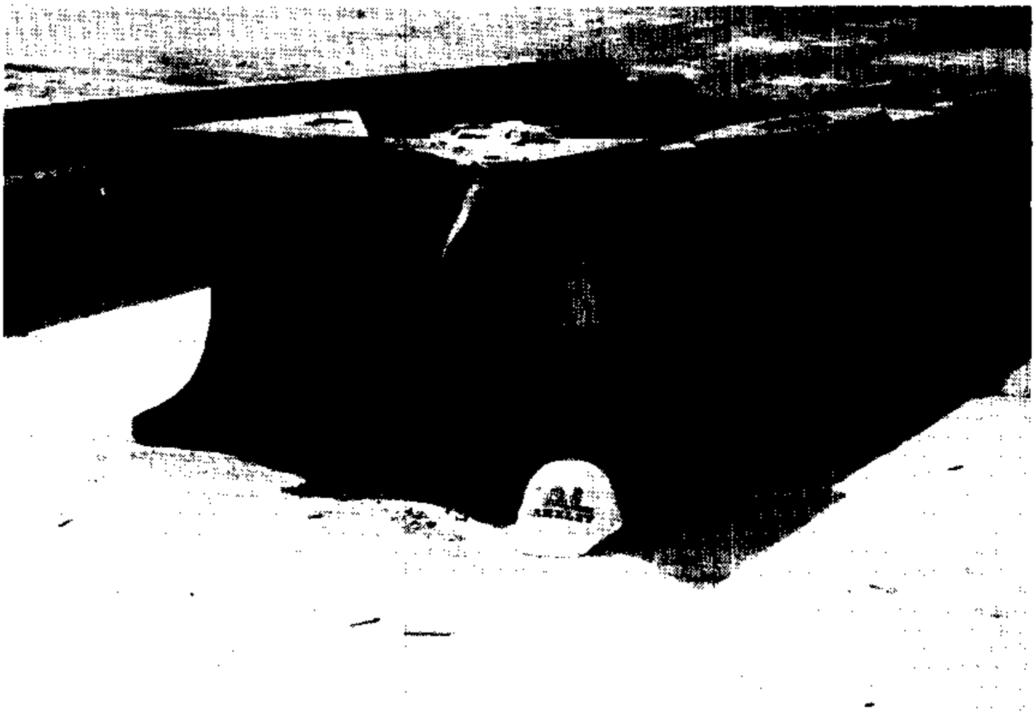


Figure 74. Secondary element excavation device. The curved sections ride the adjacent primary elements.

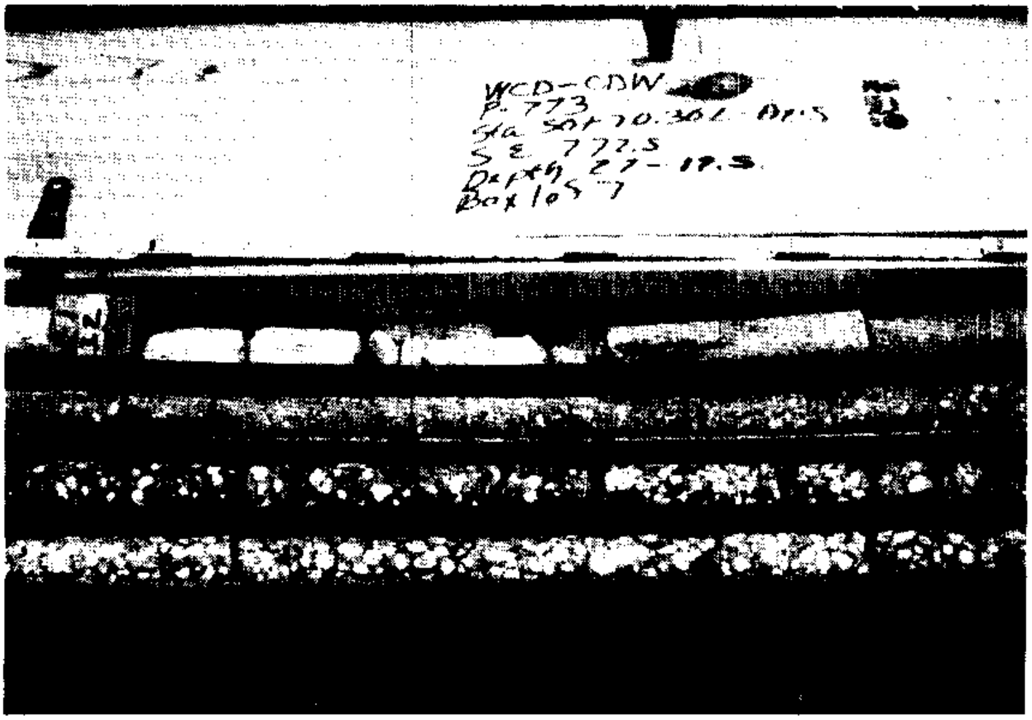


Figure 75. Cores taken from primary element, P-773. Note variations in concrete quality.

of ball collapse, the wooden balls did not fit snugly inside the tremie pipes (neither did the basketballs) (Figure 76). There is approximately 0.25 in. (0.64 cm) clearance between the pine sphere and the tremie pipe; therefore, as the ball and concrete moved vertically down the pipe, some amount of washing of the concrete was taking place.

The procedure followed to introduce the first concrete into the tremie was also designed to guard against loss of seal. The pipe was initially raised only 0.3 ft (9 cm) as the first concrete was placed. After about 40 seconds (approximately one cubic yard (0.8 m^3)), the tremie was raised an additional 0.6 ft (18 cm) to allow the pine sphere to escape. By the time the tremie was raised this second increment, sufficient concrete had been fed into the tremie to insure that the mouth was adequately embedded.

Although there was undoubtedly leakage around the sphere, a zone of poor quality concrete has not been consistently found at or near the bottom of various elements as would be expected. Perhaps the laitance or washed material was carried upward on the sound concrete of perhaps it was lost as an identifiable area due to remixing. There is no evidence to indicate that the zones of poor quality concrete found throughout the vertical sections are a result of initial leakage around the sphere. Finally, the queston remains, if the leakage were responsible for the poor quality concrete, why was the problem evident only in the primary elements?

One possible explanation relates not to the leakage but to the sphere itself. Due to the size of the primary elements, it was not possible for the sphere to pass the tremie on the way back up to casing (Figure 77). Perhaps the sphere was following the tremie as it was withdrawn and was inhibiting concrete flow and remixing. Since the secondary elements were larger, the spheres were able to return to the surface without causing a problem.

4.3.3 Tremie joint leakage. One factor which is often suspect in cases of vertically scattered poor concrete is leakage between joints in the tremie pipe. The rapid downward flow of concrete in the tremie can suck water through any leaks which may be present at the joints. The result is a randomly washed and segregated concrete.

At Wolf Creek the tremie sections were threaded together and the threads were liberally covered with grease each time the tremie was assembled. The sections were torqued together by two men while a third hit the pipe with a sledge hammer to tighten the connection. The tremie was tested for leakage by lowering a light inside and found to be satisfactory. From the precautions being taken, it is doutbful that tremie leakage was causing the problems.

4.3.4 Tremie centering. Another potential problem area was the centering of the tremie in the holes - particularly the primary elements. If the pipe were not centered, there was a possibility of inhibiting the flow of the concrete as it left the tremie mouth. To eliminate this possibility, centering fins were added to one section of the tremie pipe (Figure 78). Cores taken after addition of the fins contained to show anomalies, indicating that poor centering was not the sole cause of the poor quality concrete.

4.3.5 Concrete placement rate. In large volume placements (such as Pier 12 of Chapter 3) the placement rate of tremie concrete is often an area of concern. Too slow a placement rate allows the concrete in place to stiffen which inhibits flow. Table 22 examines placement rates for six elements at Wolf Creek for which data were available. These rates are based upon total elapsed time from beginning to end of the placement and, therefore, include time for removal of pipe sections, waiting on concrete trucks, etc.

The lower volumetric rate (yd^3/hr) (m^3/hr) for the primary elements is a reflection of the more frequent stopping for removal of pipe sections. Yet even with this slower volumetric rate, the primary elements have a higher linear rate (ft/hr) (m/hr) due to their smaller cross-sectional area. The linear rate appears to be significantly higher for the primary elements.

Although problems with rate are usually associated with too slow a placement, perhaps too rapid a rate may also be detrimental. No reports on the effects of too rapid a placement have been found in the literature. Intuitively, however, a higher rate would seem to favor remixing within the elements as the concrete is placed.

4.3.6 Tremie removal rate. An aspect closely related to the placement rate is the rate at which the tremie pipe is raised as sections are removed (the mouth of the tremie must remain embedded in the concrete). Here, the theory is that too rapid a pull rate could result in voids or honeycomb if the concrete did not flow fully into the void left by the tremie pipe. This problem is particularly prevalent if overall placement rates are low.

To guard against too rapid removal of the pipe from the elements, an inspector timed and recorded the pull rate for each section of the tremie. The same rate (0.3 ft/sec) (9 cm/sec) was used for both the primary and secondary elements.

Again, the question may be raised as to why the problems, if a result of pipe pull speed, were evident in only the primary elements. This question is particularly bothersome since the tremie sections were removed more frequently from the primary elements. Hence, the concrete had less time to stiffen and lose the ability to flow into the void created by the withdrawing tremie. Therefore, if pipe removal rate were a factor, the problem would seem to be less likely to occur in the primary elements.

Figure 76. Pine sphere inside tremie at beginning of placement. Note leakage around sphere.

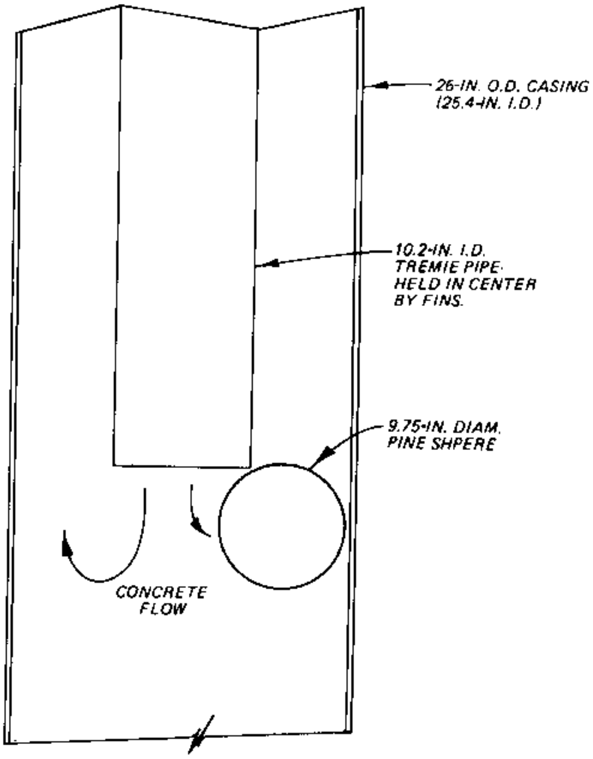


Figure 77. Position of pine sphere upon leaving tremie. Note possible inhibition of concrete flow (1 in. = 2.54 cm).

Figure 78. Fins added to tremie pipe to insure proper centering.

TABLE 22 - TREMIE CONCRETE PLACEMENT RATES

Element	Elapsed Time, hr	Element Depth ft (m)	Linear Rate, ft/hr (m/hr)	Volume of Concrete, (yd^3) (m^3)	Volumetric Rate (yd^3/hr) (m^3 /hr)
P611	1.1	212.8 (64.9)	193 (59)	30 (23)	27 (21)
P771	1.2	212.1 (64.9)	177 (54)	29.5 (23)	25 (19)
P773	1.4	213.1 (65.0)	152 (46)	29.5 (23)	21 (16)
P791	1.1	212.9 (64.9)	194 (59)	30 (23)	27 (21)
P795	1.2	212.9 (64.9)	177 (54)	30 (23)	25 (19)
P807	1.2	212.7 (64.8)	177 (54)	29.5 (23)	25 (19)
P985	0.9	173.2 (52.8)	192 (59)	25 (19)	28 (21)
P1001	0.9	173.3 (52.8)	193 (59)	25 (19)	28 (21)
PRIMARY ELEMENT AVERAGE			182 (56)	NA NA	26 (20)
S576	1.6	212.5 (64.8)	133 (41)	72 (55)	45 (34)
S594	1.7	212.6 (64.8)	125 (38)	72 (55)	42 (32)
S676	2.1	212.7 (64.8)	101 (31)	75 (57)	36 (27)
S746	1.8	212.9 (64.9)	118 (36)	73 (56)	41 (31)
S858	2.2	263.2 (80.2)	120 (36)	97 (74)	44 (34)
S956	1.5	172.7 (52.6)	115 (35)	64 (49)	43 (33)
SECONDARY ELEMENT AVERAGE			119 (36)	NA NA	42 (32)

4.3.7 Breaks in placing. Another area of concern was the resumption of concrete placing at the beginning of each new truck load. A certain amount of sand and laitance does collect on the top of the tremie concrete as the placement moves up the hole. To prevent trapping this material and to insure a better remixing at the resumption of placement, the initial amount of concrete was trickled into the tremie. The remainder of the load was unloaded at normal speed. This same procedure was followed when a truck load was broken into two placements to allow removal of a tremie section. As can be seen from the figures in section 4.3.11, below, there does not appear to be a correlation between stopping/ restarting points and zones of poor quality concrete.

4.3.8 Water temperature during placement. In the original construction sequence there was not a delay between placement of the grout in the annular space surrounding the primary elements and placement of the tremie concrete in the elements. The temperature of the water in one element was measured at 100°F (38°C) due to the heat generated by the hydration of cement in the annular grout. Placement of tremie concrete into hot water can result in rapid and unpredictable setting or loss of slump, both of which could inhibit flowability. In one instance, a rapid set required removal of a portion of the concrete in an element.

These problems let to the practice of allowing 10 days between placement of annular grout and tremie concrete. The water in the primary elements was also exchanged for cooler water prior to concrete placement.

Although this change in procedure did eliminate rapid set problems, it did not preclude the concrete quality problems as described.

4.3.9 Concrete mixture. One area in which there was a noticable improvement was the tremie concrete mixture itself. Characteristics of the mixture are shown in Table 23. This mixture is of particular interest due to the use of the fly ash which was used to improve workability and to reduce heat generation.

None of the problems observed have been attributed to the mix. However, the slump loss characteristics of such a rich mix and the high ambient temperature at the site suggested that the addition of a retarder to the mix would be beneficial. A retarder was added and subsequent placements appeared to be very successful. The Resident Engineer stated that the retarder made a significant difference, most noticeably in the appearance of the concrete as it returned to the top of the holes at the conclusion of a placement.

4.3.10 Obervation of placements. Shortly after the addition of the retarder to the mix, one of the authors of this report (Holland) visited the site and observed placement of several primary elements and one secondary element. During the placements which were observed, the concrete returning to the surface appeared to be of the same quality as that which was being supplied to the tremie (Figure 79).

Another area which had been questioned was how to determine when sound concrete had reached the top of the elements. For the primary elements there was no difficulty making this determination. Initially, clear water overflowed the casing. Near the end of the placement, the small amount of slurry which was added to the primary elements began to appear. This slurry gradually thickened and contained more and more granular material. Approximately 12-18 in. (30-46 cm) of very granular material came to the surface before a concrete containing fine and coarse aggregate was visible. This concrete appeared evenly on all sides of the tremie and had a very uniform appearance. (Before the retarder was added, elevation differentials of up to 18 in. (46 cm) on opposite sides of the tremie were reported as the concrete began to return.)

The placement of the concrete in the secondary element was identical to that in the primary elements except that all fluid which was displaced was slurry rather than water. The same thickening of the slurry was noted and, again, there was no difficulty determining when sound concrete had returned.

As of the date of this visit, none of the elements containing the retarded mix had been cored. The personnel at the site agreed that the placements had been very successful and were quite confident about the expected coring results.

4.3.11 Core and placement logs. The results obtained from coring those elements which were observed being placed were surprising and disappointing. While the secondary elements continued to be free of problems, the zones of poor quality concrete continued to be found in the primary elements. While the problems did not appear to be as severe as before the addition of the retarder, they were still evident.

The Resident Engineer established an excellent system for inspecting and recording the work, excavation, tremie concreting, and coring. Reports were filed on a day by day and on an element by element basis. Using the records of four placements and the corresponding core logs, Figures 80 through 84 were prepared in an attempt to correlate zones of poor quality concrete with any of the following factors:

- Initial pipe embedment;
- Breaks in placement to withdraw tremie sections, and;
- Location of the end of the tremie.

As can be seen by studying these figures, none of these factors appears to be related to the zones of poor quality concrete.

4.3.12 Tremie resistance to flow. Another area considered was the balance of the tremie

TABLE 23 - TREMIE CONCRETE MIXTURE, WOLF CREEK DAM

Cement	564 lb/yd^3	335 kg/m^3
Pozzolan (Flyash)	123 lb/yd^3	73 kg/m^3
Coarse aggregate	1,619 lb/yd^3	961 kg/m^3
Fine aggregate	1,369 lb/yd^3	812 kb/m^3
Water	275 lb/yd^3	163 kg/m^3
Air entraining admixture	6 to 9 oz/yd^3	(232 to 348 ml/m^3)
Retarder/water reducer	18 oz/yd^3	(696 ml/m^3)
Slump range	6.5 to 7.5 in.	(16.5 to 19.0 cm)
28 day compressive strengths		
with retarder	4,690 lb/in.^{2}	32.3 MPa
without retarder	4,770 lb/in.^{2}	32.9 MPa
specified	3,000 lb/in.^{2}	20.7 MPa

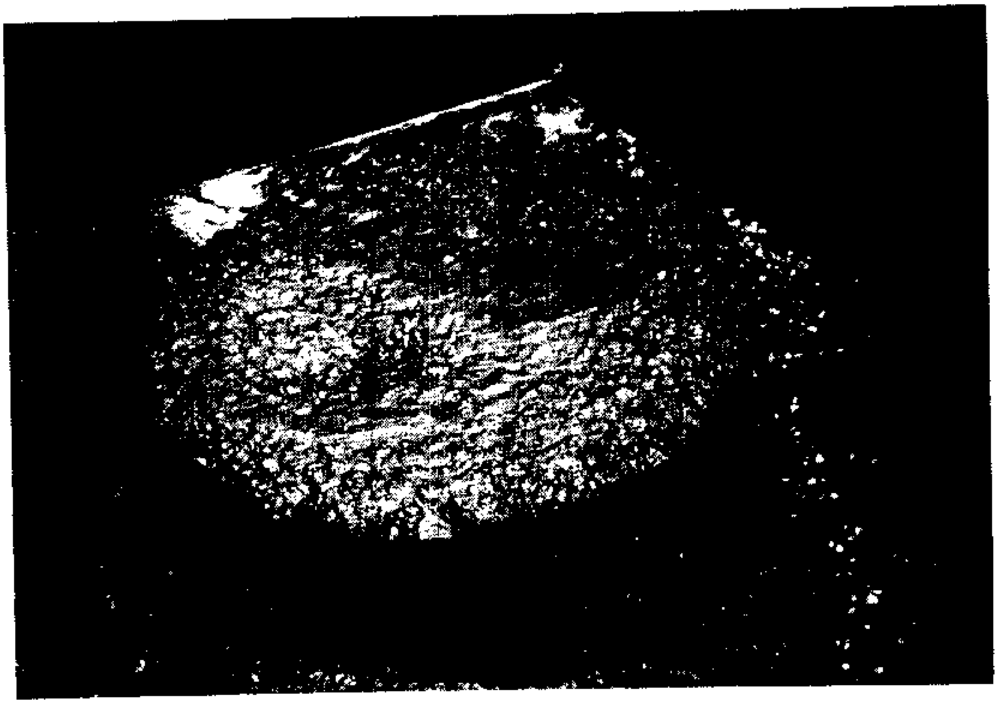
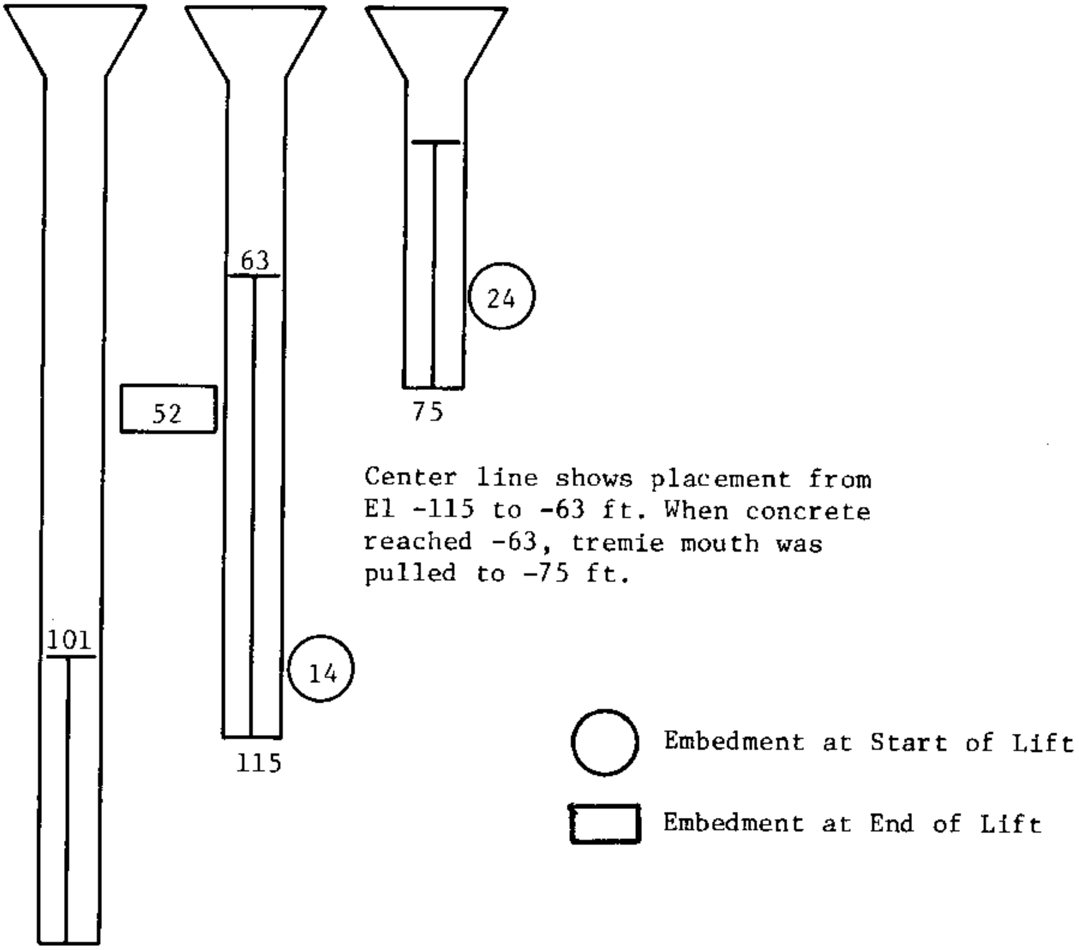


Figure 79. Primary element at completion of tremie placement. Concrete returning to the surface appeared to be of excellent quality.

1. Each Figure (81 through 84) presents an analysis of the tremie pipe location on the left of the page and a summary of the core log on the right of the page.

2. Each vertical line represents placement of concrete from the bottom to the top of the line. The tremie is fixed during each placement with the mouth at the bottom of the line.

3. Example:



Center line shows placement from El -115 to -63 ft. When concrete reached -63, tremie mouth was pulled to -75 ft.

Figure 80. Key for Figures 81 through 84. All distances and elevations in feet (1 ft = 0.3048 m).

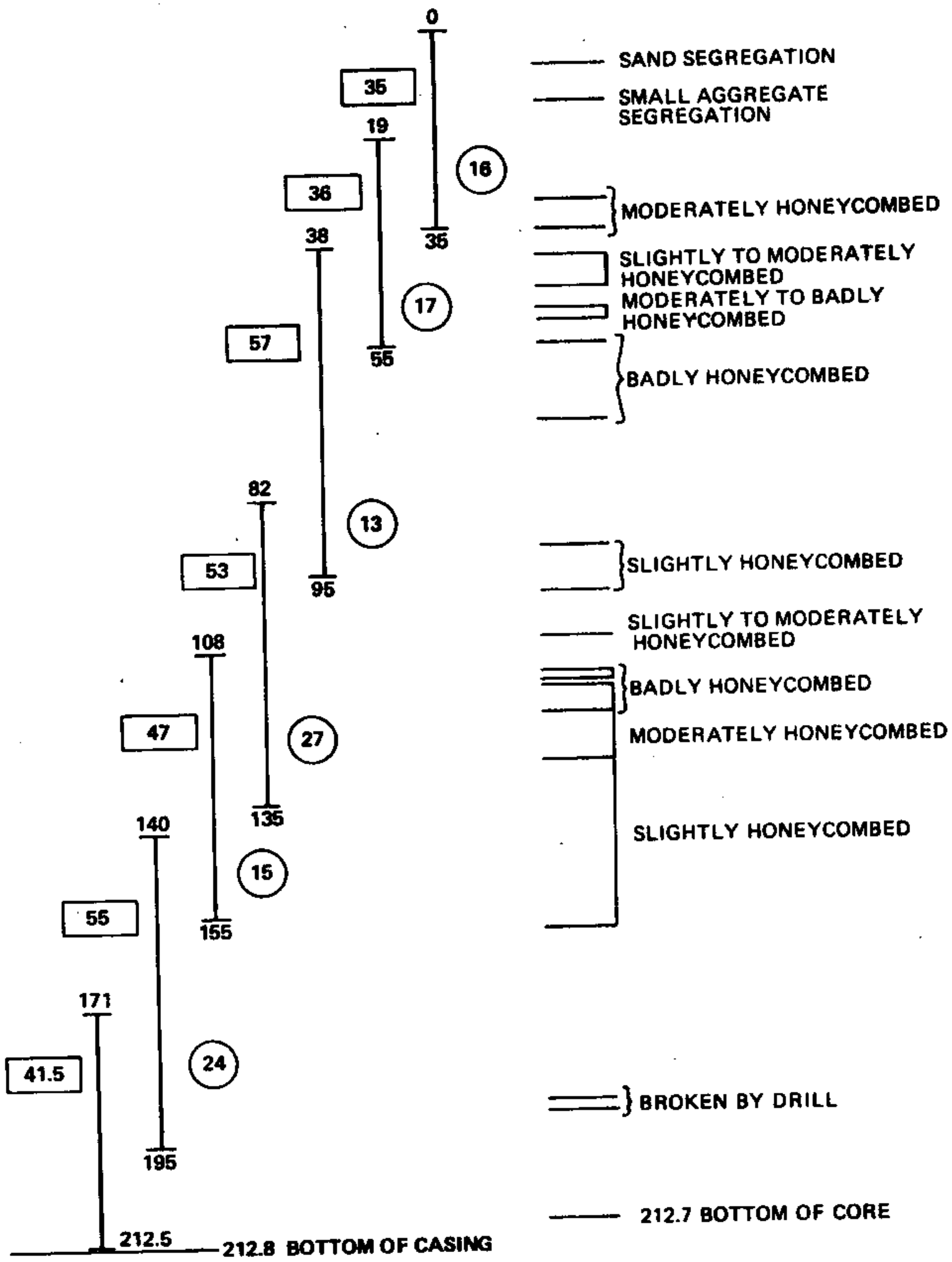


Figure 81. Analysis of element P-611. See Figure 80 for explanation. All distances and elevations are in feet (1 ft = 0.3048 m).

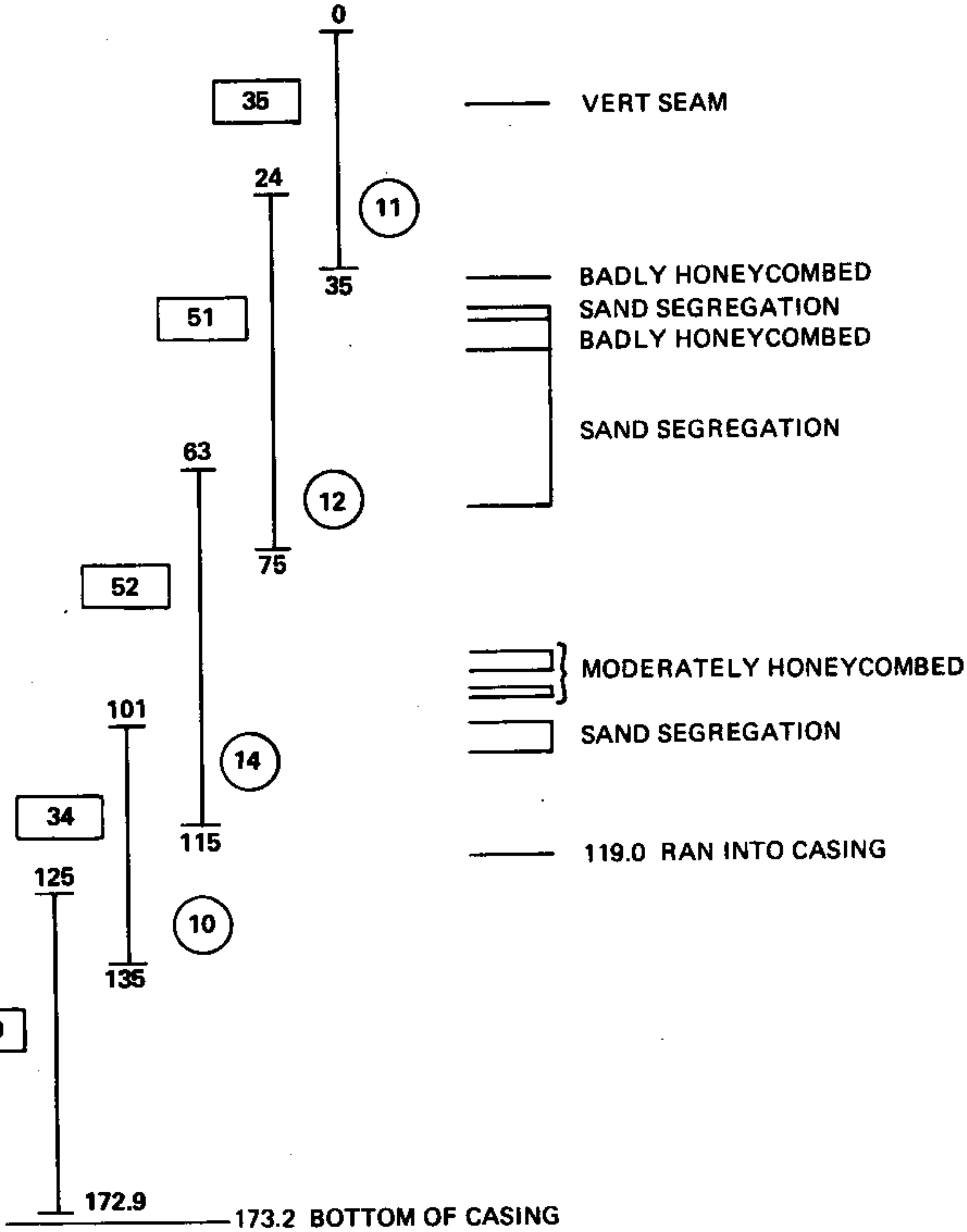


Figure 82. Analysis of element P-985. See Figure 80 for explanation. All distances and elevations are in feet (1 ft = 0.3048 m).

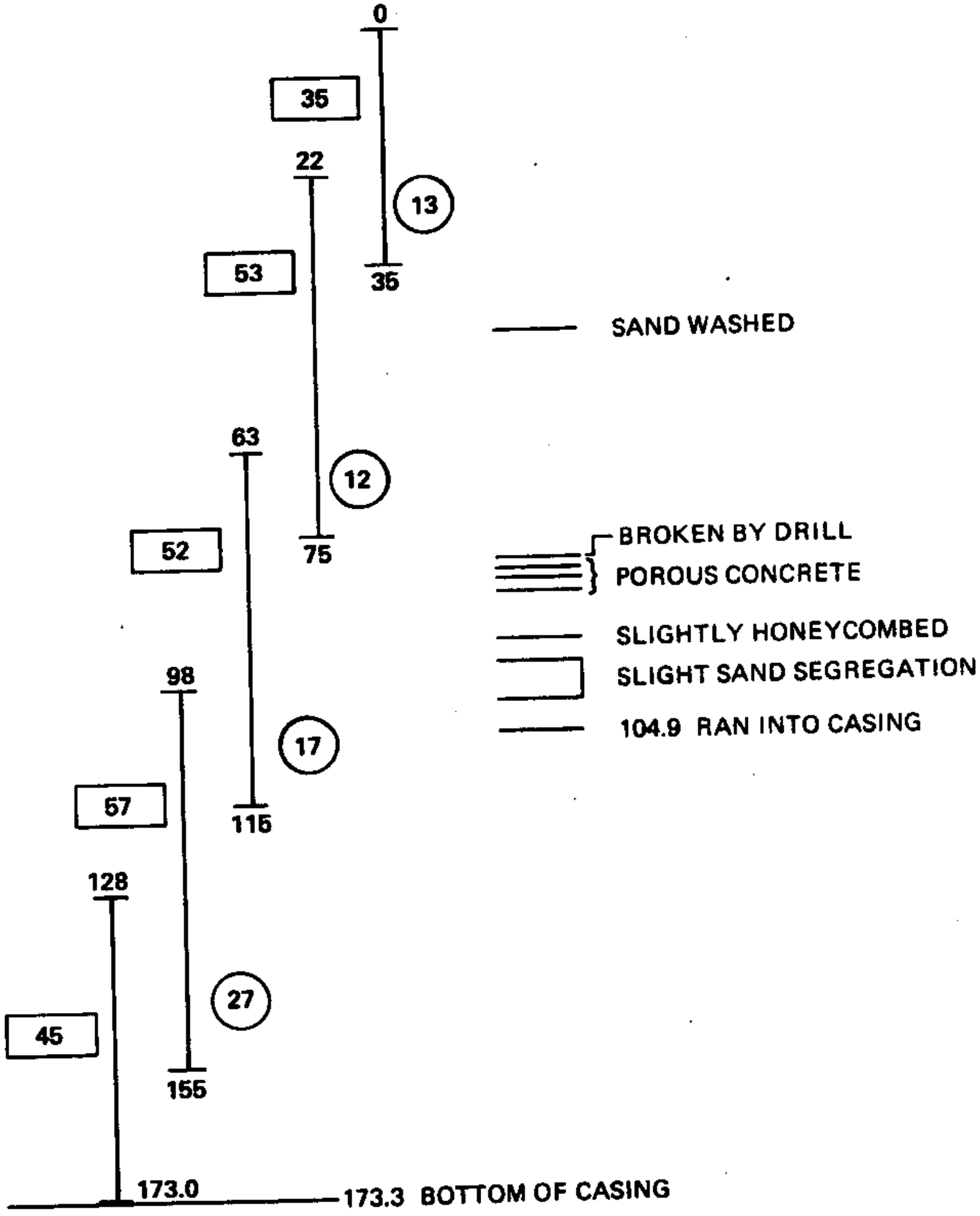


Figure 83. Analysis of element P-1001. See Figure 80 for explanation. All distances and elevations are in feet (1 ft = 0.3048).

