DEVELOPMENT OF A CONTINUOUS SHAFT LINING SYSTEM

VOLUME II

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DEVELOPMENT OF A CONTINUOUS
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ROBERT TORBIN, TOM BRUNSING
DOUGLAS OUNANIAN, RAY HENDERSON
JONATHAN KELLY, GEORGE KIRBY

FOSTER-MILLER, INC.
350 SECOND AVE
WALTHAM, MA 02154

3

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16. Abstract (Limit: 200 words)

The objectives of the Continuous Shaft Lining (CSL) System are to reduce the costs, safety hazards, and time currently required in lining mine shafts with concrete. The CSL will line machine bored shafts downward from the shaft collar on a continuous basis using an inverted, pressurized slipforming technique. The technique for slipforming downwards has been demonstrated and refined under this program. The approach taken involved laboratory scale testing of key features of the CSL concept. These feature tests included concrete distribution, concrete sealing, concrete slipforming and development of a reliable concrete mix. Based on these results, a full scale above-ground test facility and CSL were designed and fabricated. The objectives of these tests were to demonstrate the viability of the basic concept; to establish operating limits; and to provide input data and information for the design of a second generation shaft lining system. The results of the program have led to a CSL design and operational philosophy which will need to be tested in an underground environment before industry will accept the technology. However, the next generation CSL promises to meet all the original program technical objectives.

17. Document Analysis   a. Descriptors

MECHANIZED SHAFT LINING SYSTEM
CONTINUOUS CONCRETE SHAFT LINING
CONCRETE SLIPFORMING DOWNWARD

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

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4

VOLUME II

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

6

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

8

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

10

LIST OF TABLES

ACKNOWLEDGEMENT

1. BACKGROUND LABORATORY STUDIES

1.1 Introduction

As contractually structured, the CSL program plan was organized in a logical step-by-step sequence of events. Initially, feature tests were done in the laboratory to study key, elementary aspects of the total concept. In other words, specific attributes of the continuous downward slipforming process were separately examined in individualized test rigs. In this manner, if there was something inherently incorrect with the concept it would be detected early in the program and corrected. This would prevent costly problems from occurring during the later phases of full scale tests. After careful consideration, four features of the CSL concept were isolated for feature testing. These included:

a. Concrete mix design

b. Concrete distribution

c. Concrete slipforming

d. Concrete sealing.

Each of these feature tests will be discussed in detail in the following subsections.

1.2 Concrete Mix Design

1.2.1 Objectives and Scope of Testing

The concrete mix design study was undertaken to develop a concrete that would meet the short- and long-term behavioral requirements set out in Volume I, subsection 2.4. These requirements were chosen to ensure safe slipforming and provide a void-free, durable lining.

The short-term performance requirements were as follows:

a. Initial slump of 6 to 8 in.

b. Slump loss not to exceed 4 in. in 30 min

c.   Strength gain of 25 to 50 psi (in compression) within 3 hr and 100 psi within 4 hr of mixing

d.   Measured air content of 4 to 6 percent.

The long-term performance requirements were:

a.   Final strength - 3000 psi minimum

b.   Shrinkage limited to 800 µin./in. (0.08 percent)

c.   Sulfate resistance - expansion limited to 1000 µin./in. (0.10 percent)

d.   Adequate freeze-thaw resistance.

It was decided at the outset of laboratory testing that if a concrete could not be designed to meet both short- and long-term requirements, the short-term behavior would be given primary consideration. This would at least facilitate demonstration of the CSL concept. Further, if a mix could not be designed to meet all of the short-term performance criteria, the mix with the best performance would be used for testing while the investigation of other formulations and combinations continued in the laboratory.

1.2.2   Materials

This subsection describes the materials used in developing the CSL mix design.

1.2.2.1   Aggregates

All the aggregate used in the CSL mix design studies was from New England Sand and Gravel Company, Framingham, Massachusetts.

The coarse aggregate was a blend of nominal 3/4-in. (19-mm) and 3/8-in. (10-mm) maximum sized washed bank run gravel, containing crushed stone. The sand was concrete sand.

Gradations, bulk specific gravities, absorption at saturated surface dry conditions, and unit weights are reported in Tables 1 and 2, and Figures 1 and 2.

TABLE 1. - <u>Sieve analysis of fine and coarse aggregate</u>

Sieve	Sand	Percent retained		
		3/8-in.	3/4-in.	Combined 3/8-in. and 3/4-in.
3/4-in. (19-mm)	0.00	0.00	6.98	4.19
1/2-in. (13-mm)	0.00	0.00	75.57	45.34
3/8-in. (10-mm)	0.01	12.78	95.78	62.58
No. 4	1.00	80.57	98.32	91.22
No. 8	14.58	98.03	98.55	96.45
No. 16	32.72	99.27	98.82	97.28
No. 30	57.30	99.38	98.76	99.01
No. 50	76.91	99.49	99.18	99.30
No. 100	92.87	99.61	99.32	99.43
No. 200	97.80	99.72	–	–
Fineness modulus	2.75	5.89	7.71	6.95

TABLE 2. - <u>Properties of fine and coarse aggregate</u>

Property	Sand	3/8-in.	3/4-in.
Dry rodded unit-weight lb/ft^3 (kg/m^3)	100.50 (1610)	100.00 (1602)	100.00 (1602)
Bulk specific gravity, SSD	2.69	2.61	2.68
Moisture content, SSD	1.96	1.15	0.71
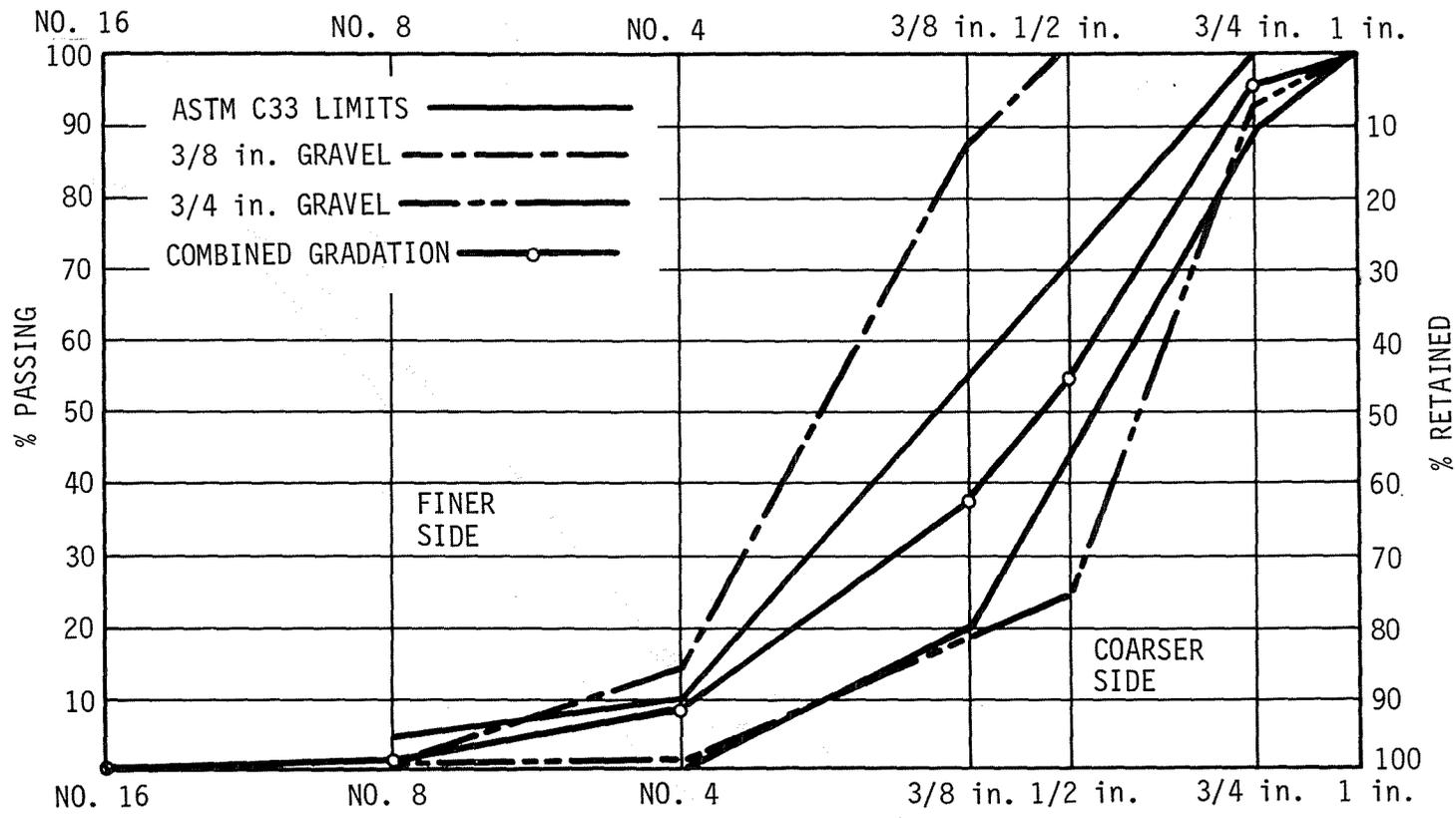
FIGURE 1. - Coarse aggregate gradation.
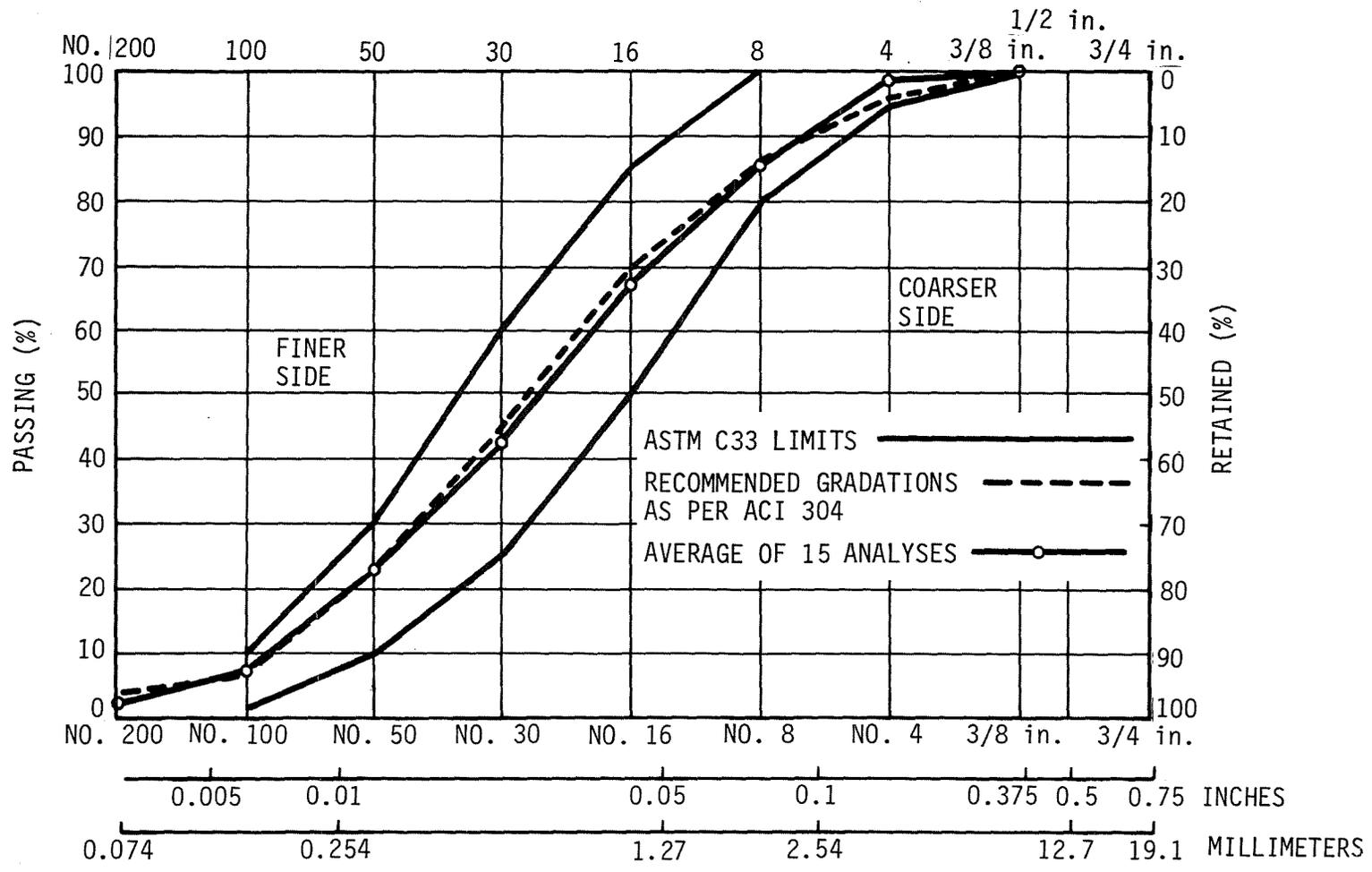
FIGURE 2. - Fine aggregate gradation.

1.2.2.2 Cement

Several cements were used in the laboratory concrete batches during the design mix experiments. A listing of these cements follows:

a.   Martin Marietta Type II Portland Cement, Martin Marietta Cement, Eastern Division, Thomaston, Maine. Material properties are listed in Appendix F.

b.   Martin Marietta Type III Portland Cement. Material properties are listed in Appendix F.

c.   Shrinkage – compensation cement Type K. Chemcomp cement. CTS Cement Manufacturing Co., Sherman Oaks, California. Material properties are listed in Appendix F.

d.   Iron Clad Type III Portland Cement, Flintkote Cement Company, Glens Falls Division, Glens Falls, New York. Material properties are listed in Appendix F.

e.   Fondu® Calcium Aluminate Cement, Lone Star Lafarge, Inc., Norfolk, Virginia. The material properties are listed in Appendix F.

g.   Atlas Lumnite Calcium-Aluminate Cement, Universal Atlas Cement Division, United States Steel Corporation, Pittsburgh, PA. The material properties are listed in Appendix F.

1.2.2.3 Fly Ash

Fly ash from Detroit Edison Co., Detroit, MI was used in some of the mixes in the test program. It conformed to pozzolan Class F of ASTM C618.

1.2.2.4 Admixtures

Accelerators

The accelerator used in most of the mixes was regular flake calcium chloride made by Allied Chemical Company, Solvay, New York. The calcium chloride was packaged in 100-lb bags of which 77.8 lb was pure calcium chloride.

Other accelerators used during the laboratory mix design tests were:

a.   Darex$^{®}$ Set Accelerator (DSA), W.R. Grace & Co.,
     Cambridge, Massachusetts. Darex Set Accelerator
     is a nonchloride accelerator. It is a dry white
     powder that can be added directly to the cement or
     aggregate. DSA is an ASTM 494 Type C admixture.

b.   Darex$^{®}$ Corrosion Inhibitor (DCI) was used as an
     accelerator. It is also marketed by W.R. Grace.
     Darex$^{®}$ Corrosion Inhibitor is a liquid and gen-
     erally added to concrete to prevent electrolytic
     corrosion of reinforcing steel. Representatives
     of W.R. Grace indicated that DCI may also act as
     an accelerator, therefore, it was used in a few
     mix trials. DCI is an ASTM C494 Type C admixture.

c.   Admixture LL-880, Master Builders, Division of Martin
     Marietta Corp., Independence, OH. LL-880 is a liquid,
     nonchloride accelerator which meets ASTM C494 Type C
     and E designations.

d.   Lithium carbonate - nonproprietary inorganic compound.

1.2.2.5 Water-Reducers and Superplasticizers

The following water-reducers and superplasticizers were
used in the mix design testing:

a.   Mighty$^{®}$ 150 is a superplasticizer marketed by ICI
     Americas, Inc., Wilmington, Delaware. This super-
     plasticizer contains 42 percent naphtalene sulfonate
     formaldehyde condensate, the active ingredient, and
     58 percent water. The specific gravity is 1.2.
     Mighty 150 meets ASTM C494 Type A and C requirements.

b.   Mighty$^{®}$ RD2 super water-reducer and retarder, ICI
     Americas, Inc. The specific gravity is 1.2. Mighty
     RD2 meets ASTM C494 Type D requirements.

c.   Plastiment is a water-reducing retarder marketed by
     Sika Chemical Corporation, Lyndhurst, New Jersey.
     Plastiment contains 32 percent solids. The active
     ingredient is a metallic salt of hydroxylated carboxy-
     lic acid. Plastiment meets ASTM C494 Type D
     requirements.

d. Pozzolith 122-R water-reducer and retarder, Master
    Builders, Division of Martin Marietta Corporation,
    Independence, Ohio. This admixture meets ASTM C494
    Type B and D requirements

e. Pozzolith 100-XR water-reducer and retarder is also
    marketed by Master Builders. It also meets ASTM C494
    Type B and D requirements.

f. Pozzolith 300N water-reducer marketed by Master
    Builders. It is an ASTM C494 Type A admixture.

g. Pozzolith 122-HE water-reducer marketed by Master
    Builders. It is an ASTM C494 Type C and E admixture.

h. WRDA Hycol water-reducer marketed by W.R. Grace Co.
    It is an ASTM C494 Type A admixture.

i. Lomar D superplasticizer marketed by Diamond Shamrock
    Corp., Morristown, NJ. It is an ASTM C494 Type A
    admixture.

1.2.2.6 Air Entraining Agents

The final design mix air entraining agent was Daravair®,
a product marketed by W.R. Grace & Co., Cambridge, Massachusetts.
Daravair is neutralized vinsol resin in aqueous solution. The
specific gravity is 1.02 to 1.09 and the pH is 11.0 to 13.0.

Prior to July 12, 1982 all mix designs used Darex AEA®.
Darex AEA is also marketed by W.R. Grace. Darex AEA contains
organic acid salts in aqueous solution. It has a specific
gravity of 1.02. Both Daravair and Darex AEA are ASTM C260
type air-entraining admixtures. Daravair was used in the mix
design after Darex AEA could not produce more than 4 percent
air content in the simulation test trials.

1.2.3 Standard Tests and Specifications

American Society for Testing and Materials standard tests
and specifications are cited throughout this report. The fol-
lowing is a list of pertinent specifications:

C 29-78   Unit Weight and Voids in Aggregate

C 31-69   Making and Curing Concrete Test Specimens in the
          Field

C 33-81   Concrete Aggregates

C 39-80   Compressive Strength of Cylindrical Concrete
           Specimens

C 88-76   Soundness of Aggregates by use of Sodium Sulfate
           or Magnesium Sulfate

C 127-80   Specific Gravity and Absorption of Coarse
           Aggregate

C 128-79   Specific Gravity and Absorption of Fine
           Aggregate

C 136-81   Sieve Analysis of Fine and Coarse Aggregates

C 138-77   Unit Weight, Yield, and Air Content (Gravimetric)
           of Concrete

C 143-78   Slump of Portland Cement Concrete

C 150-81   Portland Cement

C 192-81   Making and Curing Concrete Test Specimens in
           the Laboratory

C 231-81   Air Content of Freshly Mixed Concrete by the
           Pressure Method

C 403-80   Time of Setting of Concrete Mixtures by Pene-
           tration Resistance

C 452-75   Potential Expansion of Portland Cement Mortars
           Exposed to Sulfate.

1.2.4   Laboratory Test Facility

All the work performed in support of the concrete mix
design study was done in the concrete laboratory at Foster-
Miller's Waltham facility. The facility is fully equipped
for formulating and evaluating various mix designs. The
laboratory is completely enclosed and has independent tempera-
ture and humidity control.

Major components of the laboratory include:

a.   250,000-lb electrically powered, hydraulic, concrete
      specimen tester

b.   Temperature controlled fog curing room

c.   Wash-down sump for trapping waste concrete

d.   Microwave oven for drying aggregates to determine moisture content

e.   Vibrating table for consolidating test specimens

f.   Aggregate bin hatches for access to raw aggregate supplies

g.   Work tables for general tasks

h.   Water tub for water-curing specimens.

In addition to major components of the laboratory, there are a number of other pieces of laboratory test equipment. These include:

a.   Length comparator for volume change measurements

b.   Complete United States sieve set and shaker

c.   Gilmore and Vicat needle time of setting apparatus

d.   Immersion concrete vibrator

e.   Tumble type, 3.5-ft^3 concrete mixer

f.   Slump cones and tamping rods

g.   Compressive strength cylinder molds (6 × 12 in.)

h.   Flexural strength molds (6 × 6 × 12 in.)

i.   Bar molds (2 × 2 × 10 in.)

j.   Air content measuring device

k.   Unit weight containers.

1.2.5 Organization of Test Results

The concrete mix design test results are organized by cement type. For each cement used the following data is provided:

a.   Number of batches tried

b.   Range of water-cement ratio used

c.   Admixture combinations used

d.   Slump trends

e.   Strength gain trends

f.   Suitability for CSL use.

Specific data for each of the 127 mix trials made is provided in Appendix F. Only summary data is provided herein. For all of the mix designs long-term properties were measured only in the event the short-term behavior was acceptable.

Some mixes were formulated with more than one admixture. In these cases precautions were taken to make sure the admixtures were added separately. Some admixture combinations proved not to be compatible despite mixing procedures. No combination of admixtures was used that was known to cause a problem such as the addition of calcium chloride to high-alumina cement.

1.2.5.1 Results Using Type II Cement

A total of four mixes were tested using Type II cement. Mixes made with Type II were not expected to show early strength. The purpose for the testing was to determine general mix proportions and water demand without the use of a plasticizer. It also allowed observation of the effect of Darex Set Accelerator (DSA) on slump behavior. Sizeable slump loss did occur within 1 hr of mixing, however, the mix remained workable well into the second hour.

The results are summarized below:

a.   Number of batches made - 4

b.   Range of water-cement ratio - 0.40 to 0.43

c.   Cement factor - 564 lb/yd^3

d.   Admixtures used - Darex AEA, Darex Set Accelerator (DSA) (4 percent)

e.   Slump trend - gradual slump loss from 6 to 3 in. in 60 min

f.   Strength gain - no strength up to 4 hr

g.   Suitability for use - not suitable.

1.2.5.2 Results Using Type III (Martin-Marietta)

Fifty-eight trial batches using Martin-Marietta brand
Type III cement were made. Accelerator additions of 4 to
6 percent DSA and 2 to 4 percent calcium chloride were used
to increase early strength. Various plasticizer types and
contents were used in an attempt to prolong slump without
adversely affecting strength development.

In general, the results were not very good. Mixes with
high accelerator contents usually stiffened very quickly,
usually reaching zero slump within 15 to 20 min after mixing.
Early compressive strengths for these mixes were fairly good
with about 20 psi in 2 hr and 300 psi in 3 hr. Attempts to
improve slump behavior using more plasticizer, more water, or
less accelerator resulted in a sharp loss in early strength.
Mixes that did exhibit a favorable workability range up to
45 min had very little measurable strength within 3 hr.

Although some mix designs using an accelerated Type III
showed some potential for use; it appeared that another compo-
sition or brand of Type III might provide better performance.

The mix result summary for Martin-Marietta Type III is
provided below:

  a. Number of batches made - 58

  b. Range of water-cement ratio - 0.35 to 0.50

  c. Cement factor - 564, 658, and 752 lb/yd^3

  d. Admixtures used - Darex AEA, 4 to 7 percent DSA,
      2 to 4 percent CaCl$_2$, 1.2 to 5.5 percent water-
      reducers and plasticizers

  e. Slump trend - slump loss could be controlled ade-
      quately with water-reducers and plasticizers, but
      strength gain was reduced with improved workability

  f. Strength gain - poor strength gain for all mixes
      except those with rapid slump loss in which case
      strength was good

  g. Suitability for use - some possible use for slowest
      slipforming rates, however, generally unsuitable.

1.2.5.3 Results Using Expansive Cement (Type K)

Mix trials were performed using Type K cement. Twenty-three trial batches were made. Based on the cement manufacturer's recommendations, only nonchloride DSA accelerator was used. Mixes were made with and without water-reducers.

Results were generally inconclusive. Some formulations using no water-reducer and 6 percent DSA performed fairly well. Both adequate slump history and some early strength was measured. Air content, however, was very erratic. In addition, many of the strength samples were friable and mealy.

Other mix combinations, especially those containing plasticizers, exhibited high air content with little or no air entraining agent. Mixes also appeared to have an uneven, clumpy texture. Admixture or admixture/cement incompatibility was suspected.

Due to the erratic behavior of these mixes further testing was suspended. If a proper combination of admixtures could be identified, Type K cement concretes may perform to required specifications. The summary for Type K formulation trials follows:

a. Number of batches made - 23

b. Range of water-cement ratio - 0.35 to 0.48

c. Cement factor - 564 and 658 lb/yd^3

d. Admixtures used - Darex AEA, 3 to 6 percent DSA, 0.3 to 1.5 percent water-reducers and plasticizers

e. Slump trend - slump loss could be controlled if air content did not exceed 7 percent. Many mixes appeared lumpy and not well mixed.

f. Strength gain - some early strength measured, however, well below desired minimums. Hardened samples were friable.

g. Suitability for use - some potential if problems with air content and friable texture can be resolved.

1.2.5.4 Results Using Fondu© and Lumnite© High-Alumina Cements

Only seven mixing trials were performed using high-alumina cement. Three were made with Fondu and the remaining four with Lumnite. Lithium carbonate in powdered form was used as the accelerator following recommendations provided by the cement manufacturer. Plastiment® retarding densifier (plasticizer) was used with the lithium carbonate to improve workability.

All of the mix trials showed about the same behavior. In general, slump loss was rapid and strength gain low although one combination produced 30 psi in 2 hr and 600 psi in 3 hr. Slump for this particular batch was zero at 15 min after mixing.

One major problem encountered in using accelerated high-alumina cement mixes is controlling the admixture addition. The amount of accelerator required is very small and the behavior of the concrete is sensitive to small changes in accelerator content. Only 5 grams of lithium carbonate addition for each 100 lb of cement changes the stiffening time from 2 hr down to minutes. Twice this amount may cause flash set. The logistics of adding an accelerator in well-controlled dosages of grams per cubic yard of concrete is impractical.

Since no other accelerator such as calcium chloride could be used with high-alumina cement, no further trials were performed. The summary of the test results follows:

a. Number of batches made - 7

b. Range of water-cement ratio - 0.35

c. Cement factor - 752 lb/yd^3

d. Admixtures used - Darex AEA; Lithium Carbonate accelerator - 1 to 9 grams per 100 lb cement (0.002 to 0.02 percent); plastiment water-reducer - 1 to 3 fluid oz. per 100 lb cement

e. Slump trend - rapid slump loss in most cases, one flash set

      f.   Strength gain - despite poor workability most strengths were low with one exception (flash set)

      g.   Suitability for use - none.

1.2.5.5 Results Using Ironclad Type III Cement

Short-Term Properties

Thirty-five trial batches were made with Ironclad (Flint Kote Cement Co.) Type III cement. This cement was the second Type III used. The mill test report for this cement indicated a potential for more rapid early strength development than other Type III cements. This was due to a higher fineness which favorably influences the setting and early strength character- istics. However, this cement also had a high tricalcium alumin- ate ($3C_AO \cdot Al_2O_3$) content. This reduces sulfate resistance and set time, and may also affect long-term strength. Despite these potential drawbacks the Ironclad Type III was tested.

Three different admixtures were used as accelerators. These were calcium chloride, Masters Builder's LL880, and Darex Corrosion Inhibitor (DCI). LL880 is a nonchloride accelerator. DCI is not generally used as an accelerator, but has been ob- served to reduce set time in certain applications, according to the manufacturer.

Mighty 150 and Lomar D superplasticizers were used for most of the mixes although a number of other water-reducer combinations were tried.

Of all of the mix combinations, only mixes made with calcium chloride showed any promise. Additions of 2 percent, which is normally considered the maximum dosage, produced fairly low strengths through 4 hr after mixing. Three percent calcium chloride increased early strength to about 20 to 80 psi at 3 hr. Attempts made to further increase early strength by lower- ing the water-cement ratio and increasing the plasticizer content did not work consistently. Slump behavior became er- ratic at plasticizer contents near 2 percent. Calcium chloride additions in excess of 3 percent were not attempted.

A summary of the test results using Ironclad Type III follows:

a.   Number of batches made - 35

b.   Range of water-cement ratio - 0.35 to 0.44

c.   Cement factor - 752 lb/yd^3

d.   Admixtures used - Darex AEA and Daravair; calcium chloride, LL-880, and DCI used as accelerators. Mighty 150 and Lomar D used as plasticizers for most trials.

e.   Slump trend - satisfactory slump behavior with 3 percent calcium chloride and 1.5 to 1.8 percent plasticizer.

f.   Strength gain - only moderate strength (average 50 psi in 3 hr)

g.   Suitability for use - best candidate.

Long-Term Properties

Since the short-term behavior of mixes made with Ironclad Type III cement was promising, a series of long-term was conducted.

The long-term testing included:

a.   Strength-time testing up to 90 days

b.   Measurement of shrinkage potential

c.   Measurement of expansion for assessing sulfate resistance.

Strength-Time Testing

A series of 6 in. diam, 12 in. long compressive strength samples was made using the final mix design to assess long-term strength.

Testing was conducted at 1, 4, 7, 28 and 90 days after casting. At least three samples were tested at each time interval. The strength-time results are presented in Table 3.

TABLE 3. - <u>Results of long-term strength-time testing</u>

Test age	1 day	4 days	7 days	28 days	90 days
Average compressive stress	3350	5090	5970	7220	8370
Number of samples	7	3	5	5	11

Results indicate that the long-term strength continues to improve through 90 days with no sign of strength regression. Isolated samples at 180 days exceeded the capacity of the laboratory testing machine (8850 psi).

Shrinkage Potential

Shrinkage measurements were made on eleven 2 × 2 × 10 in. long bars. Concrete sampled from the long-term strength measurements was used for all bars. Measurements were made in accordance with ASTM C157. Measurements were taken periodically for 200 days. A plot of the average length change for all eleven samples is provided in Figure 3.

The total shrinkage is in excess of 1100 μin./in. The high values are most likely due to both high cement and calcium chloride content. In general, this level of shrinkage is considered to be excessive for almost all structural uses.

For shaft lining applications, the impact of the shrinkage test results varies depending on the water conditions in the shaft. The test specimen measurements only indicate the shrinkage potential of the in-place lining. The actual shrinkage is primarily dependent on the amount of moisture that is allowed to escape from the concrete. In dry ground conditions, the shrinkage will reach the full potential indicated by the specimens, but over a longer period of time because of the lower surface to volume ratio of the lining. For more common conditions, where the lining remains either completely saturated or saturated at the ground/lining interface, less total shrinkage will occur. In the latter case, however, differential shrinkage and resulting stresses will be induced. Therefore, for most in-place conditions, except those when the lining remains saturated, it would be desirable to use a concrete with lower shrinkage potential.
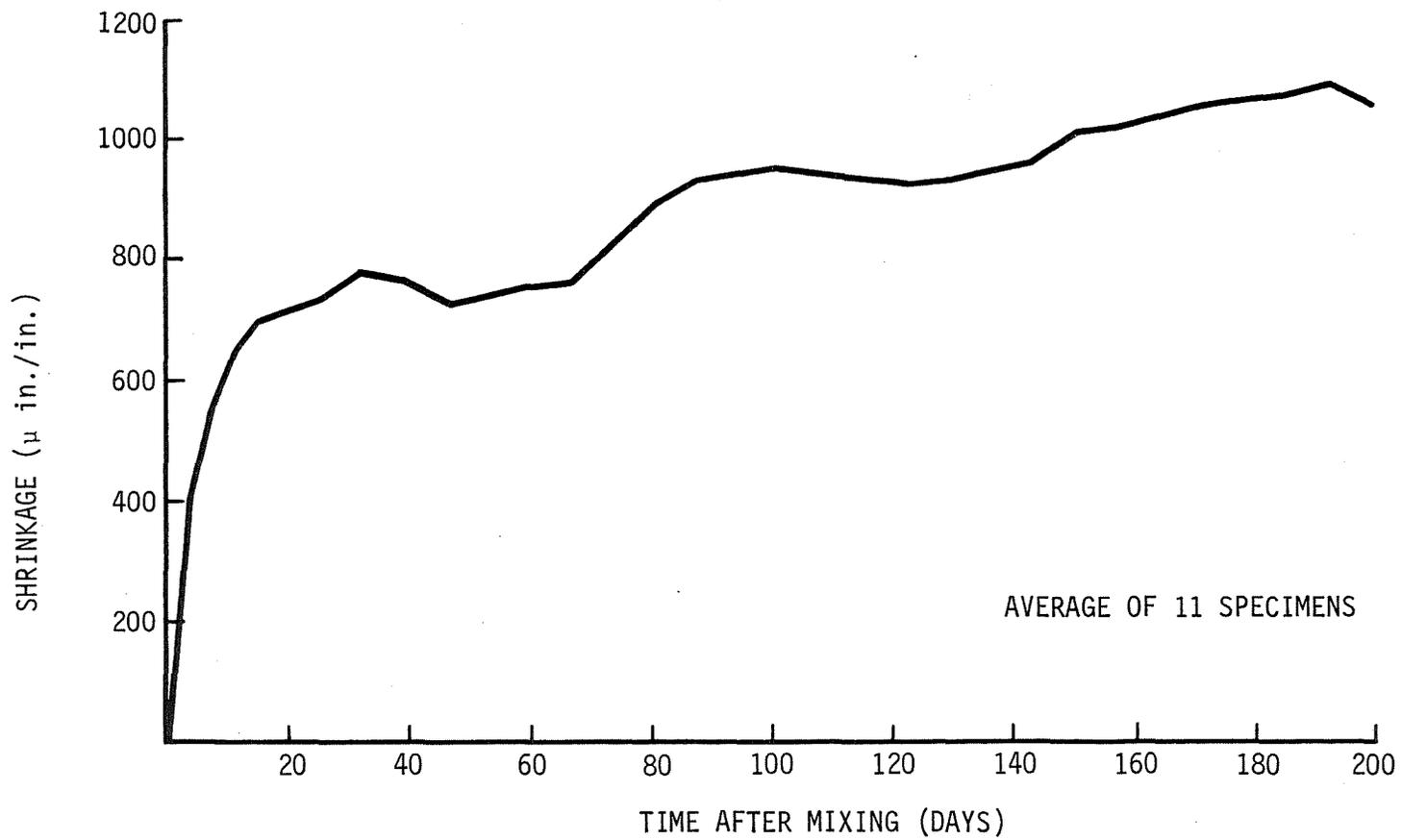
FIGURE 3. - Shrinkage potential of CSL concrete (2 × 2 × 10-in. specimens).

Sulfate Resistance

The expansion of eleven 2 × 2 × 10-in. bars placed in a
10-percent sodium sulfate solution was monitored. Length change
measurements were made throughout a period of 160 days after
casting.

Figure 4 shows the average expansion of the bars placed in
sulfate solution. Measurements on the bars in sulfate solution
were abandoned at 160 days after the concrete had reached a
point of severe degradation. Concrete subject to expansion is
considered to have reached failure at about 0.02 percent elongation.
This failure level is identified on Figure 4 and was reached after
about 80 days of exposure.

Although testing was conducted under accelerated conditions
by using a strong sulfate solution, the results clearly indicate
that this concrete formulation has very poor sulfate resistance.
This is due to the large amount of calcium chloride in the mix
and the use of a cement with a high tricalcium aluminate
content. This particular concrete mix should not be used in
applications where sulfate groundwaters would be encountered.

1.2.6 Conclusions from Mix Design Testing

Of all of the cements considered, only Ironclad Type III
showed promise for use in demonstrating the CSL. The remaining
candidates Type II, Martin-Marietta Type III, Expansive Type K,
and High-Alumina were all deficient.

Based on the results of the mix design testing a final mix
design was chosen for the CSL demonstration tests. The final
mix design proportions are shown in Table 4.

The following specific conclusion can be drawn from the
results of the test program:

a.   Workability time and strength gain are interrelated -
      increases in workability time result in a direct
      delay in strength gain. Despite the array of ad-
      mixtures and combinations used it was not possible
      to prolong workability while decreasing set time.

b.   High-alumina cements are difficult to control. Be-
      havior is sensitive to very small accelerator additions.
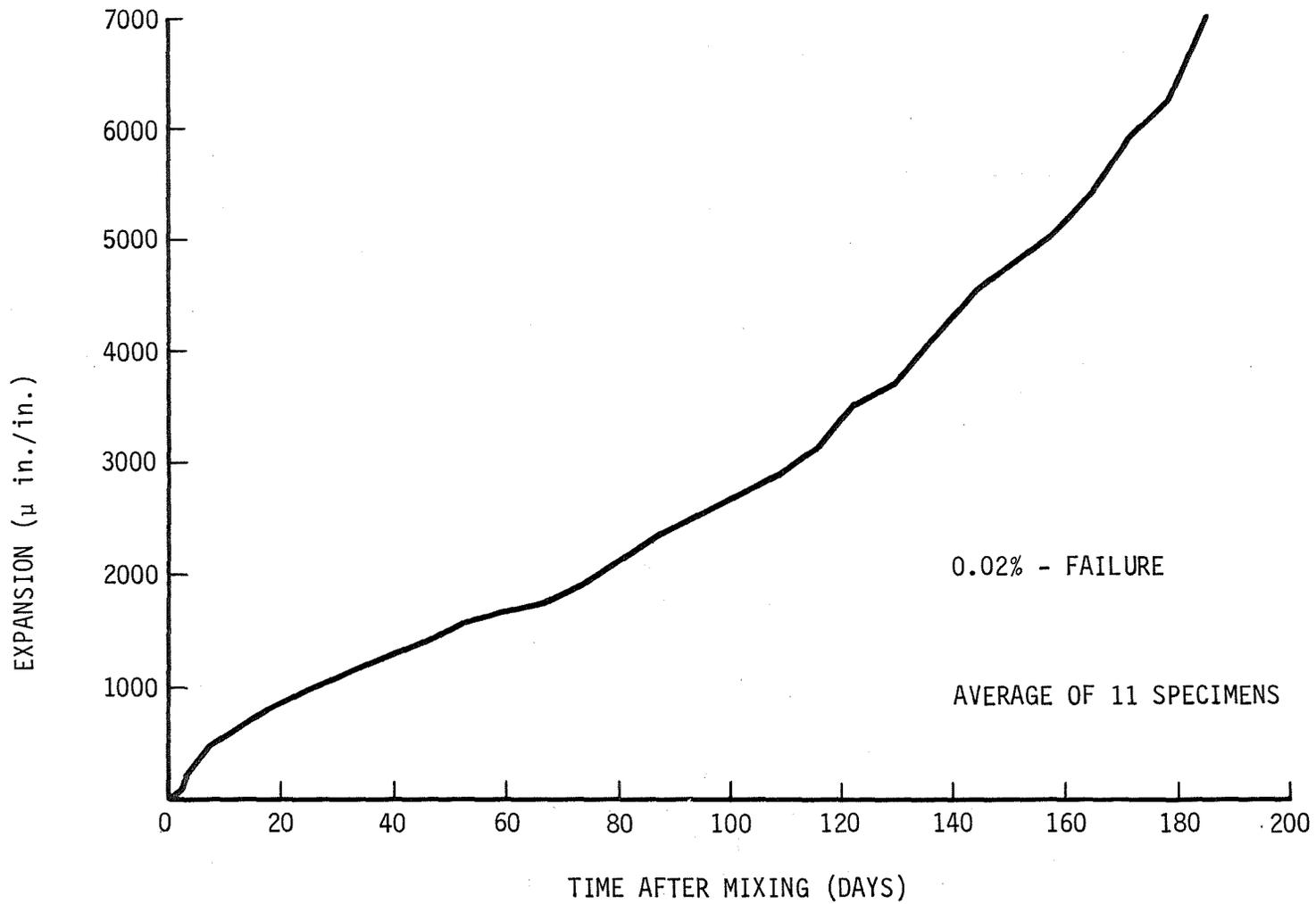
FIGURE 4. - Expansion of CSL concrete due to sulfate exposure
(2 × 2 × 10-in. specimens).

TABLE 4. - Final CSL mix design

a.	Ironclad Type III Portland Cement - 752 lb/yd^3
b.	Sand - 1225 lb/yd^3
c.	3/8-in. stone - 600 lb/yd^3
d.	3/4-in. stone - 900 lb/yd^3
e.	0.42 water-to-cement ratio
f.	1.5%* Mighty 150 superplasticizer
g.	11.5 fl. oz Daravair air entraining agent
h.	3%* Allied Chemical calcium chloride
*By weight of cement.	

c. Type K expansive cement shows some promising trends in terms of strength development. Air content and mix consistency were erratic. Some of the hardened samples were friable and mealy.

d. Type III cement showed the best short-term behavior. Workability properties were adequate, but strength gain was slower than desired. The calcium chloride content of 3 percent exceeds the standard limit of 2 percent.

e. The long-term properties of the final mix design are as follows: Strength-time results show high ultimate strength values with no strength regression. Shrinkage potential and sulfate resistance test results indicate poor performance. The combination of high calcium chloride content and high cement content created excessive shrinkage. High tricalcium aluminate content and high calcium chloride content are responsible for poor sulfate resistance.

1.3 Concrete Distribution

1.3.1 Description of Test Objectives

An obvious characteristic of the CSL process is the ability of concrete to distribute laterally along a downward moving curb ring. Since concrete is placed through a discrete number of inlet ports, the concrete must travel to the mid-point between ports, in both directions. It is desirable to minimize the number of inlet ports, from an operational point of view. Therefore, it is important to know the maximum distance from a port that concrete can be expected to travel. Furthermore, it is crucial to the continuous slipforming process that concrete that enters the void behind the slipform not only translate along the curb ring, but also depart from the curb ring as it is displaced by newer concrete entering behind it. If concrete does not leave the curb ring when newer concrete enters, then it would only be a matter of time before set concrete would build up on the curb. Eventually, the buildup of set concrete would terminate the distribution process.

The objectives of the concrete distribution tests were as follows:

a.   Determine the feasibility of distributing concrete under pressure within a closed form above a downward moving curb; and the ability of the placed concrete to be displaced off the curb by incoming concrete

b.   Determine the number of inlet ports required for full form filling. Determine the distance traveled by the concrete from each port

c.   Determine the value of the back pressure required for full form filling

d.   Determine the need and extent of curb vibration

e.   Assess the distribution of concrete pressure along the curb

f.   Qualitatively assess the nature of the concrete flow patterns

g.   Determine the sensitivity of concrete placement to changes in the four (4) port valve operating and switching times.

A complete description of the experimental test plan is included in Appendix A.

To accomplish the feature tests, a special test rig was designed and fabricated. The rig, as shown on Figure 5, is a structural steel form, capable of being opened and closed, to allow examination and removal of each test slab. The rig
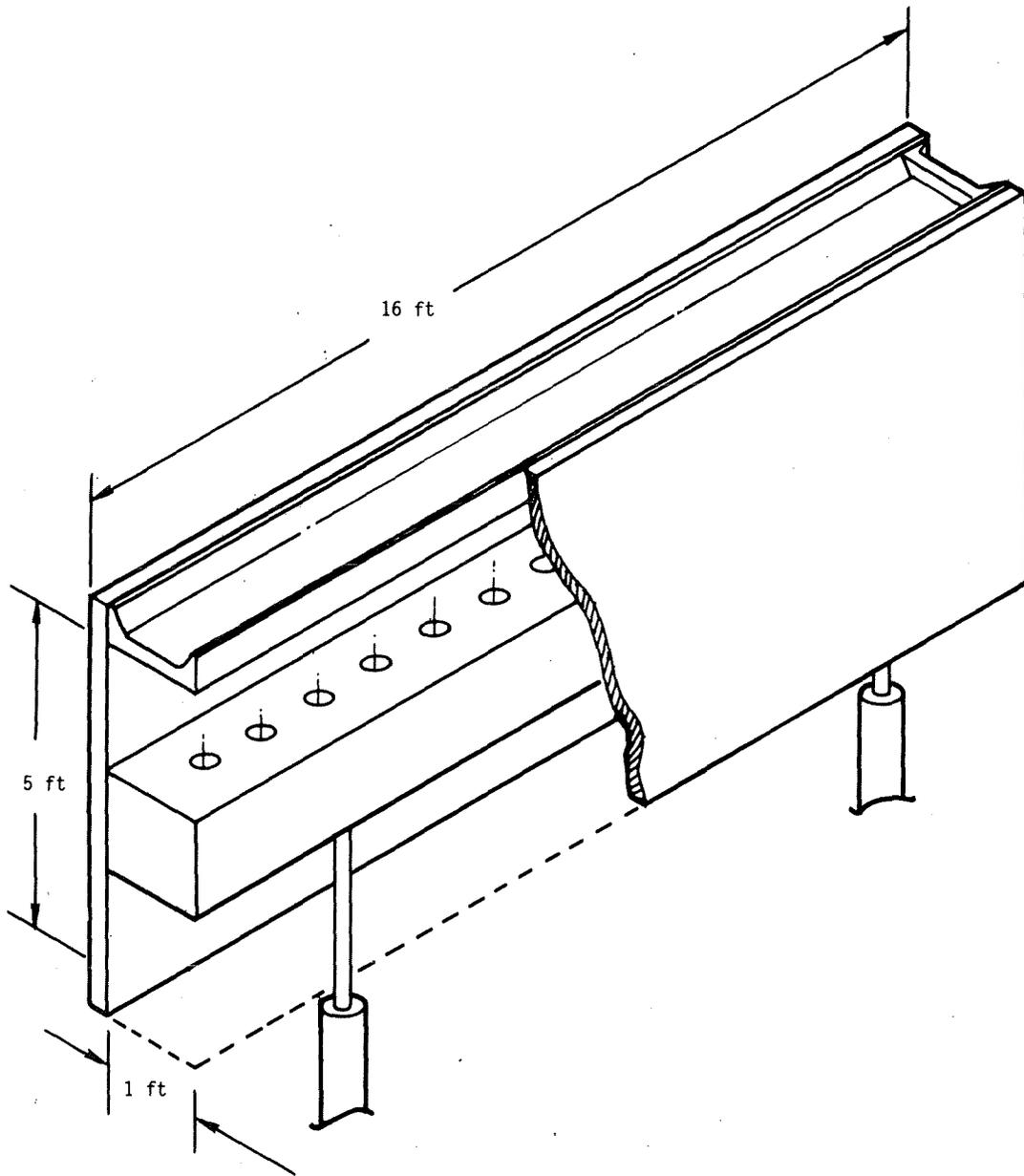
FIGURE 5. - Distribution test rig.

was 16 ft long, 5 ft high and 1 ft wide. The test was started
by placing the curb 1 ft down from the top plate. This allowed
the initial flow of concrete a chance to enter and distribute
inside the form. Once the void was filled and pressurized, the
curb would advance downward against a pre-set hydraulic back
pressure. The rate of advance was determined by the pumping
rate of concrete. The pressure on the fluid concrete within
the form was set by the hydraulic back pressure in the curb
hydraulic actuators. The curb had multiple inlet ports which
allowed for variations in the number of ports and the port
spacing from test to test.