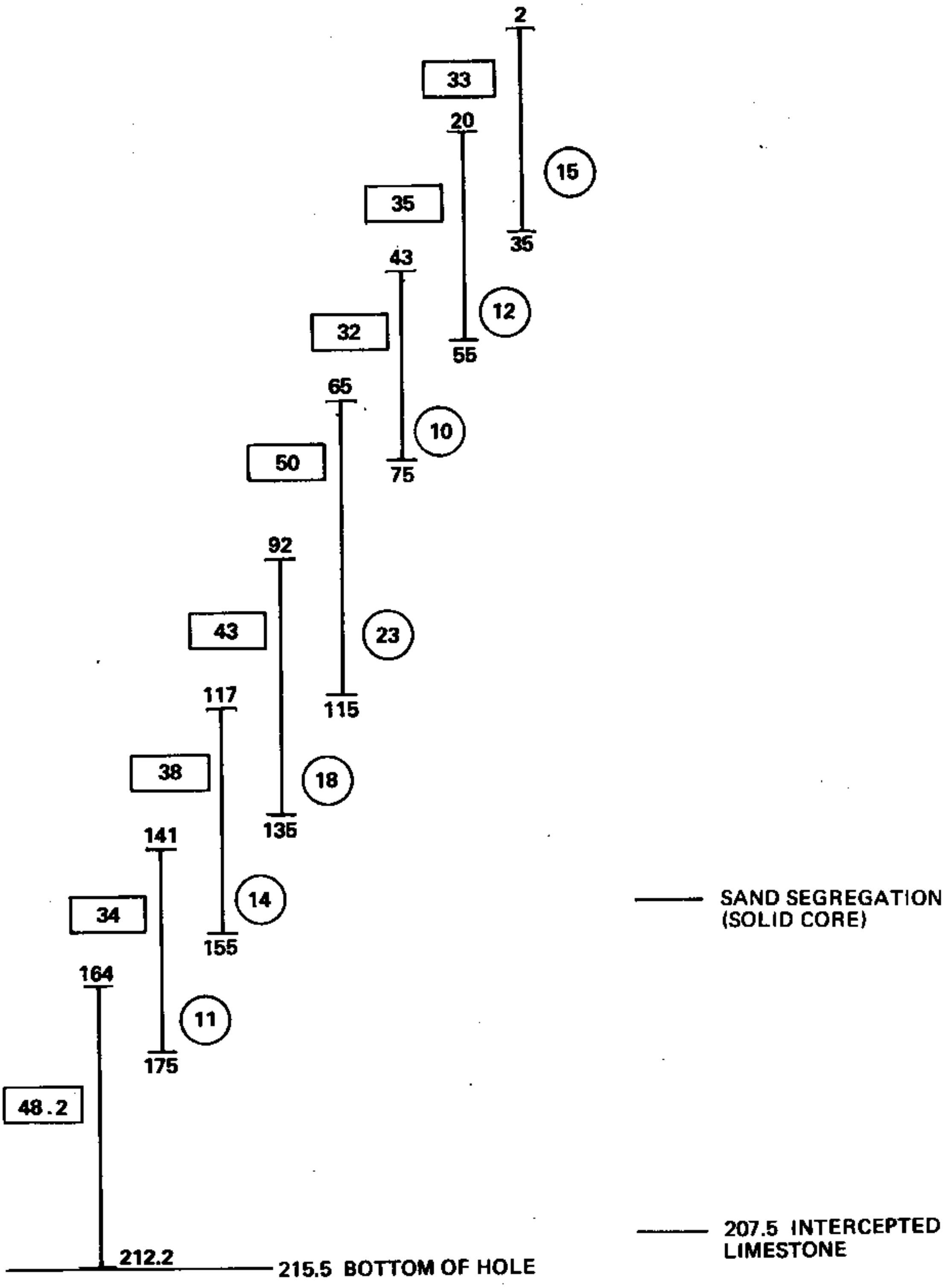


Figure 84. Analysis of element S-576. See Figure 80 for explanation. All distances and elevations are in feet (1 ft = 0.3048).

system when flow a was not occurring due to breaks in the placement. This balance may be thought of in terms of resistance to flow which may be calculated as the difference between the theoretical hydrostatic balance of the tremie system and the actual measured value. The difference which is obtained may be attributed to friction between the concrete and the tremie pipe, to internal friction or cohesion of the concrete, or to a blockage or any other type of restriction to flow. Figure 85 shows the geometry of the tremie system and the technique used to calculate this resistance to flow.

Measurements made on other projects have indicated that the tremie system is normally very close to the balance point and very little resistance to flow can be measured. One set of measurements was made by Gerwick at Wolf Creek. This data is presented in Table 24.*

The resistance to flow varies greatly from measurement to measurement. The variations in the range of 500 to 1000 lb/ft^2 (2.39×10^4 to 4.79×10^4 pa) are believed to be typical. However, note readings number 1 and 4 which are an order of magnitude greater than the remainder. This variation is not believed to be typical. It was not possible to correlate these measurements with a core log of the element.

While these variations in resistance to flow are not believed to be causing the problems seen in the concrete, they may be indicative of a blockage or other restrictions to concrete flow which could result in the anomalies detected. If these variations are related to zones of poor quality concrete, measurements made inside and outside the tremie pipe during placement could serve as an additional inspection tool. Further research should be conducted in this area.

4.3.13 Potential for concrete segregation. The data used to develop the resistance to flow values also show that a significant potential for segregation occurred whenever there was a break in the placement. Since the system returned very nearly to the balanced point, concrete placed immediately after a break could have fallen through distances great enough to cause segregation.

In massive tremie concrete placements the flow of the concrete through the tremie is controlled by the depth of the pipe mouth embedment in the fresh concrete. Such control was not possible in the limited volume placements of Wolf Creek since the concrete in the elements did not have adequate time to stiffen and be able to control the flow. Therefore, not only the concrete placed after breaks but also most of the concrete placed may have been subjected to long free falls resulting in segregation. There is no reason to believe that the potential for segregation was different for the primary and secondary elements.

4.4 Summary. The following items summarize this placement:

1. A concrete cutoff wall was constructed through an existing earthfill dam using tremie-placed concrete. A total of 1,256 individual elements were constructed, with the deepest tremie placement being approximately 280 ft (85 m).

2. The cutoff wall was made up of alternating cased (primary) and uncased (secondary) elements. The primary elements were cased with 26 in. (66 cm) diameter steel pipe. The secondary elements were rectangular and were slightly wider than the primary elements. Their volume was approximately two and one-half times that of the primary elements.

3. An extensive coring program has shown the quality of the concrete in the secondary elements to be excellent. The concrete in the primary elements has been plagued with minor but persistent problems of segregated materials, trapped laitance, and moderate to severe honeycomb. The anomalies are scattered vertically and horizontally within the primary elements and do not seem to follow any pattern.

4. The construction of the tremie concrete cutoff wall has been a highly successful operation which will help to insure the continued safety of the structure. Since the concrete problems were limited to the cased elements, there is no reason to believe that the wall will not perform its indended functions.

5. An examination of the mixture design and various aspects of the placement technique such as starting procedure, joint leakage, tremie centering, placement rate, tremie removal rate, and breaks in placement has failed to disclose a single, responsible factor for the small localized areas of poor quality concrete. Instead, the problems are believed to result from the interaction of at least two factors. First, the concrete was probably segregating during its fall through the tremie pipe. Second, the concrete in the secondary elements was apparently remixing and overcoming the segregation while the concrete in the primary elements was not as successful in remixing. The inhibition of remixing in the primary elements is believed to be due to the following items:

a. The primary elements had a much smaller cross sectional area than the secondary elements. This smaller area may have been acting in conjunction with the wooden sphere and centering fins to create a condition which restricted flow and remixing.

b. The walls of the permanent casings which were filled to create the primary elements were much smoother than the walls of the secondary elements. These smoother walls may have reduced

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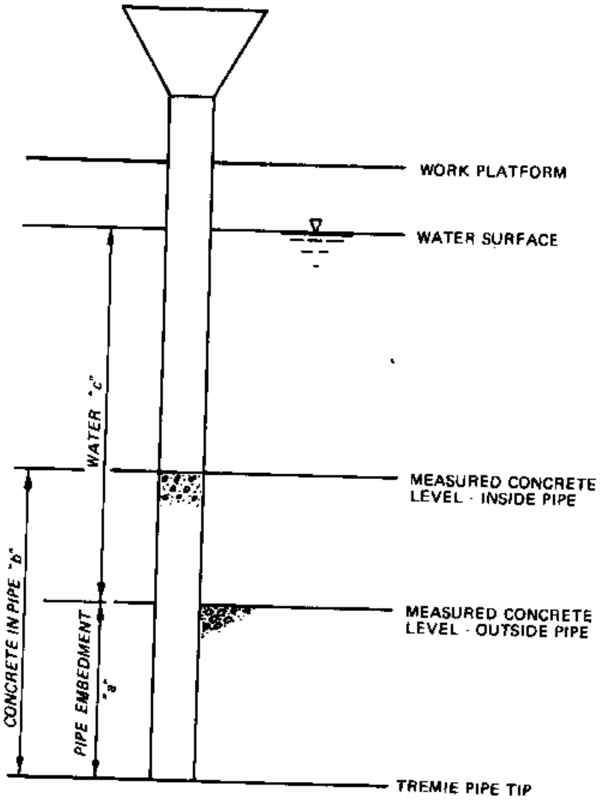
*Additional data concerning resistance to flow is available in reference 30.



NOTE: AT PIPE TIP: $b\gamma_{conc} = c\gamma_{water} + a\gamma_{conc}$ + (RESISTANCE TO FLOW)

RESISTANCE TO FLOW = $(b - a)\,\gamma_{conc} - c\gamma_{water}$ ·

Figure 85. Tremie geometry and derivation of resistance to flow.

TABLE 24 - TREMIE RESISTANCE TO FLOW MEASUREMENTS

Reading	Deck Pipe Tip, Ft (m)	Deck to Concrete Outside Tremie Ft (m)	Deck to Concrete Inside Tremie Ft (m)	Resistance to Flow, Lb/Ft^2 (Pascals)
1	236 (71.9)	197 (60.0)	87 (26.5)	3,948 (1.89×10^5)
2	215 (65.5)	160 (48.8)	86 (26.2)	987 (4.73×10^4)
3	175 (53.3)	132 (40.2)	73 (22.3)	546 (2.61×10^4)
4	155 (47.2)	100 (30.5)	40 (12.2)	2,709 (1.30×10^5)
5	115 (35.1)	70 (21.3)	35 (10.7)	924 (4.42×10^4)
6	95 (29.0)	40 (12.2)	19 (5.8)	756 (3.62×10^4)
7	55 (16.8)	7 (2.1)	0	777 (3.72×10^4)

NOTES: (1) Deck 3 ft (1m) above water
(2) Unit weight of concrete 147 lb/ft^3 (2,355 kg/m^3)
(3) Unit weight of water 63 lb/ft^3 (1,009 kg/m^3)

the tendency of the concrete to tumble and remix. The slurry put into the primary elements at the beginning of a placement may also have reduced wall roughness and thus contributed to the problem.

c. The concrete was placed in the primary elements very rapidly. The rate may have been too rapid to allow for adequate remixing to take place.

6. A definite reduction in concrete problems was seen over the duration of the project. This reduction may be attributed to a series of modifications in the placement technique and to the addition of a retarder to the concrete mixture. All of the modifications enhanced the flowability of the concrete and therefore contributed to better remixing in the primary elements. Since the effects of these modifications were cumulative, it is impossible to state which made the greatest difference. The Resident Engineer strongly believes that the addition of the retarder to the concrete mixture was the most significant change.

7. Measurements made to determine the state of hydrostatic balance of the tremie system are postulated to be an indication of areas in which to expect anomalies to occur. Additional measurements and correlations with core logs need to be completed to evaluate this hypothesis.

CHAPTER 5

TEMPERATURE PREDICTIONS FOR TREMIE CONCRETE

5.1 Objective. The objective of this portion of the project was to develop a generalized finite-element approach for predicting temperatures in massive tremie concrete placements. Emphasis was placed upon developing a program which, given the characteristics of the placement, would develop an appropriate grid system and output the grid in a format suitable for use as input to an independent finite-element program which would perform the temperature calculations.

5.2 Background.

5.2.1. Need for finite-element analysis. The use of a simple one-dimensional technique (Carlson Method) for predicting temperature development in a tremie concrete placement has been described in Chapter 3. As was noted there, this technique accurately predicts temperature development in the center of the mass where heat flow in other than the vertical direction may be neglected. However, the technique is not applicable to areas near the extremes of the placement. These areas are of particular interest due to the possibility of thermally-induced cracking as was also described in Chapter 3.

It was felt that the best way to obtain the temperature distribution at the boundaries of the structure was to develop a capability to perform a finite-element analysis of a tremie placement.

5.2.2. Finite-element program selected. The finite-element program selected to perform the analysis was one which is commercially available at U.C. Berkeley. It was developed by Ronald M. Polivka and Edward L. Wilson in 1976 (ref. 33). This program, entitled DETECT (DEtermination of TEmperatures in ConsTruction), provides a two-dimensional linear analysis of structures constructed incrementally. A complete listing and description of the program may be found in the reference.

5.2.3. Cracking predictions. Prediction of temperatures in a massive concrete placement is only the first step in predicting if thermally-induced cracking will occur. Both the factors which tend to cause cracking (primarily temperature changes for tremie-placed concrete) and those factors which resist cracking (tensile creep and strength of the concrete) must be examined. A detailed examination of these factors is beyond the scope of the present work. Carlson, Houghton, and Polivka (ref. 34) present an excellent overview of the factors involved in cracking of mass concrete.

Therefore, development of a program which will allow predictions of temperatures in massive tremie placements will not lead directly to predictions of cracking. However, use of the program will allow comparisons of temperatures and gradients based upon changes in placement temperature, cementitious materials types and amounts, and placement rates.

5.3. Observations and discussion

5.3.1. General description of program TEMP. The program which was developed, TEMP, produces input data compatible for use with program DETECT. The output available includes element identification and creation information and an appropriate heat generation function. A listing of program TEMP is in Appendix K.

The user of program TEMP has the following options:

1. Vary placement geometry.

2. Vary placement rate.

3. Vary heat generation characteristics of the concrete being placed.

4. Use of incremental or nonincremental construction approach.

5. Use of own rather than program generated grid system.

6. Use of own rather than program generated heat function.

7. Vary site conditions to include effects of insulating surfaces, if any. (insulating surfaces are handled directly through input to program DETECT.)

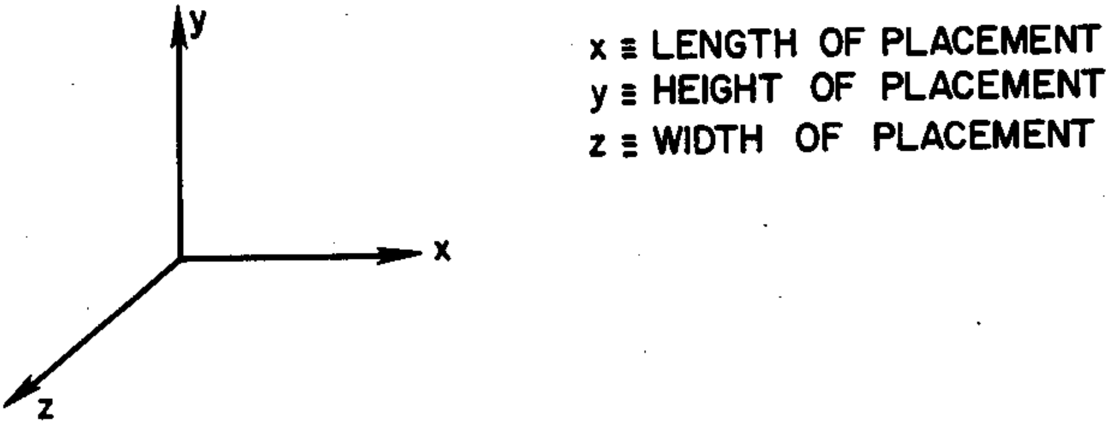
5.3.2. User options and variables. Following is a detailed description of the options available to the user and a description of how these options relate to the variables which are involved in a typical tremie placement. Detailed user instructions for program TEMP are in Appendix L, while instructions for interface with program DETECT are in Appendix M.

1. Pier geometry. The length, width, and thickness of the concrete placement may be varied as desired. The orientation of the axes is as shown in Figure 86. Elements are generated for input to DETECT for two-dimensional analysis in the X-Y plane.

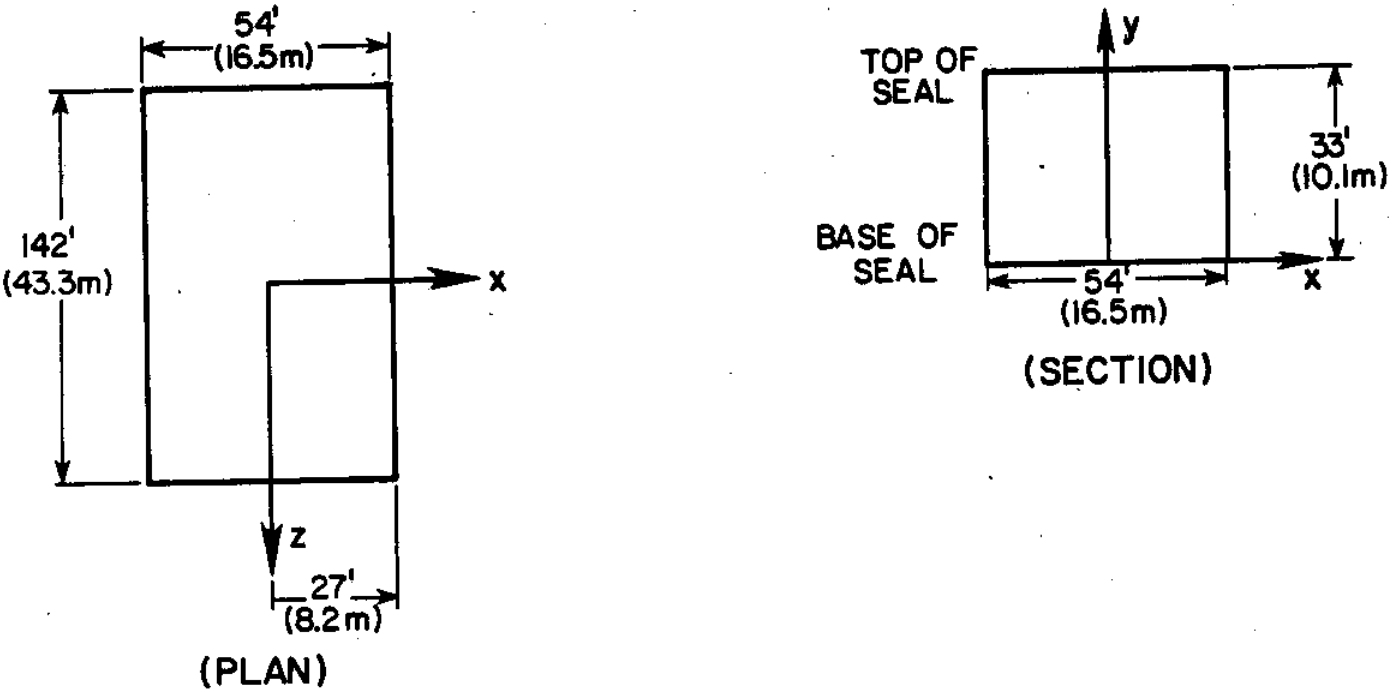
2. Tremie location. The program assumes that one tremie pipe, located at 0.0 on the X-axis, is in use in any plane perpendicular to the Z-axis. Additional tremie pipes may be simulated by adjusting the placement rate as is described below.

3. Grid generation. The program will automatically generate an appropriate grid, or the user may input a specific grid, if desired.

The automatic grid generation option establishes a two-dimensional grid which will allow for an



a. BASIC GEOMETRY



b. GEOMETRY APPLIED TO PIER 12, I - 205 BRIDGE. (Chapter 3)

Figure 86. Geometry used by program TEMP.

adequate evaluation of the temperature distribution within any size structure while minimizing the number of elements necessary to define the structure for the finite-element temperature analysis. The grid spacing generated is the most intense at the boundaries of the structure where the temperature gradients are expected to be the greatest. The grid decreases in intensity near the center of the structure.

In Figure 87 a total of six grid spacings are illustrated for different base lengths and heights. For a given structure, the base and height grids are created and then superimposed to obtain the two-dimensional grid pattern.

From Figure 87 it can be noted that the base grid is established using even 20, 10, 5, 2, and 1 ft (6.1, 3.0, 1.5, 0.6, and 0.3 m) intervals from the center outward with a standard boundary established at the outside edge of the structure. The height grid is created using a similar scheme except that the spacing is based upon 10, 5, 4, 2, and 1 ft (3.0, 1.5, 1.2, 0.6, and 0.3 m) intervals with standard boundaries at the top and base of the structure. In addition, two foundation elements with boundaries 10 and 20 ft (6.1 and 3.0 m) below the base of the structure are included in the grid layout.

The grid interval at all boundaries is set at 0.5 ft (0.2 m), a spacing found to provide an adequate definition of the temperature distribution at the boundaries.

The automatic grid generation is recommended for use in preliminary analysis. If desired, the automatic spacings may be modified by changing the appropriate values in subroutine GENGRD in program TEMP.

4. Incremental construction. The normal mode for the program is to create elements at appropriate times in accordance with the placement option selected. There is also the option of creating all elements simultaneously.

5. Concrete placement rate. There are three options available:

a. Constant rate of concrete rise over the entire placement area. The user is asked to specify a production rate (yd^3/hr)(m^3/hr) or a total time to complete the placement for this option.

b. Specified rate of rise at center (tremie pipe location) or at the X-boundary. This rate is then constant over the entire surface.

c. Specified rate of rise at center and at X-boundary. When this option is selected, a linear variation is used between these two points. The production rate specified for the center is used as a constant along the Z-axis.

6. Concrete heat generation. The user is asked to specify the amount of cement and pozzolan in the mixture to be evaluated. Three heat generation curves are then available for selection.* These curves represent a typical Type I cement, typical Type II cement, and a higher than average heat Type II cement. The cement and pozzolan data is used in conjunction with the curve selected to produce the heat generation function used as input for DETECT.

The user also has the option of modifying any or all of the 13 points which make up each of the three available curves by entering desired multiplication factors.

Finally, the user has the option to completely bypass this portion of the program and enter a heat generation function directly into program DETECT.

7. Boundary conditions. Values for the following variables must be entered directly into DETECT: concrete placement temperature, thermal characteristics of concrete, water temperature during and after placement, insulation characteristics, if any, and thermal characteristics of foundation materials. The number of time periods to be included in the evaluation is also handled directly by DETECT. See Appendix M and the user instructions for DETECT for more details concerning input of these variables.

5.3.3 Example of program TEMP usage. Programs TEMP and DETECT were used to produce temperature predictions for a placement similar to that of Pier 12 of the I-205 Bridge described earlier in Chapter 3. Variables were selected to be consistent with those in the actual placement. Table 25 presents the values of the variables involved.

The option for a continuous placement rate of 150 yd^3/hr (115 m^3/hr) was selected for program TEMP. This rate corresponds well to the actual average placement rate of 135 yd^3/hr (103 m^3/hr).

Two of the optional heat curves available in program TEMP (Type II average heat cement and Type II higher than average heat cement) were used to produce heat function input data for program DETECT. Additionally, three other heat functions were used by being input directly into DETECT. Table 26 shows the values associated with these five heat functions.

Temperatures predicted by Program DETECT using input generated by Program TEMP are

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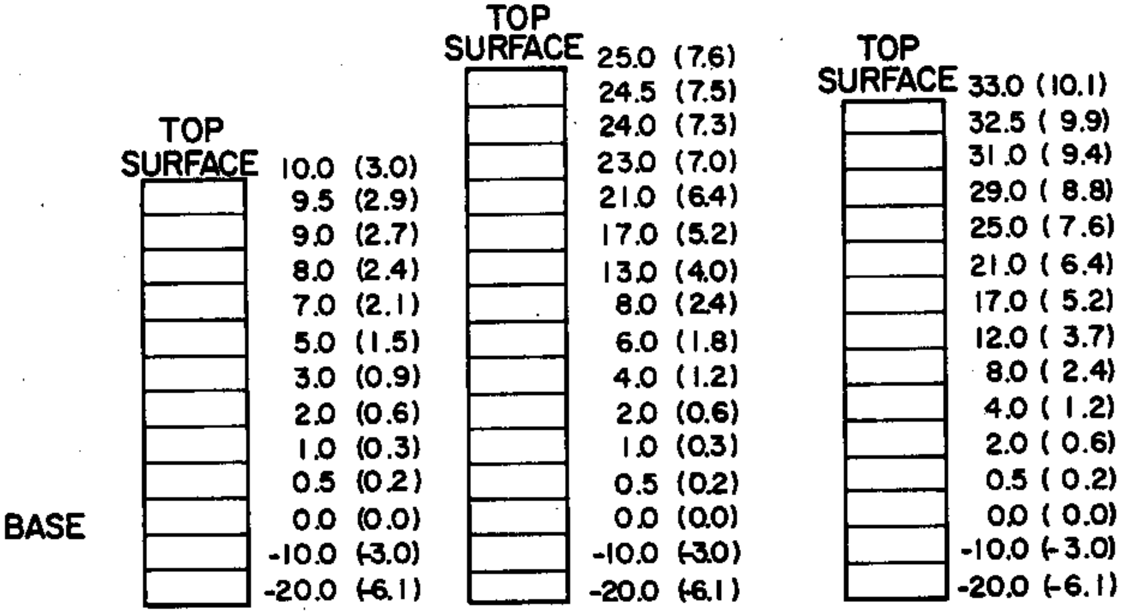
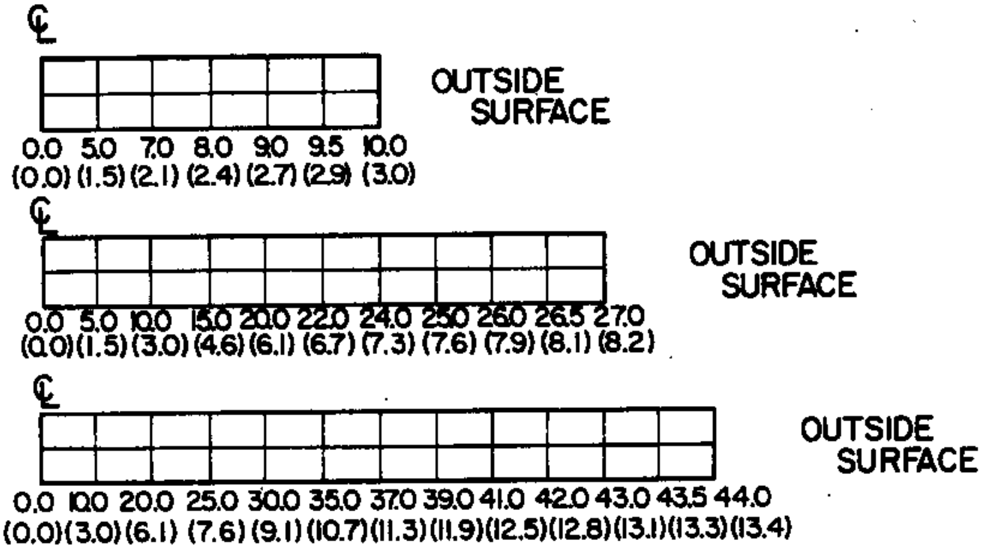
* These curves are taken from those shown in Reference 34.



a. TYPICAL VERTICAL GRIDS, FT. (m)



b. TYPICAL HORIZONTAL GRIDS, FT. (m)

Figure 87. Typical finite-element grids generated by Program TEMP (schematic - no scale).

TABLE 25 - VARIABLES USED IN EXAMPLE PROBLEM

Placement Geometry:

X: 54.0 ft (16.5 m)
Y: 33.0 ft (10.1 m)
Z: 142.0 ft (43.3)

Total volume: 9372 yd^3 (7166 m^3)
Placement rate: 150 yd^3/hr (115 m^3/hr)
Foundation material:

Thermal conductivity: 0.917 BTU/hr-ft-°F (1.59 W/m-K)
Specific heat: 0.194 BTU/lb-°F (812 J/kg-K)
Density: 125 lb/ft^3 (2002 kg/m^3)

Concrete:

Thermal conductivity: 1.30 BTU/hr-ft-°F (2.25 W/m-K)
Specific heat: 0.231 BTU/lb-°F (967 J/kg-K)
Density: 148 lb/ft^3 (2371 kg/m^3)

Concrete placement temperature: 60°F (16°C)
Water Temperature: 55°F (13°C)
Mixture proporations: (Used for heat functions generated internally by Program TEMP)

Cement: 526 lb/yd^3 (312 kg/m^3)
Pozzolan: 165 lb/yd^3 (98 kg/m^3)

TABLE 26 - HEAT FUNCTIONS USED FOR TEMPERATURE PREDICTIONS*

Time, hrs	Type II, Average heat**	Type II, higher than Average**	Heat Function #1	Heat Function #2	Heat Function #3
0	0	0	200	200	200
2	79	82	30	30	30
4	88	90	100	100	100
6	103	105	106	106	106
8	-	-	75	75	60
12	109	110	-	-	-
20	64	65	20	20	15
32	27	28	10	10	14
48	11	15	15	15	13
60	7	10	15	12	12
96	4	6	10	5	10
180	1	2	5	3	3
290	0	0	1	1	2
1000	0	0	0	0	1

* Values shown are BTU/Ft^3-hr. Multiply by 10.34 to obtain W/m^3.

**Curves available within program TEMP.

compared to temperatures measured in Pier 12 in Figures 88, 89, 90 and 91. For these figures, representative temperature instruments at various locations in the seal were selected.* Then, the finite-element node closest to the instrument location was determined. The figures show the measured temperatures as well as the predicted values based upon all five heat functions.

Figure 88 presents measured temperatures for two instruments located at mid-depth in the seal, on the centerline (X = 0. Y = 18.5 ft (5.6 m) for Program TEMP).

Figure 90 presents measured temperatures for an instrument below mid-depth, off of the centerline (X = 13.0 ft (4.0 m), Y = 10.25 ft (3.1 m) for Program TEMP).

Figure 91 presents measured temperatures for two instruments located at mid-depth near the outside of the seal (X = 23.7 ft (7.2 m), Y = 18.5 ft (5.6 m) for Program TEMP).

The following points may be made concerning these curves:

1. The predicted temperatures are in good general agreement with the measured values.

2. There does not appear to be one heat function which provides the most accurate agreement in all cases. The curves based upon the Type II average heat cement are close in Figures 89 and 90 while the curve based upon heat function two appears to be the closest in Figure 88. The curves based upon heat functions one and three appear to be the closest in Figure 91.

3. The predicted temperatures are obviously very dependent upon the heat function used. Minor differences in the heat functions can lead to major differences in predicted temperatures during the period of interest. If predictions of actual temperatures within a placement are desired, it is recommended that the concrete to be used be tested to develop an accurate heat function. However, if relative predictions concerning the effect of changing placement variables such as placement temperature or cement or pozzolan content are desired, the heat curves built into Program TEMP should be adequate.

4. The sensitivity of the temperature predictions to variations in difficult-to-define variables such as the thermal characteristics of the concrete and the underlying rock was not examined. Such an examination is recommended prior to use of the program for actual temperature predictions.

In addition to the comparison made with actual measured temperatures, curves were prepared showing temperature variations horizontally and vertically within the seal. These curves were prepared for the heat function based upon the higher than average Type II cement as is available within Program TEMP. Figure 92 shows the locations of the nodes which were plotted while Figure 93 shows horizontal variations and Figure 94 shows vertical variations.

Using the data presented in Figures 92 and 93, two additional figures were prepared which show temperature gradients within the seal concrete at 80 and 200 hours after the beginning of the placement. Figure 95 shows the gradients which exist across a horizontal plane 12 ft (3.7 m) above the base of the seal. Figure 96 shows the gradients which exist in a vertical plane at the centerline of the seal. Note that these two figures are plotted as temperatures of concrete above the temperature of the water surrounding the seal.

The following points can be made concerning these figures:

1. Significant temperature gradients can be expected to develop near the outside surfaces of a massive tremie-placed seal. These gradients develop soon after placement begins and remain evident for a significant period of time.

2. The gradients predicted by the finite-element program are consistent with the data obtained in the Pier 12 seal placement described in Chapter 3.

3. Without specific strain capacity and modulus data, predictions of cracking cannot be made. However, the temperature gradients appear to be large enough to be capable of inducing cracking in most concretes.

5.4. Summary. The following items summarize this portion of the project:

1. A Fortran program, TEMP, was prepared which accepts variables associated with a massive tremie placement and processes those variables to develop input for an existing finite element program, DETECT, which can be used to predict temperatures within the tremie concrete. Program TEMP has a wide range of options available to the user to allow accurate modeling of a planned placement.

2. Predictions of maximum temperature and temperature gradients near surfaces of tremie-placed concrete made using programs TEMP and DETECT were shown to be in good general agreement with temperatures measured in an actual placement.

3. Predicted temperatures were shown to be very dependent upon the heat function used. The sensitivity to other variables was not explored.

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* Temperature instrument locations are presented in Appendix H.

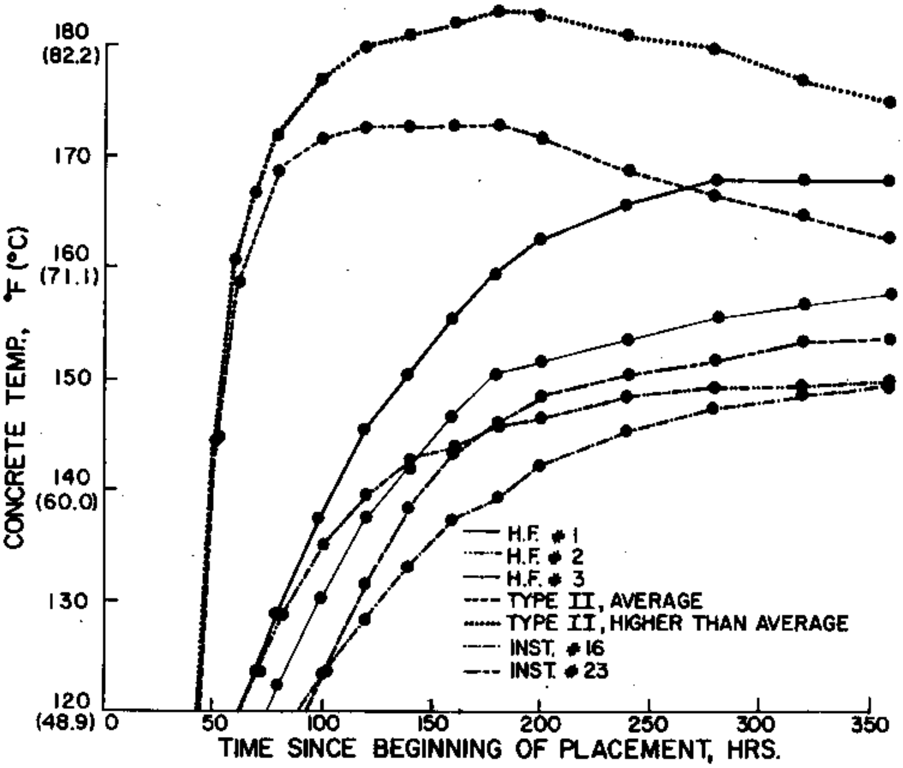

Figure 88. Predicted versus measured temperatures, centerline, mid-depth.

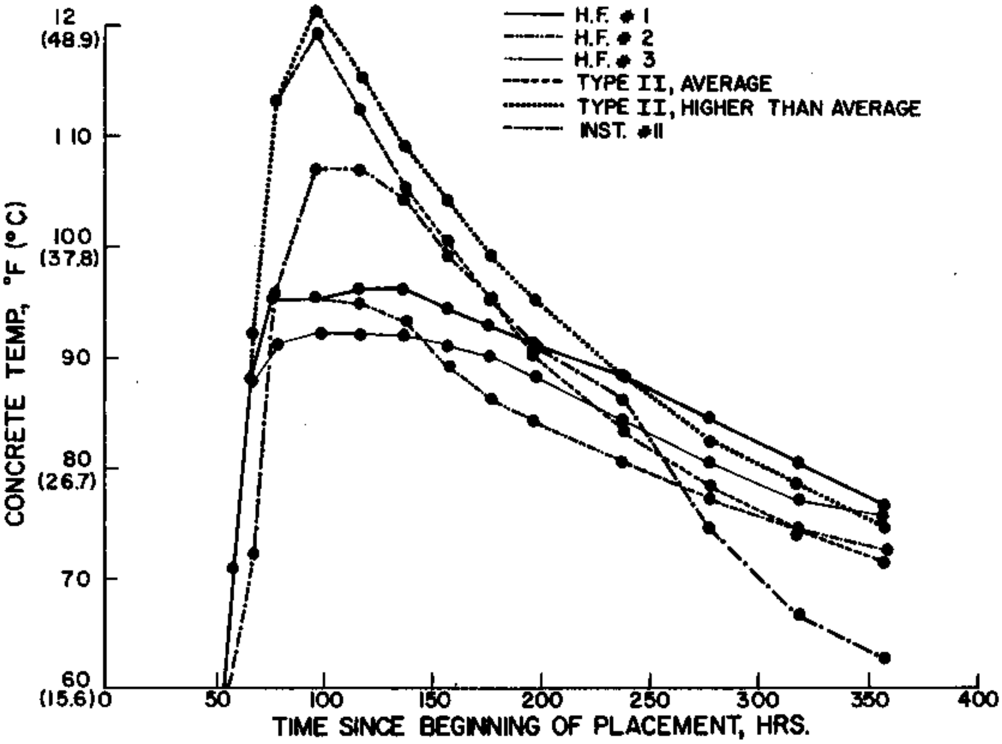

Figure 89. Predicted versus measured temperatures, outside edge, upper surface.

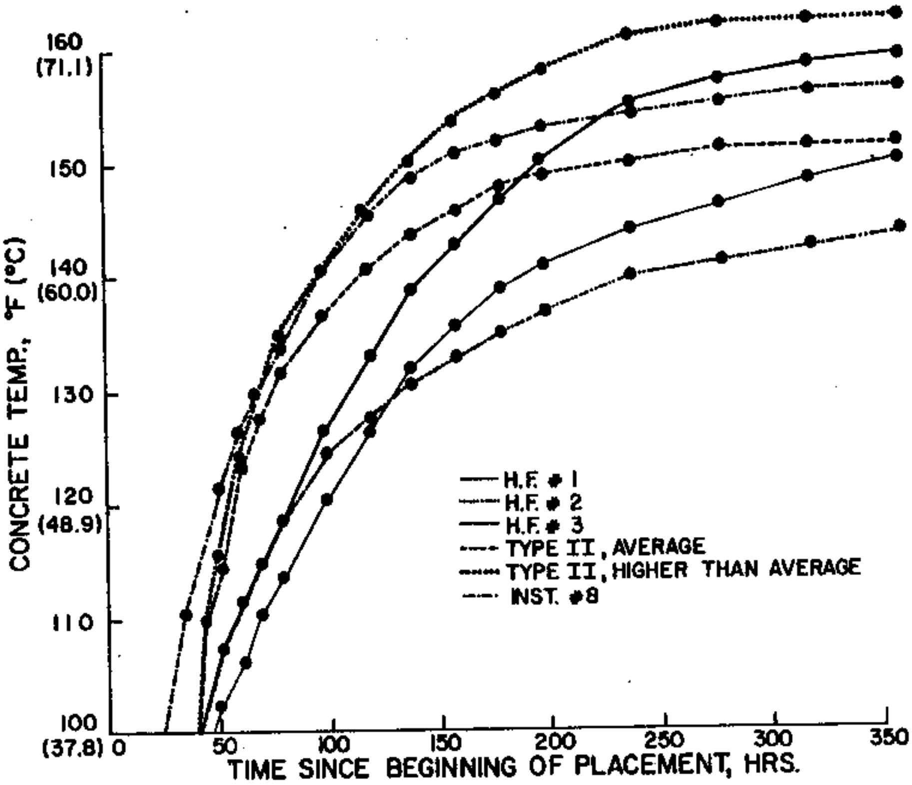

Figure 90. Predicted versus measured temperatures, off centerline, mid-depth.

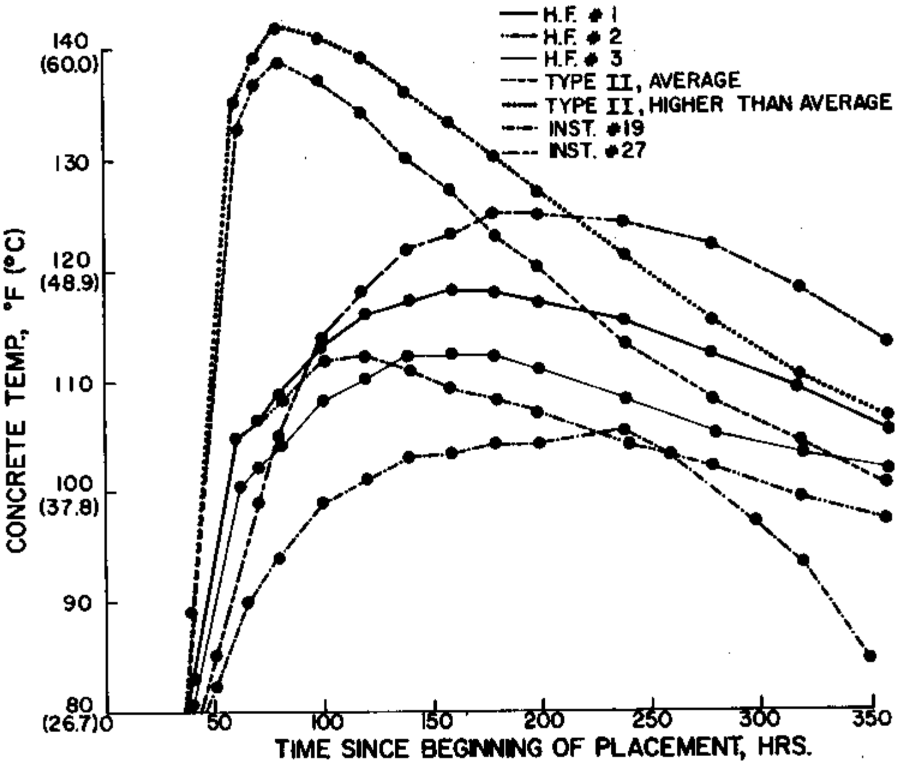

Figure 91. Predicted versus measured temperatures, outside edge, mid-depth.

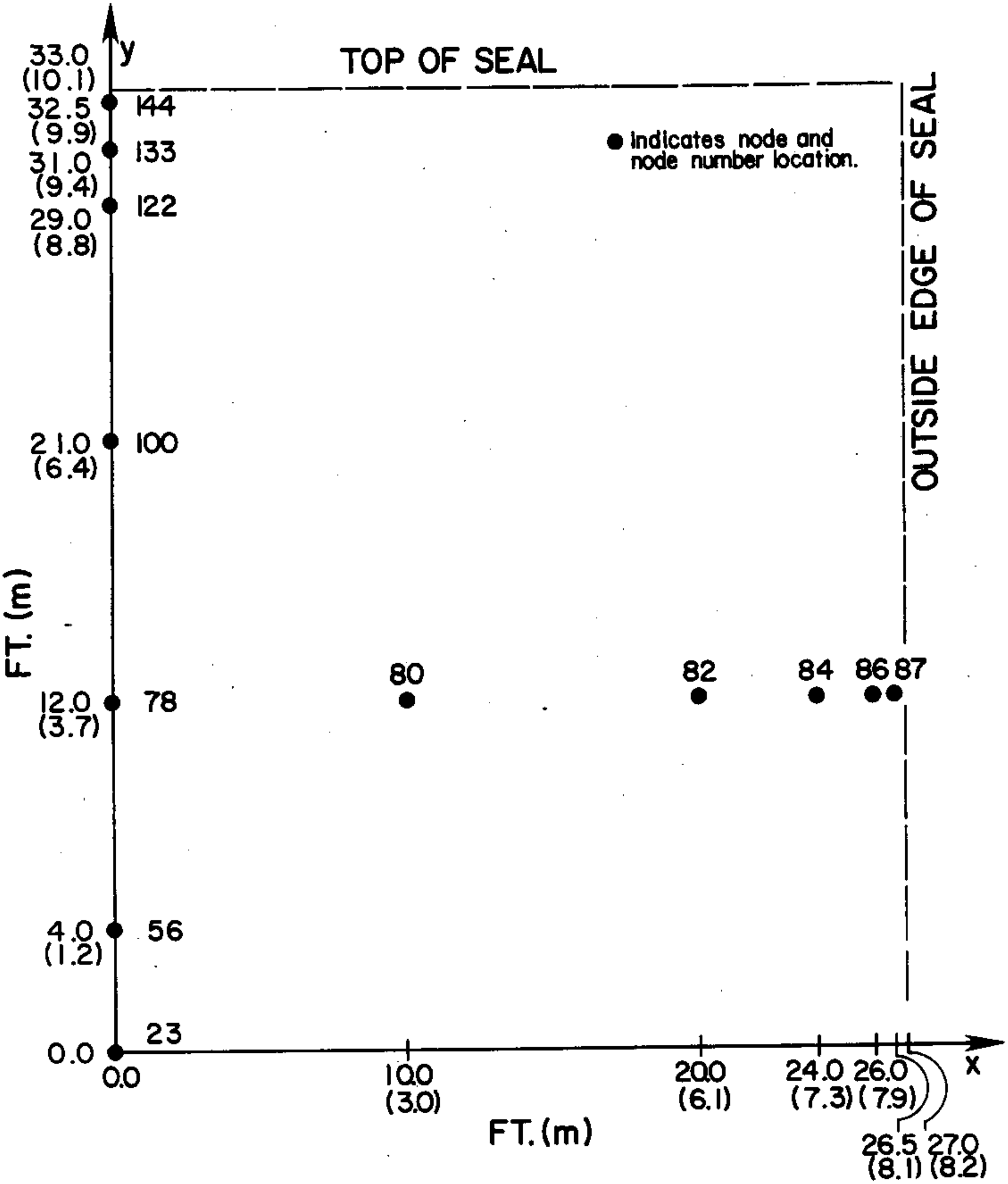

Figure 92. Section through seal showing locations of nodes plotted in Figures 93 and 94.

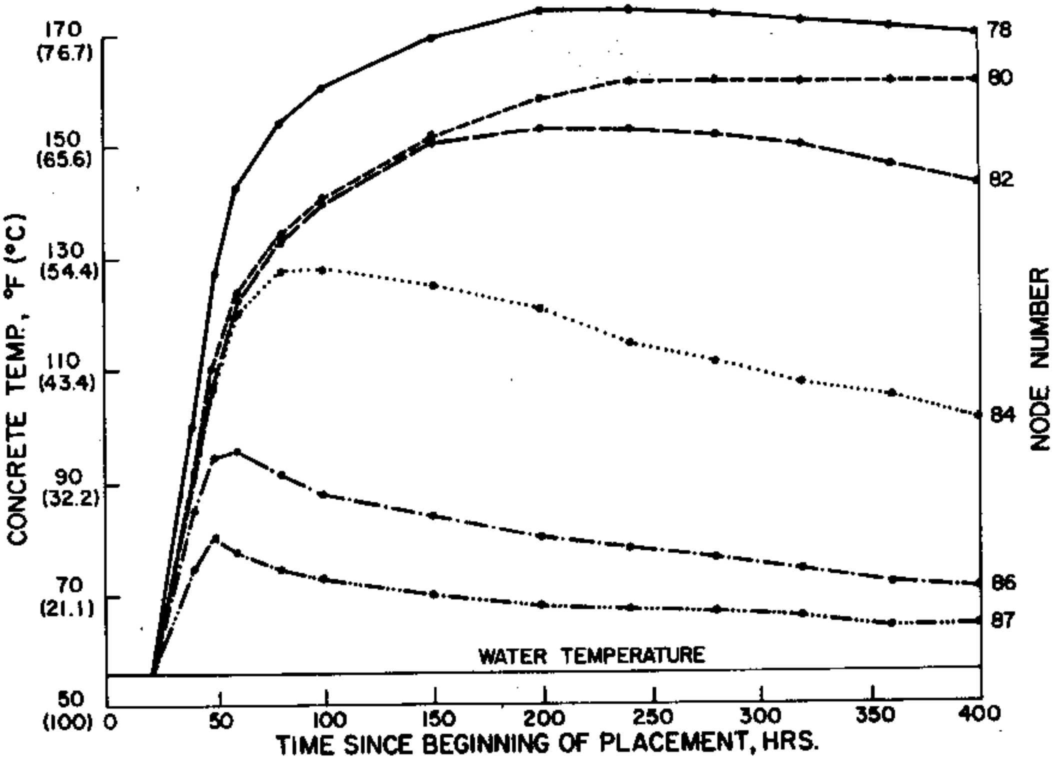

Figure 93. Horizontal variation in predicted temperatures. See Figure 92 for location of nodes shown.

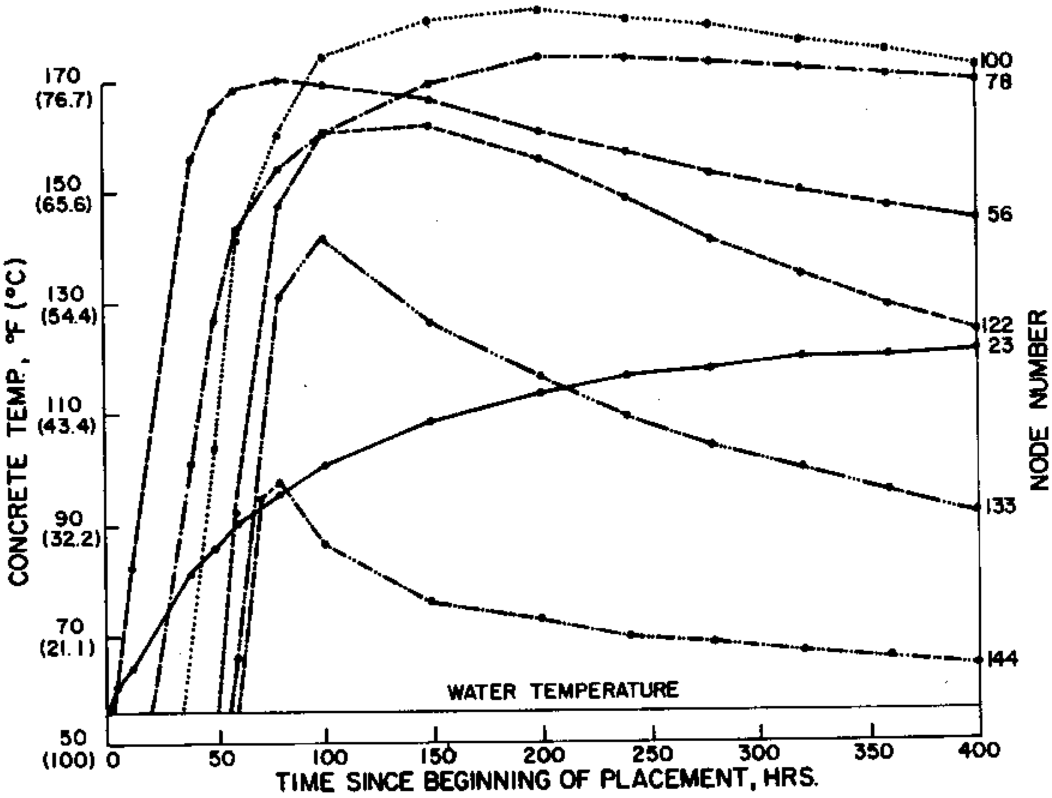

Figure 94. Vertical variation in predicted temperatures. See Figure 92 for location of nodes shown.

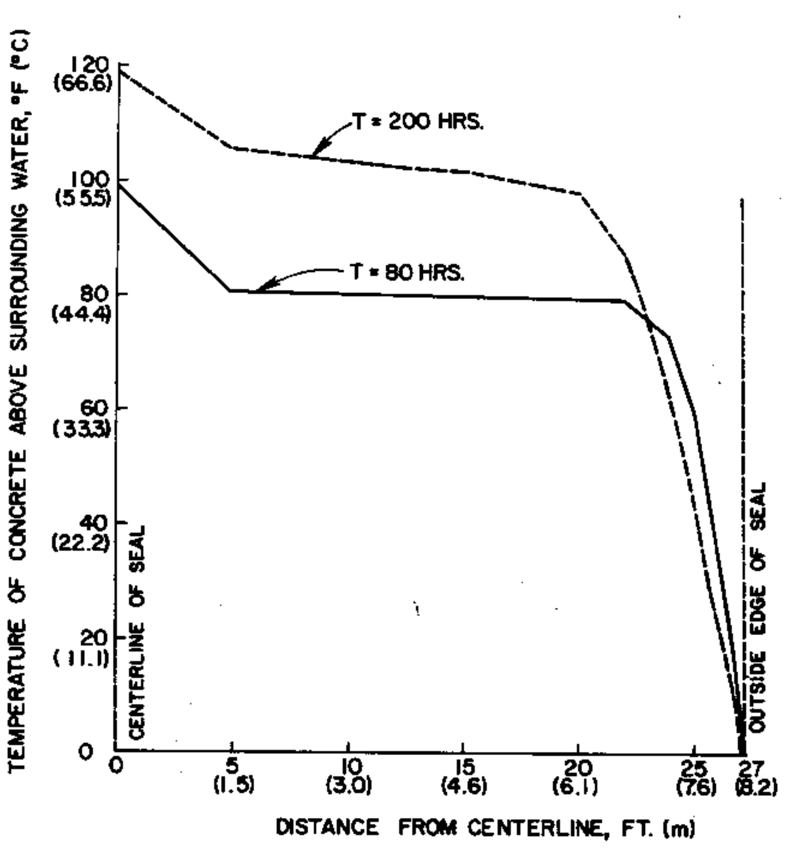

Figure 95. Section through seal showing horizontal temperature gradients at two times after beginning of placement.

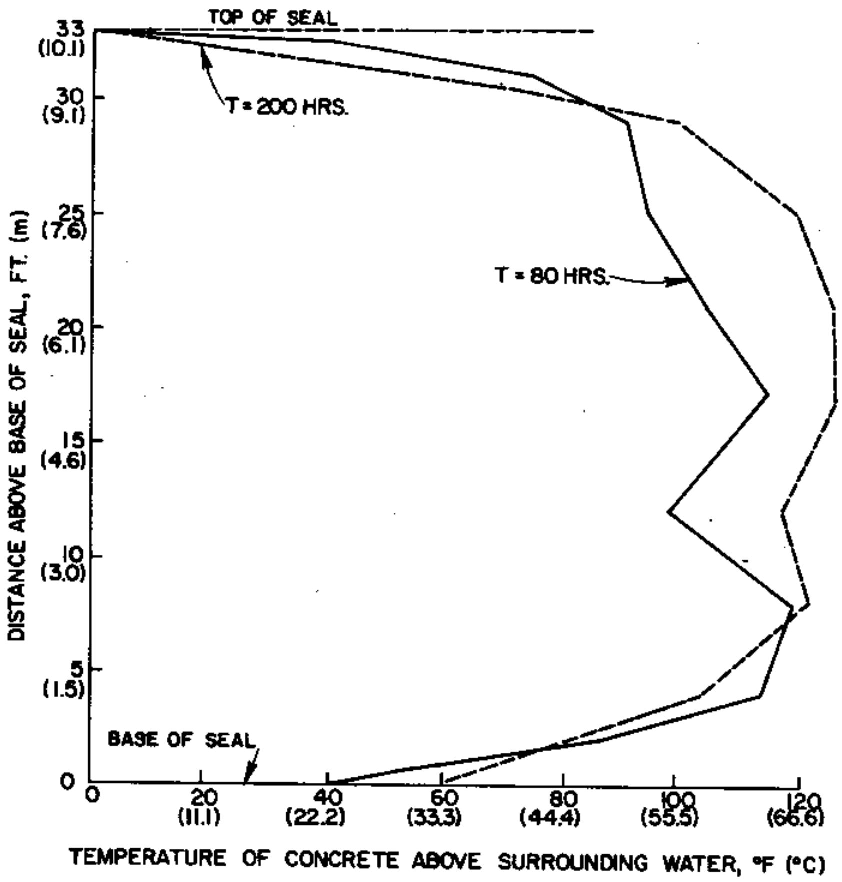

Figure 96. Section through seal showing vertical temperature gradients at two times after beginning of placement.

CHAPTER 6

FLOW PREDICTIONS FOR TREMIE CONCRETE

6.1. Objective. The objective of this portion of the project was to examine the possibility of using a computer model to predict flow patterns of tremie-placed concrete. Two areas relating to tremie concrete flow were of particular interest: first, the relationship of concrete placement rate and pipe spacing to concrete quality; and second, the influence of the depth of tremie pipe embedment on the flatness of the completed concrete surface. Additionally, it was thought that if an accurate flow prediction model could be developed, that model could be used in conjunction with the temperature prediction programs described in Chapter 5 to increase the accuracy of the temperature predictions.

6.2. Background.

6.2.1. Literature review. A brief sampling of the literature dealing with tremie concrete flow, pipe spacing, and pipe embedment follows:

1. The American Concrete Institute Committee 304 in its "Recommended Practice for Measuring, Mixing, Transporting, and Placing Concrete" (ref. 1) writes:

> "Pipe spacing varies depending on the thickness of placement and congestion from piles or reinforcement. The spacing is usually about one pipe for every 300 sq ft (approx. 28 m^2) of surface or about 15 ft (approx. 4 1/2 m) centers. However, this may be increased to as much as 40 ft (approx. 12 m) centers in an uncongested deep mass using retarded concrete."

The Committee also writes concerning the concrete surface that, "Faster rates may produce flatter surfaces" and "the deeper the embedment in concrete, the flatter the finished slope will be." A placement rate resulting in a vertical rise of concrete of 1.5 to 10 ft/hr (0.5 to 3.0 m/hr) is recommended.

2. The Corps of Engineers in its Civil Works Construction Guide Specification, Concrete (ref. 35) requires that "a sufficient number of tremies shall be provided so that the maximum horizontal flow will be limited to 15 feet" (4.6 m). The Corps' Standard Practice for Concrete (ref. 36) recommends a 5 ft (1.5 m) embedment depth, but does not relate embedment depth to surface flatness.

3. Strunge (ref. 15) recommended the following:

a. The coverage of each tremie pipe should be approximately 250 ft^2 (23 m^2).

b. The largest horizontal dimension of the forms should be less than 15 ft (4.6 m). Partitions should be used to break up larger placements.

c. The maximum distance from a tremie to a form should not be greater than 10 ft (3.0 m).

d. The depth of embedment should be a minimum of 3 ft (1.0 m).

e. Vertical rise of the concrete should be 2 ft/hr (0.6 m/hr).

4. Concrete Construction magazine (ref. 2) made similar recommendations which included coverage per tremie pipe of approximately 300 ft^2 (28 m^2) or a spacing of 15 ft (4.6 m) on centers, and that a higher placement rate will lead to flatter slopes in the tremie concrete. A rate of concrete rise of 3 ft/hr (1.0 m/hr) was recommended. Concerning embedment, a depth of 2 to 5 ft (0.6 to 1.5 m) was given with the comment "to get flatter slopes in the seal, a deeper embedment is required."

5. Gerwick (refs. 4 and 5) also recommended a coverage of 300 ft^2 (28 m^2) or 15 ft (4.6 m) centers for the tremies along with an embedment depth of 1.5 to 5 ft (0.5 to 1.5 m). He wrote "Deeper embedment gives a flatter slope provided initial set has not taken place." Concerning placement rate, Gerwick recommended 1.5 to 10 ft/hr (0.5 to 3.0 m/hr).

6. Halloran and Talbot (ref. 17), writing of their experiences constructing tremie-placed drydocks during World War II, made these comments:

a. Tremie spacing should depend upon the continuity with which concrete is delivered to the tremies.

b. The tremies should be spaced on 12 to 16 ft (3.7 to 4.9 m) centers with the outside tremie being less than 9 ft (2.7 m) from the forms.

c. Closer spacing of tremies leads to flatter surfaces.

d. A deeper embedment of the tremie pipe leads to flatter slopes, with an embedment of 3 to 5 ft (1.0 to 1.5 m) recommended.

e. Placement rate should be sufficient to provide a rate of rise for the concrete of 2 to 3 ft/hr (0.6 to 1.0 m/hr).

The recommendations given by the authors above were based on experience gained on a wide variety of tremie placements. These sources may be summarized as follows: Tremies should be closely spaced to minimize flow distance; the greater the embedment depth of the tremie pipe, the flatter the surface of the completed placement; and, the higher the concrete placement rate, the flatter the concrete surface. Typical numerical values for these recommendations are:

- pipe spacing: 15 to 40 ft (4.6 to 12.2 m) on centers.

- pipe coverage: 300 ft^2 (28 m^2).

- pipe embedment: 3 to 5 ft (1.0 to 1.5 m).

- rate of rise: 1 to 3 ft/hr (0.3 to 1.0 m/hr).

Only one source was found in the literature which attempted a mathematical description of these flow considerations. That work is described in the next section.

6.2.2. Dutch investigation. The work published by the Netherlands Committee for Concrete Research (ref. 3) also included a chapter in which the factors of pipe spacing, placement rate, and tremie embedment were treated in a mathematical model. The basic Dutch model was founded upon the theory of viscous fluids and was solved using an iterative finite difference procedure. The Dutch investigators noted an important limitation in their approach which must be kept in mind: "Although the calculated results appear reliable, their value must not be overrated. To treat fresh concrete as a viscous fluid in such calculations is a rough approximation."

The parameters of the basic flow model were following:

- the cofferdam is circular, with a diameter of 5.30 m (17.4 ft); at the start of the calculations a layer of concrete is assumed to be already present in the cofferdam; the thickness of this even and horizontal layer is H;

- at the center of the cofferdam is a vertical concreting pipe with a diameter d (=300 mm) (11.8 in.);

- at the start of the calculation the pipe is embedded a distance h in the concrete;

- the effect of the dead weight of the concrete is neglected;

- the viscosity of the fresh concrete is 0.1 m^2/sec. (1.1 ft^2/sec.).

The findings of the Dutch investigators based upon the use of this model are summarized below.

1. A mound of concrete built up around the tremie pipe similar to the mound seen in the large-scale placement tests (Chapter 2). The mound extended for a distance of approximately twice the embedment depth from the center of the tremie pipe. There is nothing in the Dutch descriptions which suggests that the mound was formed by vertical flow adjacent to the tremie.

2. The shape of the concrete surface was found to be independent of the distance from the pipe outlet to the cofferdam bottom.

3. "If there is sufficient immersion depth, the concrete feed into the cofferdam will take place in such a manner that concrete which is at the surface will remain at the surface." This statement, and figures in the Dutch report describe a horizontally layered flow pattern in which the first concrete placed may be expected to be found on the surface of the finished placement. Such a flow pattern is inconsistent with the data obtained during the large-scale placement tests (Chapter 2).

4. The concrete mound which builds up around the tremie develops a slope of approximately 1:5. The mound continues to develop until the shear resistance of the fresh concrete is overcome. At that time, a failure occurs (a semi-circular soils type failure) which results in a mixing occurring at the toe of the mound (Figure 97). This failure can occur after only a small volume of concrete has been placed and must be tolerated. The Committee explains

> "In the mixing zone the concrete, so long as it has not stiffened, will be able to coalesce. With sufficient concreting capacity to maintain an adequate rate of feed it will be possible to ensure that this will happen."

5. The Committee used its findings on tremie concrete flow to develop a model which relates pipe spacing and production rates for a square placement. This model is examined in detail in section 6.3.1, below.

6. Recognizing that the initial model imposed limitations that might not be realistic in actual placements, a model without the requirement that the placement be divided into squares was developed. This model uses an advancing sloping front; and it is described in detail in section 6.3.2, below.

7. The Dutch investigators also considered the hydrostatic balance of the tremie system to determine how much concrete would be required in the tremie pipe to achieve flow. This work is considered in section 6.3.4, below.

8. In regard to tremie pipe embedment, the Dutch wrote, "It should be borne in mind, however, that better surface evenness is obtained according as the pipe immersion depth is greater." Unfortunately, they do not explain the basis of that statement.

6.3. Observations and discussion. The various Dutch models noted above are examined in the following sections. Additionally, sample calculations based upon maximum flow distances and concrete production capability are presented for a typical placement.

6.3.1. Square placement model. The basic Dutch placement model involves a tremie placement which is divided into squares with a length of D units on a side.* The other parameters are shown in Figure 98.

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* The model is developed in terms of meters. Since the use of the model is independent of the units involved, only meters will be shown in the text.

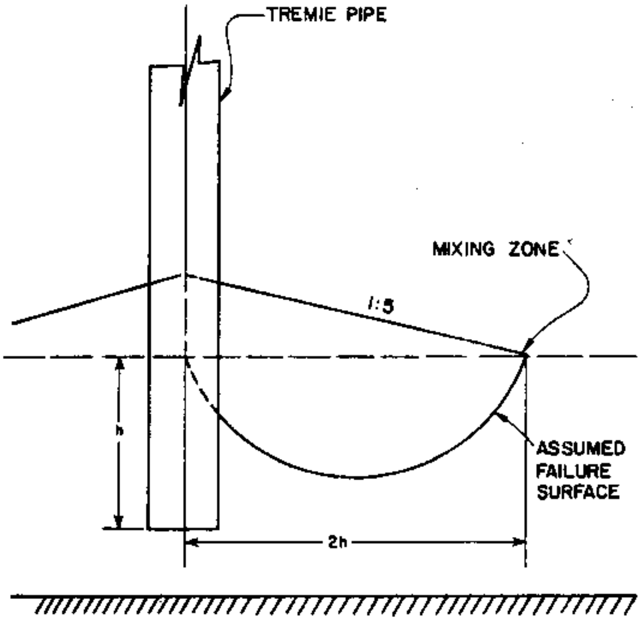


Figure 97. Dutch failure model (after ref. 3).