Figure 6 depicts the actual test rig. In addition to the
test rig itself, there were three other test support systems.
Figure 7 shows the concrete batching and supply system, com-
prised of a concrete pump, raw concrete ingredients metering
and mixing subsystem, and admixture metering and supply
subsystem.

Figure 8 depicts the multiport slide valve which was de-
veloped for this concept to allow concrete placement to any
one of four possible inlet ports. The testing of this valve

FIGURE 6. - Distribution test rig.
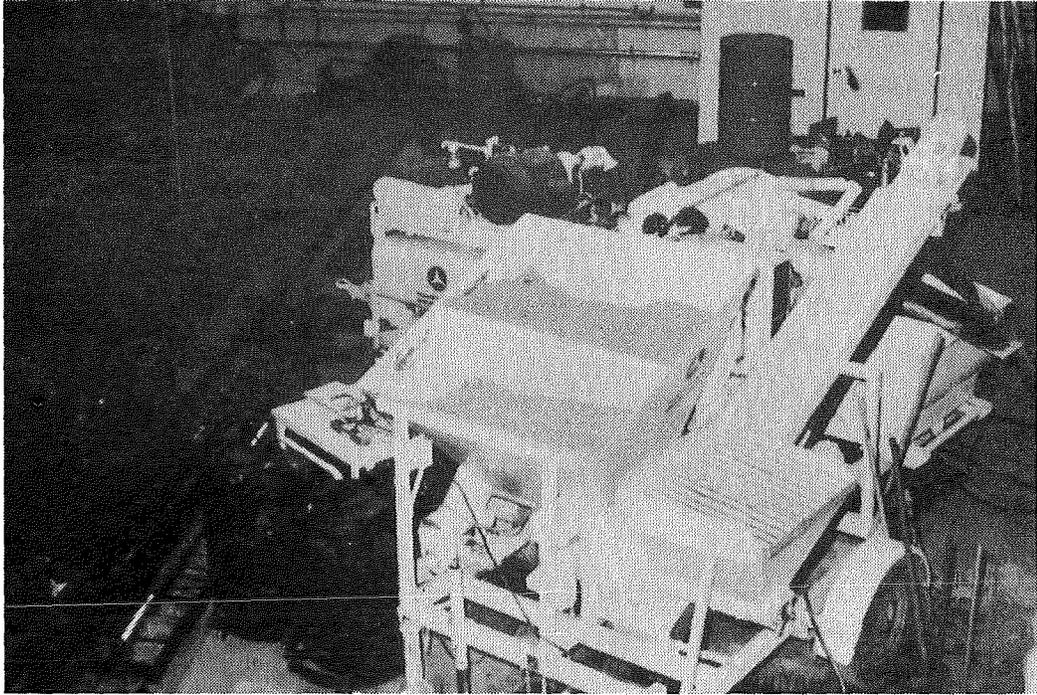
FIGURE 7. - Concrete batch plant.
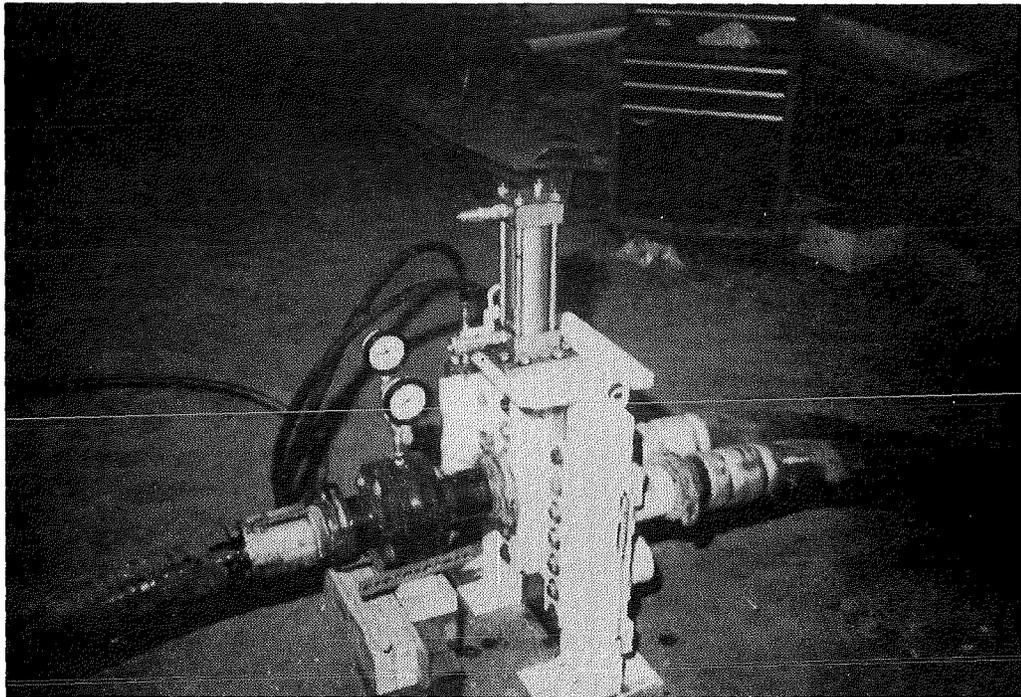
FIGURE 8. - Multi-port slide valve.

was an important sub-set of the concrete distribution test pro-
gram. Figure 9 shows the hydraulic power unit which operated
all the hydraulic cylinders on the test rig. Data from the
control panel was recorded manually. Position and pressure
data from the test rig were recorded continuously on strip charts.

1.3.2 Summary of Results

As mentioned earlier, the complete test plan is included in
Appendix A. Included in Appendix B is a summary of each of the
seven distribution tests conducted; specifying the operating
conditions, test rig configuration and test results. The seven
tests are summarized on Table 5. The arrangement of the
multiple inlet ports on the curb is summarized for each test on
Figure 10.

1.3.3 General Conclusions from the Distribution Tests

The following general conclusions can be drawn from the
concrete distribution test program:
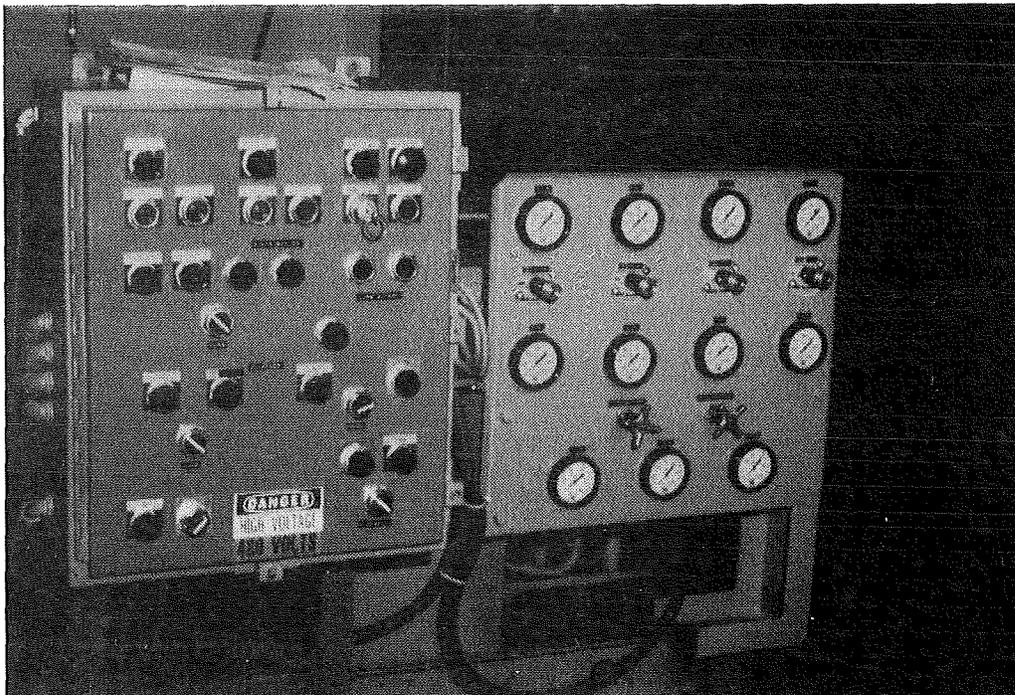
FIGURE 9. - Hydraulic power unit.

TABLE 5. – Summary of distribution tests

Test number	Test date	Cement type	Concrete inlet ports	Batch weights (lb/yd³)					Advance rate (ft/hr)	Dyes used	Concrete placed (ft³)	Form pressure (psi)	Compressive strength (psi)	Curb vibration
				Cement	Flyash	Sand	3/8 in. stowe	3/4 in. stowe						
1	1/21/81	III	1	752	–	1225	600	900	–	No	2	–	–	No
2	1/27/81	I	1	752	–	1225	600	900	2.90	No	57	25	–	Yes
3	2/3/81	III	1	752	–	1225	600	900	–	No	–	–	–	Yes
4	2/11/81	III	1	752	–	1225	600	900	3.25	Yes	68	25	3290 at 24 hrs	Yes
5	2/18/81	III	1	752	–	1225	600	900	1.65	Yes	77	25	2918 at 24 hrs	Yes
6	3/5/81	VHE	1	611	94	1325	570	1055	3.00	Yes	68	5 to 50	1600 at 2 hrs	Yes
7	3/13/81	VHE	2	611	94	1325	570	1055	4.5	Yes	73	25	1700 at 2 hrs	Yes
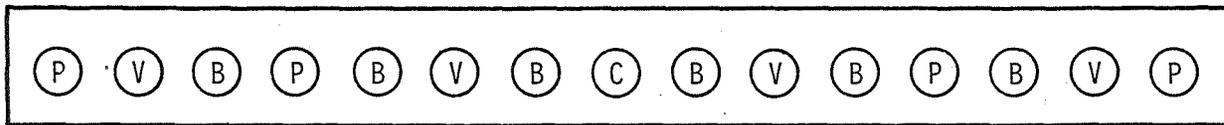
TESTS 1 & 2
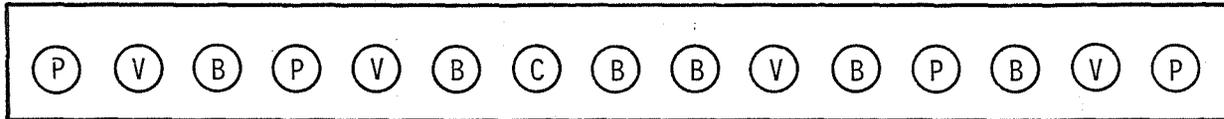
TESTS 3 & 4
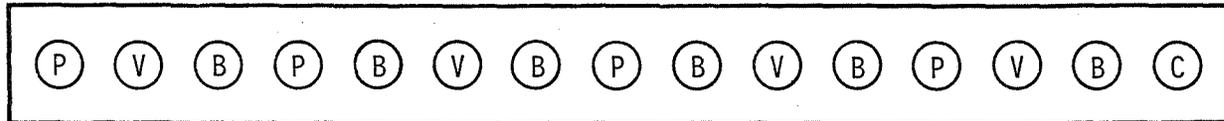
TESTS 5 & 6
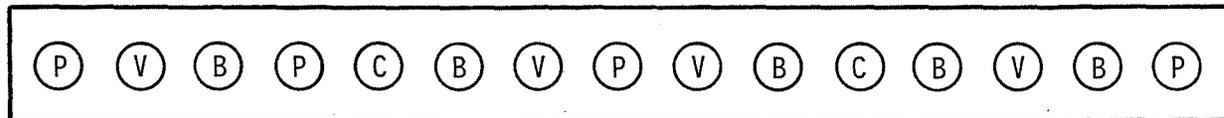
TEST 7

KEY:

P - PRESSURE TRANSDUCER   C - CONCRETE INLET PORT
V - VIBRATOR   B - BLANK PLATE

FIGURE 10. - Arrangement of ports during distribution tests.

a. Concrete will laterally distribute along a downward moving curb inside a pressurized form.

b. Lateral distribution will be limited by the plastic nature of the concrete which, in turn, is a function of its age and setup time. The distribution tests successfully demonstrated lateral motion in one direction of 15 ft, as well as bidirectional motion.

c. Concrete will also depart from the curb as newer concrete arrives to displace it. Thus, any section within the concrete slab (within a reasonable width) will be of the same age concrete.

d. Curb advance rate appears to have little, if any, affect on concrete distribution. The quality of the concrete slab did not vary over a range of advance rates from 1.6 to 4.5 ft/hr.

e. Intermittent vibration of the curb facilitates the concrete distribution by reducing the pumping pressure required.

f. A small void at the start-up position is required for initial concrete distribution.

g. Rapid setting concretes can be safely mixed, pumped and distributed without operational problems. The multi-port valve is a valuable aid in proper concrete placement.

1.4 Concrete Slipforming

1.4.1 Description of Test Objectives

The ability to slipform inverted and under pressure from the shaft collar downward was an unproven technique. From an operational point of view, it is desirable to reduce any induced loads on the concrete lining from the slipform. This load is primarily in the form of slipform drag forces. Another critical area of investigation was the ability of the concrete mix to set quickly enough to permit slipforming at a rate of 4 to 5 ft/hr.

The objectives of the concrete slipforming tests were as follows:

a. To determine the feasibility of slipforming concrete under pressure behind a moving form and above a downward moving curb

b. To determine the level of concrete pumping pressure required for slipforming

c. To determine the effect of coating the slipform surface on form drag

d. To determine the effect of tapering the slipform on the slipforming process and on form drag

e. To determine the effect of changes in slipform advance rates on the slipforming process

f. To verify the suitability of different concrete mix designs to the slipforming process.

A complete description of the experimental test plan is included in Appendix C.

The concrete slipforming tests were conducted in a specially designed test rig. The rig, as shown in Figure 11, is a structural steel form, capable of performing the operational slipforming tasks of a functional CSL. Although the rig represents only a segment of shaft circumference, the width is sufficiently large to adequately study the phenomenon of slipforming. The rig is 11 ft high by 4 ft long and 1 ft wide. The moving slipform is 5 ft by 4 ft, is capable of being tapered, and is controlled by a hydraulic actuator. The curb is 4 ft long and 1 ft wide, and is lowered by a hydraulic actuator. A single 3-in. concrete inlet line is used due to the limited width of the curb.

The test is started by placing the curb 1 ft down from the top plate of the form. The slipform is positioned to completely cover the gap between the curb and this top plate. The initial void is filled with concrete and pressurized. Once concrete pressure has built up to a pre-set limit, the curb will advance down against the hydraulic back pressure in the actuator. The
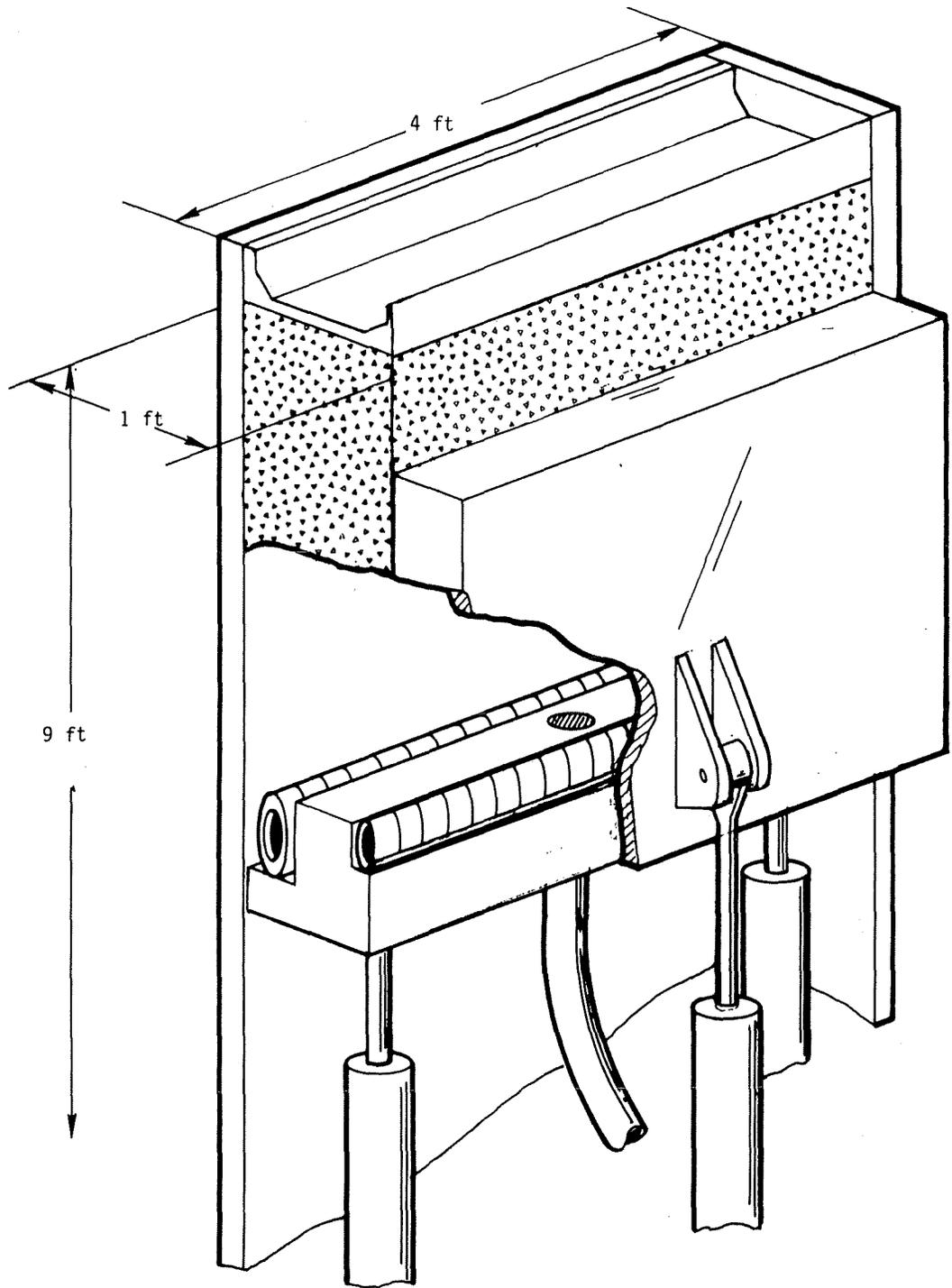
FIGURE 11. - Slipform test rig.

rate of advance is determined by the pumping rate of concrete. Once the curb has advanced a sufficient distance down the face of the slipform (this distance is determined by concrete age), the slipform is independently advanced. Eventually a concrete slab will be partially exposed as the slipforming process continues. Once the curb has reached the limits of travel of the test rig, concrete pumping is terminated. However, the slipform is allowed to continue until the full slab is exposed.

Figure 12 shows the actual test rig in the start position. Rig components have been labeled, to aid in understanding. The same concrete batch plant and delivery system, used in the distribution tests, was used again. The hydraulic power unit that was used for the distribution tests, was also designed to operate the slipform rig. Data from each test was recorded on strip charts or manually from inspection.

1.4.2 Summary of Results

Five slipforming tests were conducted. The detailed summary of each test is described in Appendix D. The five tests are summarized in Table 6.

1.4.3 General Conclusions from the Slipforming Tests

The following general conclusions can be drawn from the concrete slipforming tests:

a. Concrete can be slipformed, vertically downward behind an advancing, pressurized curb.

b. A Portland cement (Type III) concrete mix was shown to meet the CSL operational specifications in regard to early strength gain and workability.

c. Advance rate of 3 ft/hr was demonstrated with the Portland cement mix. Faster rates of advance may be achievable in a full size test facility with the same mix due to mass casting effects.

d. Form taper was shown to reduce form drag.

e. Form coatings improved the quality of the lining, but had negligible effect on reducing form drag.
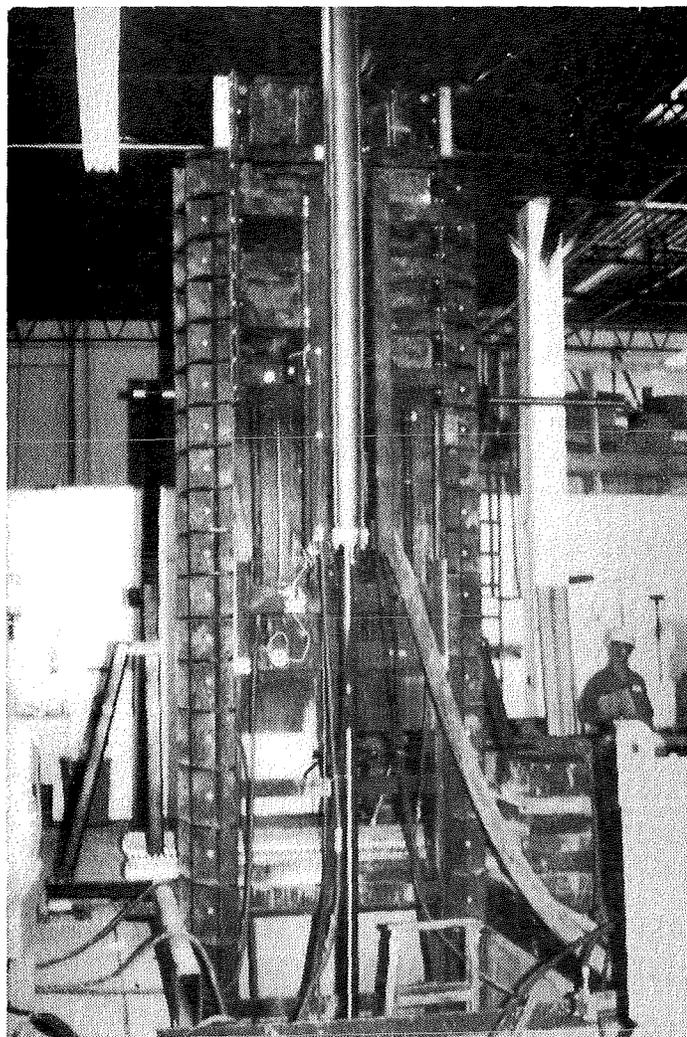
FIGURE 12. - Slipform test rig.

TABLE 6. – <u>Five slipforming tests conducted</u>

Test number	Test date	Taper (in/6 ft)	SEL* (ft)	Coating used	Mix temperature (°F)	Unit weight (lb/ft³)	Air content (%)	Slab length (in.)	Advance rate (ft/hr)	Form pressure (psi)	Slump (in.)					Compressive strength (psi)	
											Initial	At 15 min	At 20 min	At 25 min	At 30 min	At 2.0 hrs	At 3.0 hrs
1	5/12/81	1/8	5	No	75	147	3.5	87	2.0	25 to 40	6-1/2	4-1/4	4	3-3/4	3-3/4	10	72
2	5/19/81	1/8	5	No	71	145	4.5	104	3.0	10	7-1/4	4-1/2	4-1/4	4	3-3/4	14	54
3	5/21/81	1/4	5-4	Yes	72	146	4.3	104	2.2	10	6-1/2	4-1/2	4	3-3/4	3-1/2	14	69
4	5/27/81	3/4	4	Yes	79	146	3.4	71	1.8	10	6-3/4	5	4-3/4	4-1/2	4-1/4	20	173
5	6/2/81	1/8	4	No	75	146	3.7	93	1/6	10	7-1/2	5-1/4	5	4-3/4	4-1/2	14	76

*SEL – Slipform effective length

f.   The jump mode was successfully demonstrated.

g.   Information was gathered regarding operation of the test rig in order to prevent tension cracking of the lining from occurring.

h.   The placement and distribution of concrete into the lining is relatively insensitive to the operation of the test rig.