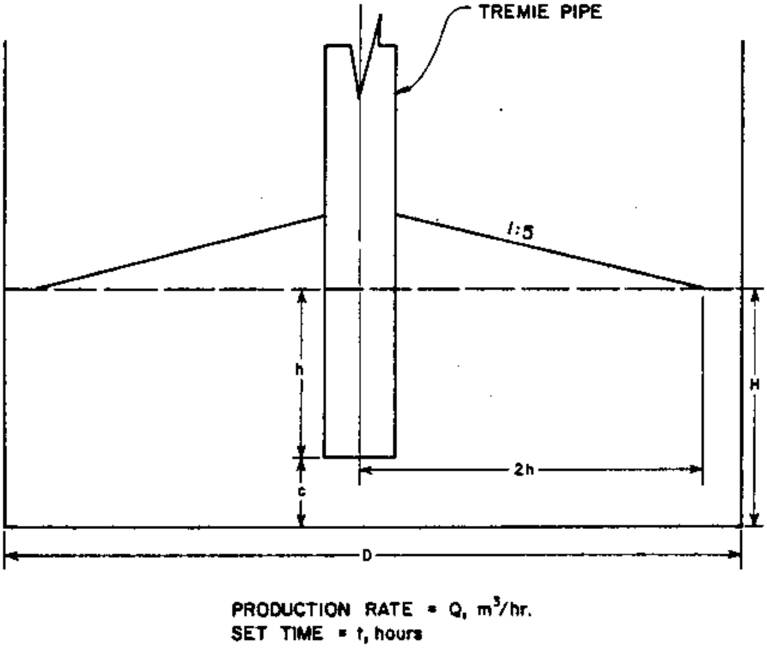


Figure 98. Dutch square placement model. Case shown is $H<(0.25\ D + C)$. Shearing can be expected throughout the placement (after ref. 3).

Based on consideration of a 1:5 slope and shear failures in the toe of the slope resulting in the mixing described above, the objective of the model is to reach the point at which the pipe embedment becomes equal to 0.25 D by the time the set time of the concrete is reached. If that depth of embedment is not reached before the set time is exceeded, the concrete would not be able to remix and coalesce when the shear failures occur. Once the embedment exceeds 0.25 D, the toe of the slope will theoretically be outside the placement area and no further shear failures may be expected to occur.

Two cases may exist for the variables describing the thickness and size of the concrete placement. Each case leads to a different required placement rate.

Case I: $H < (0.25\ D + C)m$*

$$Q = D^2H/t\ m^3/hr$$

Case II: $H \geq (0.25\ D + C)$

$$Q = D^2\ (0.25\ D + C)/t\ m^3/hr$$

Consider the following two examples:

Ex. 1. $D = 4.0$ m
$C = 0.25$ m
$t = 2.0$ hrs
$H = 1.0$ meter

Volume required = 16 m^3

$H < 0.25\ D + C$

$Q = D^2\ H/t$

$= 8\ m^3/hr$

Shear failures can be expected to occur throughout the placement. However, the placement will be completed at the same time the first concrete placed reaches its set.

Ex. 2. Same conditions except

$H = 3.0$ m

Volume required = 48 m^3

$H > 0.25\ D + C$

$Q = D^2\ (0.25\ D + 0.25)/t$

$= 10\ m^3/hr$

Time of placement = 4.8 hours.

Shearing will take place until the concrete reaches a depth of $h = 0.25\ D + 0.25$, ($h = 1.25$ m). This depth requires a placement of 20 m^3 which is two hours production which is also the set time of the concrete. The workings of the model are unclear during the remaining 2.8 hours of the placement since the concrete at the surface has set. The Dutch report does not consider this problem.

Disregarding the above short coming, the two equations for determining placement rate may be rewritten to solve for pipe spacing given available production capacity. Using this approach, the curves shown in Figure 99 were developed. The curves are used as follows: With a placement capacity of 75 m^3/hr, a seal thickness of 2.0 m, and a set time of 2 hours, what is the maximum allowable pipe spacing? The answer, from the curves is 8.6 m. Using these curves leads to pipe spacings which are generally well above those recommended in the literature.

The failure of the model to consider placement time after the set time of the concrete leads to the same curve being developed for all placements above a critical thickness for each set time, where $H_{crit} = 0.25\ D + C$. Once this critical thickness is exceeded, pipe spacing becomes fixed for a given production rate. For example, given a placement capacity of 75 m^3/hr and a set time of 3 hrs, the maximum recommended spacing for all placements 3 m or more in thickness is 9.3 m. However, $H_{crit} = 0.25\ (9.3) + 0.25 = 2.6$ m, which means that no such placements would be completed before the initial concrete placed has set. To overcome this problem, placements which are thicker than H_{crit} apparently must be divided into squares small enough to be completed within the set time of the concrete. A very thick placement, therefore, would require sub-division into many smaller placements.

6.3.2. Advancing slope placement model. Realizing that it will not always be practical to divide a tremie placement into the squares required for the above model, the Dutch investigators modified their model to use an advancing, sloping front edge. The geometry of this model is shown in Figure 100. The model requires the concrete shown as cross-hatched be placed with the tremie in the location shown. Then, the tremie will be moved toward the far end of the placement to place the next increment of concrete.

The same requirement that no shear failures occur after the time that it takes for the concrete to set is also imposed: "This can be satisfied by choosing the rate of placing at least so high that the concrete which at first is at the top of the slope will, on completion of the concreting, have arrived at the final surface of the concrete." Thus, the required production rate becomes equal to the volume to be placed divided by the set time of the concrete. Using the notation shown on Figure 100, the required placement rate becomes:

$$Q = (5H^2 \times \text{width})/t\ m^3/hr$$

Consider the following examples:

---

* Variables are defined in Figure 98.

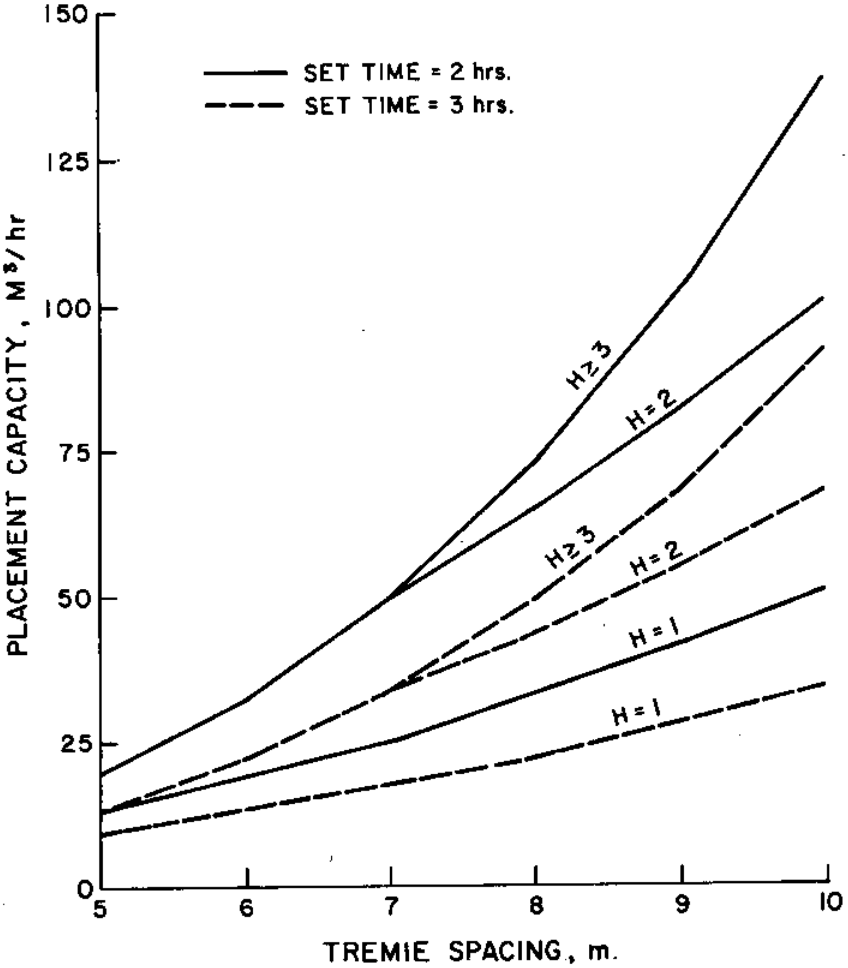


Figure 99. Placement curves derived from Dutch square placement model.

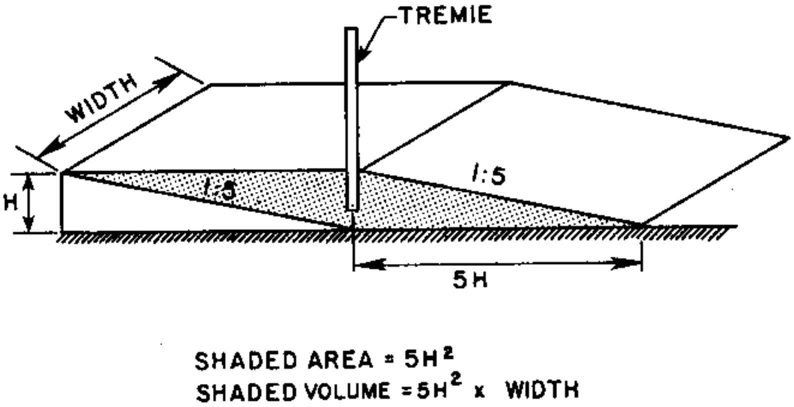


Figure 100. Dutch advancing slope placement model (after Ref. 3).

Ex. 1. A tremie seal is to be 15 x 30 m in plan and 4 m thick. The set time of the concrete is 3 hrs.

$$Q = 400 \ m^3/hr$$

Ex. 2. A tremie seal is to be 26 x 43 m in plan and 9 m thick (approximate dimensions of Pier 12 of the I-205 Bridge described in Chapter 3). The set time of the concrete is 3 hrs.

$$Q = 2160 \ m^3/hr$$

Obviously, such production rates are beyond those normally available.

6.3.3. Summary of Dutch placement models. The Dutch Committee summarized its work on these two placement models in the following statements:

> "If high quality of the concrete is required and the slab to be constructed is of considerable thickness, it may be advisable to concrete it in individual bays. This will, of course, necessitate extra arrangements.
>
> "If the cofferdam is not subdivided into bays, the concrete obtained is likely to be of somewhat poorer quality unless the concreting capacity is high enough to compensate for this. In the Committee's investigations on core specimens it was found that the tremie methods produced relatively homogeneous concrete possessing high compressive strength. Yet the concreting capacity used on the jobs inspected was substantially lower than the theoretically required capacity.
>
> "From this it can be inferred that a subdivision into bays or a very high concreting capacity appear necessary only in cases where very stringent demands are applied to homogeneity,"

The Committee further stated, "In practice the concreting scheme will be drawn up, suited to the available capacity." This statement identifies the greatest shortcoming of the models.

The two models do provide additional general insight into the flow of tremie concrete. Perhaps their most practical use is to serve as a starting point for calculations of the nature of those shown in section 6.3.5, below. The usefulness of the models for determining pipe spacing or required placement rates appears to be limited.

6.3.4. Dutch hydrostatic balance model. Another area covered by the Dutch investigators was the hydrostatic balance of the tremie system (this balance was described earlier in Chapter 4 and the geometry was shown in Figure 85). It is not clear if the Dutch balance model was also based on the viscous fluid calculations used to develop the two flow models.

The Dutch model was developed using these considerations:

1. The depth of embedment of the tremie is h.

2. The height of water above the concrete surface is z.

3. The ratio of unit weights of concrete and water is γ , which is approximately 2.4.

4. The height of concrete necessary to overcome internal concrete friction is twice the embedment depth, 2h.

5. Approximately 10 percent additional height of concrete is required to overcome the friction between the concrete and the tremie pipe.

Therefore, the level of concrete required above the mouth of the tremie for flow to occur will be:

$$L_c = 1.1 \ (h + 2h + z/\gamma)$$

This equation may be solved for various values of z and an assumed embedment depth of 3 ft (1.0 m) as is shown below. Also shown is the height of concrete required above the tremie mouth to achieve a hydrostatically balanced condition, neglecting internal friction.

z, ft (m)	L_c, ft (m)	Balance, ft (m)
10 (3.0)	14.5 (4.4)	7.2 (2.2)
20 (6.1)	19.1 (5.8)	11.3 (3.4)
30 (9.1)	23.7 (7.2)	15.5 (4.7)
40 (12.2)	28.2 (8.6)	19.6 (6.0)
50 (15.2)	32.8 (10.0)	23.8 (7.3)

Limited measurements made at actual massive placements have shown that the concrete returns very nearly to the balanced condition whenever there is a break in the placements. Additional work performed at Wolf Creek Dam (ref. 30) involved numerous measurements in the confined placements. In those placements the concrete also returned very closely to the balanced condition. Thus it appears that the Dutch model somewhat over estimates the friction which resists flow.

The Dutch model may be rearranged and used to solve for the depth of embedment necessary to control concrete flow. Based upon recommendations found in much of the literature that the tremie hopper be kept full of concrete during the placement, assume that a concrete level 2 ft (0.6 m) above the water surface is desired. The values below are obtained:

z, ft (m)	h, ft (m)
20 (6.1)	5.6 (1.7)
40 (12.2)	10.3 (3.1)
60 (18.3)	15.3 (4.6)

Obviously, in a massive placement such embedment depths would be impractical without very high placement rates. These calculations and the hydrostatic balance measurements made certainly question the feasibility of controlling the flow of tremie concrete solely by adjusting the embedment depth of the tremie pipe.

6.3.5. Example placement calculations. The basic scheme suggested by the Dutch models, but without the restriction that the first concrete placed must remain alive throughout the placement, may be used to relate the factors of pipe spacing, concrete flow distance, and plant production rate. The calculations in the example below represent the considerations which should be included in a pre-placement evaluation.

1. Situation. A tremie-placed seal which is to be 60 x 150 ft (18.3 x 45.7 m) in plan and 42 ft (12.8 m) thick. Total volume required is 14,000 yd^3 (10,700 m^3). Concrete production capacity is 150 yd^3/hr (115 m^3/hr) leading to an anticipated placement duration of 94 hrs.

2. Tremie locations and spacing. Both fixed pipe locations and advancing slope techniques are to be considered. Figure 101 shows the geometry and notation involved.

a. Fixed locations. All tremies will be started simultaneously and will remain in their original locations for the duration of the placement.

b. Advancing slope. Tremies at one end of the placement will be started initially. Additional tremies will be started once a predetermined embedment depth is reached. This approach requires calculation of longitudinal flow distance when each new tremie is started as is shown in Figure 102.

Data showing concrete flow distances for various numbers of tremies in the two placement methods are given in Table 27. This data may be evaluated by selecting the single row of tremies in the fixed locations as a base against which the other cases may be compared. This comparison is shown in Table 28.

The use of a single row of tremies started simultaneously appears to offer favorable maximum flow distances with a minimun number of tremies. However, it must be remembered that the apparent maximum for the sloping front technique exists only until the next row of tremies is started. Then, the maximum flow reverts to the diagonal distance for the number of tremies involved.

Additionally, the problem of laitance accumulation should be considered. Placements involving simulataneous starting of tremies offer the potential for laitance accumulation at all intersecting faces of concrete. The advancing slope technique forces laitance toward the end wall where it may be collected and removed.

3. Volume considerations. Assume that the advancing slope technique with five pairs of tremies is selected. Using the geometry shown earlier in Figure 102, the volume of concrete in place when each new row of tremies is started, the time when each row is started, and the rate of rise of the concrete may be calculated. These values are shown in Table 29.

4. Summary. These calculations offer a rough approximation of an actual tremie placement. While reasonable flow distances have been achieved, the practical problem of delivering concrete to ten tremies has been raised. Also, once all ten tremies are in use, the rate of rise becomes slow enough that there is a danger of the concrete setting around the tremie if embedment depths are not closely monitored.

The solution to these problems appears to have three parts:

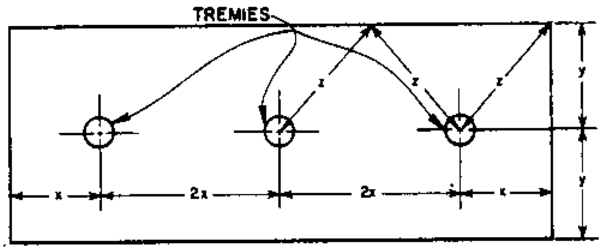
- tolerate greater flow distances.
- use a retarder in the concrete to allow for a slower rate of rise.
- examine the possibility of adding additional concrete production capacity.

6.4. Summary. The following items summarize this portion of the project:

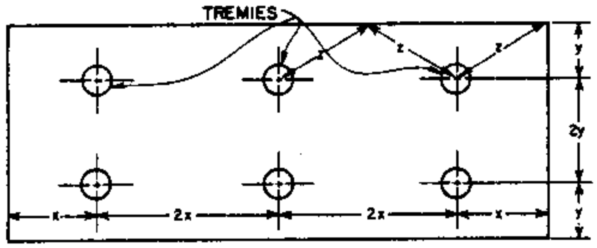
1. The recommendations found in the literature for pipe spacing and rate of concrete placement appear to be very conservative and difficult to achieve in actual massive placements.

2. The flow models, based on viscous flow theory, which were examined do not appear to offer potential for determining optimum pipe spacing and required production rates. The models do provide a starting point for examining the variables involved using a simplified approach.

3. An example of simplified calculations examining tremie spacing and concrete production rates for a typical seal was presented. Such calculations offer a good approximation of actual placement conditions with enough accuracy for pre-construction planning.

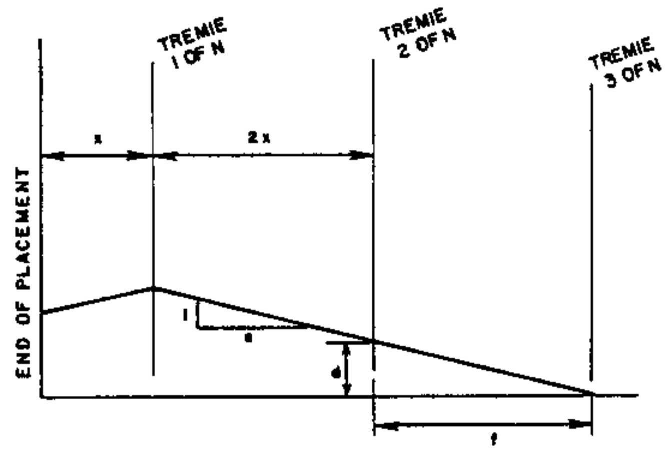


a. GEOMETRY FOR SINGLE ROW OF TREMIES (PLAN). THREE TREMIES SHOWN.



b. GEOMETRY FOR DOUBLE ROW OF TREMIES (PLAN). TWO ROWS OF THREE TREMIES SHOWN.

Figure 101. Geometry and notation for example spacing calculations. Notation remains the same as additional tremies are added.



d = DEPTH OF EMBEDMENT REQUIRED TO START NEXT TREMIE

f = CONCRETE FLOW DISTANCE BEYOND PIPE WHEN d IS ACHIEVED

s = HORIZONTAL COMPONENT OF SLOPE

f = ds

Figure 102. Geometry and notation of advancing slope technique (elevation). Concrete will flow 2x + f when each tremie after the first is started.

TABLE 27 - CALCULATED FLOW DISTANCES*

Case I - Single Row of Tremies Started Simultaneously

No. of Tremies	Flow distances, ft (m) x	y	z
1	75.0 (22.9)	30.0 (9.1) (all)	80.8 (24.6)
2	37.5 (11.4)		48.0 (14.6)
3	25.0 (7.6)		39.1 (11.9)
4	18.8 (5.7)		35.4 (10.8)
5	15.0 (4.6)		33.5 (10.2)
6	12.5 (3.8)		32.5 (9.9)

Case II - Double Row of Tremies Started Simultaneously

No. of Tremies	Flow distances, ft (m) x	y	z
2	75.0 (22.9)	15 (4.6) (all)	76.5 (23.3)
4	37.5 (11.4)		40.4 (12.3)
6	25.0 (7.6)		29.2 (8.9)
8	18.8 (5.7)		24.1 (7.3)
10	15.0 (4.6)		21.2 (6.5)
12	12.5 (3.8)		19.5 (5.9)

Case III - Single Row of Tremies, Advancing Slope Technique

Slope of concrete = 1:6
Depth when next tremie is started = 2 ft (0.6 m)

No. of Tremies	Flow distances, ft (m) z	2x + f
2	48.0 (14.6)	87.0 (26.5)
3	39.1 (11.9)	62.0 (18.9)
4	35.4 (10.8)	49.6 (15.1)
5	33.5 (10.2)	42.0 (12.8)
6	32.5 (9.9)	37.0 (11.3)

Case IV - Double Row of Tremies, Advancing Slope Technique

Same constraints as Case III

No. of Tremies	Flow distances, ft (m) z	2x + f
4	40.4 (12.3)	87.0 (26.5)
6	29.2 (8.9)	62.0 (18.9)
8	24.1 (7.3)	49.6 (15.1)
10	21.2 (6.5)	42.0 (12.8)
12	19.5 (5.9)	37.0 (11.3)

---

*See Figures 101 and 102 for notation used.

TABLE 28 - COMPARISON OF PLACEMENT ALTERNATIVES

Case I		Needed to Better Case I							
		Case II		Case III			Case IV		
No. of Trem-ies	Maximum flow ft (m)	No. of Trem-ies	Maximum flow ft (m)	No. of Trem-ies	Maximum flow ft (m)	Nominal flow* ft (m)	No. of Trem-ies	Maximum flow ft (m)	Nominal flow* ft (m)
2	48.0 (14.6)	4	40.4 (12.3)	5	42.0 (12.8)	33.5 (10.2)	10	42.0 (12.8)	21.2 (6.5)
3	39.1 (11.9)	6	29.2 (8.9)	6	37.0 (11.3)	32.5 (9.9)	12	37.0 (11.3)	19.5 (5.9)
4	35.4 (10.8)	6	29.2 (8.9)	>6			>12		

*Nominal flow = maximum flow distance once next row of tremies is started.

TABLE 29 - ESTIMATED PLACEMENT CONDITIONS*

Time, Hours		Tremies in Use	Concrete Placed, Yd^3 (m^3)	Rate of Rise at Tremies, ft/hour/(m/hour)
From	To			
0.0	3.5	2	518 (396)	2.0 (0.6)
3.5	8.8	4	1,318 (1,008)	0.9 (0.3)
8.8	16.3	6	2,452 (1,875)	0.7 (0.2)
16.3	26.1	8	3,918 (2,996)	0.5 (0.2)
26.1	-	10	-- --	0.45** (0.1)

*Values derived from geometry previously shown. Assumptions:

- Concrete is level across short dimension of seal;
- slope in long dimension is 1:6;
- production rate is 150 yd^3/hour (115 m^3/hour);
- production is evenly distributed among tremies in use.

**Theoretical rate of rise based on production capability and size of seal.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Specific conclusions. The conclusions presented in this section relate to the stated objectives in the six areas of this investigation. These conclusions are presented in the same topic sequence as are the chapters of this report.

1. For the concrete characteristics evaluated using a series of standard and non-standard tests, a traditional tremie concrete mixture was significantly outperformed. Concrete mixtures containing pozzolanic replacements of significant amounts of the cement (up to 50 percent) or containing entrained air were the best overall performers.

2. Development and selection of a concrete mixture for placement by tremie should be based upon more information than is available from the standard slump test. Three of the non-standard tests evaluated, the tremie flow test and the two segregation susceptibility tests, appear to have potential for further use in evaluating tremie concrete mixtures. Finally, the slump loss test, conducted using the standard slump test, should be included in the testing program.

3. Additives which lead to thixotropic concretes appear to offer no advantages for use in massive tremie placements. Such concretes have poor flow characteristics, are extremely difficult to restart flowing after a break, and offer problems of manufacture and control during field use. Thixotropic additives may be of benefit in other types of underwater placements such as very small volume or thin sections or in placements subjected to flowing water.

4. The flow pattern of tremie-placed concrete is extremely complex -- much more so than is normally described in the literature. The flow pattern as seen in these tests does not appear to be that of a simple injection into a mass of previously placed concrete. Instead, the process appears to be as follows: Concrete leaving the tremie forms a bulb around the mouth of the pipe. The size and nature of this bulb appear to depend upon the nature and consistency of the concrete mixture. For concretes with low shear resistance, the bulb simply expands and forces previously placed concrete radially away from the tremie pipe. For a concrete mixture which is stiffer, the bulb tends to be quite constricted. In this case, initial flow takes place vertically adjacent to the tremie pipe. After flowing upward, this concrete then flows outward over the concrete placed earlier rather than pushing it away from the tremie pipe. In both modes of flow the resultant concrete can be of high quality and homogeneity.

It appears that the differing descriptions of tremie concrete flow presented by other researchers (see Chapter 2) may have resulted from differences in the concrete mixtures tested rather than from observations of different flow mechanisms. As far as is known, the role that the concrete mixture plays in the flow pattern of tremie-placed concrete has not been reported previously.

5. The configuration of the surface of tremie-placed concrete appears to be a function of the type of flow which occurred when the concrete was placed. For the first type of flow described (expanded bulb), surfaces were very flat and there was essentially no mounding at the tremie location. For the second type of flow (upward and over), surfaces were much rougher and a significant mound developed at the tremie location.

6. The density of tremie-placed concrete decreased with distance from the tremie pipe. Although these decreases were very small for the resultant sound portions of concrete, significant reductions were observed when laitance was included in the calculations. This reduction in unit weight could have serious consequences in a seal placement in which the weight of the concrete is necessary to offset uplift forces. Therefore, a conservative approach in evaluating required seal thickness is indicated.

7. The observations of the colloidal layer at the beginning of the placements reemphasize the requirement for care in starting, handling, and restarting concrete flow through tremie pipes. In particular, when a tremie pipe is moved, care should be taken to restart concrete flow slowly in order to minimize formation of such a layer and the subsequent washing of the concrete already in place.

8. Reinforcing steel was securely embedded by tremie-placed concrete in the laboratory tests. However, as has been shown, even the presence of well-spaced bars will impede the concrete flow to some extent. These tests have reemphasized the need for care in detailing reinforcing steel for tremie concrete placements to insure adequate clear space for flow between bars.

The possibility of embedment of the reinforcing steel in laitance rather than concrete (as occurred in Tests 1 and 2) must be kept in mind. Positive measures must be taken to insure that sound concrete reaches and surrounds the steel, particularly if bars are near the extremities of the concrete flow pattern.

9. Even in carefully controlled laboratory placements, varying amounts of laitance were formed. Planning for the removal of this laitance during placement is a necessity, particularly for reinforced tremie concrete structural elements. Monitoring of concrete surface elevations during placement should be done to identify any low areas in which laitance may be trapped. Suitable equipment (air lifts or

pumps) must be available for use in any low areas that may develop during a placement.

10. The presence of substantial amounts of pozzolan (up to 50 percent by weight) in the concrete placed by tremie in the large scale laboratory tests seemed to have no detrimental effects on the nature of the product of the placement. The use of substantial proportions of pozzolan offers potential economy and reduction in thermal strains, but may require a longer curing period in order to gain adequate strength.

11. The presence of a water reducing and retarding admixture had a significant beneficial effect on the tremie-placed concrete -- surface slopes were flatter, the mound at the tremie location was eliminated, and laitance was reduced. This effect is believed to be due to a reduction in the shear resistance in the fresh concrete which allowed a more favorable flow pattern to develop. This beneficial effect was not seen with all types of water reducing and retarding admixtures which were tested.

12. The work on Pier 12 of the I-205 Bridge showed that temperatures within the general mass of the tremie concrete may be evaluated with reasonable accuracy using a simple iterative method. However, this method is subject to serious limitations in providing temperature predictions for concrete at and near the outside surfaces of the placement.

13. The temperatures measured in the critical outside areas of the Pier 12 seal showed that steep thermal gradients develop. Since precise information on the early age characteristics of the concrete was not obtained, it is not possible to state with certainty that thermally-induced cracking did occur. However, the temperature gradients observed were within the range of values which could cause such cracking.

14. Acceptable quality concrete was found at the extremes of the seal of Pier 12 after flowing approximately 70 ft (21 m). This flow distance is much greater than that normally recommended in the existing literature for tremie-placed concrete.

15. An area in the seal concrete was seen to have abnormally low temperature development during the placement. This area was later found to contain poorly cemented and uncemented materials. This same area appeared as an anomaly in the placement cross sections developed by soundings (although not striking enough to cause concern during the placement). This indicates that temperature and sounding data can be used as indicators of locations of possible anomalies and thus suggest locations for coring in order to verify quality of tremie concrete.

16. Water flow was seen in core holes which did not penetrate the full thickness of the seal. This flow is believed to have been due to a combination of thin seams of laitance and thermally-induced cracks in the concrete.

17. The concrete placed for the Pier 12 seal contained a fly ash replacement in order to reduce temperatures. This concrete performed well and no problems were attributed to the presence of the fly ash.

18. The mounds seen on the surface of the seal were very similar to those seen in the laboratory placements. The same flow mechanism may have been responsible for both cases of mounding. The sounding data do not provide sufficient information to determine the precise flow mechanism which occurred during the Pier 12 seal placement.

19. The examination of the Wolf Creek placement revealed generally high quality concrete. Some minor nonhomogeneities and laitance were found in the primary elements. There appears to be no procedural step which could be easily changed and which would clear up the scattered problems found in these primary elements. The concrete was apparently segregating while flowing down the tremie pipe itself. Due to a combination of several factors (listed below), there was not adequate remixing to overcome the initial segregation. The factors believed to have been responsible are:

a. The small cross-sectional area of the primary elements;

b. The smooth walls of the primary elements;

c. The rapid rate of placement in the primary elements.

20. Measurements taken inside and outside the tremie pipe at Wolf Creek indicated that the placement system was nearly at balance whenever the placement was stopped, with the exception of a few anomalies. The significance of these anomalies is not understood. The return of the tremie system to a hydrostatically balanced state indicates that earlier concepts recommending the control of flow by means of pipe embedment depth may not be correct or may require embedment lengths too great to be practical, particularly for small volume placements.

21. With the exception of the few scattered anomalies found in the primary elements, high quality concrete was successfully placed by tremie at Wolf Creek in very deep (278 ft (85 m)) confined elements. Given adequate conditions to allow remixing and a properly designed concrete mixture, there is no reason to believe that tremie placement depths could not be extended.

22. There is no reason to expect that the Wolf Creek cutoff wall should not perform in a satisfactory manner since the primary elements were encased in permanent steel pipes. However, the use of very small diameter, uncased elements for cutoff walls, as used in some previous dam rehabilitation and improvement projects, does not appear to insure a complete cutoff.

23. The concrete mixture (which contained a fly ash replacement of a portion of the cement) used at Wolf Creek was cohesive and flowed well. The inclusion of fly ash in this tremie concrete mixture had no apparent detrimental effects.

24. An accurate prediction of temperatures within a tremie seal (including areas near the concrete surfaces) can be obtained using a finite-element approach. The program which was developed allows the significant variables in a tremie placement to be changed easily for input to an existing finite-element program. Use of this technique will allow for more accurate and complete evaluation of thermal considerations for massive underwater placements than has been the case to date.

25. The flow models which were examined were derived from viscous flow theory. Their usefulness for direct predictions concerning tremie pipe spacing and placement rates appears to be very limited. However, the models do provide a good starting point for an analysis of these variables.

26. Simple calculations which consider the variables involved in a tremie placement appear to offer an acceptably accurate evaluation for construction purposes. Such calculations are easily performed and will highlight areas which should be more closely examined -- excessive flow distances or low placement rates. Once such areas have been identified, they must be resolved to the satisfaction of all parties involved in the placement.

27. In most cases, the critical factor in a massive tremie placement will be the concrete production capacity available. Use of a properly proportioned concrete mixture will do as much as any other factor to offset production limitations.

7.2. General conclusions. The following conclusions are of a more general nature or were developed from the interrelationships of the various portions of this project:

1. Testing done during this project indicates that the flowability characteristics of the concrete are extremely important. These characteristics determine the nature of the flow pattern which the concrete exhibits after leaving the tremie pipe which in turn determines the surface characteristics of the concrete placement.

2. Measurements taken inside and outside the tremie pipe during placements have revealed that concrete being placed by tremie does not flow gently down the pipe. Instead, it may fall significant distances inside the pipe resulting in segregation. This segregation is generally overcome provided there is adequate space and roughness within the placement area to allow remixing to occur. Care is recommended for any placement in which there may be factors which could inhibit this necessary remixing.

3. The development of high temperatures from hydration of cement within concrete placed by tremie must be taken into account as would be done for any other mass concrete placement. Due to the typically rich concrete mixtures used and the inaccessible placement locations, temperature problems are potentially more serious for a tremie placement than for other mass placements. Adequate techniques are available to predict temperature distributions within tremie-placed concrete.

4. The three items mentioned above lead to an increased understanding of the required characteristics for a concrete mixture which will be used in a massive tremie placement. The concrete must resist segregation during what may be a significant fall in the tremie pipe; it must flow readily to provide for adequate remixing and to provide a flat surface; and it must not generate excessive amounts of heat. A fourth requirement, the ability to resist washing out of cement from the concrete may not be as significant as is traditionally believed, particularly if the concrete is designed to develop the expanding bulb type of flow pattern. Additionally, a concrete which resists segregation will inherently resist loss of cement.

5. Unfortunately, with the exception of the heat generation requirement, measurement of these desired concrete characteristics cannot be made using standardized procedures. It is clear that the slump test must be supplemented by nonstandard tests during mixture development. As a final step, large-scale placements similar to those in Chapter 2 (but not necessarily as complex) are recommended prior to actual use of a concrete mixture. Once the mixture has been developed and verified, the standard tests should be adequate for production control.

6. A "good" tremie concrete has traditionally been characterized as being cohesive yet possessing good flow characteristics. (Unfortunately, neither of these qualities are readily measurable) These characteristics are usually achieved by means of a high cement content, high percentage of fine aggregate, and a low water-cement ratio. Both the small- and large-scale tests showed that the traditional tremie concrete mixture can be improved upon. These improvements include replacement of a portion of the cement with a natural pozzolan or fly ash, use of entrained air, and use of a water reducing and retarding admixture. Concrete mixtures which followed the traditional "recipe" but which in addition possessed increased flowability due to the addition of a water reducing and retarding admixture performed better in the large-scale laboratory test placements. This confirms reports from field placements conducted over a number of years. However, note that improvements in flowability were not seen with all types of water reducing and retarding admixtures which were tested.

7. The significance of possible thermally-induced cracking in tremie-placed concrete is a function

of the role of the concrete. In a massive cofferdam seal, limited cracking may be acceptable and extensive precautions may not be necessary. For a reinforced structural tremie placement, the possibility of thermally-induced cracking may require additional temperature control measures. The degree of restraint must also be considered when evaluating the potential for cracking. Tremie placements may range from essentially unrestrained conditions such as in a seal on a soft foundation, to highly restrained conditions if the tremie concrete is placed on rock or on previously placed concrete. If deemed necessary, the techniques for controlling temperature development in mass concrete placed above water as described by Carlson, Houghton, and Polivka (ref. 34) may be applied, with some exceptions, to tremie-placed concrete.

8. Of the available techniques for controlling temperatures within mass concrete, perhaps the most readily adaptable to tremie concrete is the replacement of a portion of the cement with a pozzolanic material. None of the field placements covered by this report showed any detrimental effects due to a concrete containing a pozzolan being placed by tremie. Additionally, concrete mixtures containing pozzolan replacements were among the outstanding performers in the small- and large-scale laboratory tests.

9. Recommendations from the literature on pipe spacing and placement rates appear to be very conservative and extremely difficult to achieve in massive placements. In the placement of Pier 12 (and others) concrete was allowed to flow much greater distances and was placed much more slowly than is normally recommended. This concrete turned out to be of very high quality. Longer flow distances and slower placement rates should be allowed in specifications for massive tremie placements.

10. Very accurate temperature predictions were achieved using simple models of concrete flow. It is doubtful that significant improvements in temperature predictions could be achieved by developing and using a more complex flow model.

11. Existing recommendations concerning controlling the flow of concrete through a tremie by raising and lowering the tremie may be misleading. The concrete in the tremie will generally come to rest at or near the hydrostatically balanced condition. In most instances with a normal embedment depth (3 to 5 ft (1.0 to 1.5 m), it will not be possible to keep the tremie hopper full as is often recommended. To keep the tremie hopper full, pipe embedment would have to be deep enough to extend into concrete which is stiffening. In such a case the expanding bulb type of flow may be prevented from occurring. Thus for deep placements, it will usually be necessary to accept a concrete level somewhere in the tremie pipe below the hopper and to realize the potential for segregation which will exist. (Although in most cases, adequate remixing will take place in the pipe or after exit from the pipe).

12. No definitive relationship between pipe embedment depth and flatness of the concrete surface was found. The work done in the large-scale tests suggests that very flat surfaces can be achieved if the proper concrete mixture is used. Proper embedment may be more important for maintaining the tremie seal than for surface slope control.

13. Tremie concrete was successfully placed in a massive seal (9700 yd^3 (7400 m^3) and in deep confined elements (278 ft (85 m)) during the projects observed while preparing this report. At first glance it may seem that the mechanisms and phenomena identified herein may only serve to add additional restraints and complexity to an already complex process. However, it is the hope of the authors that the identification and examination of these areas will serve to insure greater reliability in future applications of underwater concrete placement technology.

14. The work done in this research project has shown that high quality concrete, structural and nonstructural, can be placed under water by tremie methods. This work is believed to make a significant contribution to improve practice and results.

7.3. Recommended practice. Following is a recommended practice for massive tremie placements. This recommended practice is intended to serve as a planning tool and to amplify the items included in the Guide Specification presented in section 7.4.

These recommendations are based on the research presented in this report, other research conducted by the authors, and upon the experience of the authors on a variety of placements.

1. Applicability. This recommended practice is applicable to all massive tremie concrete placements - structural or nonstructural (reinforced or nonreinforced). Typical placements would include cofferdam seals, filling of precast concrete elements or steel forms for bridge piers, or elements of offshore structures.

These recommendations are also generally applicable to other types of tremie concrete placements such as small volume placements, thin overlay placements, and deep confined placements. However, the special requirements of these nonmass placements must be considered in conjunction with these recommendations.

2. Basic concepts. These recommendations are based on the following:

a. The concrete is placed under water using gravity flow through a tremie pipe.

b. Appropriate steps must be taken to insure that the first concrete introduced into the tremie is protected from the water until a mound of concrete has built up at the mouth of the tremie and a seal is established.

c. The mouth of the tremie pipe must be kept embedded within the mass of fresh concrete. At no time should concrete be allowed to fall directly through water.

d. The tremie pipe must remain in a fixed position horizontally at all times while concrete is flowing. Horizontal distribution of the concrete is accomplished by the flow of the concrete after exiting the tremie; by halting placement, moving the tremie, reestablishing the seal, and resuming placement; or, by the use of multiple tremies.

3. Concrete materials and mixture design.

a. General materials requirements. The precautions normally applied to concrete materials should also be applied for materials intended for use in tremie-placed concrete. Cement and pozzolans must meet appropriate specifications. Aggregates must be clean, sound, free of deleterious materials, and evaluated for potential harmful chemical reactions. Mixing water must be clean and free of potentially harmful materials. Admixtures must meet appropriate specifications. All materials should be tested to insure compatibility.

b. Cement and pozzolans. Selection of the appropriate type of cement and determination of the suitability of including pozzolans must be based upon evaluation of service conditions, available aggregates, heat generation, and availabilities of various types of cements and pozzolans. The acceptability of a particular pozzolan (increased workability, changes in water demand, rate of strength gain) should be verified before final selection.

c. Aggregates. Well rounded natural aggregates are preferred due to the increased flowability of concretes containing these aggregates. If manufactured aggregates are used, the fine aggregate and cementitious materials contents may have to be increased to achieve satisfactory flowability. Aggregates should be well graded. Maximum size for aggregates used in reinforced placements should be 3/4 in. (19.0 mm) and in nonreinforced placements should be 1 1/2 in. (38.1 mm). Fine aggregate content should be 42 to 50% of the total aggregate weight.

d. Desired characteristics. Concrete for tremie placements must be cohesive and resist segregation as well as flow readily. Nonstandard tests are available which allow evaluation of these characteristics for comparison of concrete mixtures. Tremie concrete should not be proportioned on the basis of strength and/or slump alone.

e. Basic mixture proportions. A starter mixture, developed to include these characteristics found to be beneficial in the present report, is as follows:

Cement: 600 lb/yd^3 (356 kg/m^3)
Pozzolan: (15% by weight of cementitious materials) 105 lb/yd^3(62 kg/m^3)
Coarse Aggregate: 3/4 in. (19.0 mm)
Fine Aggregate: 45% by weight of total aggregate content
Air Content: 5 percent ± 1 percent
Maximum water-cementitious material ratio: 0.45
Admixtures: Water reducer and retarder
Slump: 6 to 7 1/2 in. (15 to 19 cm)

f. Modifications to the basic mixture. The basic mixture may be modified as necessary depending upon materials availability, service conditions, temperature considerations, etc. Modifications should be made with an aim of retaining the flow and cohesiveness of the basic mixture.

g. Testing. The proposed concrete mixtures should be tested using standard ASTM tests for bleeding, time of set, air content, unit weight, slump loss, compressive strength and yield to insure compatibility of components and suitability of the concrete for its intended purpose.

h. Final selection. Final selection of a concrete mixture should be based upon test placements made under water in a placement device similar to that described in Chapter 2 of this report or in a pit which can be dewatered after the placement. Test placements should be examined for concrete surface flatness, amount of laitance present, quality of concrete at the extreme flow distance of the test, and flow around embedded items, if appropriate.

4. Temperature considerations.

a. The potential temperature increase should be evaluated using a simple interative or a finite-element technique. Anticipated thermal gradients should also be considered.

b. Based upon predicted concrete temperatures and gradients and the nature of the concrete placement, a determination of the seriousness of the predictions may be made. Limited cracking may be acceptable in a nonstructural placement while the same degree of cracking may be unacceptable in a structural element.

c. Maximum temperatures and gradients may be reduced by employing the following steps:

- Use a lower heat cement.

- Replace increased amounts of cement with a suitable pozzolan.

- Lower the concrete placement temperature.

5. Concrete manufacture.

a. Materials handling. The same requirements for materials storage and handling used for ingredients for concrete to be placed in the dry must be imposed for concretes placed under water.

b. Batching and mixing. The same requirements for accuracy in batching concrete ingredients used for concrete placed in the dry must be used for concrete placed under water. Control of the amounts of concrete ingredients is one of the most important inspection items available for underwater placements. The same requirements for concrete mixer performance used for placements in the dry must also be applied for placements under water.

c. Testing during production. Once a concrete mixture has been approved, slump, air content, unit weight, and compressive strength testing should be adequate for production control. Because of the significance of the flowability of the concrete to the success of the placement, slump and air content tests should be performed more frequently than is done for concrete placed in the dry. A minimum testing schedule would be:

- Slump: every 250 yd^3 (190 m^3)
- Air content: same as slump
- Unit weight: every 500 yd^3 (380 m^3)
- Compressive strength: 6 cylinders for every 1000 yd^3 (765 m^3)
- Temperature: Whenever other testing is done

Compressive strength testing should be accomplished at 7 and 28 days. Seven day strengths may be used as a basis for determining when the concrete has gained enough strength to allow dewatering the structure.

d. Sampling during production. The location for sampling during production and placement will depend upon the elapsed time between production and arrival at the tremie hopper. For example, in the placement described in Chapter 3 a portion of the concrete was produced in a floating plant at the site. Sampling at the mixer was essentially the same as sampling at the tremie hopper. The remainder of the concrete was produced off site and was trucked and pumped to the tremies. For that concrete, sampling at the tremie hopper would be more appropriate. In any case, the objective is to insure that concrete with the proper characteristics is arriving at the tremies.

e. Slump and air content loss. Tests to determine the slump and air loss characteristics of the selected mixture should be performed using the type of equipment which will be used to transport the concrete from the point of manufacture to the tremies. Based on this testing, limits may be established on the length of time between mixing and arrival at the tremie or on the number of revolutions of the transit mixer drum, if appropriate. Specification provisions limiting elapsed time or drum revolutions must complement any provisions for testing at the tremie hopper, if included In cases of conflict, concrete performance provisions rather than time or revolutions should prevail. A summary of recommended testing would be as follows:

(1) Mix at site - Test at mixer

(2) Mix off site - Deliver within specified time or revolutions - and - Test at tremie

f. Concrete temperature. The maximum allowable concrete temperature should be established based upon anticipated thermal conditions within the placement. Depending upon the volume of the placement, maximum temperatures in the range of 60° to 90°F (16° to 32° C) have been specified.

A Minimum concrete temperature of 40°F (15° C) should be imposed. Normally, freezing of concrete placed under water will not be a problem. However, the flowability of concrete at lower temperatures may be reduced. Because of the potential for erratic slump loss behavior, extreme care should be used in heating water or aggregates to raise concrete temperatures.

6. Placement equipment.

a. The tremie should be fabricated of heavy guage steel pipe. The pipe and all connections must be strong enough to withstand all anticipated handling stresses.

b. The tremie should have a diameter large enough to insure that aggregate caused blockages will not occur. Pipes in the range of 8 to 12 in. diameter (20 to 30 cm) are adequate for the range of aggregates recommended.

c. For deep placements the tremie should be fabricated in sections such that the upper sections can be removed as the placement progresses. Sections may be joined by flanged, bolted connections (with gaskets) or may be screwed together. Whatever joint technique is selected, joints between tremie sections must be water-tight. The joint system selected should be tested for watertightness before beginning placement. (Flanged connections are included in the Guide Specification.)

d. The tremie pipe should be marked to allow quick determination of the distance from the surface of the water to the mouth of the tremie.

e. The tremie should be provided with a funnel or hopper to facilitate transfer of concrete from the delivery device to the tremie.

f. A stable platform should be provided to support the tremie during the placement. Floating platforms are generally not suitable. The platform should be capable of supporting the tremie while sections are being removed from the upper end of the tremie.

g. A suitable power hoist should be on the tremie support platform to facilitate vertical movement of the tremie during the placement. Use of a crane to provide this vertical adjustment is not recommended.

h. A crane should be available to lift the entire tremie pipe in case the tremie must be moved or lifted out of the water to be resealed.

i. Depending upon the method selected for sealing the tremie at the beginning of the placement (see paragraph 8), an adequate supply of end closure devices or go-devils should be available.

j. Airlifts or pumps must be available to remove laitance and other unsuitable material which accumulates in low areas during the placement.

7. Preplacement planning.

a. Planning for the tremie placement must begin as soon as the decision to use tremie-placed concrete is made, not just prior to the beginning of actual placements. Items with a long lead time in the tremie process include:

- detailing reinforcing steel (if any) to minimize restrictions to flow.
- detailing of forms, particularly if precast elements are to be filled with tremie concrete, to eliminate abrupt changes in sections, openings, or areas in which laitance could accumulate or be trapped.
- consideration of overexcavating the placement area to preclude concrete removal if tremie-placed concrete is above design grade.
- consideration of incorporating members required to support the tremie platforms into the internal bracing scheme of a cofferdam, if appropriate.

b. The overall placement scheme should be developed considering the following items:

- Available concrete production capability.
- Availability and capacity of equipment for transferring concrete to the tremies.
- The total volume of concrete to be placed.
- The various placement schemes available - fixed tremie locations or an advancing slope.
- Any restrictions to flow such as reinforcing steel or piles which must be embedded in the concrete.
- Maximum flow distance of the concrete. Flows in the range of 30 to 70 ft (9 to 21 m) have produced concrete of excellent quality.

c. Consideration of the above items should result in the development of a placement plan which includes tremie pipe spacings and locations throughout the duration of the placement. The plan should also include the planned locations to be used for relocating tremies as the placement progresses.

d. The method of sealing the tremies at the beginning of the placement must be considered in detail. The most common techniques are:

- Initial dry pipe achieved by using a plate and gasket tied to the mouth of the tremie. This method is recommended for most placements (and is included in the Guide Specification.).
- Use of a go-devil to separate concrete and water. This method can be very disruptive to material beneath the mouth of the tremie as the go-devil forces water out of the tremie. Due to the possibility for washing concrete in place, this method should not be used to restart tremies. If inflatable balls are used as go-devils, consideration should be given to the depth at which the balls will collapse due to water pressure.
- Use of a double pipe for deep placements in which pipe bouyancy is a problem. This method involves use of a smaller diameter tremie within the main tremie to gain the initial seal.

e. An inspection plan detailing sounding locations and frequency of soundings should be developed. Soundings should be taken over the entire area of the placement on a regular basis, such as every hour or every 200 yd^3 (75 m^3). Locations for taking soundings should be marked on the structure to insure that all soundings are made at the same location. Additionally, soundings should be required on a more frequent basis adjacent to each tremie to monitor pipe embedment. Data obtained from soundings should be plotted immediately to monitor the progress of the placement.

f. A concrete sampling and testing plan, consistent with the agency's other concrete testing requirements and the recommendations above (paragraph 5c) should also be developed. This plan should detail all testing and corrective actions to be taken by the contractor to insure that concrete of the desired characteristics is delivered to the tremie.

g. A preplacement conference should be held in which all details of the placement are presented to the owner's engineer. Placement should not be allowed until the placement plan, concrete mixture, inspection plan, and concrete sampling plan are approved.

8. placement procedures.

a. All areas in which there is to be bond between steel, wood, or hardened concrete and fresh concrete should be thoroughly cleaned immediately prior to beginning concrete placement to remove mud, algae or other objectionable materials.

b. Tremies started using a dry pipe technique should be filled with concrete before being raised off of the bottom. The tremie should then be raised a maximum of 6 in. (15 cm) to initiate flow. These tremies should not be lifted further until a mound is established around the mouth of the tremie pipe. Initial lifting of the tremie should be done slowly to minimize disturbance of material surrounding the mouth of the tremie.

c. Tremies started using a go-devil should be lifted a maximum of 6 in. (15 cm) to allow water to escape. Concrete should be added to the tremie slowly to force the go-devil downward. Once the go-devil reaches the mouth of the tremie, the tremie should be lifted enough to allow the go-devil to escape. After that, a tremie should not be lifted again until a sufficient mound is established around the mouth of the tremie.

d. Concrete supply to a tremie at the beginning of a placement should be uninterrupted until a mound sufficient to seal the tremie has been established.

e. Tremies should be embedded in the fresh concrete from 3 to 5 ft (1.0 to 1.5 m). Exact embedment depths should depend upon placement rates and set times of the concrete.

f. Tremies shall not be moved horizontally while placing concrete.

g. All vertical movements of the tremie pipe must be done slowly and carefully to prevent loss of seal.

h. If loss of seal occurs in the tremie, placement through that tremie must be halted immediately. The tremie must be removed, the end plate must be replaced, and flow must be restarted as described above. To prevent washing of concrete in place, a go-devil should not be used to restart a tremie after loss of seal.

i. Concrete placement should be as continuous as possible through each tremie. Excessive breaks in placement may allow the concrete to stiffen and resist restarting of flow once placement resumes. Interruptions of placement of up to approximately 30 minutes should allow restarting without any special procedures. Interruptions of between 30 minutes and the initial set time of the concrete should be treated by removing, resealing, and restarting the tremie. Interruptions of a duration greater than the initial set time of the concrete should be treated as a construction joint as discussed below.

j. If a break in placement results in a planned (or unplanned) horizontal construction joint, the concrete surface should be "green-cut" after it sets. The concrete surface should be jetted immediately prior to resuming concrete placement.

k. The rate of placement should be as high as the production capacity allows. Representative rates of concrete rise range upward from 0.5 ft/hr (0.2 m/hr). These values should be calculated by dividing the entire placement area by the plant capacity, as was done in the example provided in Chapter 6.

l. The volume of concrete in place should be monitored throughout the placement. Underruns are indicative of loss of tremie seal since the washed and segregated aggregates will occupy a greater volume. Overruns are indicative of loss of concrete from the forms.

m. Tremies and airlifts should be relocated as governed by soundings and the placement plan. Tremies which are relocated should be resealed in accordance with the procedures given above.

n. Tremie blockages which occur during placement should be cleared extremely carefully to prevent loss of seal. If a blockage occurs, the tremie should be quickly raised (6 in. to 2 ft (15 to 61 cm)) and then lowered in an attempt to dislodge the blockage. The depth of pipe embedment must be closely monitored during all such attempts. If the blockage cannot be cleared readily, the tremie should be removed, cleared, resealed, and restarted.

o. Soundings should be taken as specified in the inspection plan.

p. Concrete samples should be tested in accordance with the concrete sampling plan.

9. Post-placement evaluation.

a. Coring should be conducted in areas of maximum concrete flow or in areas of suspect concrete quality.

b. After dewatering, the surface of the concrete should be accurately surveyed to evaluate the adequacy of the concrete mixture and the placement plan.

c. After removal of forms or sheet piling, the exterior surface of the concrete should be inspected by divers for evidence of cracking, voids, honeycomb, etc.

7.4 Guide specification. The following specification is based upon the recommended practice presented above. This specification is intended for massive placements such as for bridge piers or major offshore construction. The guide specification was prepared based upon the following assumptions:

1. The using agency has its own specifications covering concrete materials and manufacture.

2. This guide specification will be part of a larger project specification; it is not intended to stand alone.

3. The contractor will be responsible for quality control testing as specified by the owner.

4. The term "Contracting Officer" has been used to denote the owner's representative. This term should be replaced by "Resident Engineer" as appropriate.

Underwater Mass Concrete (Tremie Concrete)

1.1 General

1.1.1. Underwater mass concrete in bid item____ shall be placed by the tremie process.

1.1.2. The contractor shall conduct a preplacement conference to review all details of the concrete mixture proportions, tremie equipment, placement procedure plan, concrete sampling and testing plan, and inspection plan.

1.1.3. No underwater placements shall be made until all concrete materials, concrete mixture proportions, tremie equipment, placement procedure plan, concrete sampling and testing plan, and inspection plan are approved by the Contracting Officer.

1.2. Materials

1.2.1. All materials for underwater mass concrete shall meet the requirements for materials for concrete placed in the dry as specified in section _____ of these specifications. The following additional requirements shall also apply:

a. Cement shall be Type I or II meeting the requirements of ASTM C 150. (NOTE: The optional heat of hydration requirement of ASTM C 150 shall be invoked if calculations indicate thermal problems.)

b. Chemical admixtures governed by ASTM C 494 shall be tested in conjunction with the air-entraining admixture and cement proposed for use on the project to insure compatibility.

1.2.2. The following weights and volumes of proposed concrete materials shall be provided to the Contracting Officer for approval (and mixture proportioning) no later than ____ days prior to the beginning of placements.

Coarse Aggregate (NOTE: Specify required weights and volumes.)
Fine Aggregate
Cement
Pozzolan (if any)
Admixtures
Water

1.3. Concrete proportions

1.3.1. Concrete proportions shall be (provided by the contractor (provided by the Contracting Officer). The following mixture shall be used for bidding purposes:

Cement: 705 lb/yd^3 (356 kg/m^3), Type I or II.
Pozzolan: If required or permitted, replace up to 15% by weight of cement with an equal weight of pozzolan meeting the requirements of ASTM C 618, Class F or N.
Coarse Aggregate: 3/4 in. (19.0 mm) maximum for reinforced placements; 1 1/2 in. (38.1 mm) maximum for unreinforced placements.
Gravel aggregate (rounded) shall be used. (NOTE: If gravel is unavailable, suitable workability will normally require higher sand percentages up to 50% and additional cementitious material)
Fine Aggregate: 42-50 percent by weight of total aggregate.
Air Content: 5 percent ± 1 percent
Maximum Water-Cementitious Material Ratio: 0.45
Slump: 6 to 7 in. (15 to 19 cm)
Admixtures: Water Reducer and retarder.

1.3.2 Final approval of a concrete mixture developed by the contractor shall be based on concrete performance in a large-scale flow test in which a minimum of 10 yd^3 (8 m^3) shall be placed per test. Concrete for these tests shall be placed in a water-filled box or pit using the tremie equipment and procedure proposed for the project. The water temperature shall be close to that anticipated in the actual field placement.

1.4. Concrete Manufacture

1.4.1 All materials for concrete placed under water shall be stored in accordance with the requirements for materials for concrete placed in the dry as specified in section ____ of these specifications.

1.4.2. All batching, mixing, and transporting equipment for concrete placed under water shall meet the requirements for batching, mixing and transporting equipment for concrete placed in the dry as specified in section ____ of these specifications.

1.4.3. The method(s) of transporting concrete to be placed under water from the point of manufacture to the tremie hopper shall ensure delivery without segregation or excessive delay.

1.4.4. Concrete to be placed under water shall have a minimum temperature of 40°F (15°C) and a maximum temperature of ______°F. (NOTE: Maximum temperature should normally be between 60° to 90°F (16° to 32°C) and should be determined on the basis of anticipated thermal problems.

1.4.5. Concrete to be placed under water shall arrive at the tremie hopper (no later than _____ minutes after discharge from the mixer) (after no more than _____ revolutions of the transit mixer drum). (NOTE: These limits should be established by slump and air content loss testing.) (NOTE: The provisions of this section must agree with those of section 1.5.4.

1.5. Sampling and Testing Requirements

1.5.1. The contractor shall develop a concrete sampling and testing plan which shall include the testing shown in Table 1.1. This plan shall be submitted to the Contracting Officer _____ days prior to beginning placement.

1.5.2. The contractor shall be responsible for conducting all testing on the sampling and testing approved plan.

TABLE 1.1 MINIMUM TESTING REQUIREMENTS

Test	Standard	Frequency 1 Test for each:	At Mixer	At Tremie Hopper
Slump	ASTM C 143	250 yd^3 (190 m^3)	6-7.5 in. (15-19 cm)	6-7 in. (15-18 cm)
Air Content	ASTM C 231	250 yd^3 (190 m^3)	5 ± 1%	3 - 6%
Unit Weight	ASTM C 138	500 yd^3 (380 m^3)	*	*
Compressive Strength	ASTM C 31 ASTM C 39	6 cyls 1000 yd^3 (765 m^3)	3500 psi (24 Mpa)	3500 psi (24 Mpa)

* No requirement - report measured value.

1.5.3. Results of testing (except for compressive strength testing) shall be provided to the Contracting Officer at the end of each shift during which testing is conducted. Results of compressive strength testing shall be reported within 24 hours of testing.

1.5.4. Testing shall be accomplished using samples of concrete taken at (the point of discharge from the mixer) (the tremie hopper) (or both). (NOTE: Location of sampling should be based upon elapsed time between mixing and arrival at tremie hopper.) (NOTE: The provisions of this section must agree with those of section 1.4.5.).

1.5.5. Compressive strength tests shown in Table 1.1 shall be conducted using three 6- by 12-in. (15- by 30 cm) cylinders at 7 and 28 days.

1.5.6. Concrete temperature shall be measured and recorded whenever other testing is conducted.

1.6. Placement Equipment

1.6.1. The tremie pipe shall be of heavy guage (minimum 0.25 in. (6.4 mm) wall thickness) steel pipe with a minimum inside diameter of 10 in. (25 cm). The tremie shall be marked to allow determination of depth to the mouth of the tremie.

1.6.2. Joints between sections of tremie pipe shall be gasketed and bolted so as to be watertight under project placement conditions.

1.6.3. A hopper or funnel of at least 0.5 yd^3 (0.4 m^3) capacity shall be provided on top of the tremie pipe to facilitate transfer of concrete to the tremie.

1.6.4. A power hoist (which is capable of steady vertical control) shall be provided to accommodate vertical movements of the tremie. A stable platform shall be provided to support the tremie pipe, hopper, and hoist.

1.6.5. A supply of extra end plates and gaskets shall be maintained to allow resealing of tremies, if necessary.

1.6.6. A crane or other lifting device shall be available to completely remove the tremie from the water for the purpose of resealing or horizontal relocation.

1.7. Placement Procedure

1.7.1. The contractor shall develop a comprehensive placement procedure plan in accordance with the provisions of this specification. This plan shall be submitted to the Contracting Officer for approval at least _____ days prior to beginning placements.

1.7.2. All areas in which there is to be bond between steel, wood, or hardened concrete and fresh concrete placed under water, shall be thoroughly cleaned immediately prior to beginning placements. Cleaning shall be accomplished using high pressure air or water jetting. Airlifts or pumps shall be used to remove mud, silt, or sand from placement areas.

1.7.3. Placement of underwater mass concrete shall be as continuous an operation as possible. Placement shall continue uninterrupted until the entire placement is completed. Interruptions of placement through a single tremie shall not exceed 30 minutes without removal of the tremie and carrying out the restarting procedure.

1.7.4. The concrete placement rate shall be sufficient to produce a minimum vertical rise of concrete of 0.5 ft/hr (0.2 m/hr), calculated by dividing the entire placement area (ft^2) (m^2)) by the concrete production rate ((ft^3/hr) (m^3/hr)).

1.7.5. Tremie pipes shall be spaced to give a maximum concrete flow distance of 50 ft (15 m).

1.7.6. The placement shall begin with the tremie pipe sealed with a watertight plate. The empty tremie pipe shall be sufficiently heavy to be negatively bouyant when empty. "Rabbits" or "go-devils" shall not be used to start the tremie. The tremie shall be sealed, lowered to the bottom, and filled with concrete. The tremie shall then be lifted 6 in. (15 cm) to initiate concrete flow. Concrete supply shall be continuous until soundings indicate the required embedment is developed.

1.7.7. The mouth of the tremie shall remain embedded in the fresh concrete at all times unless the tremie is being completely removed from the water. At no time shall concrete be allowed to fall through water. Embedment shall be from 3 to 5 ft (1 to 1.5 m) at all times.

1.7.8 A tremie shall not be moved horizontally while concrete is flowing through it. To relocate a tremie, it shall be lifted from the water, resealed, relocated, and restarted in accordance with section 1.7.6.

1.7.9. All vertical movements of the tremie shall be carefully controlled to prevent loss of seal. If loss of seal occurs, placement through that tremie shall be halted immediately. The tremie shall be removed, resealed, replaced and restarted in accordance with section 1.7.6.

1.7.10. Tremies shall be relocated during the placement in accordance with the placement plan and as indicated by soundings.

1.7.11. If circumstances force a suspension in placement greater than the time of initial set (as determined by testing during mixture development), then the surface of the concrete shall be green-cut after the concrete has set. Placement shall not be resumed until the concrete surface has been prepared in accordance with section 1.7.2.

1.7.12. Airlifts or pumps shall be provided to remove laitance which accumulates during placement. Airlifts and pumps shall be relocated as indicated by soundings.

1.8 Inspection

1.8.1 The contractor shall develop an inspection plan covering locations and methods of taking soundings during the placement and post-placement inspection. Soundings shall be taken each hour during placement. Soundings shall be spaced so as to cover the area, plus corners and at the tremie pipe discharge. This plan shall be submitted approval by the Contracting Officer ______ days prior to beginning placements.

1.8.2. Data from soundings shall be furnished to the Contracting Officer at the end of each shift during which concrete is placed. Data from post-placement inspections shall be furnished no later than ______ days after the inspections are completed.

1.8.3. After the cofferdam is dewatered, a survey shall be made to establish final surface elevations of the concrete placed under water. Elevations shall be determined at each location for which soundings were required.

1.8.4. Cores shall be drilled and recovered as directed by the Contracting Officer. For bidding purposes, a minimum of _____ cores shall be drilled at locations of maximum horizontal concrete flow. Additional cores may be required at no expense to the owner at all locations in which tremie seal is lost.

1.8.5. After removal of (sheet piles) (external forms), the surface of the concrete placed under water shall be inspected by diver for evidence of cracking, voids, honeycomb, or other unsatisfactory concrete. A written report of this inspection shall be furnished within _____ days of completion of the inspection. Suitable repairs shall be made, by grout injection or underwater epoxy injection, as indicated and approved.

7.5. Recommendations for further work. Following are several areas in which the authors believe additional study would be beneficial:

1. Confined placements. Determine if the problems seen in the primary elements of Wolf Creek have occurred in other placements and if similar problems seen in filling piles and small diameter shafts with tremie concrete are related. Determine if there is a critical diameter or cross-sectional area below which successful placements are impracticable.

2. Hydrostatic balance. The anomalies in hydrostatic balance noted in the Wolf Creek placements need to be evaluated further in a program which includes measurements and coring. Do the anomalies represent areas of poor quality concrete? If so, measurements of concrete levels made during a placement could serve as an additional inspection tool.

3. Temperature monitoring system. An inexpensive system to monitor temperatures in a tremie placement and to compare measured and predicted temperatures needs to be developed. Such a system could alert field personnel to unexpected occurrences during a placement and present a starting point for post-placement verification coring.

4. Concrete density. Examine cores from several placements to determine the loss of density which may be expected for tremie-placed concrete as a function of flow distance from tremie pipe and depth of water in which placed.

5. Temperature predictions. The finite element approach to temperature prediction in tremie-placed mass concrete should be extended to determine the sensitivity of the predictions to the many variables involved.

6. Confined placements. Examine the feasibility of using a vibrator attached near the mouth of the tremie pipe for deep, confined placements and perhaps for all mass placements. Such a technique appears of interest but has not yet been tested nor proven and hence should not be used on prototype placements until testing has been carried out.

7. Temperature cracking. Examine the crack resistance of concrete which has set and cured under the thermal gradients known to exist near the extremes of a massive tremie placement.

8. Concrete flowability. The flowability of a concrete appeared to determine the flow pattern which was exhibited once the concrete left the tremie. There needs to be a test which can measure that flowability directly. Perhaps a variation of the vane shear test used in soils testing could be developed.

9. Thixotropic admixtures. Examine uses for thixotropic admixtures for concretes to be placed under water. A thixotropic concrete would be beneficial in applications in which only limited flow is desired after the concrete leaves the mouth of the tremie or is exposed to running water.

10. Mixture optimization. Develop more economical concrete mixtures for mass tremie placements. The work done in this project has defined the characteristics for successful placement. Can more economical mixtures be developed to match those characteristics?

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APPENDIX A: CONCRETE MIXTURE PROPORTIONS - MIXTURE EVALUATION TESTS

1. Mixture proportions for each of the 11 mixtures evaluated in the small-scale laboratory tests described in Chapter 1 are presented in Tables A-1 through A-11.

2. Data presented in this appendix are summarized in Table 2 of Chapter 1.

3. Only data for Mixture 1 (Table A-1) are presented in this volume. Data from remaining mixtures may be obtained from the authors.

4. The following conversion factors are required for the tables in this appendix:

1 lb (mass) = 0.4536 kg
1 lb (mass)/ft^3 = 16.02 kg/m^3
1 fl oz/lb = 65.2 ml/kg
1 yd^3 = 0.7646 m^3

TABLE A-1. PROPORTIONS-MIXTURE No. 1

DESCRIPTION: REFERENCE MIXTURE

BATCH WTS. AND VOLS., 1 YD^3, SSD.

ITEM	SPECIFIC GRAVITY	WEIGHT, LB	VOLUME, FT^3
CEMENT	3.15	705	3.59
POZZOLAN	—	—	—
COARSE AGG.	2.68	1661	9.93
FINE AGG.	2.68	1359	8.13
WATER	1.00	317	5.08
AIR, 1 %	NA	NA	0.27
TOTALS		4042	27.00

ESTIMATED UNIT WT, LB/FT^3: 149.7

WATER-CEMENT RATIO: 0.45

ADMIXTURES: WATER REDUCER/RETARDER,
2 FL OZ /94 LB CEMENT.