1.5   Concrete Sealing

1.5.1   Background

The objective of the seal development program was to design and demonstrate an effective outer curb ring seal which is located at the leading edge of the curb ring. Its purpose is to maintain pressurized conditions inside the slipform by preventing pressurized concrete from flowing out between the moving curb ring and the machine bored shaft wall. The difficulties in obtaining an effective seal for this annular space are primarily due to the surface irregularities of the shaft and the limited available space. Variations in the radial, circumferential and axial dimensions of the sealing zone occur as a result of:

a.   The helical gauge cutter pattern

b.   Gauge cutter wear

c.   Abrupt shift in centerline

d.   Distortion of shaft cross-section

e.   Slough zones

f.   Shaft wall damage due to boring machine grippers.

In order to prevent concrete from leaking out ahead of the slipform, the seal must be flexible enough to conform to the various surface contours encountered, yet it must also be rigid enough to resist the considerable force exerted on it by the concrete under pressure.

Another seal characteristic is imposed by the abrasive nature of its operating environment. As the slipform progresses along the shaft, the seal is dragged along the rough wall and is

subject to sliding wear and cutting. An abrasion and tear re-
sistant material must, therefore, be selected to insure seal
integrity over a reasonable operating life and/or shaft depth.
The seal must be designed so that it can be readily integrated
into the operation of the CSL. This involves making the seal
accessible for maintenance and replacement. This is complicated
due to the dimensional constraints and space limitations. In
addition, some minor motion in the reverse direction must be
tolerated.

Specifications have been established for the parameters
which impact the performance of the outer curb ring seal. These
specifications were used to evaluate the suitability of various
conceptual and existing seal designs. The evaluation resulted
in the selection of an appropriate design which was built and
tested in a laboratory simulation test rig. The test rig was
constructed so that the proposed seal design could be evaluated
and optimized under the conditions defined by the specifications.
A summary of the operating conditions and the performance specifi-
cations defined for the seal design are listed in Table 7. The
optimized seal candidate, based on the laboratory tests, was then
studied for integration into an existing full scale curb ring.

1.5.2 Seal Concepts

Various conceptual seal designs were generated in-house.
In addition, several commercially available seals were studied.
These seal arrangements can be divided into three generic
categories:

   a.   Lip

   b.   Inflatable

   c.   Rolling.

After careful study and in consultation with various com-
mercial seal manufacturers, the inflatable and rolling seals
were eliminated from further consideration. The rolling type
seals were eliminated primarily due to their physical complexity,
problems with space constraints, and excessive maintenance re-
quirements. The inflatable seals were eliminated due to their
vulnerability to puncture and excessive seal drag due to high
inflation pressures. The entire seal test program was, therefore,
devoted to the development of an optimal lip type seal.

TABLE 7. - <u>Outer curb ring seal performance</u>
<u>specifications</u>

Design condition	Performance specification
Surface roughness of shaft wall	3/4 in. deep (maximum) 3/4 in. pitch (maximum) helical pattern
Reduction in shaft diameter	3/4 in. reduction in diameter due to gauge cutter wear.
Abrupt shift in centerline	1 in. maximum shift due to weak/strong contact in rock formation or due to steering correction.
Slough zones	3-1/2 in. radial depth Horizontal sloughs due to bedding: 6 in. axial length, 12 in. circumferential width, sharp horizontal edges. Vertical sloughs due to thruster crushing or guide scraping: 36 in. axial length, 12 in. circumferential width.
Shaft wall damage due to boring machine grippers	3 in. deep (radially outward) 24 in. wide (axial direction of shaft) 36 in. high (circumferentially)
Concrete pressure on seal	0 to 40 psi 5 psi variation along circumferential length of seal.
Seal life expectancy	500 ft of advance/seal in highly abrasive rock. 2000 ft of advance/seal in less abrasive rock.
Space constraints on seal	3 in. radial thickness of uninterrupted hoop. 3 in. of axial width.
Direction of motion	Downward only while placing concrete. Slight reversal (1 to 2 in. maximum) following discontinuation of pumping to compensate for concrete leakage.

1.5.3 Seal Test Apparatus

A seal test rig was constructed to evaluate and optimize proposed seal designs under the conditions established by the performance specifications. The test apparatus (see Figure 13) consisted of a seal clamp 18 in. wide mounted on a 1/2-in. steel plate which was free to slide along the bottom of a box 18 in. wide by 24 in. long by 8 in. deep. The test box, designed for simulated concrete pressures of up to 100 psi, was constructed with steel channel sides, plate steel bottom and a cover plate of 1/2-in. Lexan (clear plastic) reinforced by steel bar spans bolted through the channel flanges. The sliding steel plate simulated the movement of the curb ring along the slipform, while the Lexan cover acted as the sealing surface or rock wall.

In order to evaluate the performance of a particular seal, the Lexan cover was removed, and the seal to be tested was clamped in place. Simulated concrete paste was then placed in the box behind the seal. The cover was then bolted back in place and the paste was pressurized. When the force exerted on the seal was sufficient to overcome the friction of the seal against the Lexan surface and that of the sliding plate on the floor of the test rig, the 1/2-in. steel plate upon which the seal was mounted would begin to move forward. If the desired test pressure had not been achieved, then the sliding plate could be held stationary by pressurizing a counteracting hydraulic cylinder which was also attached to the plate while the pressure was increased. This hydraulic cylinder was also used to cause the seal to move along the sealing surface at simulated concrete pressures too low to overcome the system friction.

During the initial seal tests the transparent Lexan cover permitted close observation of the test seal performance while simulating a smooth rock wall surface. As the seal test program progressed, different surface contour models were attached to the Lexan surface to simulate the clearances and surface rough-ness specified in the performance criteria.

The concrete used in an actual shaft lining application would be a mixture of coarse and fine aggregate and finer cement paste. While some segregation of these components may occur, it is expected to be minimal due to the cohesiveness of the mixture and to its fast setting characteristic. For the seal test program it was decided to simulate the concrete using a dry wall joint
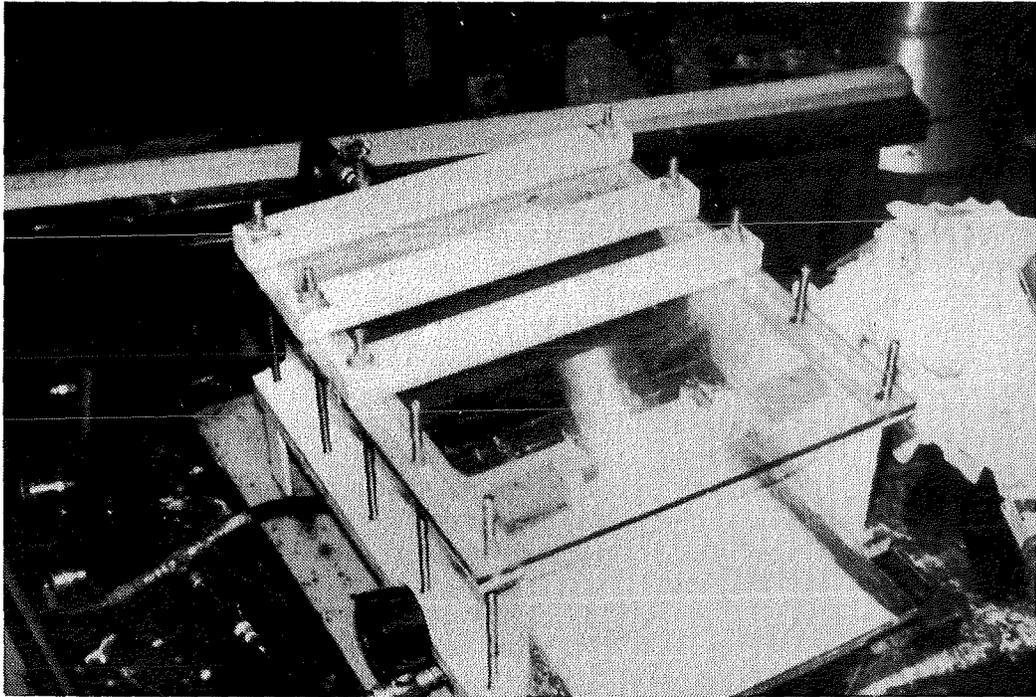
FIGURE 13. - Concrete seal test rig.

compound diluted to the consistency of the paste component of
the concrete mix. This facilitated handling and clean up during
the testing and resulted in a conservative test of seal per-
formance. Use of the actual concrete mixture would be expected
to result in even less leakage than is demonstrated by the test
procedure.

1.5.4 Seal Test Program

Since inflatable and rolling seals were judged to be less
suitable for the proposed application than lip seals, the test
program was limited to optimizing the performance of the latter
type of seal. A three-phase test program was formulated to
evaluate various lip seal configurations. A total of 37 tests
were conducted.

The goal of the first phase of the test program was to de-
termine the characteristics of a seal capable of sealing while
fully extended in a slough zone. This is the most severe duty
for the curb ring seal. Given that there is nominally 3 in. of
radial clearance between the curb ring and the rock wall, and
assuming 2 in. are occupied by the seal clamp, the normal sealing
zone is an annular space 1 in. high. When a slough zone is en-
countered during the shaft lining process part of the seal is
required to seal an area 4 in. deep. Thus, the unsupported
seal area and the force tending to push the seal out through
the sealing space may quadruple in a slough zone.

The force exerted on a lip seal by the concrete pressure
is opposed by the force due to friction between the seal and the
sealing surface (rock wall). This opposing force is proportional
to the concrete pressure, length of seal/surface contact area and
seal/surface friction coefficient. As a seal of given length
moves from a normal sealing zone into a slough zone, the length
of seal in contact with the sealing surface, and thus the force
resisting seal blowout, is reduced. This effect compounds the
problem of slough zone sealing.

The initial emphasis of the testing program was, therefore,
to determine the seal stiffness and length required to resist
the design concrete pressures in a slough zone. The basic seal
configuration tested consisted of three layers of 1/4-in. thick
polyurethane. During the first phase of testing seal performance
was improved by:

a. Tapering the sealing edges of the polyurethane layers

b. Varying the lengths of the layers so that the layer closest to the concrete was the longest and each subsequent layer was shorter

c. Modifying the seal clamp so that the initial (un-pressured) orientation of the seals was 45 deg with respect to the direction of travel.

These adjustments resulted in better seal/surface contact when concrete pressure was applied.

For the first several seal tests the sealing surface was the dry Lexan cover plate. As higher simulated concrete pressures were achieved during the course of the testing, it became apparent that the coefficient of friction between the dry Lexan surface and the polyurethane seals was very high. Since actual surface conditions are apt to be wet and/or contaminated with loosely bound particles, the sealing surface was subsequently lubricated with the simulated concrete paste for a more conservative evaluation of seal performance. This change in test procedure significantly reduced the pressure rating of the seal configuration due to the reduced friction coefficient on the seal. The friction force could be re-established by increasing the length of the seal, however, the preferred design would minimize the seal length in order to minimize friction in the normal sealing zone and to reduce the possibility of the seal becoming imbedded in the concrete lining as it cures.

Alternately, the stiffness of the seal was increased over several trials by increasing the seal material durometer and by glueing the three seal layers together for most of their length to act as a single layer. Neither of these modifications was sufficient to significantly improve seal performance. If an even stiffer material were used or if the seal cross section were increased some difficulty would be experienced in folding the seal down into the normal sealing zone which is 3 in. shorter than the slough zone.

In order to obtain the desired seal stiffness, yet retain enough flexibility so that the seal could adjust to the transitions between normal and slough sealing zones, the concept of an independent hinged seal support was developed and several

variations were tested. The purpose of the hinged support was
to limit seal deformation under pressure and to provide addi-
tional support to the seal in a slough zone. The concept showed
promise in its original form which was simply a strip of steel
attached to the seal layer furthest from the concrete. Further
development of the support was planned for the second phase of
the test program.

The second phase of the test program investigated the
ability of the seal to seal against the nominal wall geometry.
A wooden form was constructed which simulated the surface rough-
ness due to the helical cutter pattern. When this form was
attached to the Lexan surface and bolted into place the normal
sealing clearance of approximately 1 in. was duplicated. The
simulated rock wall occupied the full width and approximately
half the length of the test rig. The leading edge of the form
then sloped at approximately 45 deg into a simulated 3-in. deep
slough zone. By sliding the movable steel plate back by means
of the hydraulic cylinder, the seal performance in transition
from a normal sealing zone to a slough zone could be observed.

The seal performance in the normal sealing zone was gen-
erally good, as expected. The drag force on the seals in the
normal zone was significantly greater, however, due to the
interaction of the seal support and the ridges in the rough
surface. In fact, the clamp configuration had to be redesigned
to prevent the seal from being pulled out as the forward motion
of the curb ring was simulated.

The hinged support design was further developed, from a
2-in. wide steel strip glued to the last seal layer to a row of
multiple solid metal wedges with the deflection angle limited
by an angle bracket attached to the seal clamp. The hinged
support provides 2 in. of seal support in the slough zone leaving
only 2 in. of unsupported seal to resist the concrete pressure.
In a normal sealing zone, the hinged blocks fold into the
clearance space between the clamp and the rock wall and do not
impede curb ring motion.

In anticipation of the requirement for seal lateral flex-
ibility when moving into a slough zone of limited circumferential
dimension, the seal layers were cut into 3-in. wide strips with
the cuts staggered between seal layers. The rate of joint

paste leakage from between the seal strips in both normal and slough sealing zones was observed. Initial seal strip alignment and seal edge contact with the sealing surface were found to be important for establishing a good seal.

The third and final phase of the seal test program evaluated the ability of the seal to accommodate lateral variations in curb ring/sealing surface clearance. Since the slough zones are nominally less than 12 in. wide (circumferentially) and damage due to wall grippers is expected to be at most 36 in. wide, one section of seal may be sealing a standard 1-in. gap while the seal section a few inches away is sealing an area 3 in. deeper. In order to determine whether the seal adjusts well to changes in clearance along the seal circumference, wooden forms were fabricated and attached to the Lexan cover to simulate slough zones of variable dimensions with ramped and vertical sides.

Before the last series of seal tests were conducted, however, the seal configuration was modified. The addition of the hinged support wedges reduced the requirement for maximum seal stiffness. Also wider strips of more pliable seal material would be better suited to conform to lateral variation in sealing surface contours, and would increase the path for any leakage from between the seal layers.

The final seal configuration was a series of 3- and 6-in. overlapping polyurethane lips, approximately 8 in. in length. The seal is comprised of 5 lips which are fixed at a common base (see Figure 14). The seal is a combination of variable durometers, thicknesses and lengths. The layer which interfaces with the concrete is 1/4 in. thick low durometer polyurethane. This layer is followed by three layers of 1/8 in. thick low durometer polyurethane of decreasing lengths. The top most layer is a 1/4 in. thick high durometer and is the shortest of the five layers. The seal leafs are attached to the bulkhead on a 45-deg angle relative to the direction of travel and are combined with the unidirectional stiffener. Cuts in each leaf are arranged so that an overlapping shingle arrangement is formed.

This seal arrangement was tested in transition through various simulated slough zone configurations with concrete pressures up to 40 psi. Only slight leakage of undiluted

LOW DUROMETER LAYERS

HIGH DUROMETER LAYER

CONCRETE
PRESSURE

HINGED WEDGES
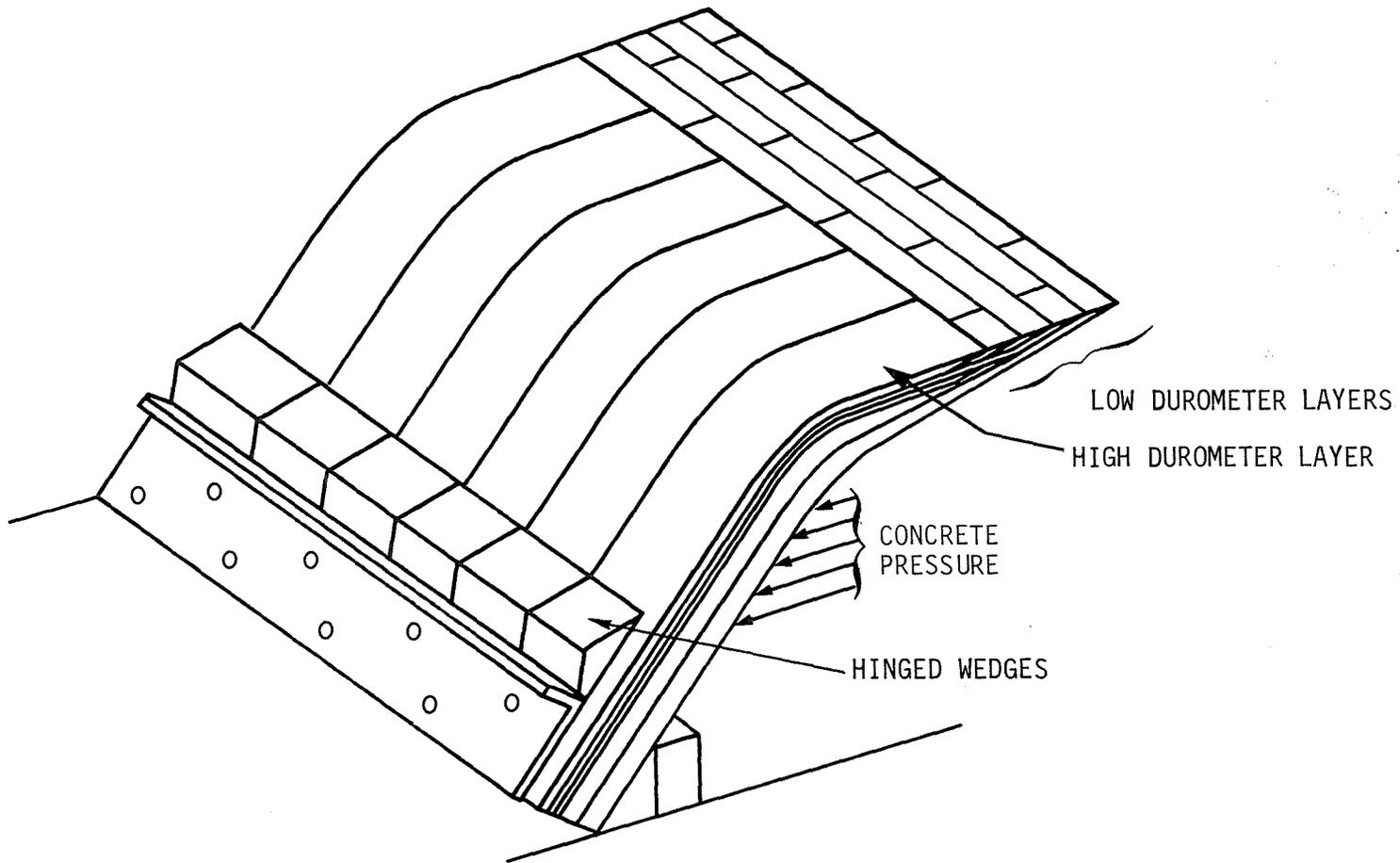
FIGURE 14. - Design of seal tested in the laboratory.

jointing compound was observed. Since the joint compound was a conservative substitute for the concrete mix, which would actually be used in a shaft lining situation, the performance of the previously described test seal was judged to be satisfactory as a basis for a full scale prototype seal design.

Detail of the individual seal tests are presented in Appendix E.

2. CSL SIMULATION TESTS

2.1 Description of Test Objectives

The fundamental objective of the simulation tests was to demonstrate the viability of the process and equipment required to continuously slipform a concrete shaft lining in the downward direction, utilizing a full-sized prototype.

The specific objectives of the program included:

- Placing uniformly distributed concrete by pumping through individual ports evenly spaced around a circular curb ring

- Continuously forming a vertically standing cylindrical concrete lining which supports itself upon exiting the slipform

- Determining the allowable variations in advance rate which the system can sustain

- Evaluating startup and stopping procedures

- Evaluating the systems adaptability to the step and jump form modes of operation

- Determining alignment control requirements for the curb ring and slipform

- Demonstrating the prototype curb ring seal performance under simulated slough zone conditions

In order to successfully place a lining, the concrete mixing system had to prepare a pre-selected concrete mix design within acceptable tolerances. The delivery system had to expediently transport and distribute the mix to the curb ring ports in equal proportions and maintain pressure on the wet concrete mix (while held within the confines of the shaft wall and the moving slipform and curb ring). The control system had to maintain alignment within the shaft in order to place a lining of uniform thickness and had to sufficiently support the previously placed concrete immediately above the slipform such that the system was safe and lining distortion or cracking was minimal.

2.2 Test Facilities Description

2.2.1 Introduction

The CSL simulation tests were conducted on a five acre site located in Framingham, Massachusetts. The testing was done inside a 150 ft wide by 350 ft long facility yard, which was surrounded by protective fencing. The remaining area was comprised of concrete aggregate storage areas, parking lots, truck turnarounds, and access roads. The CSL test facility yard was elevated above the existing ground contour, using graded and compacted backfill. For increased yard drainage, surface swales and underground pipelines were constructed to carry away excess runoff. A porous dike settling pond received all the runoff from the yard, via the drainage system.

Figures 15, 16, and 17 show the general layout of the site and the CSL testing equipment and systems. Each major site component is discussed in detail in the following paragraphs. Operation and control of the CSL and support systems are described in subsection 2.3 and results from the simulation test program are described in subsection 2.4.

2.2.2 CSL Test Facilities

a.   Trailers (Item 1) - Two eight-foot wide by twenty-foot long trailers with a shed roof between them served as a storage room, tool room, and shop area for the CSL test facility. The shed roofed area was used to temporarily store cement as well as garage the fork lift. The storage trailer held spare equipment and equipment needing protection from the weather. Concrete test equipment, cement dyes, mixing pumps, admixtures, etc., were stored in this trailer. The tool trailer held all the CSL tools; electrical supplies; hydraulic and pneumatic fittings; and also served as a work shop area for bench top serviceable equipment.

b.   Pump House (Item 2) - The non-potable water requirements were serviced by an on-site 120 ft deep well. This well provided an 8 gpm, 40 psi water supply for the site. The well cap, submersible pump, and pressurized water tank, were protected by a small pump house located next to the tool room trailer.
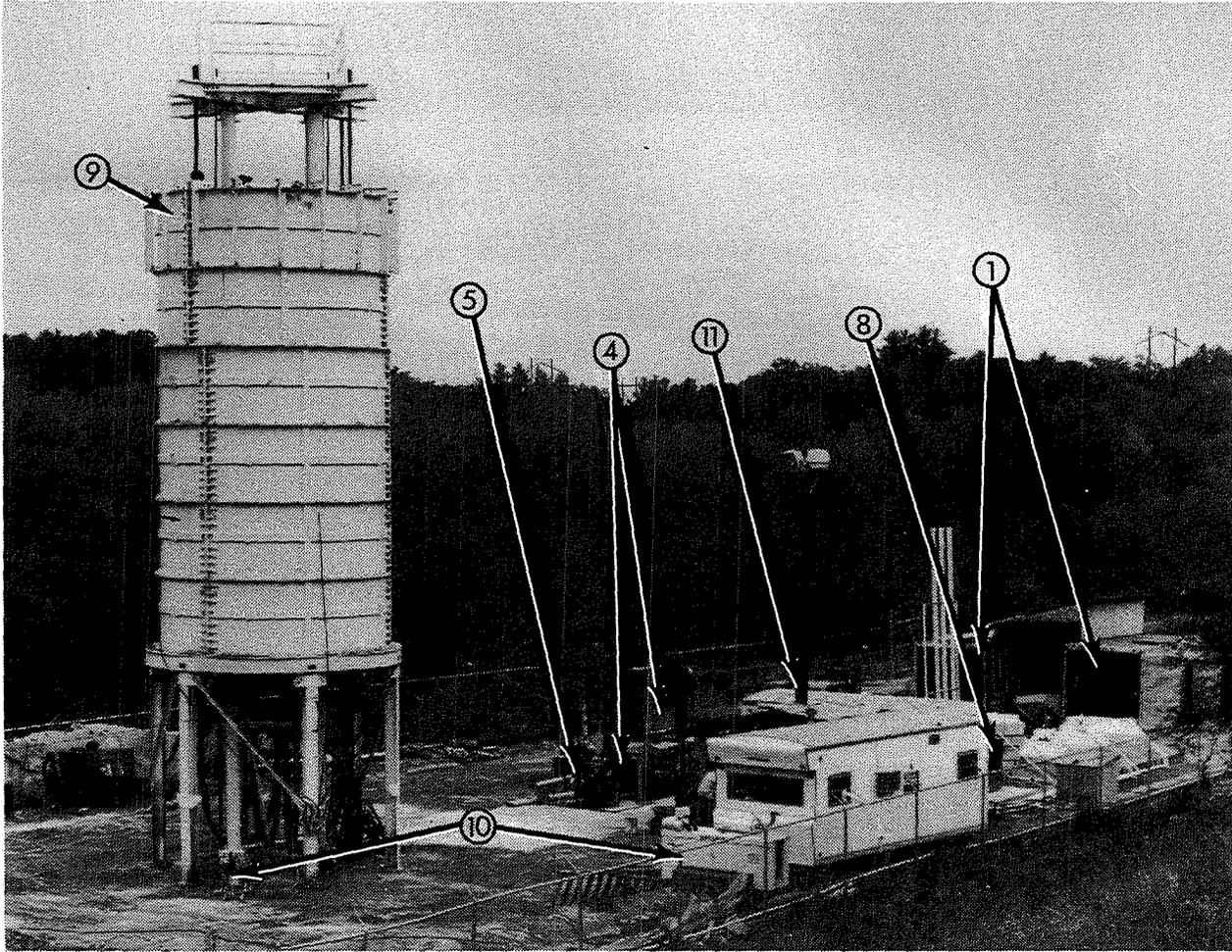
FIGURE 15. - CSL simulation test site.
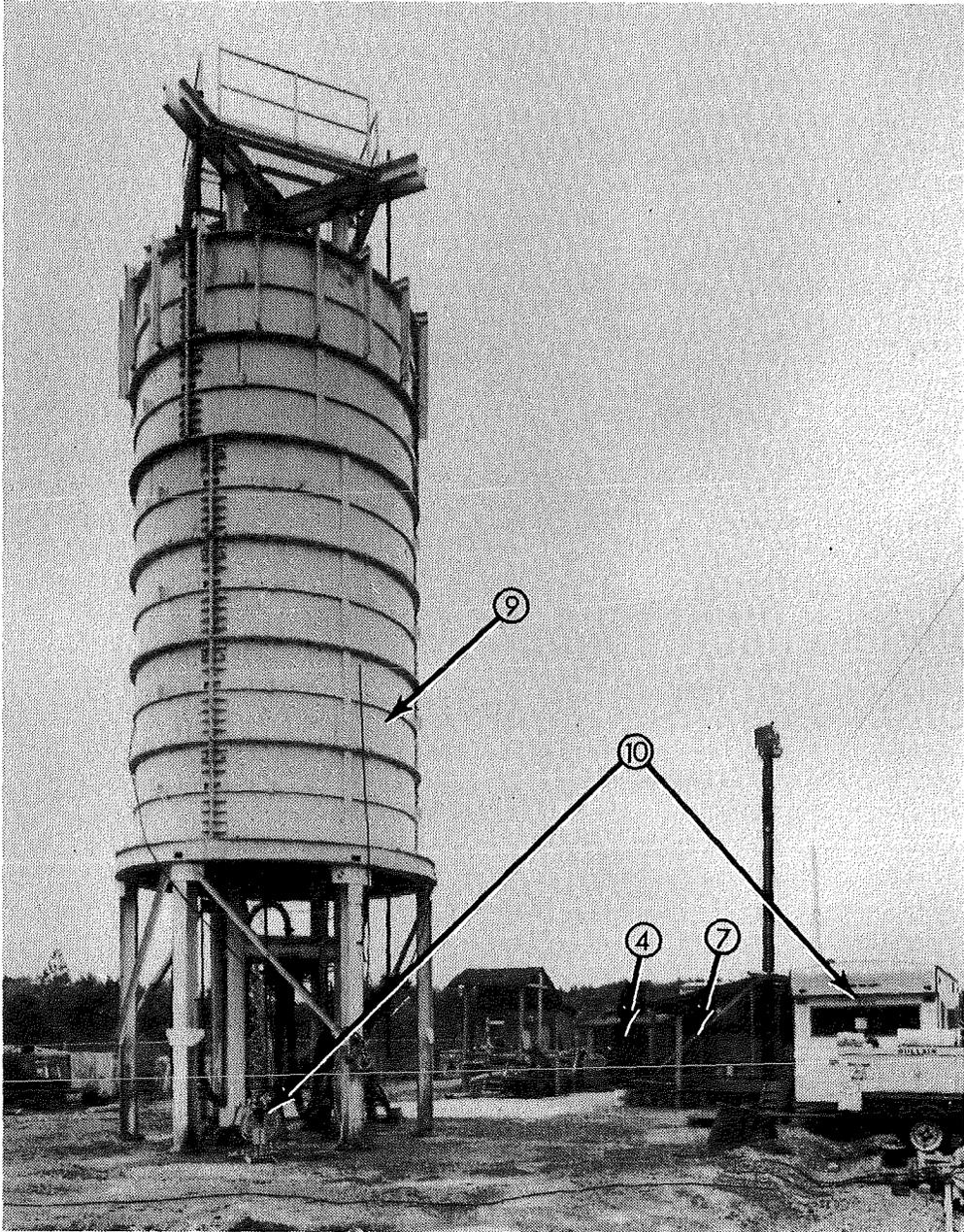
FIGURE 16. - CSL test tower.
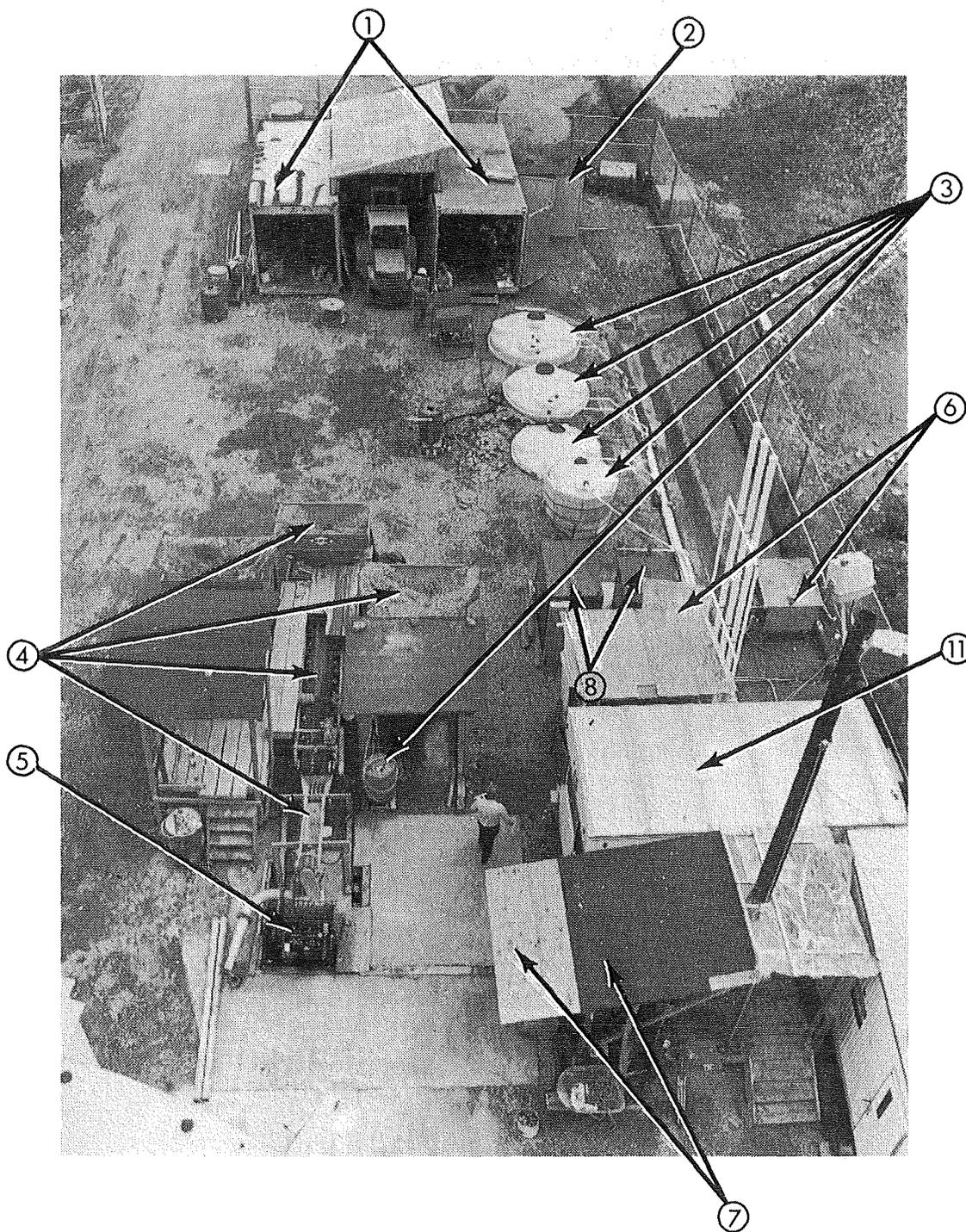
FIGURE 17. - Concrete plant and test trailer.

c.   Admixture Storage Tanks (Item 3) - There were four
     large polyethylene, cylindrical tanks on-site; one
     1500 gal tank, two 1100 gal tanks, and one 500 gal
     tank. The 1500 gal tank stored wash water and served
     as a reserve concrete mix water tank. The next tank
     in line was an 1100 gal tank used to store the concrete
     mix water. Ice was also stored in this tank when mix
     water required cooling during summer testing. The other
     1100 gal tank was used to mix and store the calcium
     cloride admixture solution. The last polyethylene
     tank was a 500 gal capacity tank used to store the
     superplasticizer. All the tanks were insulated, and
     connected to the admixture skid by 1-1/2 in. PVC suc-
     tion and return lines. The fourth admixture, the air
     entrainment solution, was stored in a plastic 55 gal
     drum located at the batch plant control station.

d.   Concrete Plant and Auger Mixer (Item 4) - The concrete
     plant consists of seven elements: four material bin
     feeders, conveyor belt, auger mixer, and the plant
     control station. The four bins contain the bulk
     constituents of the concrete mix; cement, sand, pea
     stone, and 3/4 in. gravel. At the base of each bin is
     a metering auger, which transfers materials from the
     bin to the conveyor belt at very accurately and control-
     lable rates. The conveyor belt transfers the pro-
     portioned dry bulk concrete materials to the feed hopper
     of the inclined auger mixer. Water and admixtures are
     also added at this point. The auger mixer continuously
     discharges mixed concrete at the same rate the conveyor
     delivers the dry unmixed materials to it.

     The control station, located at the back of the gravel
     bin, is the nerve center of the plant. This unit
     contains the motor speed controllers used on the bin
     augers, and the controls for the auger mixer and
     conveyor belt. (For the performance and control
     specifications of the concrete plant, refer to
     Appendix K and CSL operations and controls
     subsection 2.3.)

     Concrete Pump (Item 5) - The concrete pump is a dual
     piston, hydraulically operated, positive displacement
     pump. It was designed to be compatible with the
     concrete plant and be able to handle concrete mixes

and production rates produced by the concrete plant.
(For the performance of the pump, refer to Appendix J.)

f.   Admixture Transfer Skid (Item 6) - The admixture trans-
fer skid handled all control and processing functions
associated with the concrete fluid admixtures. The
admixture skid was capable of controlling admixture
temperature, pressure, and flow rate. The unit was
sized to match the concrete plant's operational pro-
duction range 1 to 20 yards of concrete per hour. The
skid controlled all four concrete fluid admixtures; water,
calcium chloride solution, superplasticizer, and air
entrainment agent.

g.   Hydraulic Power Units (HPU) (Item 7) - There were two
HPU's on-site; the concrete pump HPU, and CSL HPU. The
concrete pump HPU was a 35 gpm 2000 psi system that sent
fluid to hydraulic controls mounted on the concrete
pump. The CSL HPU was a complex system that powered
and controlled the CSL curb ring, slipform, slide
valve, and suspension system. It contained two
5 gpm pumps, operated at 1500 to 3000 psi, and had a
100 gal oil reservoir.

h.   Electric Transformers (Item 8) - Two electric trans-
formers supplied all electricity on the site. One
transformer stepped down 13800v to 480v with 200 amps
capacity, the other transformed the mainline voltage
to 230 and 120v, with 150 amps capacity. The main site
circuit boards were located directly adjacent to the
transformers.

i.   Test Tower (Item 9) - The CSL test tower was 55 ft high,
15 ft in diam, and supported a 30 ft section of simulated
mine shaft. The test tower contained and supported
the CSL system including, the 13 ft diam slipform,
15 ft diam curb ring, jack frame, and Heede suspension
system. For detail drawings of the tower and CSL, refer
to Appendix I.

j.   Compressed Air System (Item 10) - A mobile air compressor
was used to supply 120 psi air to the test tower. The
air was distributed to the curb ring vibrators through
a distribution manifold located at the base of the
test tower.

k.   CSL Test Station (Item 11) - The operation, control
      and monitoring of the CSL was performed from the
      CSL test station trailer. Inside this trailer was
      located the hydraulic power unit control panel, the
      operator's control panel and data acquisition system.

2.3 Operations and Control of the Simulation CSL

2.3.1   Introduction

The CSL is a slipforming system which places a continuous
concrete lining from the shaft collar downward. It differs from
conventional slipforming in that, it is pressurized, and operates
in the reverse direction; from top to bottom. The simulation
testing of the CSL was designed to prove operational concepts,
and test prototype equipment. The simulation testing also
provided a broad base of new information with which to analyze
and improve the CSL hardware in preparation for underground
testing.

The operations and controls of the simulation CSL can be
grouped into three main areas. The first is the concrete plant
and delivery system operation. The second is the instrumentation
and control system operation, and the third is the CSL test tower
operation.

Stockpiled raw materials are mixed into concrete, pumped
and distributed above the pressurized curb ring. The curb
ring and slipform, which are supported by the jack frame, then
travel together as the CSL unit down the tower shaft leaving a
finished, continuously slipformed concrete lining. To better
understand the operational details of simulation testing, the
discrete functions of individual pieces of eqiupment, areas of
operations, and individual personnel tasks will be described.
In this way, it can be seen how information, commands, controls
and materials flow from one area to another; and understand how
the integrations of these functions affect the proper operation
of the CSL. In general, the discussion will follow the materials
as they travel through the CSL system, from stockpiled stone,
sand and cement, to a finished continuously slipformed concrete
lining.

2.3.2   Concrete Plant and Delivery System

The concrete plant is the starting point of the CSL opera-
tions. Concrete is produced to exact specifications, and at
rates determined by the CSL operator in the control trailer.

To do this, the concrete plant and its subsystems must handle and process both wet and dry materials at various rates.

The dry bulk materials are; 3/4 in. gravel, 3/8 in. minus pea stone, sand, and cement. The sand and stone were stored in large stockpiles outside the fenced yard area. These materials were transported by front end loader to the individual storage hoppers of the concrete plant. During plant operations, maintaining the aggregate levels in the hoppers was a full-time job for one operator. The cement, in bags, was brought on-site on an as needed basis, and was stored temporarily on pallets. The cement was transferred by hand from individual 94 lb bags to the cement hopper of the concrete plant, at a rain sheltered, bagging station. This operation employed one operator full-time. Individually controlled auger feeders transferred the bulk materials from the hoppers onto a conveyor belt that fed the concrete auger mixer. Each auger feeder had to be calibrated (weight of material per unit time) for each rate of concrete production that the plant would operate at during testing.

In order to meet the mix specifications, care was required in calibrating the cement feed. Calibration procedures indicated that cement feed rates were strongly affected by hopper loading. To meter the cement within specification tolerances, the operator was required to incrementally load the cement hopper at the same rate as cement use.

Properly proportioned dry bulk materials were combined with the fluid admixtures at the concrete auger mixer to produce the CSL concrete. The fluids had to be prepared, stored, and properly metered for quality concrete production. Four different fluid admixtures were used in the simulation design concrete mix and included water, calcium chloride solution, Mighty 150 superplasticizer, and Darvair (AEA) air entrainment solution. Each admixture was batched by weight in large storage tanks. The tanks were sufficiently large to hold enough supply of admixture to complete a full test. The admixtures were transferred from the storage tanks to the auger mixer through the admix transfer system. The admixture transfer skid was the main fluids processing point, and contained most of the pumps, heat exchangers, and valving necessary to control the fluids. These controls included fluid temperature control, pressure regulation, fluid recirculation, and flow control. The final metering of the admixtures occurred at a remote control board located at the concrete plant control station.

Each individual admixture was calibrated by weight per unit time for every concrete production rate required. The exception to this was the water. The aggregate moisture content varied during a test day. This required the water flow to be adjusted during a test to give a constant predetermined concrete slump. The water temperature, as well as the other fluid temperatures, were also varied during a test to maintain constant concrete temperature. These fluid temperatures could be varied from 35 to 140 F. Controlling and monitoring the simulation admixture skid required a full-time operator.

The final control on the quality and production of concrete is the responsibility of the concrete plant operator. The operator monitors both the dry bulk material and fluid feed rates and is also responsible for visual quality inspection of the fresh concrete. The plant operator makes the adjustments to the water flow to account for variations in aggregate moisture content. The plant operator, along with the test director, supervises the concrete field quality testing program. It is important to realize that as the mixed concrete emerges from the auger mixer and falls into the concrete pump remix hopper, that this is the last visual inspection that can be made of the concrete until it emerges as a finished lining from behind the slipform. Several standard quality control procedures. were performed on the concrete including initial slump tests, monitoring concrete slump with time, measuring air content, and determining unit weight. In addition to these field tests, standard 6 in. by 12 in. compressive strength test cylinders were cast for later laboratory analyses.

The rate of advance of the CSL down the shaft is determined by the production rate of concrete. Therefore, it is important that the concrete plant be able to produce quality concrete and continuously at the specified rate. During simulation testing, the operator was capable of changing the concrete from one volumetric batching rate to another in less than thirty seconds.

The concrete pump, slick lines, and slide valve are the remaining components of the concrete plant and delivery system. The concrete pump serves two functions. One, it must deliver concrete to the CSL at the same rate as concrete production; and two, in so doing, the pump is providing the force that actually moves the CSL down the shaft. During simulation tests, a prototype underground concrete pump was used and evaluated. This pump was a hydraulically powered, dual piston pump. It had an automatic or manual, forward or reverse cycle, as was variable in speed from 1 to 20 yd^3/hr pumping rate. A full-time pump operator was required to monitor the pump and respond to the requirements of the CSL operator. Information such as

concrete pumping pressures, curb concrete pressure, line blockages, and slide valve position were often verbally relayed between the control room and the concrete pump operator.

From the concrete pump, the concrete traveled through a steel slick line to the multi-port slide valve. The slide valve is a four port valve that directs the concrete to any one of four possible outlet nozzles. The individual outlet nozzles are connected, by flexible concrete lines, to the four concrete inlet ports mounted in the curb ring. The position of the multi-port slide valve is instrumented and displayed to the CSL operator in the control trailer. From the control trailer, the CSL operator can position the slide valve automatically or manually.

The CSL operator needs to perform four functions: one, maintain the curb ring level; two, maintain concrete pressure on the curb ring; three, control the slipform advance rate; and four, monitor system performance instrumentation. It is critical to successful CSL operation to maintain the curb ring reasonably level, and to hold plumb and concentric the slipform alignment relative to the shaft centerline. The curb ring level is maintained through the use of the concrete placement system. This is done primarily through the concrete slide valve. By properly selecting the appropriate port, and placing concrete for the appropriate time, the curb ring can be pumped down the shaft and remain level (within limits). This can be done manually or automatically. The rate of this advance is controlled by the concrete plant production rate.

Under normal simulation test conditions, the slide valve was operated in the automatic mode, cycling to each outlet nozzle for thirty seconds. The operator only manually overrode the automatic function to correct for excessive curb ring tilt. The slide valve is the interface between the concrete plant and delivery system, and the CSL.

2.3.3 Instrumentation and Control System

2.3.3.1 CSL Simulation Test Tower Complex

The simulation test tower was designed to evaluate the performance and operational features of a full scale shaft lining system. The tower was 55 ft high, 15 ft in diam and simulated a 30 ft section of mine shaft. It contained three of the four main components that would represent a prototype underground CSL

unit. These components are the slipform, the curb ring, and the
jack frame. The slipform is a ten foot long, cylindrical, tapered
steel form. It is supported on four hydraulical cylinders which
also operated a wedging system which permitted collapsing of the
form. The curb ring is a structural steel beam which fills the
annular space between the slipform and the shaft wall. The curb
ring also contains the inner and outer seals, the concrete inlet
ports and vibrators. The curb ring is supported on four in-
dependent hydraulic cylinders. The jack frame is a structural
steel platform that supports the curb ring and slipform hydraulic
cylinders. It provides a reaction point for the CSL suspension
system. During simulation tests, the CSL suspension system was
connected to the cruciform top of the internal tower. The
fourth CSL component is the galloway which is an underground piece
of equipment that was not used during the simulation tests. In
an underground system, the galloway decks would contain the
operator's control station, the hydraulic power unit, the concrete
pump and delivery system. In simulation, these functions took
place outside the tower, in the concrete plant and delivery
system area, and in the instrumentation and control trailer.

The function of the concrete plant was to deliver concrete
to the CSL. The CSL places that concrete in the shaft as a
competent concrete lining. The operation and control of the
concrete plant and delivery system was described as it related
to the production of the concrete. The operation and control of
the CSL will be described as it relates to the placement of the
finished lining.

2.3.3.2 The Curb Ring

The CSL operator needs information to control the curb ring.
This information is displayed at the operator's control panel
and includes curb ring tilt in two axes, curb position relative
to the jack frame and slipform, active concrete port, concrete
pressure on the curb at each port, concrete line pressure at the
slide valve, and curb ring cylinder hydraulic pressure. With this
information, the operator is able to control the curb ring func-
tions. These functions include regulating the curb cylinder
pressure and the concrete pressure, maintaining curb level, and
maintaining the correct relative positions of the curb ring,
slipform and jack frame.

To control the pressure on the concrete, the hydraulic pressure
of the curb ring cylinders is adjusted by the operator. Four
pressure transducers mounted directly on the upper curb surface,
measure the actual concrete pressure. This pressure is displayed
to the CSL operator on his control panel.

When all the forces acting on the curb ring are balanced, and the concrete is being pumped sequentially to each port, the curb ring will stay level after one complete 4 port cycle. If the forces acting on the curb ring are unbalanced, then the curb ring needs to be actively controlled. To maintain level, the concrete must be proportionally distributed. In extreme cases where concrete distribution cannot maintain curb level, then individual curb ring cylinders could be locked off by the CSL operator. Curb level measurements are influenced by the level of the jack frame. This is because the curb is referenced to the jack frame. Failure to maintain the jack frame level negatively impacts the curb ring instrumentation and controls.