APPENDIX B: CONCRETE MATERIALS - MIXTURE EVALUATION TESTS

1. The components of the concretes evaluated during the small-scale tests described in Chapter 1 are described in the following paragraphs. As far as was possible, the same materials (i.e., same sources) were used for the large-scale placements described in Chapter 2.

2. Aggregates. Fine and coarse aggregates were purchased from Kaiser Sand and Gravel and were from that company's Pleasanton, California, quarry operation.

- Coarse aggregate: 3/4-in. (19-mm) nominal maximum size
    - Absorption: 1.0 percent
    - Specific gravity: 2.68
- Fine aggregate: Top sand
    - Absorption: 2.0 percent
    - Specific gravity: 2.68

3. Cement. Cement was purchased from the Kaiser Cement Company plant at Permanente, California. The cement was a Type II conforming to ASTM C 150.

4. Pozzolan. The pozzolan used was a natural material sold by Airox Earth Resources, Santa Maria, California. The material met the requirements of ASTM C 618, Class N. The specific gravity was 2.54.

5. Bentonite. The bentonite used was sold by the American Colloid Company and was marked with the trade name "Volclay 200." The specific gravity was 2.71.

6. Admixtures. Admixtures used were from laboratory stocks (with the exception of the thixotropic additive).

- Water reducer/retarder: Sika Plastiment.
- Air-entraining agent: Master Builders AE-10.
- Thixotropic additive: Sikathix manufactured by Sika Chemical Corporation.

7. Water. City water, Berkeley, California.

APPENDIX C: SUMMARIZED DATA - MIXTURE EVALUATION TESTS

1. Data for each of the three tests performed on the 11 concrete mixtures are presented in Tables C-1 through C-10. These data are summarized in Table 3, Chapter 1.

2. Each test for which data are presented in this appendix represents three batches of concrete, as is explained in Chapter 1. Detailed data on a batch-by-batch basis are presented in Appendix D.

3. Only data for Mixture 1 (Table C-1) are presented in this volume. Data from remaining tests may be obtained from the authors.

4. The following conversion factors are required for the tables in this appendix:

1 in. = 2.54 cm
1 lb (mass)/ft^3 = 16.02 kg/m^3
1 lb (force) = 4.448 N
1 lb (force)/in.^{2} = 0.006895 MPa
To convert deg F to deg C,
deg C = (deg F - 32)/1.8

TABLE C-1. DATA SUMMARY-MIX. 1

TEST ITEM		TEST 1	TEST 2	TEST 3	AVE
SLUMP, IN.		7.4	6.7	7.4	7.2
UNIT WT., lb/ft^3		149.9	150.9	151.0	150.6
AIR CONTENT, %		2.1	1.5	1.2	1.6
TEMP., °F		71	72	69	71
TREMIE FLOW, IN.		11.0	11.5	11.7	11.4
TIME OF SET, MIN.	INITIAL	366	375	408	383
	FINAL	480	470	542	497
BLEEDING, % OF AVAIL. WATER		2.6	2.0	2.5	2.4
COHESION INDEX		0.07	0.04	0.10	0.07
STABILITY FACTOR		0.79	0.78	0.79	0.79
TEMP.	INCREASE, °F	33	34	35	34
	TIME, HRS	18.2	18.6	20.2	19.0
COMP. STREN., lb/in.^{2}	7 DAYS	4070	4560	4350	4330
	28 DAYS	5960	6310	6140	6140
	90 DAYS	6910	7530	7460	7300
SPLITTING TENSILE STREN., lb/in.^{2} (28 DAYS)		785	655	790	745
SLUMP LOSS, % REMAINING OF ORIGINAL	T = 15 MIN	82	65	90	79
	= 30	79	57	66	78
	= 60	64	50	52	55
	= 90	61	43	45	50
	= 120	50	32	45	42

APPENDIX D: DETAILED DATA - MIXTURE EVALUATION TESTS

1. Detailed data for the tests performed on each batch of concrete of the 11 mixtures tested are presented in Tables D-1 through D-29. These data are summarized in Appendix C and in Table 3, Chapter 1.

2. Only data for Mixture 1, Test 1 (Table D-1), are presented in this volume. Data from remaining tests may be obtained from the authors.

3. The following conversion factors are required for the tables in this appendix:

1 in. = 2.54 cm
1 lb (mass)/ft^3 = 16.02 kg/m^3
1 lb (force) = 4.448 N
1 lb (force)/$in.^2$ = 0.006895 MPa
To convert deg F to deg C,
deg C = (deg F - 32)/1.8

TABLE D-1. CONCRETE TEST DATA

MIXTURE 1 TEST 1

1. GENERAL CHARACTERISTICS

BATCH	SLUMP, IN.	UNIT WT., lb/ft^3	% AIR	TEMP, °F
1	7	150.1	1.5	72
2	7 3/4	150.8	NA	71
3	7 1/2	148.8	2.6	71
AVE	7.4	149.9	2.1	71

2. TREMIE FLOW TEST, IN.

#1 10.0 #2 12.0 AVE 11.0

3. TIME OF SET, MIN.

INITIAL 366 FINAL 480

4. BLEEDING

ELAPSED TIME, MIN 162

VOLUME, ml 62 % WATER 2.6

5. COHESION INDEX

#1 0.06 #2 0.07 AVE 0.07

6. SEGREGATION FACTOR

#1 0.81 #2 0.77 AVE 0.79

TABLE D-1. (CONTINUED)

7. TEMPERATURE DEVELOPMENT

CYL	INITIAL, °F	MAX, °F	TIME TO MAX, HRS
1	72	106	17.3
2	71	104	19.0
AVE	72	105	18.2

8. COMPRESSIVE STRENGTH

CYL	7 DAYS		28 DAYS		90 DAYS	
	Lbs	Lb/in²	Lbs	Lb/in²	Lbs	Lb/in²
1	114,750	4060	166,000	5870	195,500	6900
2	115,000	4070	170,000	6010	194,500	6880
3	115,750	4090	169,750	6000	196,250	6940
AVE	—	4070	—	5960	—	6910

9. SPLITTING TENSILE STRENGTH (28 DAYS)

CYL	Lbs	Lb/in²
1	23,000	815
2	21,950	775
3	21,650	765
AVE	—	785

10. SLUMP LOSS

TIME, MIN	SLUMP, IN.	% OF TBD
0	7	100
15	5 3/4	82
30	5 1/2	79
60	4 1/2	64
90	4 1/4	61
120	3 1/2	50

APPENDIX E: SOUNDING DATA - LABORATORY PLACEMENT TESTS

1. As is described in Chapter 2, the tremie concrete placed in the large-scale laboratory placements was broken into three approximately equal segments. Soundings were taken at 20 locations over the surface of the placement box at the conclusion of placing each of the three segments of concrete. The sounding pattern used was shown in Figure 17, Chapter 2.

2. Soundings were taken using a weighted plate attached to a measuring tape. The plate was of sufficient area to prevent its sinking into the soft concrete.

3. The data was obtained as distance from a fixed reference point to the surface of the concrete under water. This data has been converted to thickness of concrete in place by subtracting test readings from those obtained at each point prior to each test. These reduced data for each test are presented in Tables E-1 through E-5.

4. Only data from Test 1 (Table E-1) are included in this volume. Data from remaining tests may be obtained from the authors.

TABLE E-1 . CONCRETE THICKNESS AS DETERMINED BY SOUNDINGS, TEST 1.

STATION	COLOR 1		COLOR 2		COLOR 3	
	IN.	CM	IN.	CM	IN.	CM
1	18.0	45.7	28.0	71.1	40.5	102.9
2	14.5	36.8	22.5	57.2	24.5	62.2
3	16.0	40.6	22.5	57.2	25.0	63.5
4	11.0	27.9	21.0	53.3	21.5	54.6
5	11.5	29.2	21.0	53.3	23.0	58.4
6	5.0	12.7	16.5	41.9	17.0	43.2
7	6.0	15.2	18.0	45.7	18.5	47.0
8	0.5	1.3	14.0	35.6	14.0	35.6
9	0.5	1.3	14.5	36.8	14.5	36.8
10	0.0	0.0	9.0	22.9	10.5	26.7
11	0.0	0.0	9.0	22.9	10.5	26.7
12	0.0	0.0	1.0	2.5	9.5	24.1
13	0.0	0.0	1.0	2.5	9.5	24.1
14	0.0	0.0	0.5	1.3	9.5	24.1
15	0.0	0.0	8.5	21.6	11.0	27.9
16	0.0	0.0	14.5	36.8	15.5	39.4
17	5.5	14.0	18.5	47.0	18.5	47.0
18	*	*	23.0	58.4	23.0	58.4
19	*	*	23.5	59.7	24.0	61.0
20	*	*	26.0	66.0	37.0	94.0

* NOT TAKEN

APPENDIX F: SURFACE PROFILE DATA - LABORATORY PLACEMENT TESTS

1. As is described in Chapter 2, the surface of each of the tremie concrete placements in the laboratory was mapped to establish surface profiles. Measurements were taken at five locations laterally (outside edges, 1 ft (30.5 cm) in from the outside edges, and centerline) and at every 1-ft (30.5 cm) interval along the long axis of the box.

2. Measurements were made down from a fixed plane to the surface of the concrete. The data presented in Tables F-1 through F-5 have been reduced to give actual concrete thickness.

3. Figure 14, Chapter 2, shows the left/right orientation of the placement box. The tremie was located at station 1.5 with flow toward station 20.

4. Only data from Test 1 (Table F-1) are included in this volume. Data from remaining tests may be obtained from the authors.

TABLE F-1. FINAL CONCRETE THICKNESS, INCHES, TEST 1. (1-IN. = 2.54 CM)

STATION	R. OUT	RIGHT	CENTER	LEFT	L. OUT
0	38.5	40.0	41.0	39.5	37.5
1	—	—	—	—	—
TREMIE	38.0	42.5	49.5	41.5	35.5
2	—	—	—	—	—
3	34.0	36.5	36.0	35.5	28.5
4	30.5	32.5	29.5	26.5	25.0
5	25.5	26.5	25.0	23.5	23.0
6	23.0	22.0	22.0	23.5	22.0
7	21.5	21.0	21.0	22.0	21.5
8	21.5	22.0	22.5	22.0	21.0
9	20.5	20.5	21.0	21.5	20.5
10	19.0	21.5	20.0	23.0	20.5
11	18.0	18.0	18.5	19.0	19.0
12	17.0	16.0	17.0	17.5	17.5
13	16.5	15.5	16.5	15.5	15.5
14	15.0	14.5	14.5	15.5	14.5
15	14.0	13.5	13.5	14.0	13.0
16	12.5	11.5	12.0	12.0	11.5
17	11.0	10.5	10.5	10.5	10.5
18	10.5	9.5	9.5	9.5	9.5
19	9.5	9.5	9.5	9.5	9.0
20	9.5	9.0	9.0	8.5	8.5

APPENDIX G: COLOR LAYER DATA - LABORATORY PLACEMENT TESTS

1. As is described in Chapter 2, cores were drilled in the hardened concrete to determine the final distribution of the variously colored segments of concrete. The coring pattern used was presented in Figure 14, Chapter 2.

2. Cores were recovered, measured, and logged. In cases where complete core recovery was not possible (usually due to mechanical rather than concrete problems), the total thickness of the concrete at the location of the core was used to determine the color distribution. For several cores it will be noted that the length of core recovered is not equal to the thickness of the concrete as reported in Appendix F. The discrepancies are due to ridges on the concrete surface and minor errors in measuring the lengths of the cores. In these instances, the total thickness of the colored layers has been made equal to the thickness determined during the surface profile measurements.

3. Data for the centerline and right edge of the box for the five tests are presented in Tables G-1 through G-10.

4. Only data from the centerline, Test 1 (Table G-1), are included in this volume. Data from remaining tests may be obtained from the authors.

TABLE G-1. CONCRETE COLOR DISTRIBUTION, TEST 1.

(1-IN. = 2.54 CM)

LOCATION: CENTERLINE

STATION	CONC. THICKNESS FROM PROFILE, IN.	TOTAL LENGTH OF CORE, IN.	TOP OF COLOR, MEAS. FROM BOTTOM OF BOX, IN.		
			GRAY/BROWN	RED	BLACK
TREMIE	49.5	47.0*	3.5	23.0	49.5
3	36.0	36.0	—	36.0	—
5	25.0	27.0	—	25.0	—
7	21.0	21.0	—	21.0	—
9	21.0	22.0	21.0	—	—
11	18.5	22.0 (1)	18.5	—	—
13	16.5	16.5	16.5	—	—
15	13.5	15.0 (1)	13.5	—	—
17	10.5	10.5	10.5	—	—
19	9.5	9.0 (2)	9.5	—	—

* PORTION OF CORE NOT RECOVERED.

(1) CORE TAKEN ON RIDGE OF CONCRETE.

(2) CORE INCLUDED LOOSE AGGREGATE.

APPENDIX H: TEMPERATURE INSTRUMENTATION PLAN - PIER 12, I-205 BRIDGE

1. The instruments used to record temperature development in the tremie concrete seal of Pier 12 of the I-205 Bridge were Resistance Thermometers supplied by the Carlson Instrument Company, Campbell, California. A total of 34 instruments and 4523 ft (1379 m) of lead cable were used.

2. All instruments, cables, and switches were tested under hot and cold conditions in the laboratory prior to being used in the field. All elements performed satisfactorily during testing and during actual field use.

3. As noted in Chapter 3, one quadrant of the pier was instrumented. Instruments were placed in four planes perpendicular to the long axis of the cofferdam.. These planes were designated Row 1 through Row 4. Each row was made up of two or more vertical lines of instruments. Figure H-1 shows the general instrumentation plan in relation to the cofferdam. Figure H-2 shows a blow-up of the instrumented quadrant while Figures H-3 through H-6 show the horizontal locations of the instrument lines within each of the four rows. Figures H-7 through H-17 show the detailed vertical locations of the instruments on each line.*

4. Vertical instrument lines were made up of a steel supporting cable with the instruments attached to the cable at the appropriate elevations. The steel cables were heavily weighted at the lower end and were attached to the cofferdam bracing at the upper end.

5. All lead-in cables from the instruments were connected to a central terminal/switching board. This board was in turn connected to a variable resistance bridge (Carlson Box) which was balanced to obtain the readings. A schematic of the system is shown in Figure H-18.

6. A listing of instrument numbers and recording channels is shown in Table H-1. The particular sequence shown was selected to allow channels 1 through 6 to be connected to the instruments which initially would be in contact with the concrete.

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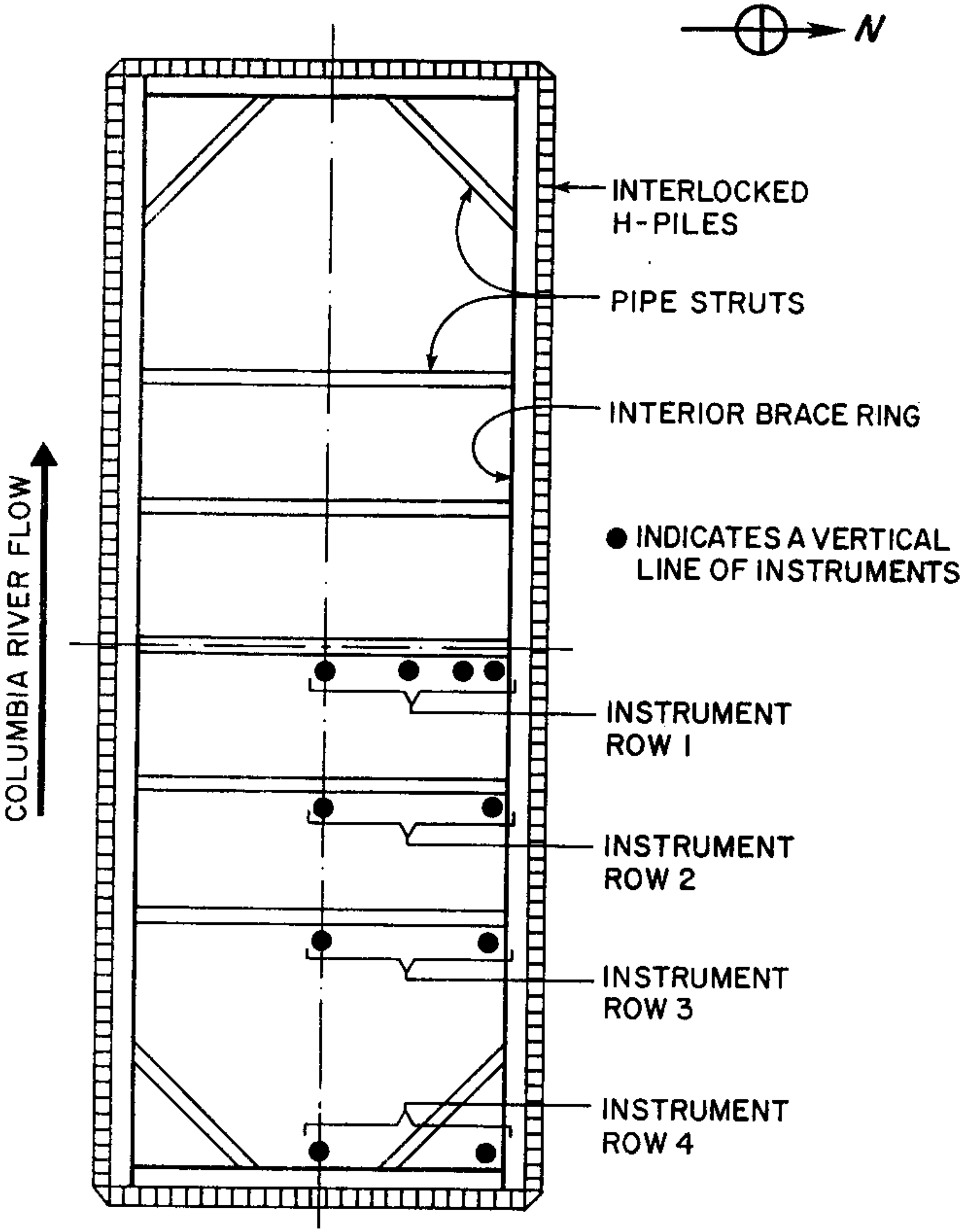
* Of the figures showing locations on each vertical line, only Figure H-7 is included in this volume. Remaining figures may be obtained from the authors.



NOMINAL 54 x 140 ft. (16.5 x 42.7 m) INSIDE SHEET PILES

FIGURE H-1. GENERAL INSTRUMENTATION PLAN, PIER 12, I-205 BRIDGE.

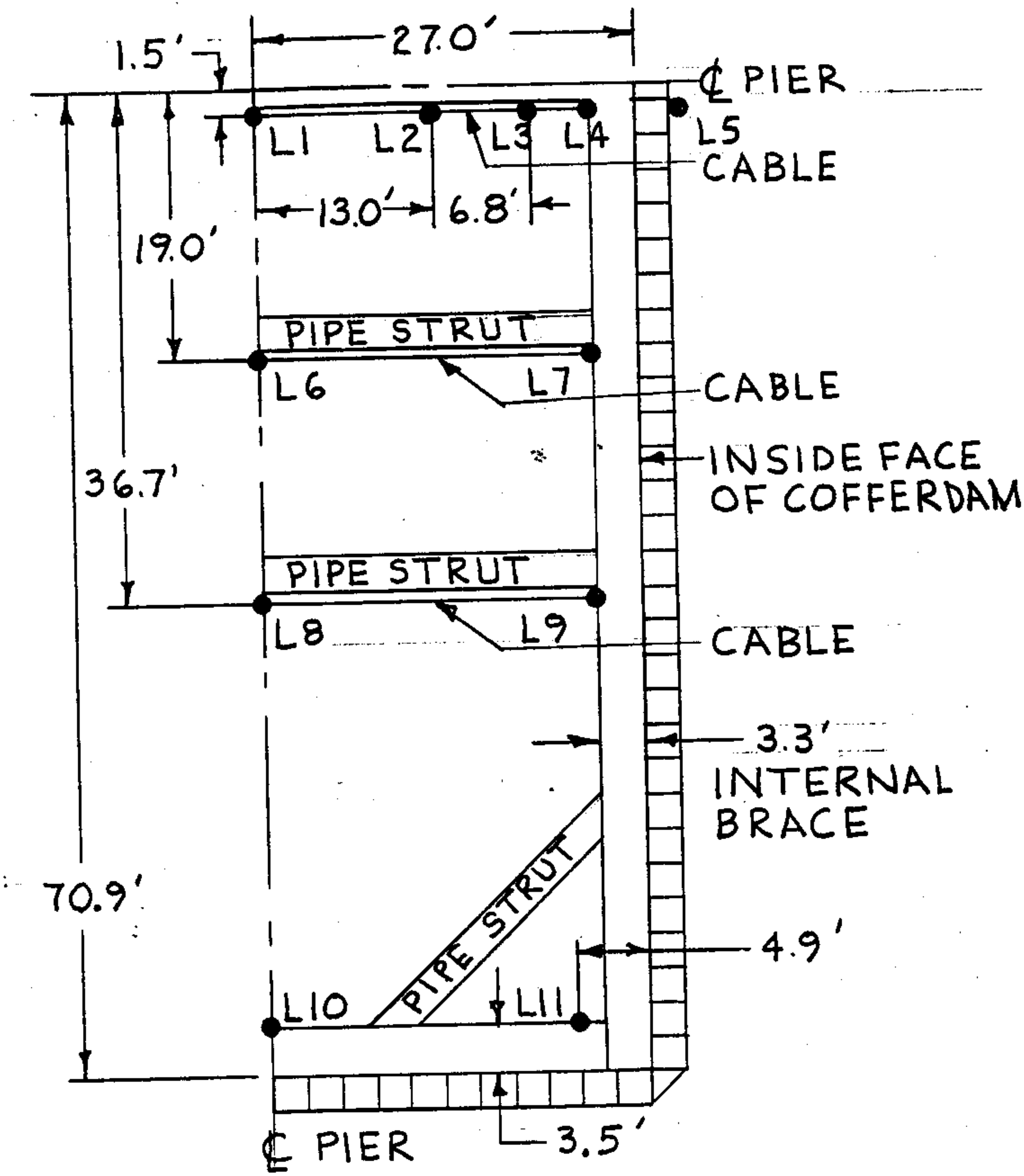
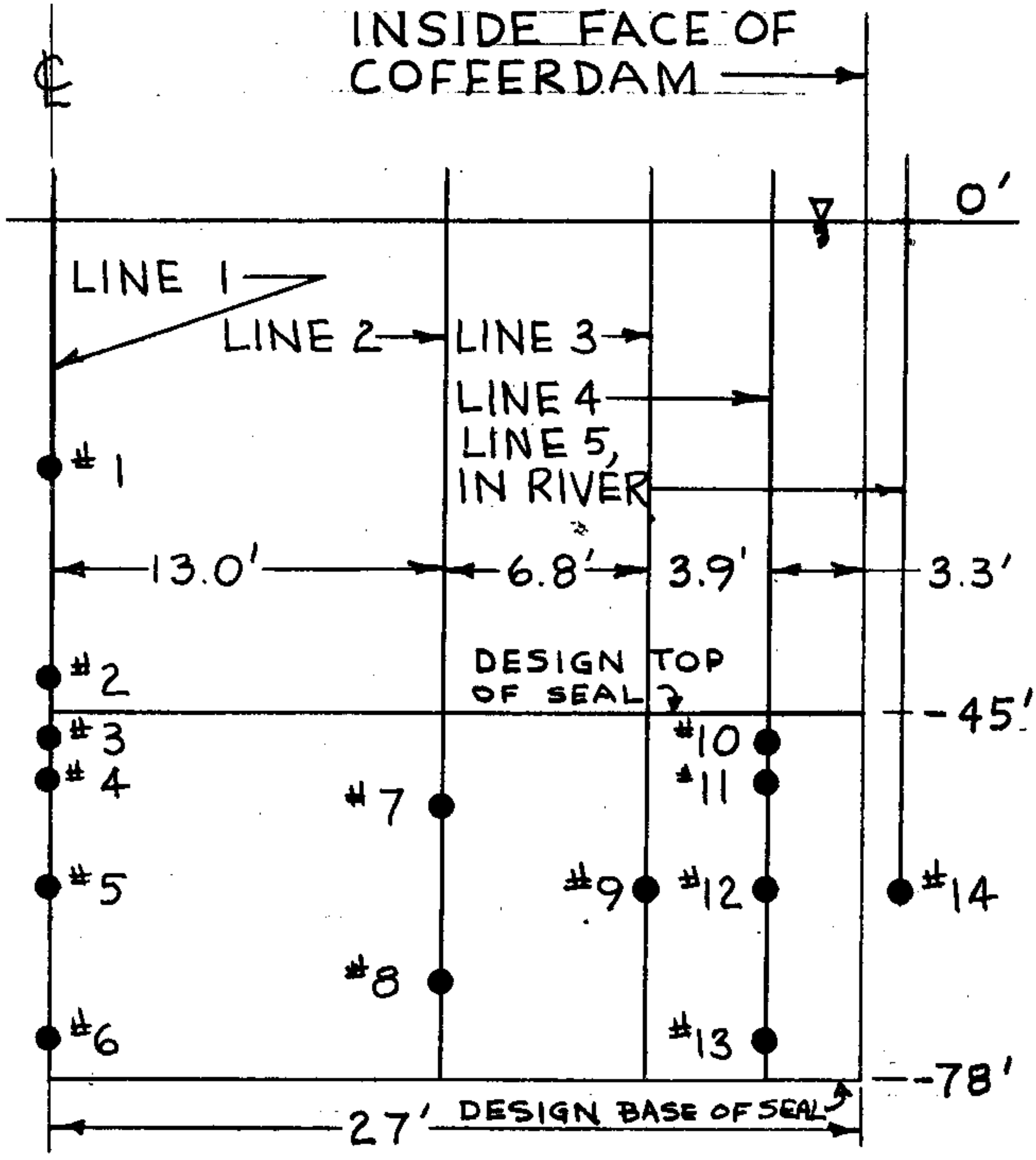


FIGURE H-2. DETAILED INSTRUMENTATION PLAN. DOTS INDICATE VERTICAL LINE OF INSTRUMENTS. (1 FT = 0.3048 M)



SECTION THROUGH TREMIE SEAL LOOKING DOWNSTREAM

FIGURE H-3. SCHEMATIC OF INSTRUMENT ROW 1. SEE FIGS. H-7 TO H-11 FOR EXACT VERTICAL LOCATIONS. NOT TO SCALE. (1FT=0.3048M)

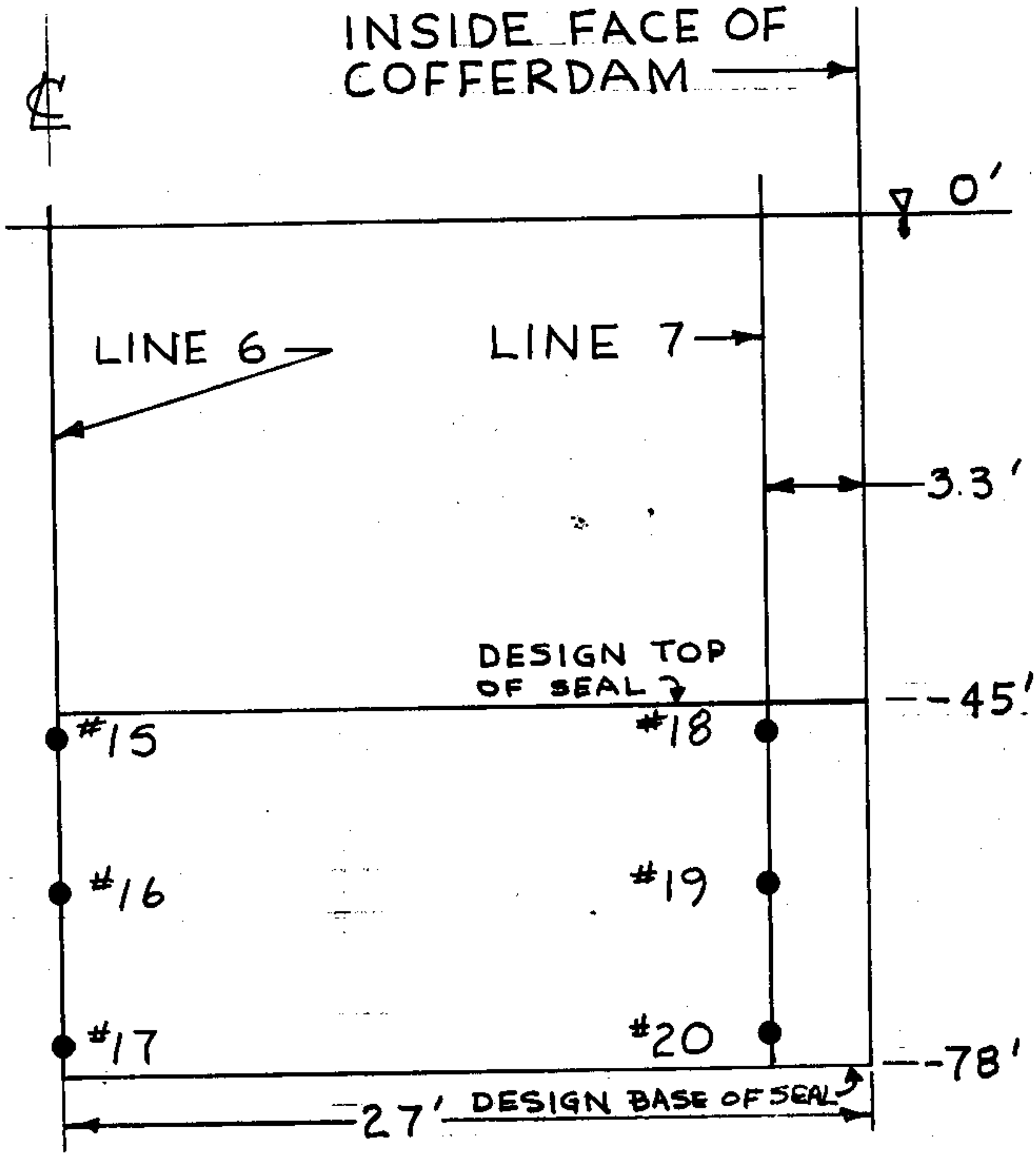


FIGURE H-4. SCHEMATIC OF INSTRUMENT ROW 2. SEE FIGS. H-12 AND H-13 FOR EXACT VERTICAL LOCATIONS. NOT TO SCALE. (1FT = 0.3048M)

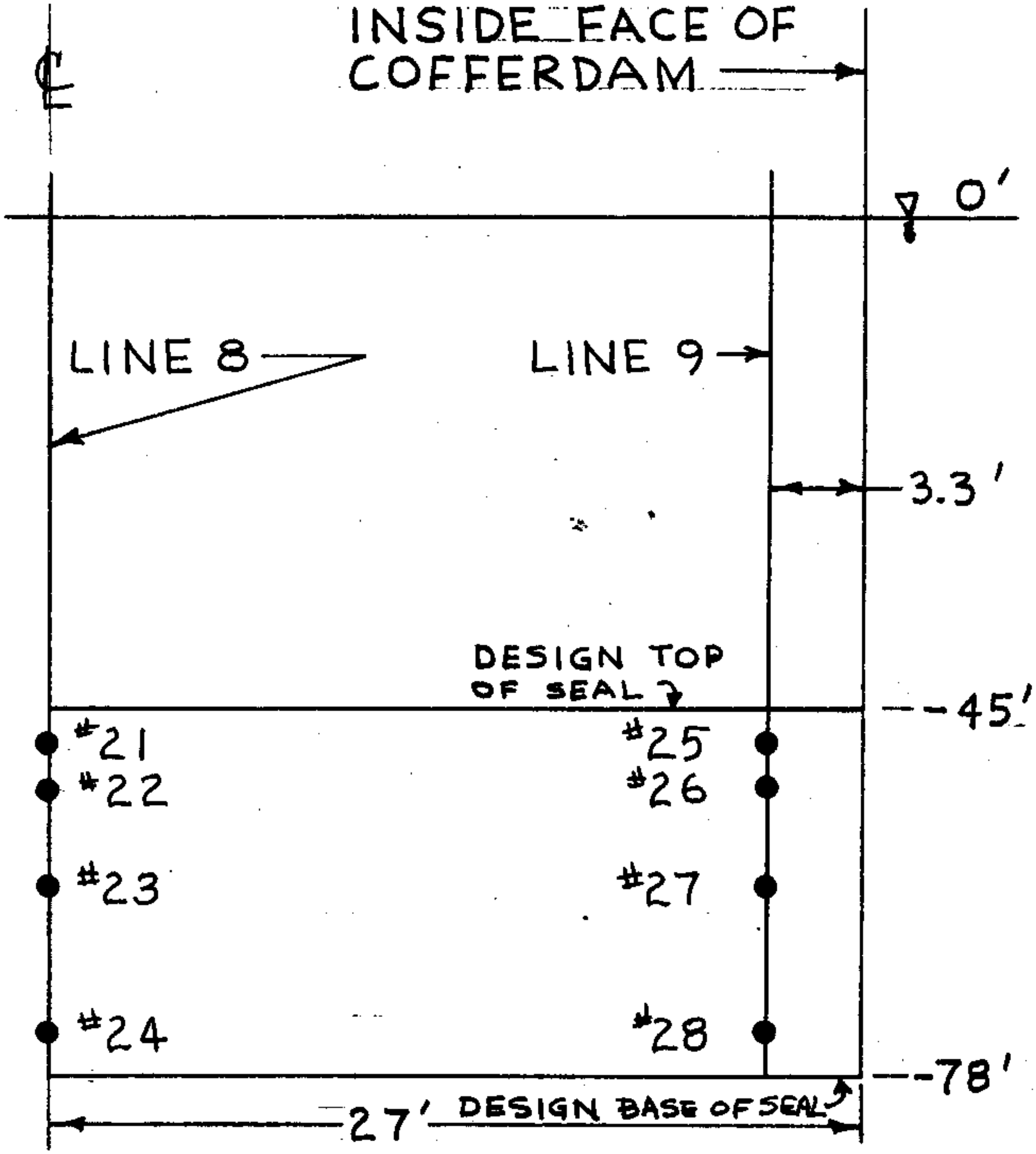


FIGURE H-5. SCHEMATIC OF INSTRUMENT ROW 3. SEE FIGS. H-14 AND H-15 FOR EXACT VERTICAL LOCATIONS. NOT TO SCALE. (1FT = 0.3048 M)