The CSL operator must maintain the proper relative positions between the curb ring, slipform, and jack frame. In the simulation test tower, linear displacement transducers continuously monitored the relative positions between these components, and displayed this information to the CSL operator. This information allowed the operator to maintain critical slipform effective length, helped prevent mechanical binding between CSL components, and enabled the operator match the descent rates of the curb and jack frame.

2.3.3.3   The Slipform

The slipform is the mold around which concrete is continuously cast. It confines the pressurized concrete until it has acquired sufficient strength to be self supporting. The slipform also determines the inside diameter of the shaft. The slipform effective length, speed, orientation, and direction must be controlled for proper slipforming.

In normal operations, the concrete strength gain characteristics determine how long it must be actively supported after placement. When this information is combined with the slipforming rate, the necessary form length is determined. The CSL operator must maintain the correct spatial relationship between the curb ring and slipform. The curb ring descent is controlled by the concrete pumping rate. The slipform descent is controlled by the CSL suspension system. Temporarily speeding up or slowing down the jack frame descent, the CSL operator can adjust the slipform effective length. This ability is especially useful during startup and shutdown procedures.

The simulation testing demonstrated the need for active slipform control. To accomplish this, the slipform cylinders were used as an active support system during a test. By controlling these cylinders, the orientation of the slipform could be manipulated.

The first time the concrete can be inspected since being batched is when it emerges from behind the slipform. Two tests were performed on the newly exposed concrete. Tower personnel would make a visual inspection of the concrete lining, looking for cracking or bulging, voids or poorly consolidate zones, and general surface appearance. A modified penetrometer test was also performed. The visual inspection and penetrometer test results would be verbally transmitted to the CSL operator. This information provided feedback for proper CSL operation.

The CSL slipform has one other feature not used during slipforming operations. The slipform was mounted on a hydraulically operated wedging system. This system allows for the rapid collapsing of the form. This feature is especially useful in the mechanized step forming and jump forming modes of CSL operation.

2.3.3.4 The Jack Frame and Suspension System

The final balance of forces from the curb ring and slipform are reacted through the jack frame to the central tower. The load transfer is accomplished through upper and lower jack frame reaction guides. The jack frame is the structural support member of the CSL system, to which the curb ring and slipform hydraulic cylinders are attached, and which the CSL suspension system supports.

The CSL operator has two functions associated with the jack frame. One, maintain the relative position and speed of the jack frame to the curb ring. Two, keep the jack frame level. Both of these operations rely on the CSL suspension system. In the simulation CSL, a four point suspension system was used, consisting of embedded steel rods and Heede jacks.

The Heede system was comprised of two main components: the climbing jacks and the equalizers. The climbing jacks are hydraulically operated, consisting of two hydraulic cylinders and upper and lower sets of jaws that clamp onto 2 in. x 2 in. square steel rods. Mounted above the climbing jacks were the equalizers. The equalizers are pairs of hydraulic cylinders that straddled the support rod. All of the equalizer cylinders were commonly plumbed together. This arrangement assured load sharing by all four Heede jacks.

In normal operations, all Heede jacks stepped down the embedded support rods in unison. The Heede jack descent rate was set to match that of the curb ring. The CSL operator in the control trailer had to monitor several displays to properly control the jack frame. The primary instrument for this task was a manometer bubble level system. This system allowed the operator to monitor the tilt of the jack frame. The jack frame descent rate was controlled by monitoring the positions of the jack frame, curb ring and slipform, and adjusting the hydraulic flow rate to the Heede jacks accordingly. The CSL operator also monitored the equalizer and Heede jack hydraulic pressures. Low equalizer pressure was an indication of high form drag, or insufficient curb pressure, or possible hang-up of the CSL.

The actual control of the jack frame during simulation testing proved quite difficult. This was due to unanticipated eccentric loadings on the jack frame, and the inability of the suspension system to compensate for these loads. The high eccentric loads were placed on the jack frame by the curb and slipform, and tended to force the jack frame out of level. The equalizer system was not set up to handle eccentric loads. Although the auxiliary reaction guides were designed to transmit these loads, they proved inadequate. The reaction guides were intended to transmit the eccentric jack frame loads into the control tower through eight contact "shoes", but often times these shoes yielded under load.

As an additional feature, each Heede jack was re-plumbed and re-wired to allow for individual control. This allowed the operator some flexibility in attempting to force the jack frame level by manipulating the individual jacks. This method, however, also proved inadequate. The effect of eccentric loads has had an important impact on the second generation design, and a compensating suspension system has been incorporated.

2.3.3.5 The Hydraulic Power Units (HPU)

There were two hydraulic power units at the CSL simulation test site. The main HPU controlled the curb ring, slipform, jack frame suspension system, and the multi-port concrete valve. The second HPU was dedicated to the concrete pump.

The concrete pump HPU was a basic design of high volumetric output. All of its controls were located on the concrete pump, directly accessible to, and operated by, the concrete pump operator.

The main HPU, although of low volume flow, was a fairly complex system. All the primary functions and controls of the main HPU were linked directly into the instrumentation and control trailer. The following is a review of the main HPU functions:

    a.   Directional control and monitoring of the:

        1.   Curb ring hydraulic cylinders

        2.   Slipform hydraulic cylinders

        3.   Equalizer hydraulic cylinders

        4.   Heede climbing jack cylinders

        5.   Concrete slide valve cylinders

    b.   Pressure control and monitoring of the:

        1.   Curb ring hydraulic cylinders

        2.   Slipform hydraulic cylinders

        3.   Equalizer hydraulic cylinders

        4.   Heede climbing jack cylinders

    c.   Flow rate control and monitoring of:

        1.   Curb ring hydraulic cylinders

        2.   Slipform hydraulic cylinders

        3.   Heede climbing jack cylinders.

Figures 18 and 19 of the test trailer interior show the three main subsystems of the operator's control panel. The systems are the hydraulic control panel, the CSL operator's control panel, and the data acquisition system.

The hydraulic control panel consists of a graphic display, with lights showing the activated hydraulic valves, and systems mode switches for the curb ring, slipform, and Heede jacks.

To the right of this panel is the CSL operator's control station. The system status display panel is located directly behind the desk mounted CSL controls. The following CSL controls were included:

    a.   Joy stick for manual slide valve operations

    b.   Auto-manual slide valve mode switch

    c.   Curb ring cylinder isolation push-buttons
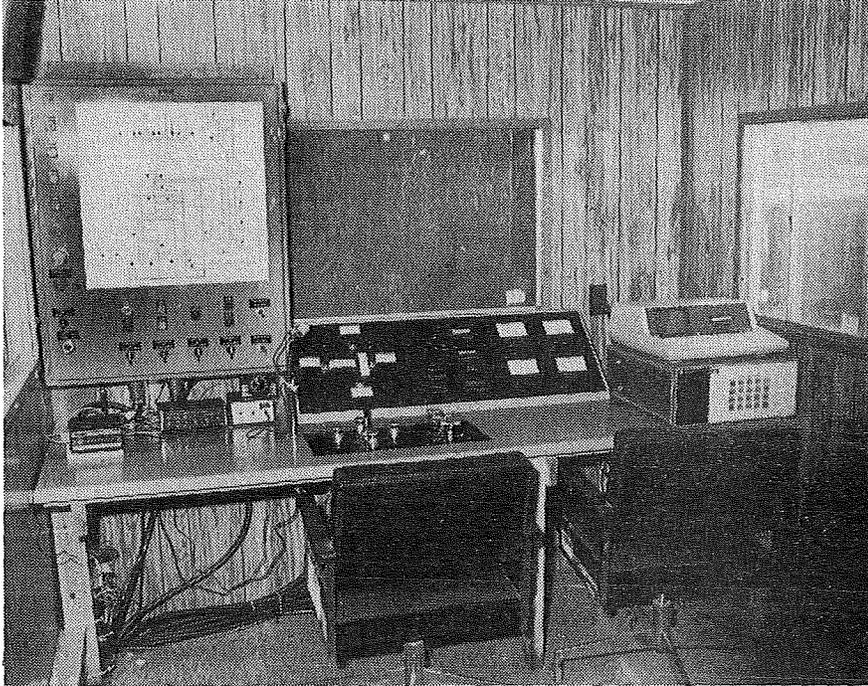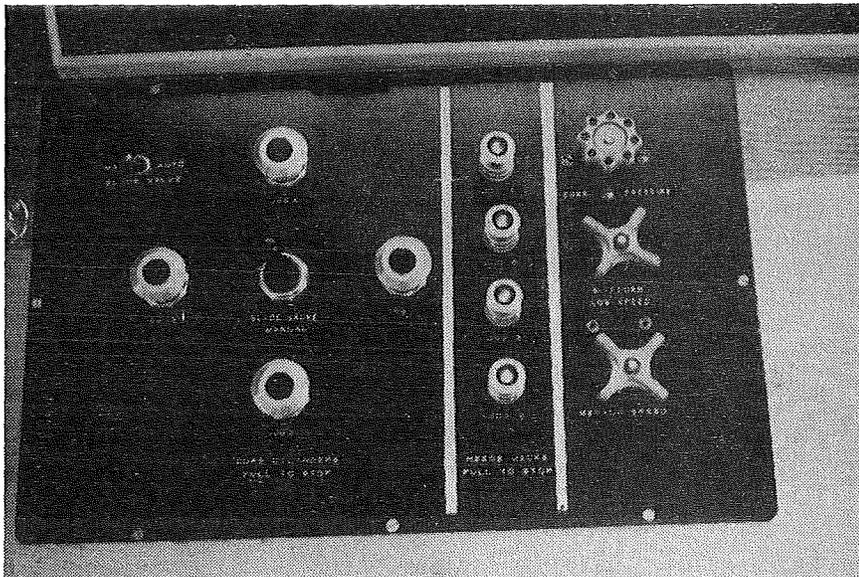
FIGURE 18. - CSL instrumentation and control trailer.

FIGURE 19. - CSL operator's control panel.

d.   Heede jack slow speed control valve

e.   Heede jack medium speed control valve

f.   Heede jack isolation push-buttons.

The data acquisition system used to monitor the various
system data points is located to the right of the operator's
panel. In normal CSL operations, two people are stationed in
the instrumentation and control trailer. One operator's duties
are to run and monitor all hydraulics and controls. The second
operator's duties are to operate and monitor the data acquisi-
tion system.

2.3.4   Test Tower and Outer Form

The tower and outer form served four main functions. The
primary function was to serve as a thirty foot section of simulated
shaft. In this capacity, it was able to provide simulation of
water inflow and slough zones. Secondly, the tower and outer
form served as the support structure for the CSL. Both the
Heede and threaded rods, which were the main and auxilary support
of the CSL, were suspended from the tower cruciform. The third
function was to provide a series of work platforms for the CSL,
both during testing and maintenance. In many ways the tower
served as a fixed galloway. The fourth function of the tower and
outer form was to act as a reaction structure for the jack frame.
Through a series of pads, wheels, and braces, eccentric jack frame
loads were transmitted into the central tower and outer form.

2.3.5   Test Personnel

Briefly, the key positions of the CSL testing personnel are:

a.   Instrumentation and controls

1.   CSL control operator

2.   Instrumentation monitor (not required
      underground).

b.   Concrete plant and delivery system

1.   Concrete plant operators (3 people)

2.   Concrete pump operator

3.   Admixture system operator

4.   Concrete quality assurance supervisor (can be admixture system operator).

c.   Tower operations

1.   CSL tower director

2.   CSL test director.

2.4   Summary of Test Results

2.4.1   Introduction

The 11 simulation tests are presented in tabular form in Table 8, and in more detail in Appendix M. The tabulation of results is followed by a more detailed discussion of the data acquisition system, data recording requirements, data analysis, and results of the analysis for the simulation test program. The simulation test plan can be found in Appendix L.

2.4.2   Data Acquisition System

The CSL data acquisition system provided process monitoring and control functions, as well as provided input to the recording system for later data analysis. Transducers were located on the CSL (as shown in Figure 20), monitoring pressure and position of the CSL system components and sending low voltage analog signals over shielded cables to the instrumentation trailer. The power supplies and signal conditioning circuitry in the trailer provided span and offset control of the signals. Displays on the control panel showed concrete and hydraulic pressures, slipform and curb positions, and denoted the active slide valve port (see Figure 21).

The data acquisition system was referenced before each test according to zero pressure on the transducer inputs and manual position measurements. The pressure transducers, Data Instruments Model AB, were factory calibrated and sealed, and required only a zero offset adjustment. Hydraulic and concrete pressures were brought to zero, and the signals and meter readings nulled. The position transducers were cable extension resistance change type, Celesco Model PT. The transducers required iterative extension and manual measurement of position to calibrate the meter outputs.

Test data were digitally recorded on a Hewlett-Packard data logging system. The data logger operates by scanning through the input channels one by one, converting each input signal to digital computer code; manipulating the signal according to the

TABLE 8. - Summary of simulation tests

| Test Number	Date	Hours of duration of pumping	Concrete placed inches	Range curb pressure psig	Curb advance rate ft/hr	Slipform advance rate ft/hr	Concrete slipformed and exposed inches	Primary test objectives
1	10/28/81	-	4	-	-	-	-	Hardware shakedown test
2	10/30/81	2.5	72	7-13	2.7	0.8	-	Concrete distribution in the "round"
3	11/05/81	1.7	57	5-10	3.8	1.7	57	Discrete slipforming
4	11/12/81	3.6	120	10-15	2.7	2.7	10	Demonstrate fully operational CSL
5	5/26/82	3.3	58	8-15	1.9	2.8	-	CSL suspension system slough zone and concrete seal
6	6/03/82	3.0	105	8-17	3.2	2.2	-	Establish CSL performance limits
7	7/13/82	3.5	105	5-11	2.8	2.2	36	Jack frame leveling system concrete pump
8	8/11/82	6.5	166	5-20	2.0	2.6	74	Investigate slough zone and concrete seals
9	8/18/82	1.0	72	0-6	6.0	-	-	Demonstrate jump mode
10	9/21/82	5.0	132	8-20	3.0	1.8	36	Establish CSL performance limits
11	9/29/82	3.8	112	15-40	2.4	-	-	Slipform steering water inflow mechanized step form mode
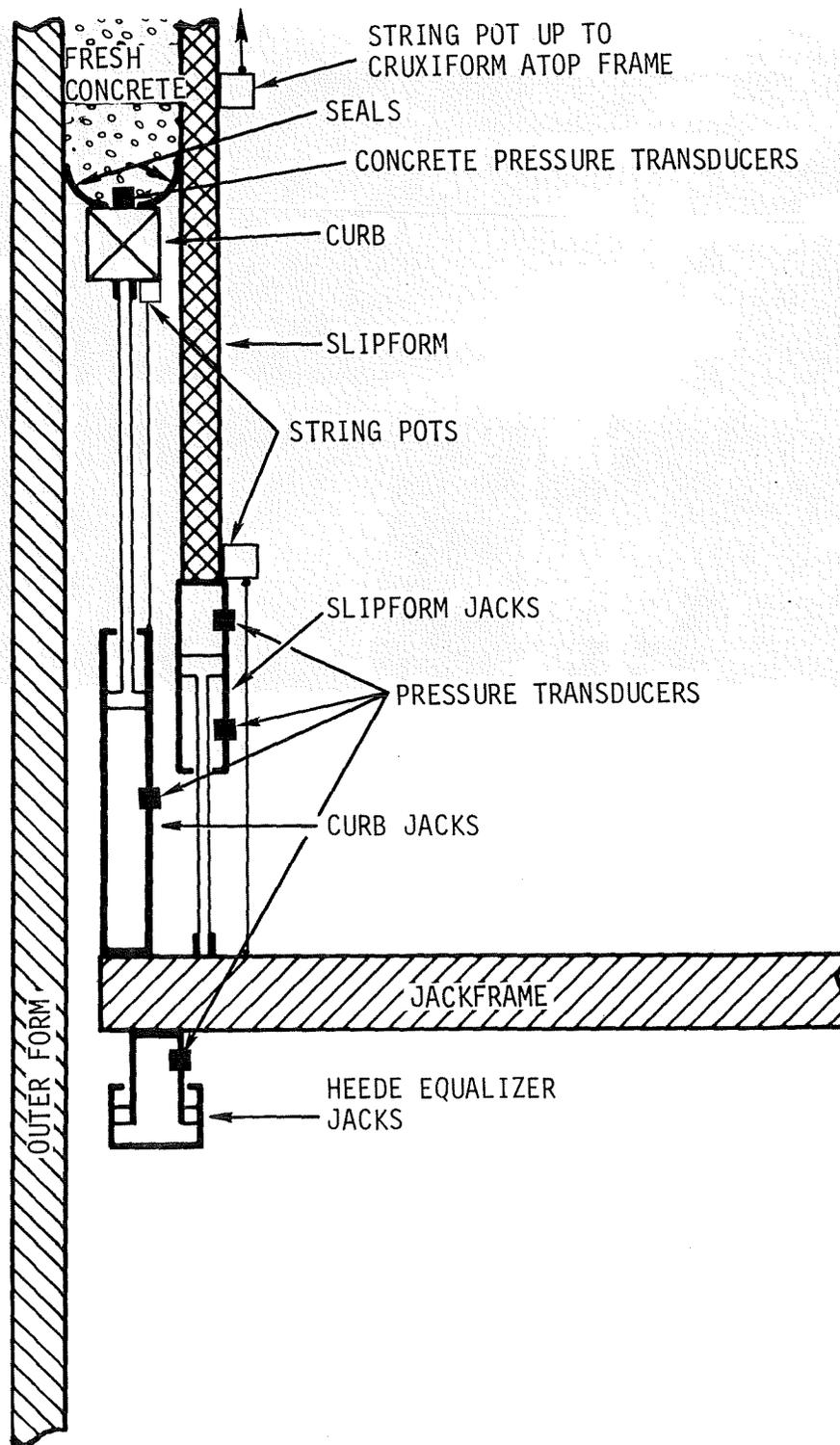
FIGURE 20. - Simulation test instrumentation.
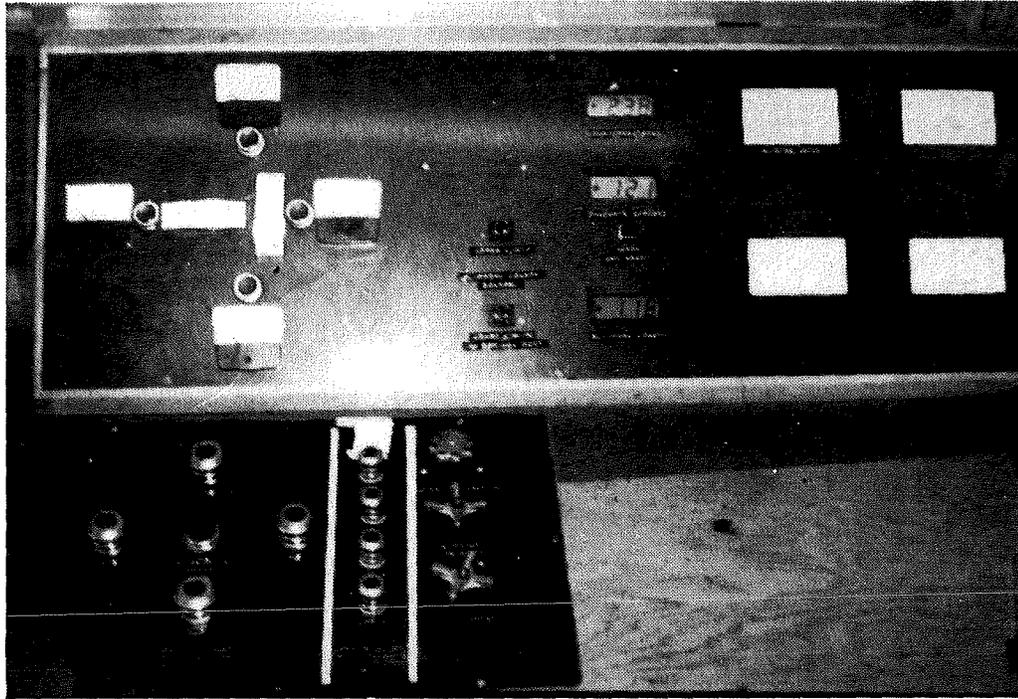
FIGURE 21. - CSL operator's control panel.

programming; and storing the information on a magnetic tape cassette. The entire sequence of operations is accomplished at very high speed, taking the system less than two seconds to scan through nearly twenty channels of data. Compared to the time frame in which the CSL system operates, the data logger recorded all channel imputs nearly simultaneously. This allowed the data points, recorded during each scan, to be interpreted against each other as an instantaneous picture of CSL system operation. The data was scanned twice a minute during the tests, with all data being recorded on the tape between scans. Calculated values of slipform drag were also displayed on the system screen between scans. In addition, the system provided audible and visual warnings of excessive CSL tilt and pressures. The data logging system, including the HP3497A analog to digital converter switching unit and the HP 85F computer controller/recorder are shown in Figure 22.

The data logger operated according to a computer program written in the BASIC language specifically for the CSL tests. The program contained instructions and timers for automatic operation, including:

- calibration of transducers

- scanning transducer channels

- conversion of voltage inputs to engineering units

- recording data on a magnetic tape cartridge

- updating data displays on the video monitor screen

- graphically displaying and printing data during the tests

- flagging over- and under-range inputs

Recovery of the stored data involved other computer programs to play back the test tape. The programs also converted the data into useful engineering units and functions. The ability of the computer to "develop and print" a complete picture of the CSL operation and to exactly match and compare system parameters proved invaluable. It enabled understanding of the test sequences and the interrelationship of slipform drag with other variables. Several typical computer generated data plots are included here as illustrations (Figures 23 and 24), and a complete record of test data from one test is included in Appendix M. Figure 25 is annotated to indicate the actual test event associated with the plot.
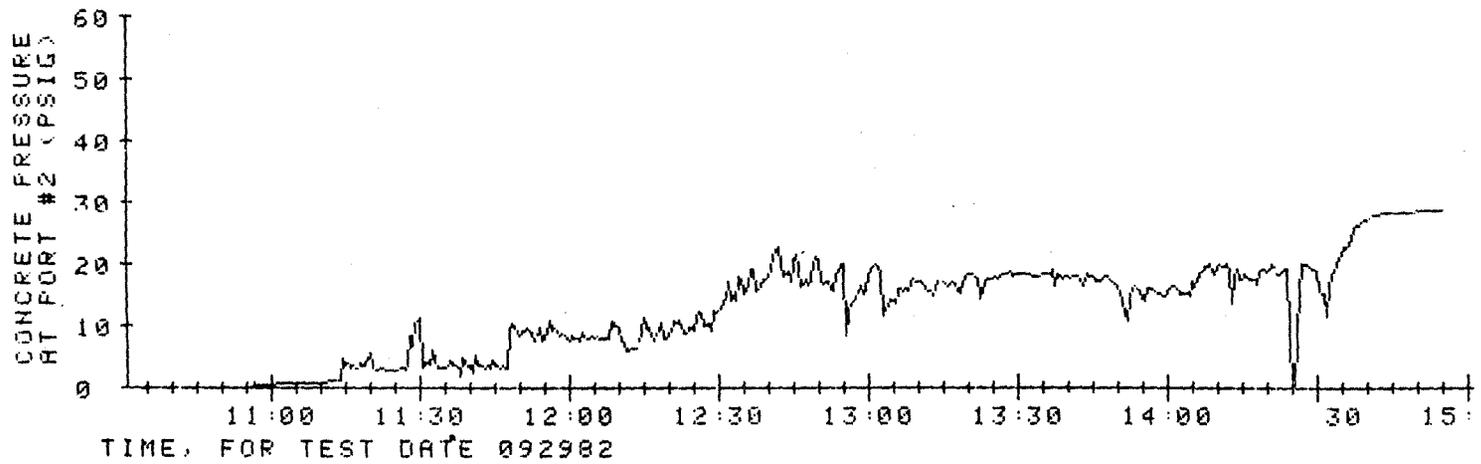
FIGURE 22. - CSL simulation test data
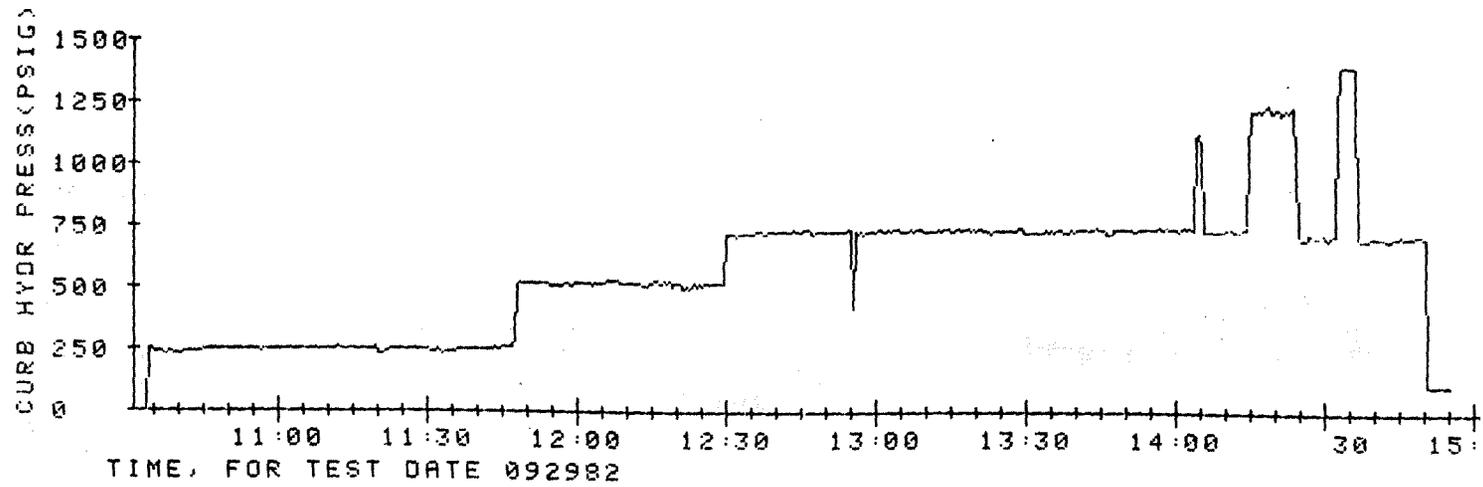acquisition system.
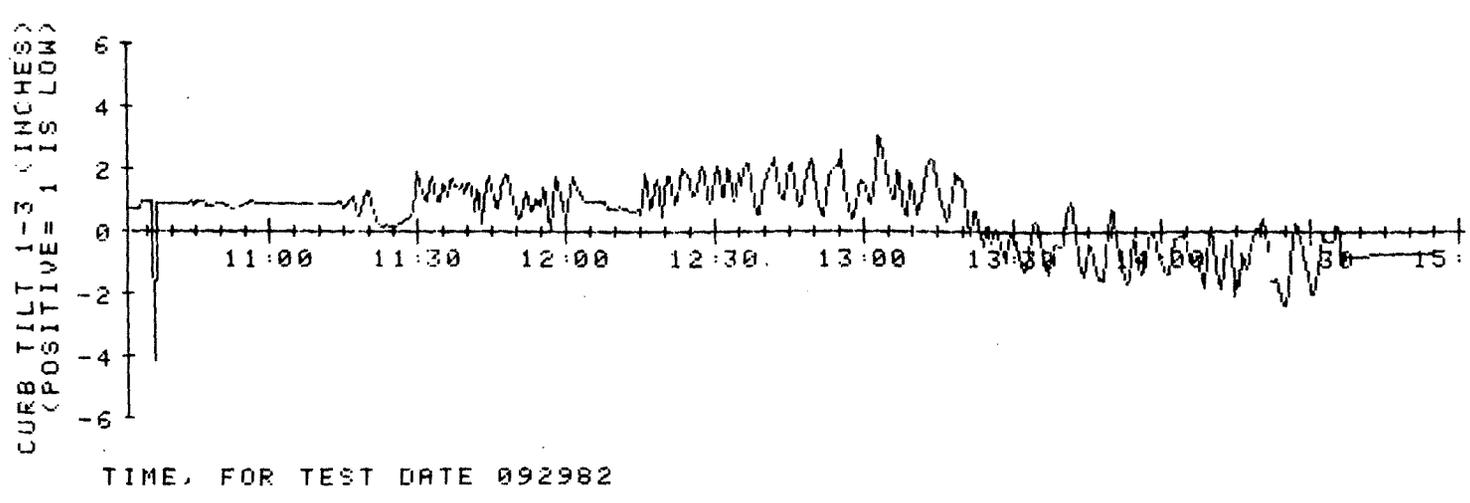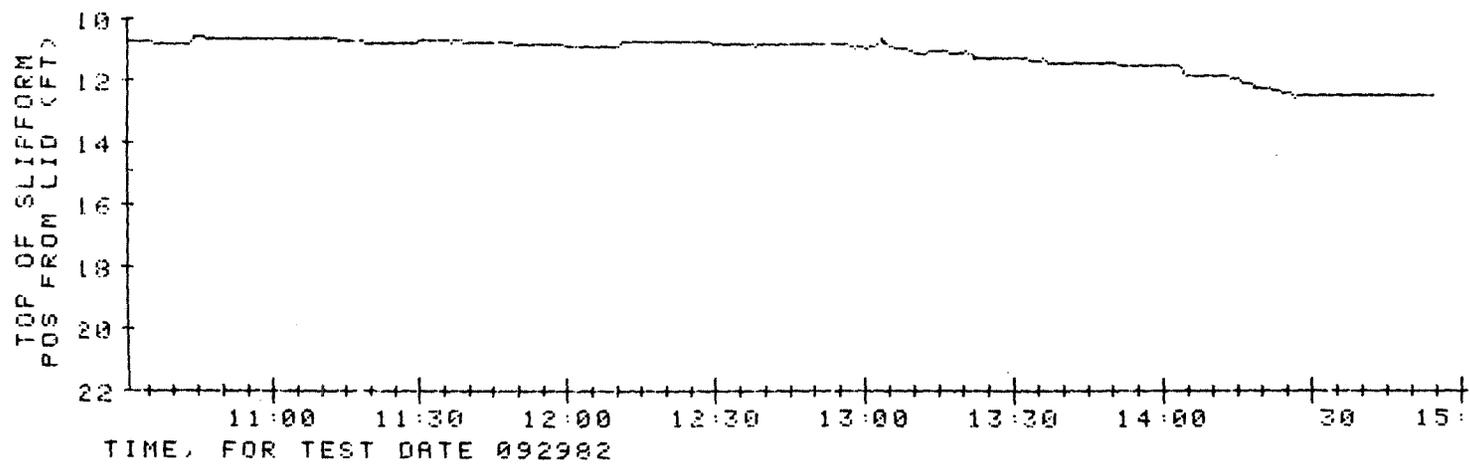
FIGURE 23. - Computer generated data plots.

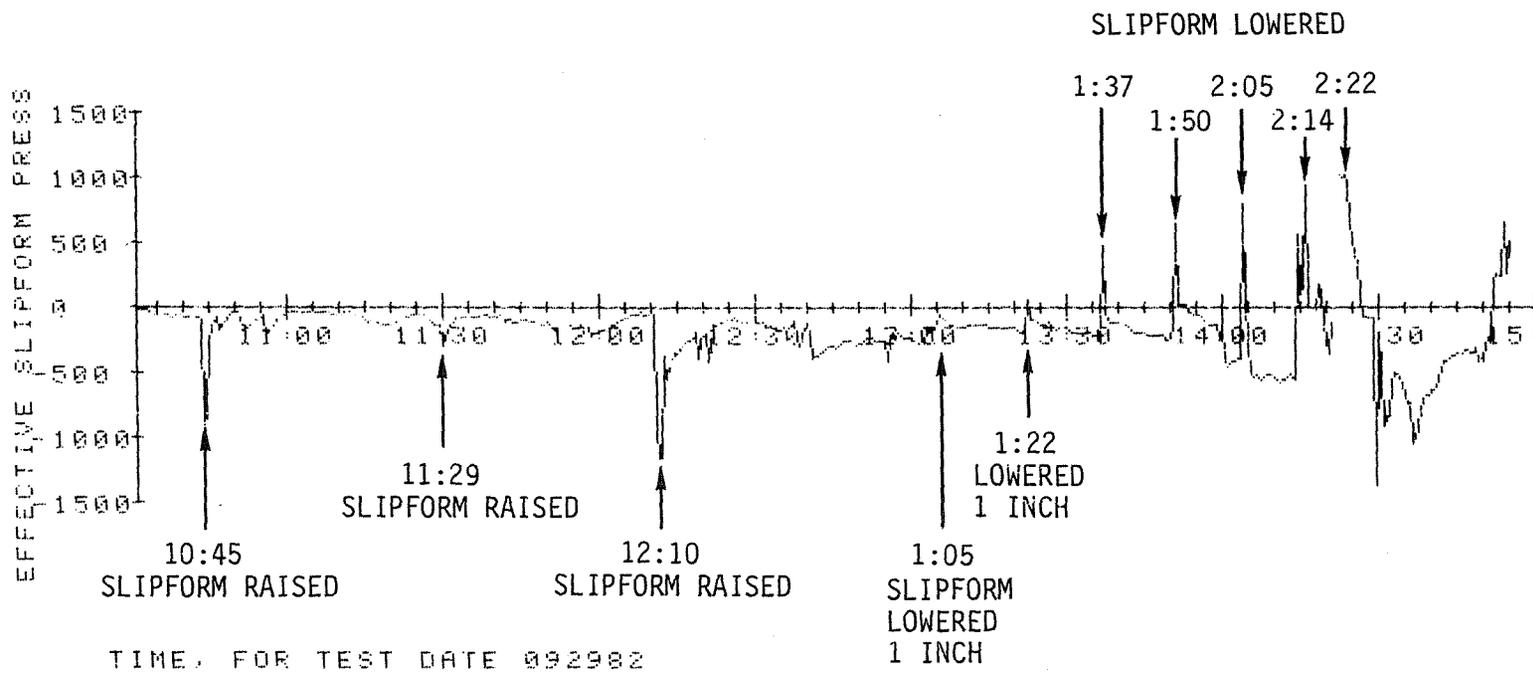FIGURE 24. - Computer generated data plots.

FIGURE 25. - Annotated data plot.

In addition to the data recorded on magnetic tape, major test events were recorded in a hand written test log. These test logs are included in Appendix M. Furthermore, all verbal communication between the CSL operator and the other various operators was recorded on an audio-cassette tape recorder.

2.4.3 Data Recording Requirements

Table 9 includes the operational relationships being explored, system parameters required, and simulation test data collected. The layout of the instrumented components on one side of the simulation CSL is shown in Figure 26. Table 10 describes the instruments used to gather the data and their operating range and recording accuracies.

2.4.4 Data Analysis

2.4.4.1 Slipform Drag

Analysis of slipform drag required identifying the periods of time during which the slipform was moving downward and examining the relevant data from these periods. Plots of slipform position with time were examined and slipform movements occurring over several minutes duration were identified. This data search identified twenty-eight instances of sustained movement (see Figure 27 for an example of slipform position and movement).

Slipform drag forces will fluctuate during steady state slipforming. The peak force corresponds to incipient motion of the slipform, and therefore, is the relevant measure of slipform drag. Data points were examined and sifted to yield the point in time with the largest slipform drag for each period. The data recorded during those twenty-eight points in time were used to obtain average curb concrete pressure, SEL, and the forces on the curb simultaneous with the peak slipform drag.

Figure 28 shows a free body diagram of the slipform, with peak slipform drag, weight, slipform hydraulic forces, and curb seal drag acting on it. The force balance equation for the slipform can be written as follows:

$$D_{s_{peak}} = F_{sv} + W_s + D_i \tag{1}$$

where $D_{s_{peak}}$ = slipform drag force

F_{sv} = force on slipform cylinder

W_s = weight of slipform

Table 9. - Data collection requirements

Operational relationships	Variation of slipform drag with SEL Variation of slipform drag with concrete pressure
System parameters	Slipform drag forces SEL Average concrete pressures Curb seal drag forces Equipment weights Slipform and curb motion Unaccounted drag forces
Raw data collected	Concrete pressures on curb (near 4 ports) Concrete pressure in line (at slide valve) Heede equalizer hydraulic pressure Curb hydraulic pressure Slipform hydraulic pressures Curb tilt (in two axes) Curb position Slipform position

FRESH CONCRETE

SEALS

CURB

SLIPFORM

SLIPFORM JACKS

CURB JACKS

JACKFRAME

OUTER FORM

HEEDE EQUALIZER JACKS
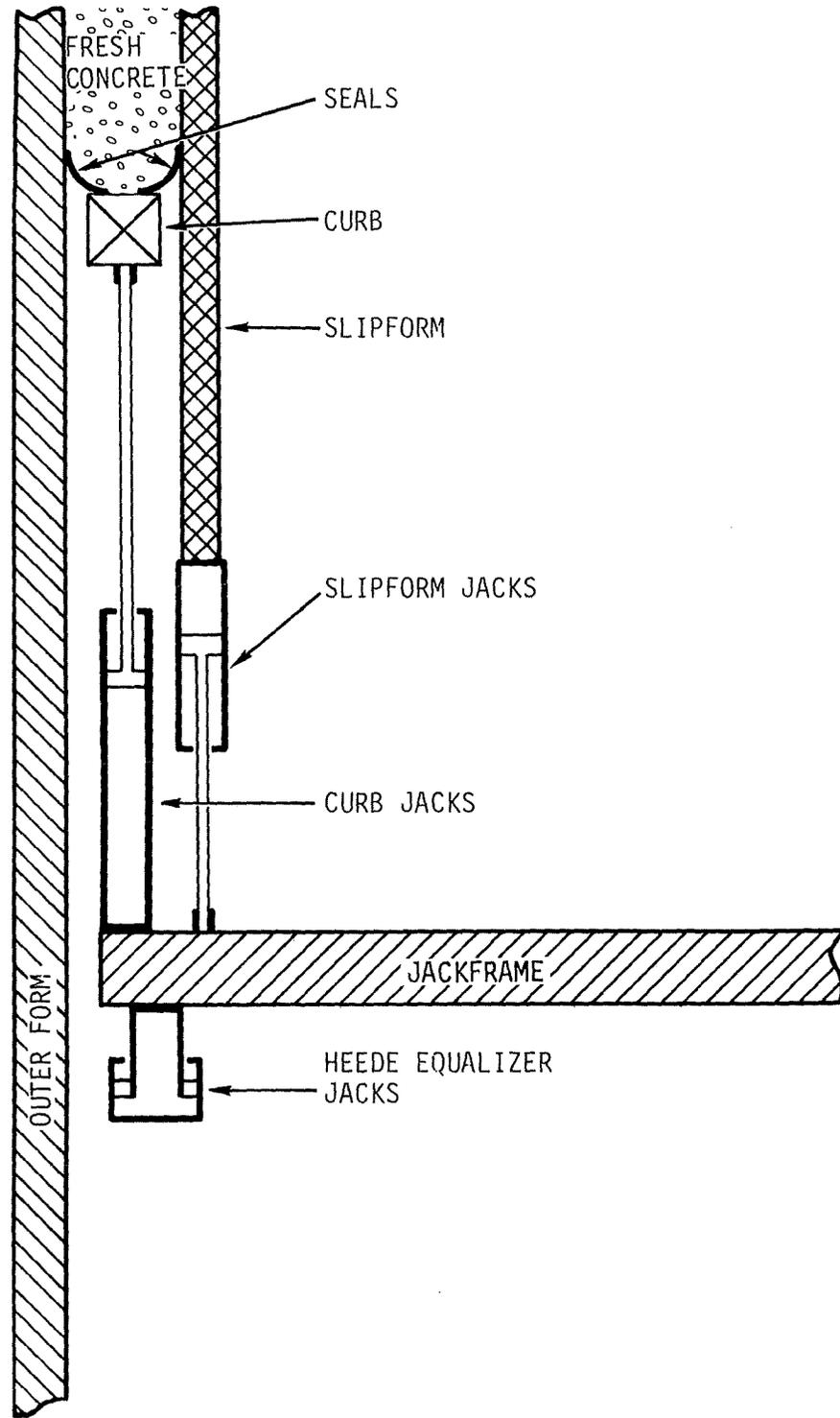
FIGURE 26. - Instrumented CSL components.

Table 10. – Data instrument specifications

Function	Instrument	Range	Accuracy
Curb concrete pressure	Data Instruments "AB" pressure transducer	0-50 psig	0.5 psig
Concrete line pressure	Data Instruments "AB" pressure transducer	0-200 psig	2.0 psig
Heede equalizer pressure	Data Instruments "AB" pressure transducer	0-3000 psig	30 psig
Curb hydraulic pressure	Data Instruments "AB" pressure tranducer	0-3000 psig	30 psig
Slipform hydraulic pressure	Data Instruments "AB" pressure transducer	0-3000 psig	30 psig
Curb tilt	Celesco "PT101" string pot	0-120 in.	0.1 in.
Curb position	Celesco "PT101" string pot	0-120 in. 0-500 in.	0.5 in.
Slipform position	Celesco PT101" string pot	0-500 in.	0.5 in.

FIGURE 27. - Graph of slipform position with time.
            Bands identify periods of downward movement.

FIGURE 28. - Free body diagram of slipform.

$$D_i = \text{inner curb seal drag force}$$

specifying curb seal drag positive in the downward direction.

2.4.4.2 Curb Seal Drag

The curb seal drag can be understood by examining a free body diagram of the curb (Figure 29). The force balance equation is:

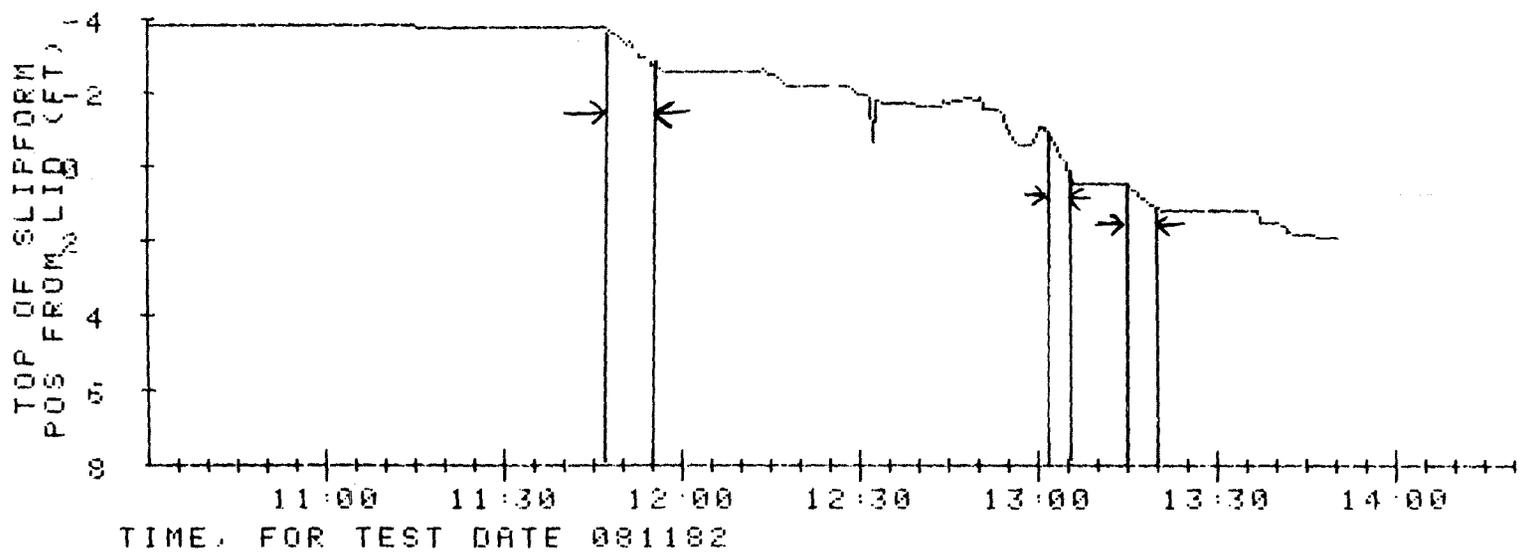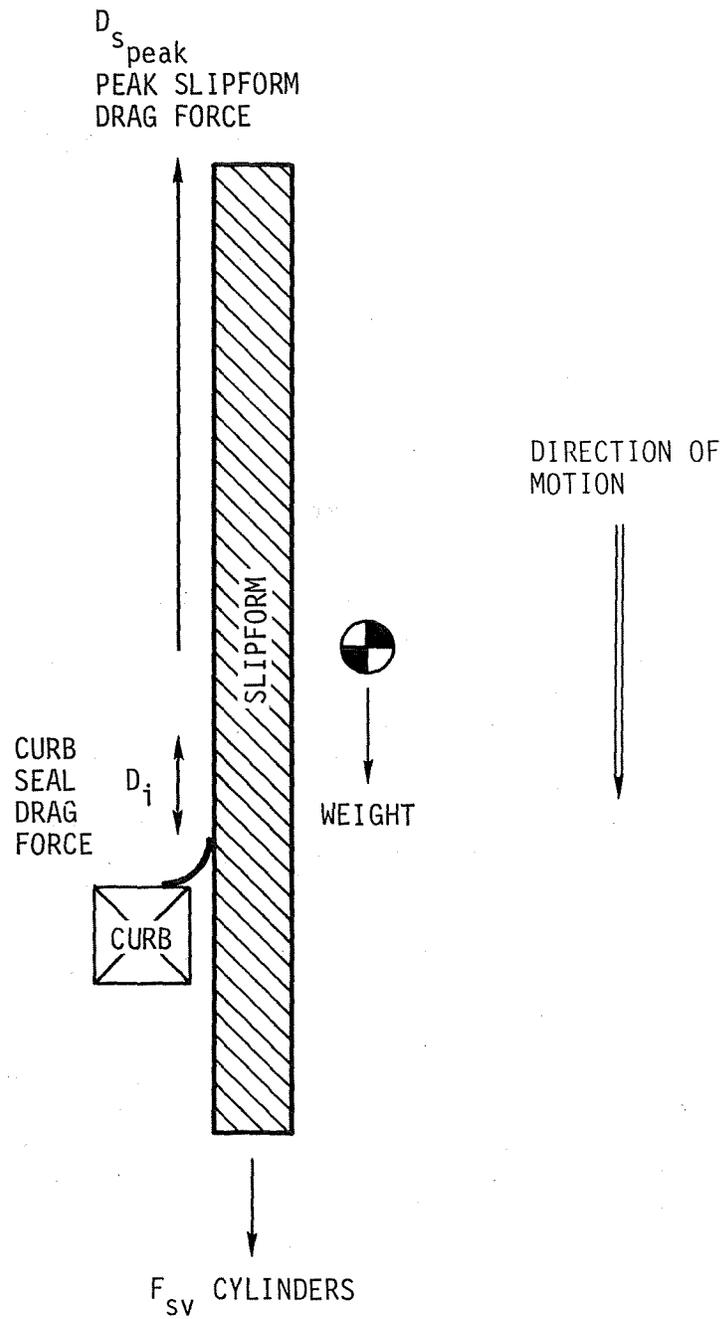$$D_i = \overline{P}_v A_c - F_{cv} - D_o \tag{2}$$

where D_i = inner curb seal drag force

$\overline{P}_v$ = average curb pressure

A_c = curb area

F_{cv} = force on curb cylinder

D_o = outer curb seal drag force

The magnitude of the forces indicated that curb seal drag is a significant part of the slipform force balance, and so an analysis was performed of the inner and outer curb seal drags.