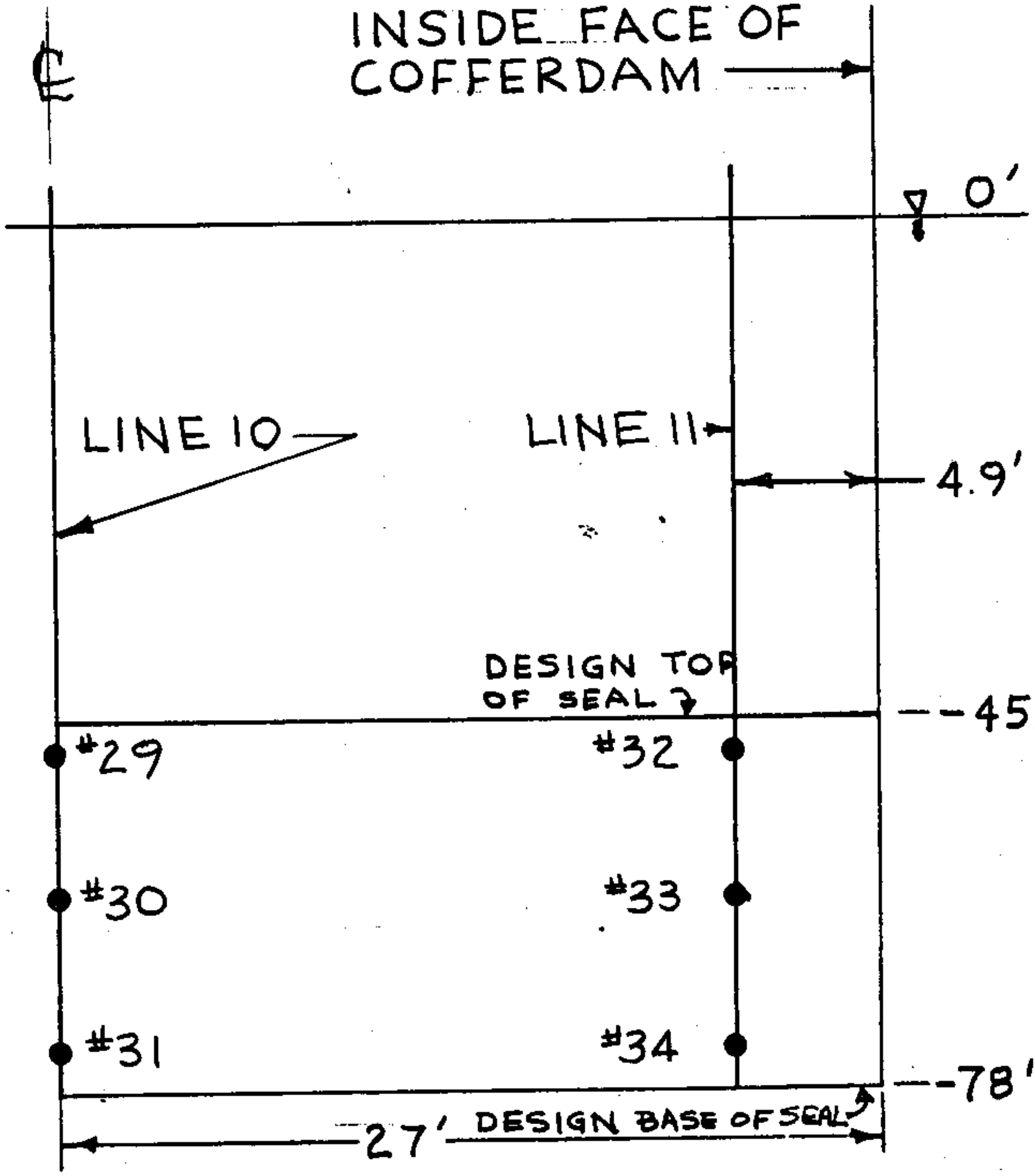


FIGURE H-6. SCHEMATIC OF INSTRUMENT ROW 4. SEE FIGS. H-16 AND H-17 FOR EXACT VERTICAL LOCATIONS. NOT TO SCALE. (1FT=0.3048M)

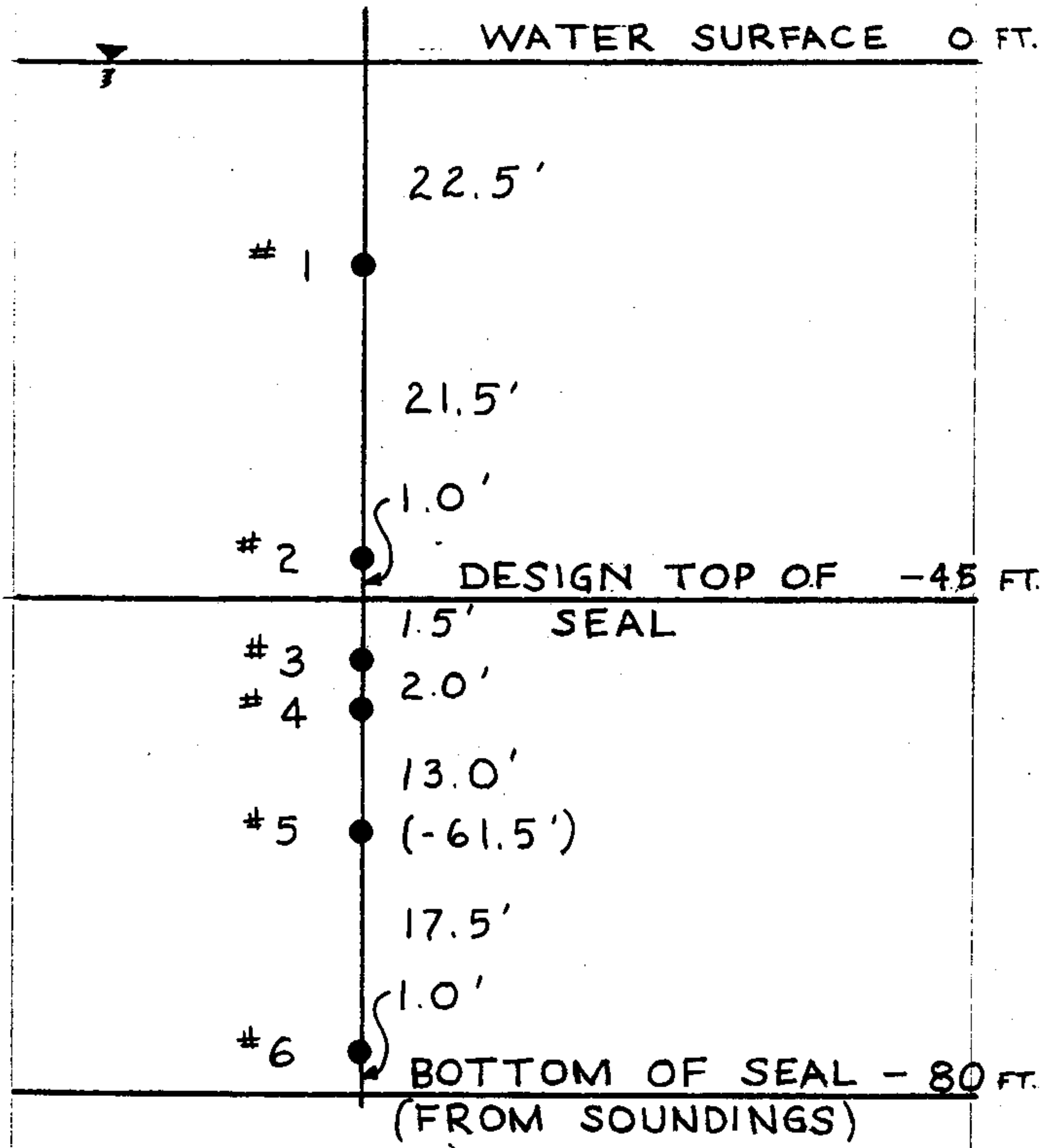


FIGURE H-7. INSTRUMENTATION LINE No. 1 , PIER 12, I-205 BRIDGE.
(1FT = 0.3048 M)
NOT TO SCALE

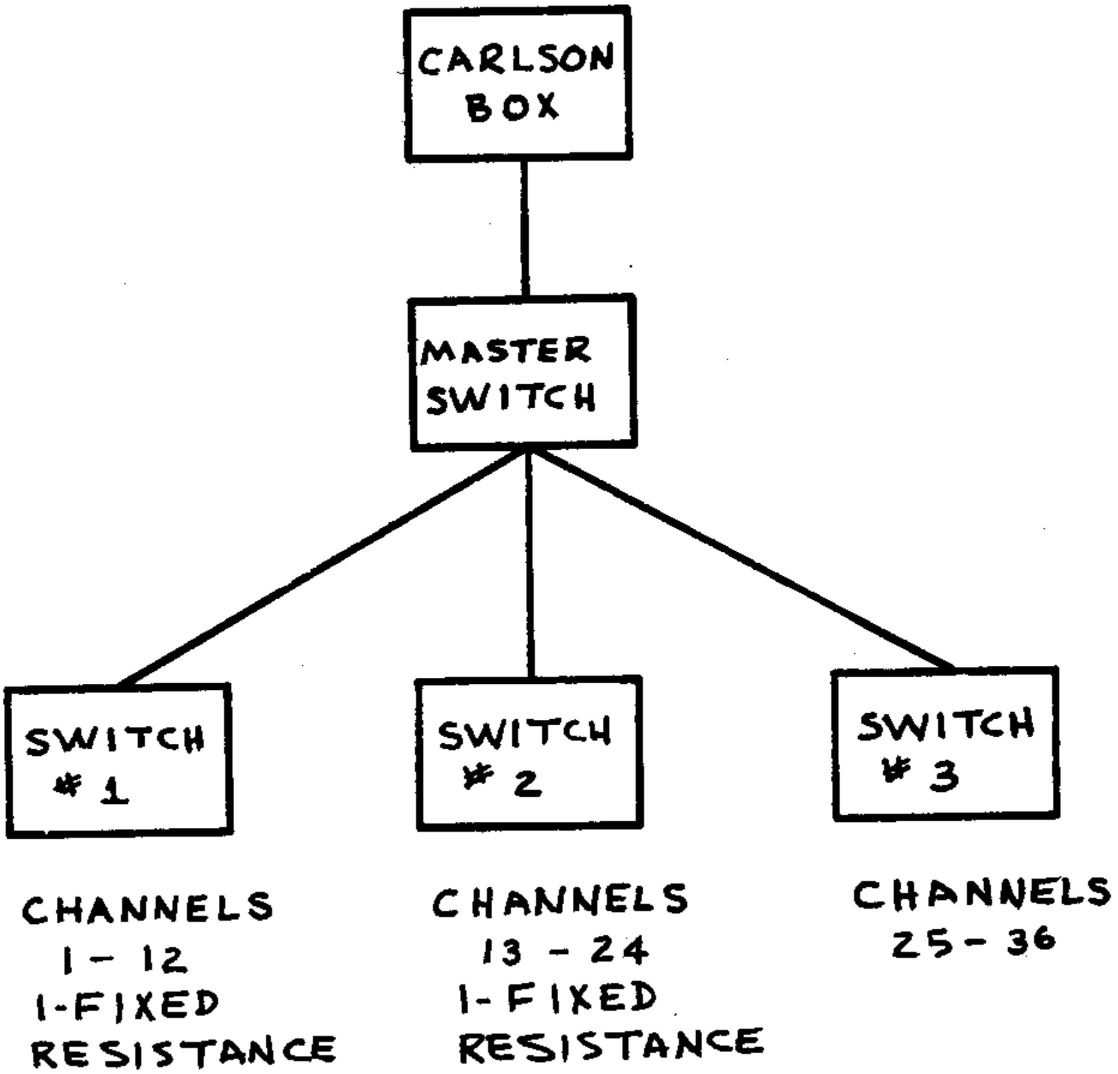


FIGURE H-18. SCHEMATIC DIAGRAM OF INSTRUMENTATION TERMINAL BOARD.

TABLE H-1. RECORDING CHANNEL AND INSTRUMENT ASSIGNMENTS.

RECORDING CHANNEL	INSTR. NUMBER	RECORDING CHANNEL	INSTR. NUMBER
1	6	19	16
2	13	20	18
3	8	21	19
4	17	22	29
5	20	23	FIXED Ω
6	5	24	30
7	FIXED Ω	25	31
8	9	26	32
9	12	27	33
10	1	28	34
11	2	29	21
12	3	30	22
13	4	31	23
14	7	32	24
15	10	33	25
16	11	34	26
17	14	35	27
18	15	36	28

APPENDIX I: DATA RECORDING AND REDUCTION - TEMPERATURES IN PIER 12 SEAL CONCRETE

1. Temperatures were read nominally every 2 hours. Actual reading times varied slightly due to conflicting activities within the cofferdam and the schedules of the persons taking the readings. Actual start and stop times for the readings were recorded on the data sheets. These two times were averaged to establish the reading time for each set of data.

2. Total time required to complete one set of readings was approximately 20 minutes. Six of the data channels were read at the beginning and end of each sequence. The values for these two readings were then averaged to offset any discrepancies which might have ocurred due to the time required to complete the entire sequence of readings.

3. Readings were taken in ohms by balancing a variable resistance bridge (Carlson Box). This raw data was converted into temperatures following instructions provided by the manufacturer of the resistance thermometers.

4. The temperatures obtained at the actual reading times were further reduced to provide temperatures at the nominal reading times (every 2 hours through 80 hours and every 10 hours from 80 to 380 hours) using a straight line interpolation technique. This last step was done to allow easier comparison with predicted temperatures.

5. Reduced temperature data for the 33 instruments are presented in Tables I-1 through I-33.

6. Only data from Instrument 8 (Table I-8) are included in this volume. Data from remaining instruments may be obtained from the authors.

TABLE 1-8. INSTRUMENT No. 8

HRS.	DEG. F.*	HRS.	DEG. F.*	HRS.	DEG. F.*
0	54	48	118	160	150
2	54	50	119	170	150
4	54	52	121	180	151
6	54	54	122	190	152
8	54	56	123	200	152
10	59	58	124	210	153
12	66	60	125	220	153
14	70	62	126	230	153
16	75	64	127	240	153
18	82	66	128	250	153
20	88	68	129	260	154
22	93	70	129	270	154
24	97	72	130	280	154
26	100	74	131	290	154
28	103	76	132	300	154
30	105	78	133	310	155
32	107	80	133	320	155
34	108	90	136	330	155
36	110	100	140	340	155
38	112	110	142	350	155
40	113	120	145	360	155
42	114	130	147	370	155
44	116	140	148	380	155
46	117	150	150		

* DEG. C. = (DEG F. - 32)/1.8

APPENDIX J: PREDICTED VERSUS MEASURED TEMPERATURES - PIER 12, I-205 BRIDGE

1. The tables in this appendix compare the temperatures predicted using the Carlson Method with those actually measured in the seal concrete of Pier 12 of the I-205 Bridge as is described in Chapter 3.

2. Due to the limitations of the Carlson Method which are described in the text, predictions made using that technique are valid only for instruments for which one-dimensional heat flow can be assumed. Therefore, the following tables include only those instruments in the interior of the pier for which this assumption is valid.

3. The following tables are included:

   a. Table J-1, Top of seal instruments.

   b. Table J-2, Mid-depth instruments.

   c. Table J-3, Bottom of seal instruments.

4. Note that in Table J-1 a range of predicted values is given. This was done since a variable thickness of concrete was actually placed over the top instruments. The cover was calculated to be:

Instrument No. 4	2.0 ft (0.6 m)
Instrument No. 15	0.7 ft (0.2 m)
Instrument No. 21	2.6 ft (0.8 m)
Instrument No. 22	4.6 ft (1.4 m)

5. Note that the readings for instruments No. 5, 7, and 9 are significantly below the predicted values. See Section 3.3.4 of the text.

TABLE J-1. PREDICTED VS. MEASURED TEMPERATURES, TOP OF SEAL, INTERIOR INSTRUMENTS.

ELAPSED TIME, HRS.	PRED. TEMPS.*, °F **	MEASURED TEMPERATURES			
		INST. 4 °F (°C)	INST. 15 °F (°C)	INST. 21 °F (°C)	INST. 22 °F (°C)
12	—	—	—	—	—
24	—	—	—	—	—
36	—	—	—	—	—
48	—	—	—	—	—
60	—	—	—	—	—
72	—	80 (27)	65 (18)	74 (23)	80 (27)
84	75-88	100 (38)	82 (28)	98 (37)	103 (39)
96	81-103	107 (42)	87 (31)	105 (41)	113 (45)
108	80-113	110 (43)	89 (32)	110 (43)	124 (51)
120	80-120	110 (43)	90 (32)	112 (44)	125 (52)
132	80-125	110 (43)	90 (32)	113 (45)	130 (54)
144	78-128	110 (43)	90 (32)	114 (46)	133 (56)
156	77-131	108 (42)	89 (32)	114 (46)	135 (57)
168	76-132	107 (42)	89 (32)	114 (46)	137 (58)
180	76-133	106 (41)	88 (31)	113 (45)	139 (59)
192	74-134	105 (41)	87 (31)	112 (44)	139 (59)
204	74-134	104 (40)	87 (31)	112 (44)	139 (59)
216	73-133	102 (39)	87 (31)	110 (43)	139 (59)
228	72-133	102 (39)	86 (30)	110 (43)	139 (59)
240	71-132	101 (38)	86 (30)	109 (43)	138 (59)

* 0.7 TO 5.0 FT BELOW TOP OF SEAL

** °C = 5/9 (°F - 32)

TABLE J-2. PREDICTED VS. MEASURED TEMPERATURES, MID-DEPTH INSTRUMENTS NEAR CENTERLINE OF TREMIE SEAL.

ELAPSED TIME, HRS.	PRED. TEMPS.*, °F (°C)	MEASURED TEMPERATURES			
		INST. 5 °F (°C)	INST. 7 °F (°C)	INST. 8 °F (°C)	INST. 9 °F (°C)
12	—	—	—	66 (19)	—
24	—	—	—	97 (36)	—
36	—	74 (23)	—	110 (43)	68 (20)
48	84 (29)	101 (38)	58 (14)	118 (48)	86 (30)
60	103 (39)	108 (42)	63 (17)	125 (52)	91 (33)
72	112 (44)	113 (45)	67 (19)	130 (54)	94 (34)
84	119 (48)	116 (47)	68 (20)	134 (57)	97 (36)
96	125 (52)	119 (48)	70 (21)	138 (59)	101 (38)
108	128 (53)	122 (50)	72 (22)	142 (61)	103 (39)
120	131 (55)	123 (51)	73 (23)	145 (63)	105 (41)
132	134 (57)	125 (52)	74 (23)	147 (64)	107 (42)
144	135 (57)	127 (53)	75 (24)	149 (65)	109 (43)
156	138 (59)	128 (53)	75 (24)	150 (66)	111 (44)
168	140 (60)	128 (53)	76 (24)	150 (66)	112 (44)
180	141 (61)	129 (54)	77 (25)	151 (66)	112 (44)
192	141 (61)	129 (54)	78 (26)	152 (67)	114 (46)
204	142 (61)	129 (54)	79 (26)	152 (67)	114 (46)
216	143 (62)	129 (54)	81 (27)	153 (67)	116 (47)
228	143 (62)	129 (54)	85 (29)	153 (67)	116 (47)
240	143 (62)	129 (54)	92 (33)	153 (67)	116 (47)

* 17 FT ABOVE BASE OF SEAL

TABLE J-2. PREDICTED VS. MEASURED TEMPERATURES, MID-DEPTH INSTRUMENTS NEAR CENTERLINE OF TREMIE SEAL (CONTINUED)

ELAPSED TIME, HRS.	PRED. TEMPS*, °F (°C)	MEASURED TEMPERATURES			
		INST. 16 °F (°C)	INST. 23 °F (°C)	INST °F (°C)	INST °F (°C)
12	—	—	—		
24	—	—	—		
36	—	—	—		
48	84 (29)	80 (27)	66 (19)		
60	103 (39)	106 (41)	94 (34)		
72	112 (44)	113 (45)	107 (42)		
84	119 (48)	117 (47)	116 (47)		
96	125 (52)	121 (49)	121 (49)		
108	128 (53)	125 (52)	127 (53)		
120	131 (55)	128 (53)	131 (55)		
132	134 (57)	131 (55)	136 (58)		
144	135 (57)	134 (57)	139 (59)		
156	138 (59)	136 (58)	142 (61)		
168	140 (60)	138 (59)	144 (62)		
180	141 (61)	139 (59)	145 (63)		
192	141 (61)	141 (61)	147 (64)		
204	142 (61)	142 (61)	148 (64)		
216	143 (62)	144 (62)	149 (65)		
228	143 (62)	144 (62)	149 (65)		
240	143 (62)	145 (63)	150 (66)		

* 17 FT ABOVE BASE OF SEAL

TABLE J-3. PREDICTED VS. MEASURED TEMPERATURES, BOTTOM OF SEAL, INTERIOR INSTRUMENTS.

ELAPSED TIME, HRS.	PRED. TEMPS.*, °F (°C)	MEASURED TEMPERATURES INST. 6 °F (°C)	INST. 17 °F (°C)	INST. 24 °F (°C)	INST °F (°C)
12	82 (28)	77 (25)	75 (24)	66 (19)	
24	96 (36)	97 (36)	96 (36)	93 (34)	
36	100 (38)	105 (41)	103 (39)	101 (38)	
48	104 (40)	110 (43)	107 (42)	104 (40)	
60	107 (42)	113 (45)	110 (43)	107 (42)	
72	107 (42)	115 (46)	112 (44)	112 (44)	
84	108 (42)	116 (47)	113 (45)	113 (45)	
96	109 (43)	118 (48)	115 (46)	115 (46)	
108	110 (43)	120 (49)	116 (47)	116 (47)	
120	110 (43)	121 (49)	117 (47)	117 (47)	
132	110 (43)	122 (50)	118 (48)	118 (48)	
144	110 (43)	122 (50)	118 (48)	118 (48)	
156	110 (43)	122 (50)	119 (48)	119 (48)	
168	110 (43)	123 (51)	119 (48)	119 (48)	
180	110 (43)	122 (50)	119 (48)	119 (48)	
192	109 (43)	122 (50)	119 (48)	119 (48)	
204	109 (43)	122 (50)	119 (48)	119 (48)	
216	109 (43)	122 (50)	119 (48)	119 (48)	
228	109 (43)	122 (50)	119 (48)	119 (48)	
240	109 (43)	122 (50)	119 (48)	119 (48)	

* 1 FT ABOVE BASE OF SEAL

APPENDIX K: LISTING OF PROGRAM TEMP

(Note: Flow chart follows listing.)

```
      PROGRAM TEMP (INPUT, OUTPUT,PUNCH)
        COMMON /DES    / B,H,D,HED(18),HED2(15)
      COMMON /TIMEVA/ V,PR,NFC,NFB,TC(400)
      COMMON /GRIDCU/ X(30),Y(30)
      DIMENSION           PX(30, 30), PY(30, 30), NE(30)
      DIMENSION NOD(5)
    1 READ 900, MODE,HED,HED2
      IF (MODE.EQ.5HSTOP ) GO TO 9999
      CALL TITLE
      READ 1000, B, H,D,IN,NB,NH,IS,IP
      IF (IP.EQ.1) PUNCH 900, MODE,HED
      PRINT 2050, B, H, D
      V=B*H*D/27.
      B = B/2.
      D = D/2.
      IF (IN.EQ.0) GO TO 50
      READ 1050, (X(I),I=1,NB)
      READ 1050, (Y(I),I=1,NH)
      GO TO 60
   50 CALL GENGRD (NB,NH)
   60 NH1 = NH-1
      NB1 = NB - 1
      NP = NB*NH
      NET = NB1*NH1
      R=-Y(1)
      DO 110 L = 1, NH
      DO 110 J = 1, NB
      PX(L,J) = X(J)
      PY(L,J) = Y(L)
  110 CONTINUE
      CALL CONCOP (NB1,NH1)
      CALL HEATGN (IP)
      CALL TITLE
      PRINT 2000, NB,B,NH,H,R,NP,NET
      PRINT 2090
      IF (IP.EQ.0) GO TO 139
      K=0
      L=2
      A=8HNODE POI
      B=8HNT DATA
      IF (IP.EQ.1) PUNCH 9000,A,B,A,B,A,B,A,B
      PUNCH 5000, NP,L
      DO 135 J=1,NH
      DO 135 I=1,NB
      K=K+1
      PUNCH 5100, K,PX(J,I),PY(J,I)
  135 CONTINUE
      K = 0
      L=1
      J=2
      A=8HELEMENT
      B=8H DATA
      IF (IP.EQ.1) PUNCH 9000,A,B,A,B,A,B,A,B
      PUNCH 5000, L,NET,L,K,K,K,J,L


      PUNCH 5000,L
      PUNCH 5000,J
  139 K = 0
      DO 150 L = 1, NH
      M=1
      IF (Y(L).LT.0.) M=2
      DO 140 J = 1, NB
      X(J) = NP + J - (L*NB)
```

```
      IF(J .EQ. NB) GO TO 140
      NE(J) = NET + J - (L*NB1)
      IF(L.EQ. NH) GO TO 140
      K = K + 1
      NOD(1) = K
      NOD(2) = NB + K + L
      NOD(3) = NOD(2) -1
      NOD(4) = NOD(3) - NB
      NOD(5) = NOD(4) + 1
      IF (IP.EQ.1) PUNCH 6000,  (NOD(I),I=1,5),M,TC(K)
  140 CONTINUE
      K1= NH + 1 - L
      PRINT 2100, PY(K1,1), (X(J), J = 1, NB)
      PRINT 2101
      IF(L .EQ. NH) GO TO 150
      N2 = NB1*L
      N = (NET + 1) - N2
      N1 = N + NB1 - 1
      PRINT 2300, (NE(J), J = 1,  NB1)
      PRINT 2400, ( TC(J), J = N, N1)
  150 CONTINUE
      PRINT 2200 , (PX(1,J), J = 1, NB)
      PRINT 4000
      PRINT 6400
      M=0
      L=2
      DO 200 L=1,NH
      IF (PY(L,1).GT.0.) GO TO 210
      M=M+1
  200 CONTINUE
  210 N=NB1+NH1-M
      IF (IP.EQ.0) GO TO 220
      A=8HCONVECTI
      B=8HON DATA
      PUNCH 9000,A,B,A,B,A,B,A,B
      PUNCH 5000, L,N
  220 L=1
      I=NB*M+NB
      J=I+NB
      IF (IP.EQ.1) PUNCH 6500,L,I,J,NB
      PRINT 6600,L,I,J,NB
      L=NH1-M
      I=NP-NB
      J=NP
      IF (IP.EQ.1) PUNCH 6500,L,I,J,NB
      PRINT 6600,L,I,J,NB


      K=1
      L=L+1
      I=NB*NH1+2
      J=I-1
      IF (IP.EQ.1) PUNCH 6500,L,I,J,K
      PRINT 6600,L,I,J,K
      L=L+NB1
      I=NP
      J=I-1
      IF (IP.EQ.1) PUNCH 6500,L,I,J,K
      PRINT 6600,L,I,J,K
      GO TO 1
  900 FORMAT (A5,3X,18A4,/15A4)
 1000 FORMAT (3F10.0,5I5)
 1050 FORMAT (8F10.0)
 2000 FORMAT (///, *       TWO-DIMENSIONAL FINITE ELEMENT ANALYSIS*,/
     1/6X,*ANALYSIS OF SECTION SYMMETRIC ABOUT CENTERLINE OF STRUCTURE*,
     2/*           TOTAL NUMBER OF BASE DIVISIONS          =*,I4,
     2  6X,*BASE     =*,F6.1,* FEET (CENTERLINE TO X-BOUNDARY)*,
     3/*           TOTAL NUMBER OF HEIGHT DIVISIONS      =*,I4,
     4      6X,*HEIGHT =*,F6.1,* FEET + *,F5.1,* FEET OF FOUNDATION*,/
     5/*           TOTAL NUMBER OF NODAL POINTS              =*,I4,
     6/*           TOTAL NUMBER OF ELEMENTS                  =*,I4,      )
```

```
2050 FORMAT (///2X, * DIMENSIONS OF STRUCTURE   *, 20X,                   *. Y*,
    1/          49X, *.*,
    2/ *          LENGTH (X)   =*,F5.1,* FEET*,        20X,                *.*,
    3/ *          HEIGHT (Y)   =*,F5.1,* FEET*,        20X,                *.*,
    4/ *          WIDTHT (Z)   =*,F5.1,* FEET*,        20X,                *.... X*
    5/          48X,   *.*,
    6/          45X,     *Z .*)
2090 FORMAT(//1X,* HEIGHT       NODAL POINTS FOR TEMPERATURE ANALYSIS,ELEM
    1ENT NUMBERS AND ELEMENT CREATION TIMES (HOURS)*)
2100 FORMAT (    /,F7.1, 3H * , 20F6.0,/)
2101 FORMAT (* *)
2200 FORMAT (8X, 121(1H*), /10X, 20F6.1)
2300 FORMAT (13X, 20I6)
2400 FORMAT (13X, 20F6.1)
4000 FORMAT(/*   CENTERLINE *,25X,* HORIZONTAL DISTANCE FROM CENTERLINE
    1 OF STRUCTURE, FEET*)
5000 FORMAT (8I5)
5100 FORMAT (I5,5X,2F10.4)
6000 FORMAT (5I5,20X,I5,10X,F10.4)
6400 FORMAT (////,3X, * CONVECTION ELEMENTS AND NODAL POINT DATA *,/
    1  8X , * ELEMENT* ,10X, * NODAL POINTS *,10X,*STEP FUNCTION*,/
    2  8X , *  NUMBER* ,10X, *  I      J *)
6500 FORMAT (3I5,15X,I5)
6600 FORMAT ( 9X,I5,11X,I5,I6,15X,I5)
9000 FORMAT (3X,8A8)
9999 STOP
     END



     SUBROUTINE TITLE
       COMMON /DES    / B,H,D,HED(18),HED2(15)
     PRINT 2000, HED,HED2
2000 FORMAT (1H1,2X,18A4,15A4)
     RETURN
     END



      SUBROUTINE CONCOP (NB1,NH1)
        COMMON /DES    / B,H,D,HED(18),HED2(15)
      COMMON /TIMEVA/ V,PR,NFC,NFB,TC(400)
      READ 1000,PR,RT,NFC,NFB
      IF (RT.EQ.0.) RT=V/PR
      IF (PR.EQ.0.) PR=V/RT
      RR=H/RT
      N=1
       IF (NFC.GT.0) N=2
       IF (NFB.GT.0) N=3
      PRINT 2070,N
      GO TO (10,20,30),N
   10 PRINT 2071
      GO TO 50
   20 PRINT 2072
      GO TO 50
   30 PRINT 2073
   50 PRINT 2100,V,PR,RR,RT
      CALL TIMECR (N,NB1,NH1)
 1000 FORMAT (2F10.0,2I5)
 2070 FORMAT (//3X,20HCONCRETING OPERATING, 8X,18HUSER OPTION NUMBER,I3)
 2071 FORMAT (8X, * (PRODUCTION RATE SPECIFIED, CONSTANT RATE OF RISE *,
     1  *OVER ENTIRE SURFACE)*,//)
 2072 FORMAT (8X, * (RATE OF RISE SPECIFIED AT CENTER OF STRUCTURE, *,
     1  *CONSTANT RATE OF RISE OVER ENTIRE SURFACE) *,//)
 2073 FORMAT (8X, * ( RATES OF RISE SPECIFIED AT CENTER AND AT *, .
```

```
     1  *X-BOUNDARY OF STRUCTURE, *,
     2  /29X, *LINEAR VARIATION BETWEEN CENTER AND X-BOUNDARY, * ,
     3  /29X, *UNIFORM RISE BETWEEN CENTERLINE AND Z-BOUNDARY)*,//)
 2100 FORMAT (6X,*TOTAL CONCRETE VOLUME *,23X,1H=,F8.2,* CUBIC YARDS *,/
     1 6X,*PRODUCTION RATE, AVERAGE*,21X,1H=,F8.2,* CUBIC YARDS PER *,
     2 *HOUR*,/ 6X,*RATE OF RISE, AVERAGE AT CENTER OF STRUCTURE =*
     3 ,F8.2,* FEET PER HOUR *, / 6X,*TIME TO COMPLETION*,27X,1H= ,F8.2,
     4 * HOURS* )
      RETURN
      END




      SUBROUTINE GENGRD (NB,NH)
        COMMON /DES    / B,H,D,HED(18)
      COMMON /GRIDCO/ X(30),Y(30)
      DIMENSION G(5), G1(5), G2(5),G3(5)
      DATA (G(I), I=1,5) /20.,10.,5.,2.,1./
      DATA (G1(I), I=1,5) /75., 31., 10., 5., 0./
      DATA (G2(I), I=1,5) /43.,18.,8.,2.,0./
      DATA (G3(I), I=1,5) /10.,5.,4.,2.,1./
      H2 = H/2.
      NH2 = H2
      CALL GRID (H2, N, X, G3,G2)
      NH = N*2 +1
      Y(1)=-20.
      Y(2)=-10.
      Y(3)=0.
      Y(NH)=H
      K1 = N - 1
      DO 100 L = 1, K1
      Y(L+3)=NH2-X(N-L)
      IF ( Y(L+3).EQ.0.) Y(L+3)=.5
      K=NH-L
      Y(K)=H-Y(L+3)
  100 CONTINUE
      CALL GRID (B,NB , X, G, G1)
      RETURN
      END




      SUBROUTINE GRID (B, N,  Z,G, G1)
      DIMENSION Z(30), G(5), G1(5)
      Z(1)  = 0
      N = 1
      DO 20 J = 1,5
      C = B-Z(N)
      IF (C .LT. G1(J)) GO TO 20
      DO 10 I = 2, 10
      N = N + 1
      Z(N) = Z(N-1) + G(J)
      IF(Z(N) .GT. (B-G1(J))) GO TO 20
   10 CONTINUE
   20 CONTINUE
      Z(N) = B
      IF (Z(N-1).EQ.B) Z(N-1)=Z(N)-G(5)/2.
      RETURN
      END
```

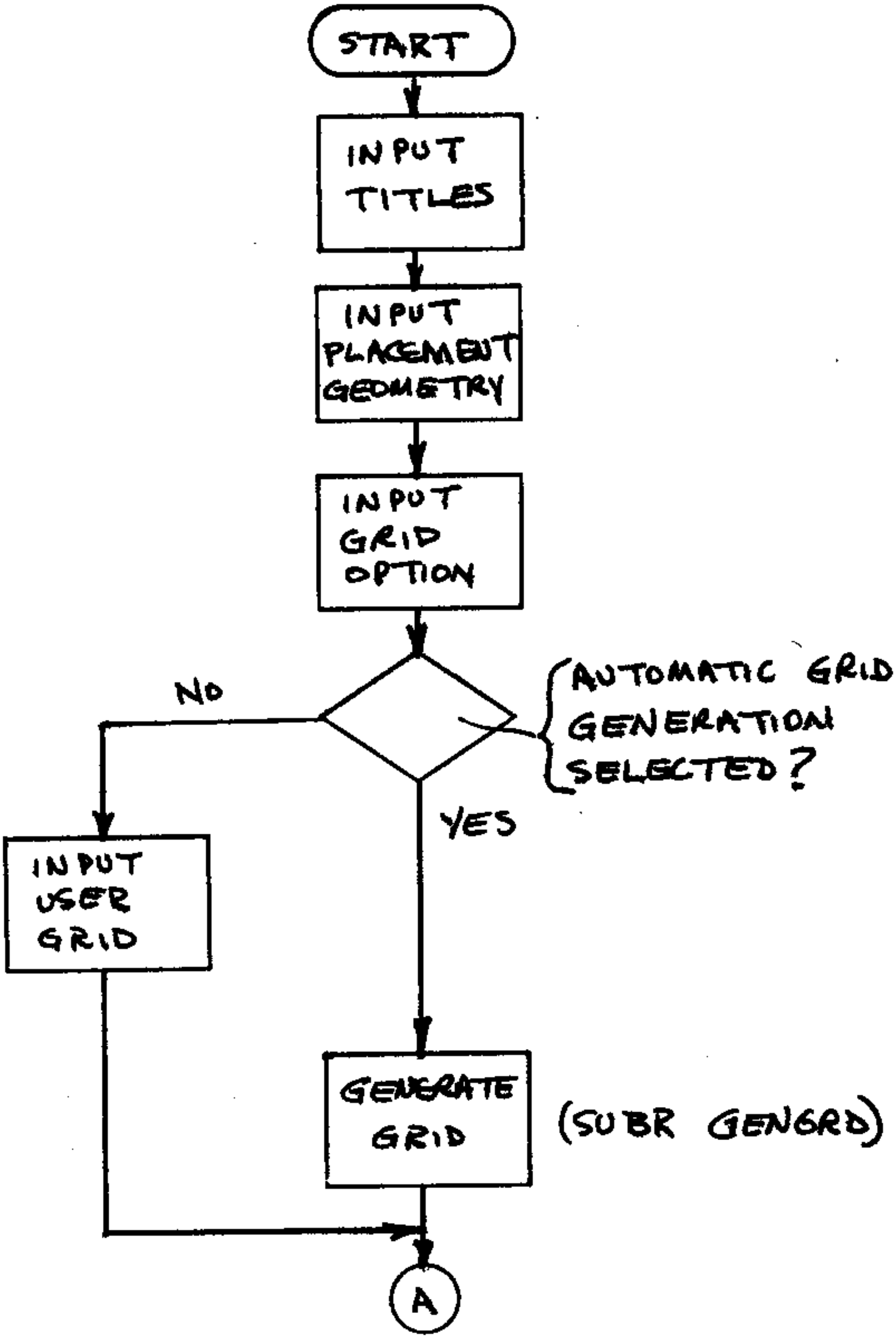
```
      SUBROUTINE TIMECR (N,NB1,NH1)
         COMMON /DES    / B,H,D,HED(18)
      COMMON /GRIDCO/ X(30),Y(30)
      COMMON /TIMEVA/ V,PR,NFC,NFB,TC(400)
      DIMENSION T1(100),T2(100)
      I1=H
      I2=H+1.
      V1=B*2.*D/27.
      V2=0.
      IF (NFC.EQ.0) GO TO 50
      PRINT 2400
      CALL TIME (NFC,T1,H)
      IF (NFB.EQ.0) GO TO 100
      PRINT 2410
      CALL TIME (NFB,T2,H)
      GO TO 150
   50 T1(1)=0.
      DO 80 I=2,I2
      V2=V1+V2
   80 T1(I)=2.*V2/PR
  100 T2(1) =T1(1)
  150 CALL TITLE
      PRINT 2000
      PRINT 2050,T1(1),T2(1)
      DO 200 I=1,I1
      IF (N.LT.3) T2(I+1)=T1(I+1)
      PROD = 4.*V1/(T1(I+1)+T2(I+1)-T1(I)-T2(I))
      D1=T1(I)/24.
      D2=T2(I)/24.
      PRINT 2100,I,T1(I+1),D1,T2(I+1),D2,PROD
  200 CONTINUE
      DO 240 I=1,NB1
  240 X(I)=(X(I)+X(I+1))/2.
      K=0
      DO 250 I=1,NH1
      IF (Y(I).LT.0.) GO TO 250
      K=K+1
      Y(K)=(Y(I)+Y(I+1))/2.
  250 CONTINUF
      M=NH1-K
      K=M*NB1
      DO 250 I=1,K
  280 TC(I)=0.
      I3=NH1-M
      I4=1
      DO 320 I=1,I3
      DO 310 L=I4,I1
      IF (Y(I).GT. L )    GO TO 310
      F3=(T1(L+1)-T2(L+1))/B
      F4=(T1(L)-T2(L))/B
      DO 300 J=1,NB1
      K=K+1
      F1=T1(L)-X(J)*F4
      F2=T1(L+1)-X(J)*F3

      TC(K)=F1+(F2-F1)*(1.-(L-Y(I)))
  300 CONTINUE
      I4=L
      GO TO 320
  310 CONTINUE
  320 CONTINUE
 2000 FORMAT (//2X,* PRODUCTION PATE *,/)
 2050 FORMAT (8X, * HEIGHT, FEET        TIME, HOURS (DAYS)          TIME, *,
     1 *HOURS (DAYS)          PRODUCTION RATE PER FOOT OF RISE *,/
     2  29X,13HAT CENTERLINE ,13X,13HAT X-BOUNDARY ,15X,
     3       * CUBIC YARDS PER HOUR *,
     4 /15X, *0 *,9X,F7.2,21X,F6.2)
 2100 FORMAT (12X,I4,2(9X,F8.2,2H (,F6.2,2H) ),15X,F8.2)
 2400 FORMAT (///3X,*SPECIFIED RATE OF RISF AT CENTERLINE OF STRUCTURE*)
 2410 FORMAT(///3X,*SPECIFIED RATE OF RISE AT X-BOUNDARY OF STRUCTURE*)
      RETURN
      END
```

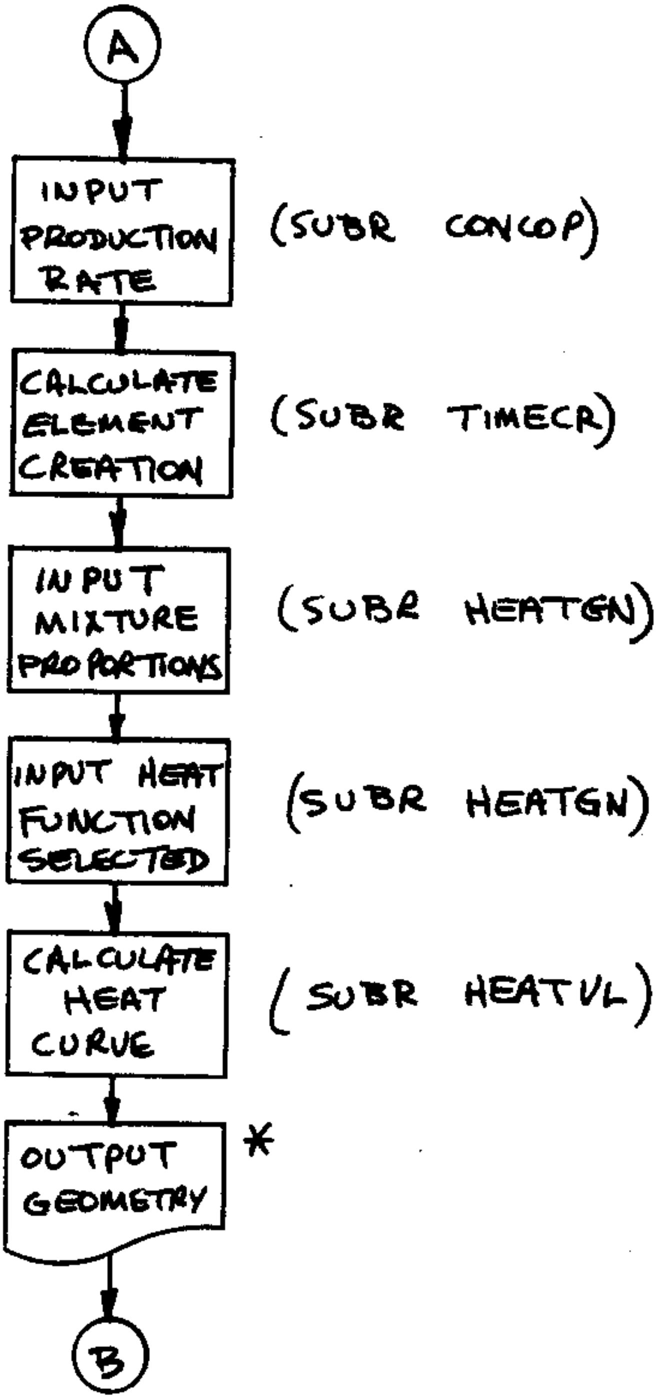
```
      SUBROUTINE TIME (L,T,H)
      DIMENSION T(100) ,FT(50),FH(50)
      READ 1000, ((FT(I),FH(I)),I=1,L)
      PRINT 1900
      PRINT 2000,((FH(I),FT(I)),I=1,L)
      I1=H
      T(1)=FT(1)
      N=2
      DO 100 I=1,I1
   40 IF (I.LE. FH(N)) GO TO 50
      N=N+1
      GO TO 40
   50 T(I+1)=T(I)+(FT(N)-FT(N-1))/(FH(N)-FH(N-1))
  100 CONTINUE
 1000 FORMAT (4(2F10.0))
 1900 FORMAT (/8X, * HEIGHT, FEET*, 6X, *TIME, HOURS *,/)
 2000 FORMAT (6X,F8.2,9X,F8.2)
      RETURN
      END
```

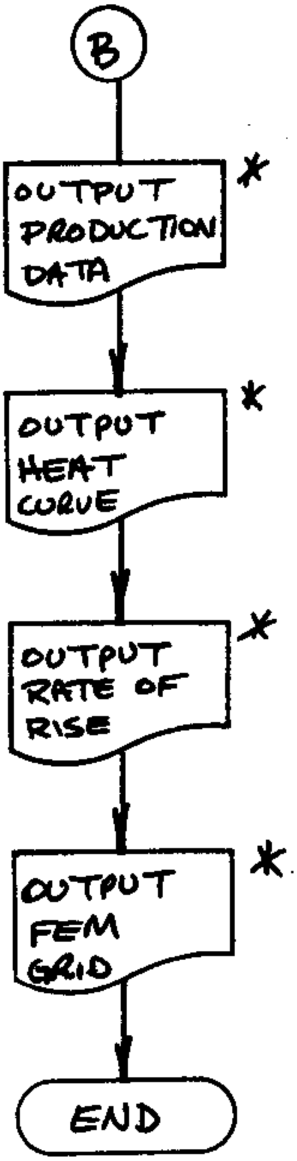
```
      SUBROUTINE HEATGN (IP)
      DIMENSION TY1(13),TY2(13),HTY2(13)
      DATA (TY1(I),I=1,13) /0.,.195,.218,.238,.248,.145,.060,.023,.015,
     1  .008,.002,.0001,.0001/
      DATA (TY2(I),I=1,13) /0.,.130,.145,.170,.180,.105,.044,.018,.012,
     1  .007,.001,.0001,.0001/
      DATA (HTY2(I),I=1,13) /0.,.135,.148,.173,.181,.107,.046,.025,.016,
     1  .010,.003,.0001,.0001/
      READ 1000, CEM,POZ,I,M
      IF (CEM.EQ.0.) GO TO 50
      CALL TITLE
      PRINT 2000
      GO TO (10,20,30),I
   10 PRINT 2010,CEM
      PRINT 2100,POZ
      CALL HEATVL (TY1,CEM,POZ,M,IP)
      GO TO 50
   20 PRINT 2020,CEM
      PRINT 2100,POZ
      CALL HEATVL (TY2,CEM,POZ,M,IP)
      GO TO 50
   30 PRINT 2030,CEM
      PRINT 2100,POZ
      CALL HEATVL(HTY2,CEM,POZ,M,IP)
 1000 FORMAT (2F10.0,2I5)
 2000 FORMAT (///3X, *CEMENT SPECIFICATIONS *,/)
 2010 FORMAT (8X, * TYPE I     *,F8.1, * POUNDS PER CUBIC YARD *,
     1  * (AVERAGE HEAT GENERATION *)
 2020 FORMAT (8X, * TYPE II    *,F8.1, * POUNDS PER CUBIC YARD *
     1  * (AVERAGE HEAT GENERATION *)
 2030 FORMAT (6X, * TYPE II    *,F8.1, * POUNDS PER CUBIC YARD *
     1 * (HIGHER THAN AVERAGE HEAT GENERATION *)
 2100 FORMAT (8X, * POZZOLLAN *,F8.1, * POUNDS PER CUBIC YARD *)
   50 RETURN
      END
```

```
      SUBROUTINE HEATVL (T,A,B,M,IP)
      DIMENSION T(13),F1(13),AGE(13)
      DATA (AGE(I),I=1,13) /0.,2.,4.,6.,12.,20.,32.,48.,60.,96.,180.,
     1 290.,1000./
      IF (T(12).EQ..0001) T(12)=0.
      IF (T(13).EQ..0001) T(13)=0.
      PRINT 2000
      IF (M.EQ.0) GO TO 90
      READ 1000,F1
      PRINT 2200
      GO TO 100
   90 PRINT 2100
  100 DO 200 I=1,13
      HR=(A+B/2.)*T(I)
      IF (M.EQ.0) GO TO 150
      IF (F1(I).EQ.0.) F1(I)=1.
      HRM =HR*F1(I)
      PRINT 2300,AGE(I),HR,F1(I),HRM
      GO TO 190
  150 PRINT 2300,AGE(I),HR
      HRM=HR
  190 T(I)=HRM
  200 CONTINUE
      IF (IP.EQ.0) GO TO 9999
      L=1
      K=13
      A=8HHEAT GEN
      B=8HFUNCT.
      PUNCH 9000,A,B,A,B,A,B,A,B
      PUNCH 3000,L,K
      PUNCH 3100, (( AGE(I),T(I)),I=1,13)
 1000 FORMAT (13F5.0)
 2000 FORMAT (//3X, *HEAT GENERATION FUNCTION * )
 2100 FORMAT (8X, *TIME,HOURS        HEAT RATE, BTU/FT 3/HOUR * )
 2200 FORMAT (8X, *TIME,HOURS        HEAT RATE, BTU/FT 3/HOUR *,
     1 4X, * FACTOR   MODIFIED HEAT RATE *)
 2300 FORMAT (8X,F8.1,9X,F8.1,20X,F6.2,6X,F8.1)
 3000 FORMAT ( 3I5)
 3100 FORMAT (8F10.2)
 9000 FORMAT (3X,8A8)
 9999 RETURN
      END
```

APPENDIX K (Continued): PROGRAM TEMP FLOW CHART.




A
INPUT PRODUCTION RATE
(SUBR CONCOP)
CALCULATE ELEMENT CREATION
(SUBR TIMECR)
INPUT MIXTURE PROPORTIONS
(SUBR HEATGN)
INPUT HEAT FUNCTION SELECTED
(SUBR HEATGN)
CALCULATE HEAT CURVE
(SUBR HEATVL)
OUTPUT GEOMETRY
*
B



* IF SELECTED, OPTION WILL PUNCH APPROPRIATE DATA FOR USE WITH PROGRAM DETECT.

APPENDIX L: USER INSTRUCTIONS - PROGRAM TEMP

Program TEMP is described in general in Chapter 5. Below are specific instructions concerning preparation of the cards required to run the program.

I. Problem Initiation and Title - (A5,3X,18A4,15A4) Total Cards = 2

Column	Variable	Description
1 - 5	MODE	Punch START, Problem Initiation
6 - 8		BLANK
9 - 80	HED	Description for Identifying Output
Second Card		
1 - 60	HED2	Continuation of Description (can be blank card)
Note:		Only information on first card can be used directly with DETECT.

II. Structure Dimensions, Grid Generation and Punch Control Card (3F10.0,5I5) Total Cards = 1

Column	Variable	Description
1 - 10	B	Total Base Length of Structure, feet (X-direction)
11 - 20	H	Height of Structure (above foundation), feet (Y-direction)
21 - 30	D	Total Depth of Structure, feet (Z-direction, normal to 2-D grid)
31 - 34	---	
35	IN	Option (a) 0: Automatic Grid Generation. Option (b) 1: Grid coordinates specified by programmer.
36 - 39	---	
40	NB	Only specified if Option (b) IN = 1; otherwise, leave blank for Option (a). Total number of grid lines specified along base length of structure from centerline to X-boundary (max. = 18 for DETECT program).
41 - 44	---	
45	NH	Only specified if Option (b) IN = 1; otherwise, leave blank for Option (a). Total number of grid lines specified along height of structure, including any in foundation (max. = 18 for DETECT program).

Column	Variable	Description
46 - 49	---	Option (c) 0: Incremental Construction - All elements have specific creation times established in this program.
		Option (d) 1: All elements exist at start of program - used for analysis of existing structure.
51 - 54	---	
55	IP	Option (e) 0: No data cards punched for input into DETECT program.
		Option (f) 1: Punch data cards.

III. Grid Generation Cards (8F10.0) If Option (a), total cards = 0 (no cards). If Option (b), two sets of cards, as many as necessary to specify X and Y coordinates of grid.

Option (b) - First Set of Cards - X Coordinates of Grid

Column	Variable	Description
1 - 10	X(1)	X coordinate of grid measured from centerline of structure. X(1) must equal 0.
11 - 20	X(2)	Consecutive X-coordinate from centerline to X-boundary.
etc.		
71 - 80	X(8)	Consecutive X-coordinate from centerline to X-boundary.
Next Card (if necessary)		
1 - 10	X(9)	
etc.		
	X(NB)	Last X-coordinate must equal total base length ÷ 2 (total number of X-coordinate lines equals NB specified on Card II).

Option (b) - Second Set of Cards - Y Coordinates of Grid

Column	Variable	Description
1 - 10	Y(1)	If foundation coordinate, specify distance below structures as negative value (example: 20 feet below structures = -20). If no foundation elements, Y(1) must equal 0.0.

Column	Variable	Description
17 - 20	Y(2)	Foundation or structure coordinate at foundation and structure intercept. The ordinate must equal 0.0.
etc.		
	Y(NH)	Last Y-coordinate must equal height of structure (above foundation). Total number of Y-coordinates lines equals NH specified on Card II.

IV. Concreting Operations (2F10.0,2I5)

Column	Variable	Description	
1 - 10	PR	Option 1(a) -	Production rate specified, average cubic yards per hour. Can be left blank if Option 1(b) selected.
11 - 20	RT	Option 1(b) -	Total time to completion, from start to finish for structure concreting operation. Can be left blank if Option 1(a) selected.
21 - 25	NFC	Option 1: 0	Constant rate of production, constant rate of rise over entire surface.
		Option 2:	Specify total number of specific data set points given to establish rate of rise at centerline of structure (max. number = 50).
26 - 30	NFB	Option 1 or 2: 0	
		Option 3:	Specify total number of specific data set points given to establish rate of rise at X-boundary of structure.

Note:

Option 1: Constant rate of rise over entire surface.

Option 2: Rate of rise specified at center of structure (or X-boundary), constant over entire surface.

Option 3: Rate of rise specified at center and at X-boundary of structure,
linear variation between center and X-boundary
constant rate between center and Z-boundary

V. Rates of Rise Specified 4(2F10.0)

If Option (1), total cards = 0 (no cards). If Option (2), as many cards as required to specify NFC number of data points (time, height) at centerline of structure. If Option (3), as many cards as required to specify NFB number of data points (time, height) at X-boundary.

Option (2) - Rate of Rise at Centerline Specified

Column	Variable	Description
1 - 10	FT(1)	Time at height No. 1 must = 0.
11 - 20	FH(1)	Height No. 1 must = 0.
21 - 30	FT(2)	Time at height No. 2.
31 - 40	FH(2)	Height No. 2.
etc.	etc.	
	FT(NFC)	Time of completion must = RT value on Card IV.
	FH(NFC)	Total height of structure above foundation must = H on Card I.

Option (3) - Rate of Rise at X-Boundary Also Specified

Same as for Option (2) set of cards - Option (3) cards follow Option (2) cards.

Column	Variable	Description
	FT(NFB)	Time of completion must = RT value on Card IV.
	FH(NFB)	Must = total height of structure = H on Card I above foundation.

VI. Heat Generation Function (2F10.0,2I5)

Column	Variable	Description
1 - 10	CEM	Number of pounds of cement per cubic yard of concrete (if blank, no heat generation function formulated).
11 - 20	POZ	Number of pounds of pozzolan per cubic yard of concrete.
21 - 25	I	Option A: 1: Type I cement heat generation (average). Option B: 2: Type II cement heat generation (average). Option C: 3: Type II higher than average heat generation.

Column	Variable	Description
26 - 29	---	Option D: 0: No modifications to internal program heat generation functions.
30	M	Option E: 1: Modifications made to internal heat generation functions.

VII. Modification Factors (13F5.0) - No cards if Option D.
One card if Option E. (Blank card if no modification.)

Column	Variable	Description
1 - 5	F1(1)	Decimal factor multiplication of heat rate function Number 1.
6 - 10	F1(2)	Decimal factor multiplication of heat rate function Number 2.
etc.		
56 - 60	F1(12)	Function number appears as 0.0 on output, but is assumed to be .0001*CEM + POZ/2 before modification made.
61 - 65	F1(13)	

Note: On first run through, no modification need be made. Heat rate functions are printed out so future adjustments can be made if necessary.

APPENDIX M: INTERFACE INSTRUCTIONS - PROGRAMS TEMP AND DETECT

As is described in Chapter 5, program TEMP was written to provide input, based upon common variables found in a tremie concrete placement, to the finite-element program, DETECT, which does the actual temperature calculations. Below are instructions which indicate how the output from program TEMP interfaces with program DETECT. Additional information on program DETECT may be found in Polivka and Wilson's description of the program (Reference 33).

		Source	
	Number of Cards	Program "TEMP"	Must Indiv. Punch
I. Problem Initiation and Title	1	✓	
II. Master Control Card	1	*Partial Info.	✓
III. Nodal Point Coordinates	As many as number of nodes.	✓	
IV. Boundary Condition Functions			
A. Control Information	1	*Partial Info.	Check
B. Time Function Data	3	✓ Heat Gen. Values (Function 1)	
	( )		✓ Any Additional Boundary Value Functions
V. Nodal Point Boundary Conditions	As many as specified IV(A).		
VI. Element Specification			
Type 1 - A. Control Information	1	✓	Check
B. Material Properties Information	One for each material - 1. concrete 2. foundation	Cards supplied with 1 & 2 punched	✓

	Number of Cards	Source	
		Program "TEMP"	Must Indiv. Punch
C. Element Data	As many as number of elements.	✓	
Type 2 - A. Control Information	1		
B. Element Data	As many as required.		
Type 3 - Cooling Pipe Elements	None Required	—	—
VII. Solution Time Span Data			
A. Lift Data Control Cards	Number of cards specified on (II).		✓
B. Initial Conditions	As specified on VII(A) - to follow a card.		✓
VIII. New Problem Data	Same as I through VII.		
IX. Termination Card "STOP"	1		✓

APPENDIX N: SAMPLE OUTPUT - PROGRAMS TEMP AND DETECT

1. Figures N-1 through N-5 present samples of output from Programs TEMP and DETECT which are described in Chapter 5.

2. The output from Program TEMP shows the automatic grid generation and the constant rate of concrete production options. The geometry of the placement is that shown in Figure 86 of Chapter 5.

```
DIMENSIONS OF STRUCTURE                                      . Y
                                                             .
   LENGTH (X)   = 54.0 FEET                                  .
   HEIGHT (Y)   = 32.0 FEET                                  .
   WIDTHT (Z)   =142.0 FEET                                  .... X
                                                            .
                                                       Z  .

CONCRETING OPERATING          USER OPTION NUMBER   1
      (PRODUCTION RATE SPECIFIED, CONSTANT RATE OF RISE OVER ENTIRE SURFACE)

   TOTAL CONCRETE VOLUME                          = 9372.00 CUBIC YARDS
   PRODUCTION RATE, AVERAGE                       =  150.00 CUBIC YARDS PER HOUR
   RATE OF RISE, AVERAGE AT CENTER OF STRUCTURE   =     .53 FEET PER HOUR
   TIME TO COMPLETION                             =   62.48 HOURS
```

Figure N-1. Sample output, Program TEMP, showing geometry of placement and program options selected.

```
CEMENT SPECIFICATIONS

          TYPE II        526.0 POUNDS PER CUBIC YARD  (AVERAGE HEAT GENERATION
          POZZOLLAN      165.0 POUNDS PER CUBIC YARD

HEAT GENERATION FUNCTION
        TIME,HOURS         HEAT RATE, BTU/FT 3/HOUR
            0.                   0.
            2.0                 79.1
            4.0                 88.2
            6.0                103.4
           12.0                109.5
           20.0                 63.9
           32.0                 26.8
           48.0                 11.0
           60.0                  7.3
           96.0                  4.3
          180.0                   .6
          290.0                  0.
         1000.0                  0.
```

Figure N-2. Sample output, Program TEMP, showing cementitious materials contents selected and resulting heat generation function.

```
PRODUCTION RATE

     HEIGHT, FEET        TIME, HOURS (DAYS)             TIME, HOURS (DAYS)
                          AT CENTERLINE                  AT X-BOUNDARY
            0             0.                             0.
            1             1.89 (   0.   )                1.89 (   0.   )
            2             3.79 (    .08)                 3.79 (    .08)
            3             5.68 (    .16)                 5.68 (    .16)
            4             7.57 (    .24)                 7.57 (    .24)
            5             9.47 (    .32)                 9.47 (    .32)
            6            11.36 (    .39)                11.36 (    .39)
            7            13.25 (    .47)                13.25 (    .47)
            8            15.15 (    .55)                15.15 (    .55)
            9            17.04 (    .63)                17.04 (    .63)
           10            18.93 (    .71)                18.93 (    .71)
           11            20.83 (    .79)                20.83 (    .79)
           12            22.72 (    .87)                22.72 (    .87)
           13            24.61 (    .95)                24.61 (    .95)
           14            26.51 (   1.03)                26.51 (   1.03)
           15            28.40 (   1.10)                28.40 (   1.10)
           16            30.29 (   1.18)                30.29 (   1.18)
           17            32.19 (   1.26)                32.19 (   1.26)
           18            34.08 (   1.34)                34.08 (   1.34)
           19            35.97 (   1.42)                35.97 (   1.42)
           20            37.87 (   1.50)                37.87 (   1.50)
           21            39.76 (   1.58)                39.76 (   1.58)
           22            41.65 (   1.66)                41.65 (   1.66)
           23            43.55 (   1.74)                43.55 (   1.74)
           24            45.44 (   1.81)                45.44 (   1.81)
           25            47.33 (   1.89)                47.33 (   1.89)
           26            49.23 (   1.97)                49.23 (   1.97)
           27            51.12 (   2.05)                51.12 (   2.05)
           28            53.01 (   2.13)                53.01 (   2.13)
           29            54.91 (   2.21)                54.91 (   2.21)
           30            56.80 (   2.29)                56.80 (   2.29)
           31            58.69 (   2.37)                58.69 (   2.37)
           32            60.59 (   2.45)                60.59 (   2.45)
           33            62.48 (   2.52)                62.48 (   2.52)
```

Figure N-3. Sample output, Program TEMP, showing rate of concrete rise at centerline and X-boundary of placement for a constant rate of concrete production.

```
TWO-DIMENSIONAL FINITE ELEMENT ANALYSIS

  ANALYSIS OF SECTION SYMMETRIC ABOUT CENTERLINE OF STRUCTURE
  TOTAL NUMBER OF BASE DIVISIONS     =  11      BASE   =  27.0 FEET (CENTERLINE TO X-BOUNDARY)
  TOTAL NUMBER OF HEIGHT DIVISIONS   =  15      HEIGHT =  33.0 FEET +  20.0 FEET OF FOUNDATION

  TOTAL NUMBER OF NODAL POINTS       = 165
  TOTAL NUMBER OF ELEMENTS           = 140

HEIGHT    NODAL POINTS FOR TEMPERATURE ANALYSIS,ELEMENT NUMBERS AND ELEMENT CREATION TIMES (HOURS)

   4.0 *    56.    57.    58.    59.    60.    61.    62.    63.    64.    65.    66.

               41     42     43     44     45     46     47     48     49     50
              5.7    5.7    5.7    5.7    5.7    5.7    5.7    5.7    5.7    5.7

   2.0 *    45.    46.    47.    48.    49.    50.    51.    52.    53.    54.    55.

               31     32     33     34     35     36     37     38     39     40
              2.4    2.4    2.4    2.4    2.4    2.4    2.4    2.4    2.4    2.4

    .5 *    34.    35.    36.    37.    38.    39.    40.    41.    42.    43.    44.

               21     22     23     24     25     26     27     28     29     30
               .5     .5     .5     .5     .5     .5     .5     .5     .5     .5

    0.  *   23.    24.    25.    26.    27.    28.    29.    30.    31.    32.    33.

               11     12     13     14     15     16     17     18     19     20
              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

 -10.0 *    12.    13.    14.    15.    16.    17.    18.    19.    20.    21.    22.

                1      2      3      4      5      6      7      8      9     10
              0.     0.     0.     0.     0.     0.     0.     0.     0.     0.

 -20.0 *     1.     2.     3.     4.     5.     6.     7.     8.     9.    10.    11.
       ***********************************************************************
            0.    5.0   10.0   15.0   20.0   22.0   24.0   25.0   26.0   26.5   27.0

  CENTERLINE                   HORIZONTAL DISTANCE FROM CENTERLINE OF STRUCTURE, FEET
```

Figure N-4. Sample output, Program TEMP, showing a portion of the finite element grid generated by the program.

```
TEMPERATURES AT TIME STEP =     2  (TIME =   .1600E+02)
    1    .550002E+02     2    .550001E+02     3    .550001E+02
    7    .549983E+02     8    .549984E+02     9    .550359E+02
   13    .550232E+02    14    .550203E+02    15    .550199E+02
   19    .549729E+02    20    .548700E+02    21    .550015E+02
   25    .621439E+02    26    .621404E+02    27    .620394E+02
   31    .608144E+02    32    .586718E+02    33    .550000E+02
   37    .835771E+02    38    .833343E+02    39    .835592E+02
   43    .718657E+02    44    .550000E+02    45    .105414E+03
   49    .942864E+02    50    .946727E+02    51    .945194E+02
   55    .550000E+02    56    .975770E+02    57    .883785E+02
   61    .882948E+02    62    .881642E+02    63    .875944E+02
   67    .745291E+02    68    .709457E+02    69    .709231E+02
   73    .708599E+02    74    .706720E+02    75    .693927E+02

TEMPERATURES AT TIME STEP =     4  (TIME =   .2000E+02)
    1    .550005E+02     2    .550001E+02     3    .550002E+02
    7    .549966E+02     8    .550005E+02     9    .550634E+02
   13    .550386E+02    14    .550337E+02    15    .550331E+02
   19    .549489E+02    20    .548213E+02    21    .550571E+02
   25    .644492E+02    26    .644442E+02    27    .643113E+02
   31    .622869E+02    32    .594572E+02    33    .550000E+02
   37    .870278E+02    38    .867608E+02    39    .869999E+02
   43    .722344E+02    44    .550000E+02    45    .116364E+03
   49    .102801E+03    50    .102256E+03    51    .102999E+03
   55    .550000E+02    56    .112664E+03    57    .999443E+02
   61    .998134E+02    62    .995791E+02    63    .984352E+02
   67    .912901E+02    68    .836533E+02    69    .835972E+02
   73    .834258E+02    74    .828236E+02    75    .794122E+02
```

Figure N-5. Sample output, Program DETECT, showing node numbers and temperatures at the nodes at 16 and 20 hours after the beginning of concrete placement.