Curb slipform motion can be divided into four categories. The categories are listed in Table 11 along with the direction in which curb seal drag is acting on the slipform. The twenty-eight data points do not fall into category 2 because they were chosen for instances of slipform movement. Category 1 only applies when the slipform is moving slower than the curb. Categories 1 and 3, where the curb is moving, offer the opportunity to calculate the curb seal drag on the slipform from Equation 2 by setting the outer seal drag equal to the coefficient of friction times the average concrete pressure on the curb (acting as a normal force). This coefficient of friction as well as the contact area of the seal is assumed to be constant. However, this definition of the outer seal drag is only applicable as long as the curb is moving downward and the outer seal is sliding freely. With the curb stopped or moving upwards, the outer seal drag is indeterminate. Therefore, the curb seal drag on the slipform cannot be calculated from Equation 2. This is the situation in category 4.
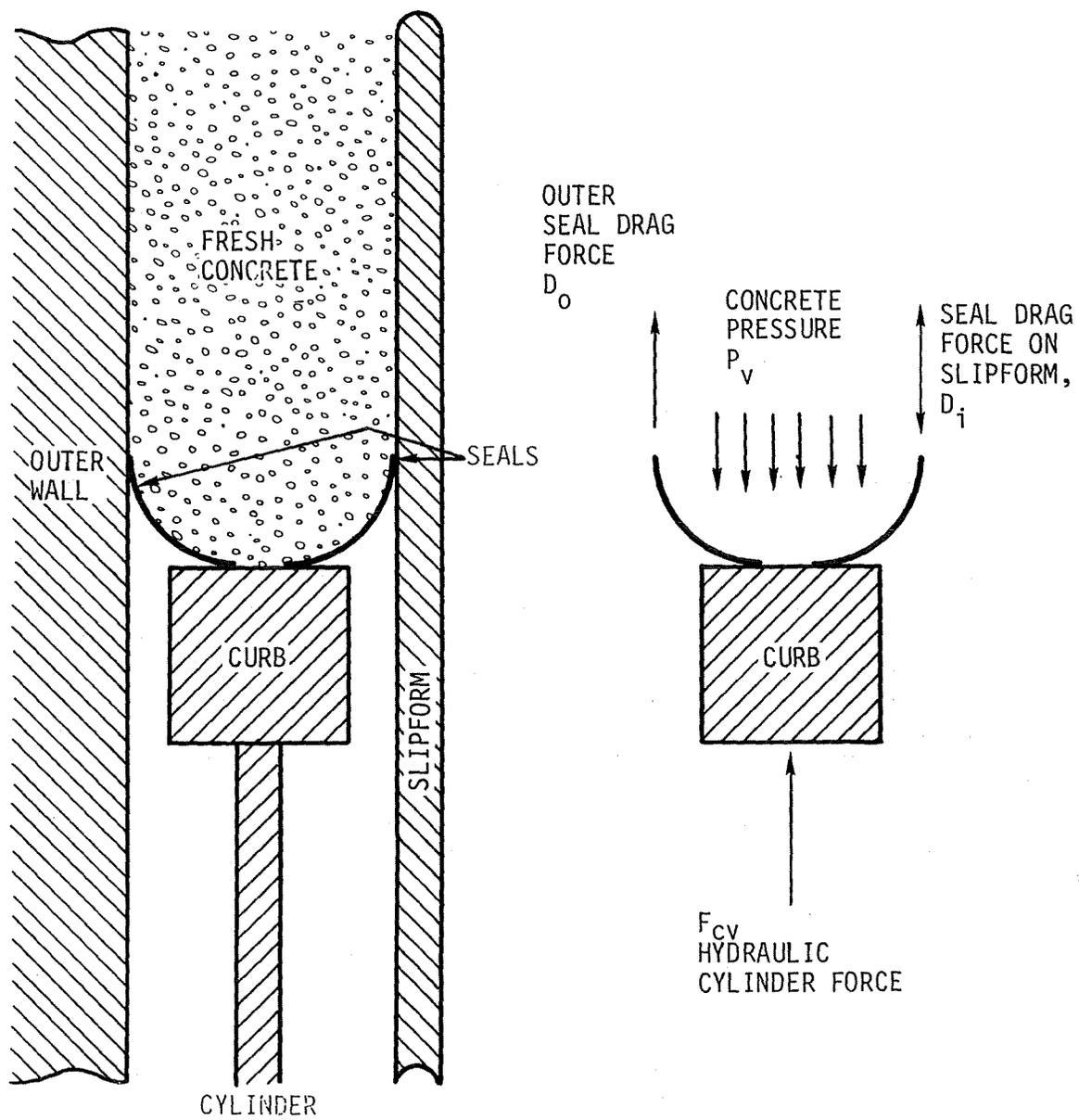
FIGURE 29. - Free body diagram of curb.

TABLE 11. - <u>Curb seal drag direction with</u>
<u>curb and slipform motion</u>

Category	Curb motion	Slipform motion	Curb seal drag on slipform
1	Down	Stop or down slower	Down(+)
2	Stop	Stop	Indeter-mine
3	Down	Down faster	Up(-)
4	Stop	Down Faster	Up(-)

Data points in category 4 were identified by checking the curb hydraulic pressure. During CSL operation, for a short period of time following an increasing curb hydraulic pressure, the outer seal drag was in category 4. Of the twenty-eight data points, only four points were in category 4. This eliminates these points from further consideration in slipform drag analyses.

The outer seal drag coefficient of friction (μ) was determined by looking at the start of the CSL operation when the slipform had not moved. With the curb moving down, the inner and outer seal drags can be assumed to be equal, yielding the following equation:

$$\bar{P}_V A_c - F_{cv} = 2(\mu) \bar{P}_V \qquad (3)$$

The curb forces (F_{cv}) due to hydraulic pressure were plotted against forces due to average concrete pressure, $\bar{P}_V$. A typical graph is shown in Figure 30. The 45 deg line would represent equal hydraulic and concrete forces with no curb seal drag. The difference in hydraulic cylinder force between the 45 deg line and the line passing through the right most data points corresponds to the maximum curb seal drag for the corresponding concrete force. The seal load for any concrete pressure force can be
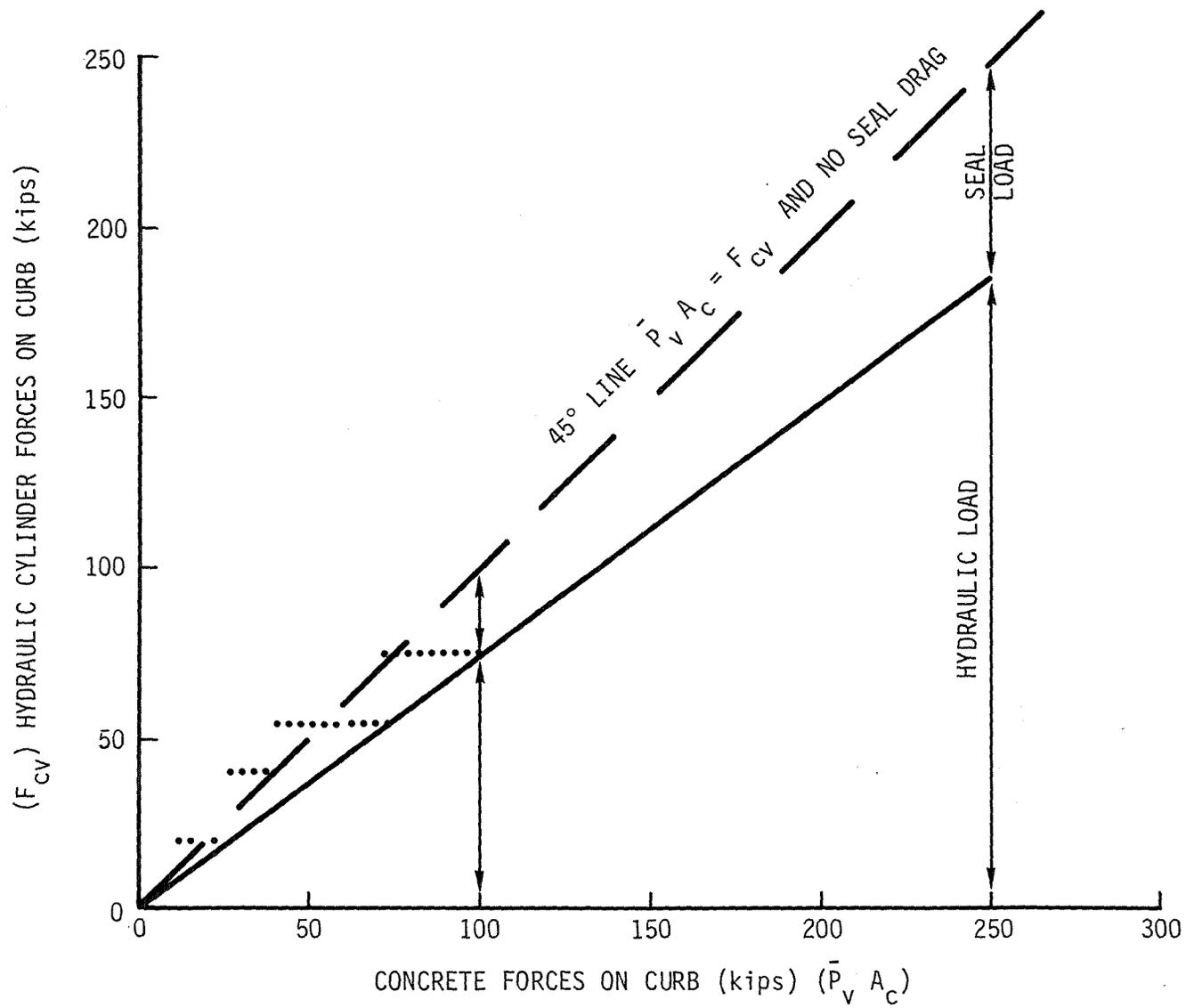
FIGURE 30. - Determination of outer curb seal drag.

read from that line up to the 45 deg zero drag line. The
combined drag of the inner and outer seals is proportional to
the concrete pressure:

$$\left(D_o + D_i \right) = \bar{P}_v A_c - F_{cv} - = 2\mu \bar{P}_v \qquad (4)$$

Values for μ were in the range of 0.4 to 0.9, and an
average of 0.6 was chosen.

2.4.4.3 Data Analysis Results

Combining equations 1, 2, and 3, the final simulation test
equation for determining peak slipform drag becomes:

$$D_{s_{peak}} = F_{sv} + W_s + \bar{P}_v A_c - \mu \bar{P}_v - F_{cv} \qquad (5)$$

where

$$\mu = 0.6$$

This equation was applied to the simulation test data to
determine slipform drag. The SEL, concrete pressure, and drag
forces were plotted graphically. This established the relation-
ship between SEL and concrete pressure and slipform drag.

The data points are listed in Table 12. Of the twenty-eight
data points, four were eliminated due to curb seal difficulties
(category 4 as previously described). Other points also are
questionable due to various problems encountered during the CSL
tests. When all of these questionable points are eliminated
from the analysis, only thirteen valid data points remain. These
are plotted in Figure 31. The figure indicates a drag force
dependence upon slipform effective length and curb concrete
pressure.

In an attempt to establish the pressure dependent relationship
of slipform drag, the data were normalized for SEL. As a first
approximation, it was assumed that the drag distribution was equal
over the entire slipform area in order to obtain values of drag
per square inch of slipform. The results are graphically dis-
played in Figure 32, which shows an excellent correlation exists
between concrete pressure and slipform drag. A best-fit curve was
generated and is defined by Equation 6:

Table 12. - <u>Slipform drag data points</u>

Points	Date	Time	SEL (in.)	Average concrete pressure (psig)	Peak drag (lb)	Peak drag and seal drag	Drag/psi (lb/psi)	Comments
1 ·	9/29/82	13:22:31	64	4.0	22,600	78,000	2.49	-
2	9/29/82	13:37:01	70	17.5	53,700	70,700	2.06	-
3	9/29/82	13:51:01	79	16.5	65,000	77,000	1.99	-
4	9/21/82	10:09:30	60	9.5	40,700	42,900	0.61	-
5	9/21/82	10:28:30	55	8.2	32,600	26,980	0.07	-
6	9/21/82	10:40:00	59	6.1	17,100	140	-	Low drag
7	9/21/82	11:06:30	60	16.9	108,800	118,850	-	Stuck
8	9/21/82	11:22:31	62	18.8	141,400	140,900	-	Stuck
9	9/21/82	12:39:31	108	16.2	47,900	-4,100	-	Seal drag number 4
10	9/21/82	12:50:01	112	16.2	62,300	-7,300	-	Seal drag number 4
11	9/21/82	13:18:01	115	20.5	190,600	151,000	2.24	-
12	8/11/82	11:56:31	92	9.6	53,200	25,350	0.56	-
13	8/11/82	12:16:31	92	9.8	58,100	17,800	0.39	Low curb H
14	8/11/82	12:54:01	96	7.4	55,600	2,050	0.04	-
15	8/11/82	13:18:31	90	13.3	78,700	54,400	1.23	-
16	8/11/82	13:42:01	94	2.4	76,400	36,060	-	Low curb C
17	7/13/82	10:46:01	88	9.5	43,800	22,900	0.53	-
18	7/13/82	11:29:01	92	9.9	49,300	30,450	0.68	-
19	7/13/82	11:36:01	68	10.0	56,700	-2,400	-	Seal drag number 4
20	6/03/82	12:03:01	84	13.3	56,600	55,200	1.34	-
21	6/03/82	12:19:01	94	7.5	79,100	45,100	-	Seal drag number 4
22	6/03/82	12:25:01	94	10.9	51,700	24,350	0.53	-
23	6/03/82	12:31:31	94	12.3	77,300	54,920	1.19	-
24	6/03/82	12:50:01	96	19.6	44,200	82,550	1.75	Low curb H
25	6/03/82	12:55:31	91	25.1	44,600	114,650	2.57	-
26	5/26/82	10:03:30	67	7.9	14,600	-1,340	-	Low curb H
27	5/26/82	10:23:30	73	7.9	20,300	4,750	0.13	-
28	5/26/82	10:32:00	67	8.9	37,300	27,250	0.83	Low curb H
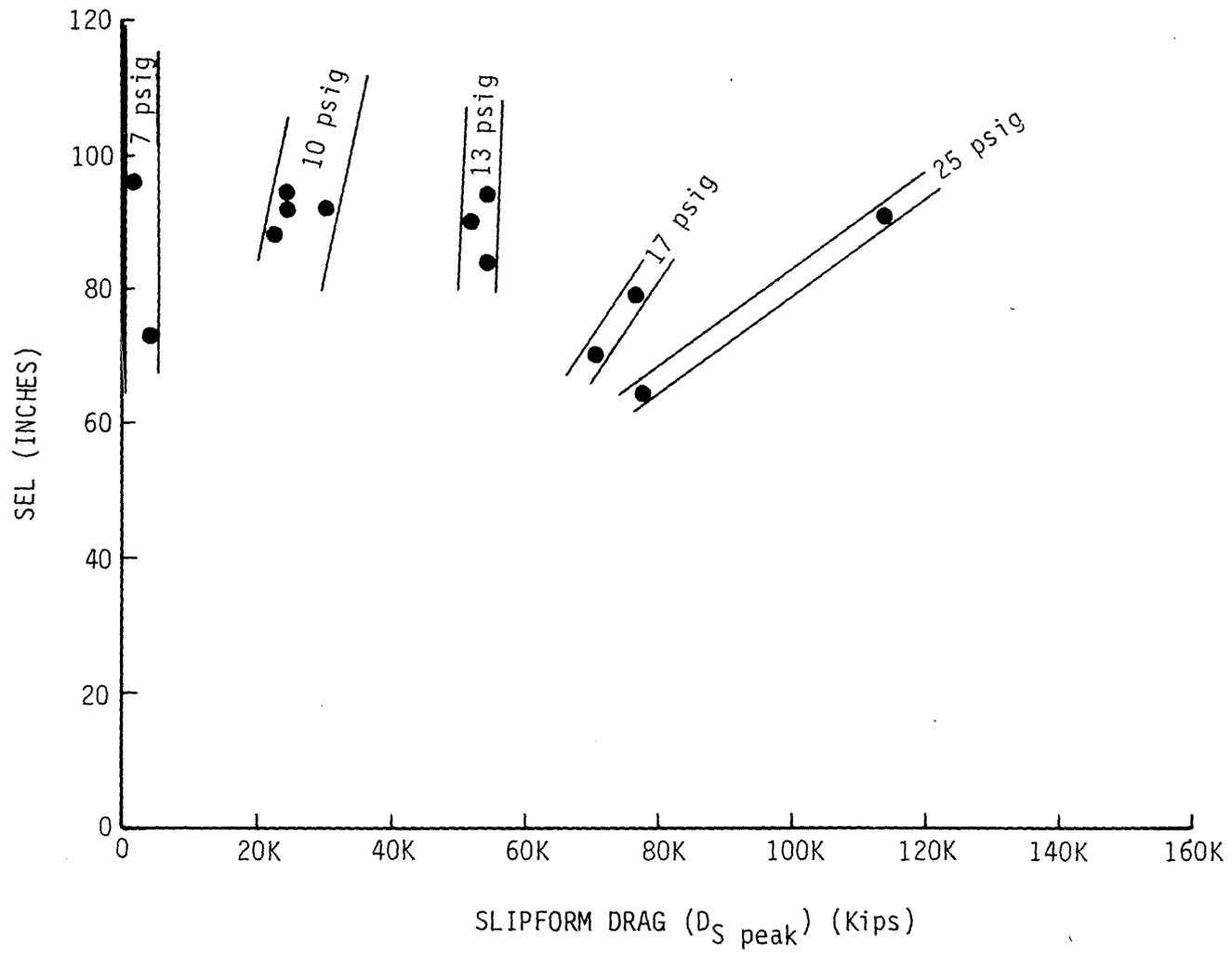
FIGURE 31. - Peak slipform drag versus SEL for various concrete curb pressures.

$$\text{DRAG/in}^2 = 2.2 \times \text{LOG}\ (\overline{P}_V) - 4.408$$
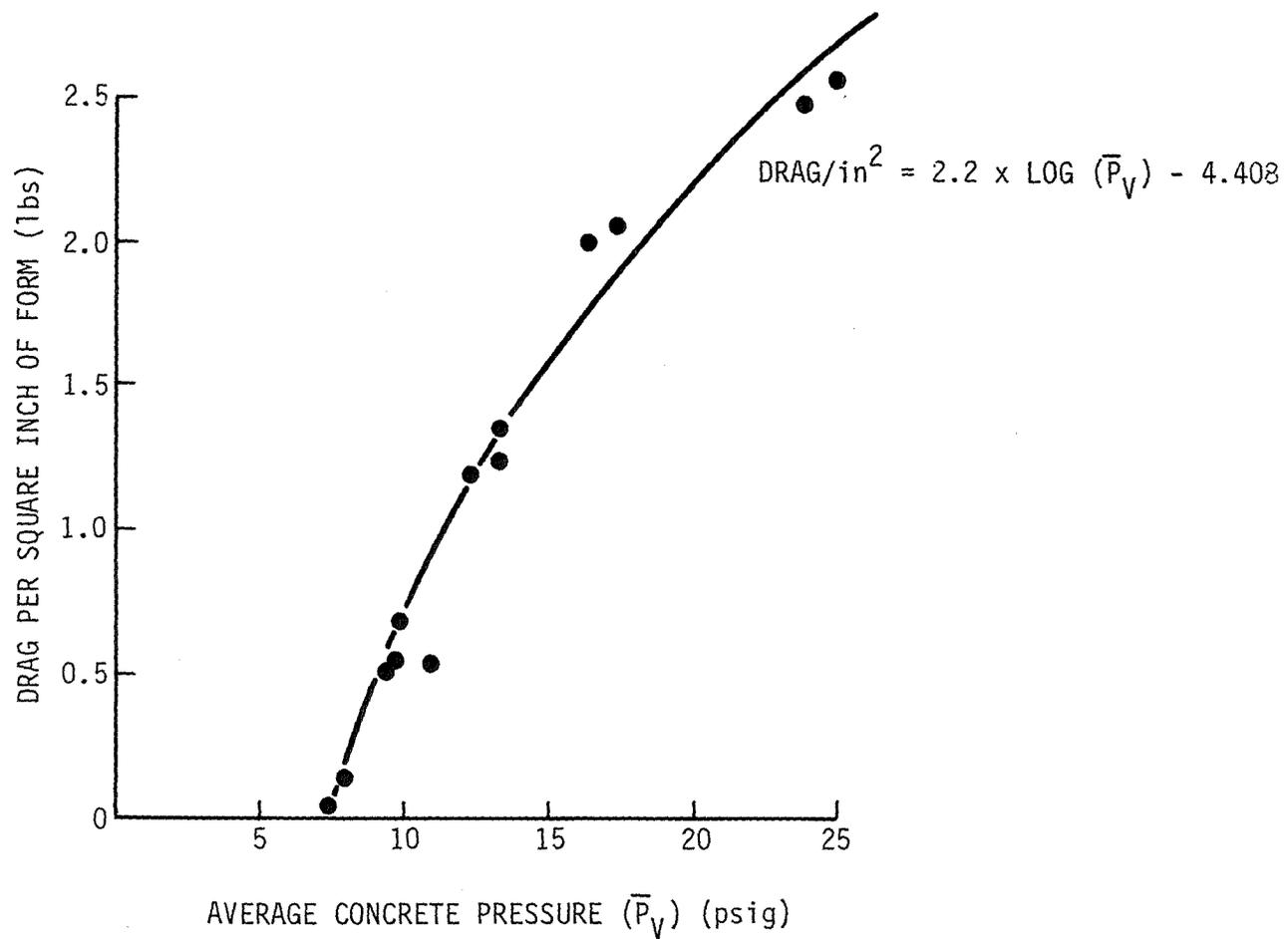
FIGURE 32. - Slipform drag data normalized for
SEL with best-fit curve.

$$\frac{drag}{unit\ area} = (2.2 \times \log (\bar{P}_v) - 4.408) \qquad (6)$$

The equation has a correlation coefficient of 0.98.

Expanding on Equation 6 yields the following:

$$D_{s_{peak}} = \pi d\ (SEL)\ (2.2 \log (\bar{P}_v) - 4.408) \qquad (7)$$

$$d = diameter\ of\ slipform\ (inches)$$

If a series of curves based on Equation 7 is plotted onto the graph of SEL versus peak drag, the result is Figure 33.

This equation was obtained using data falling within an SEL range of 60 to 100 in. and a curb concrete pressure range of 7 to 25 psig. Although the equation fits the data very nicely within these ranges, caution must be used when applying it to other situations. For instance, pressures below 7 psig do not have meaning for this equation as shown in Figure 33. Furthermore, different concrete mix designs would not necessarily behave identically due to variations in set time, strength gain characteristics and advance rates.

By examining a free body diagram and drawing the force balance of the concrete behind the slipform (Figure 34), another form of Equation 7 can be obtained per unit length of circumference of the lining (i.e., vertical slice). This allows relating the curb width to the pressure required to overcome drag. The drag will remain constant on the slipform surface regardless of the curb width.

Per unit length of lining circumference (vertical slice through the concrete ring 1 in. wide), Equation 8 can be used:
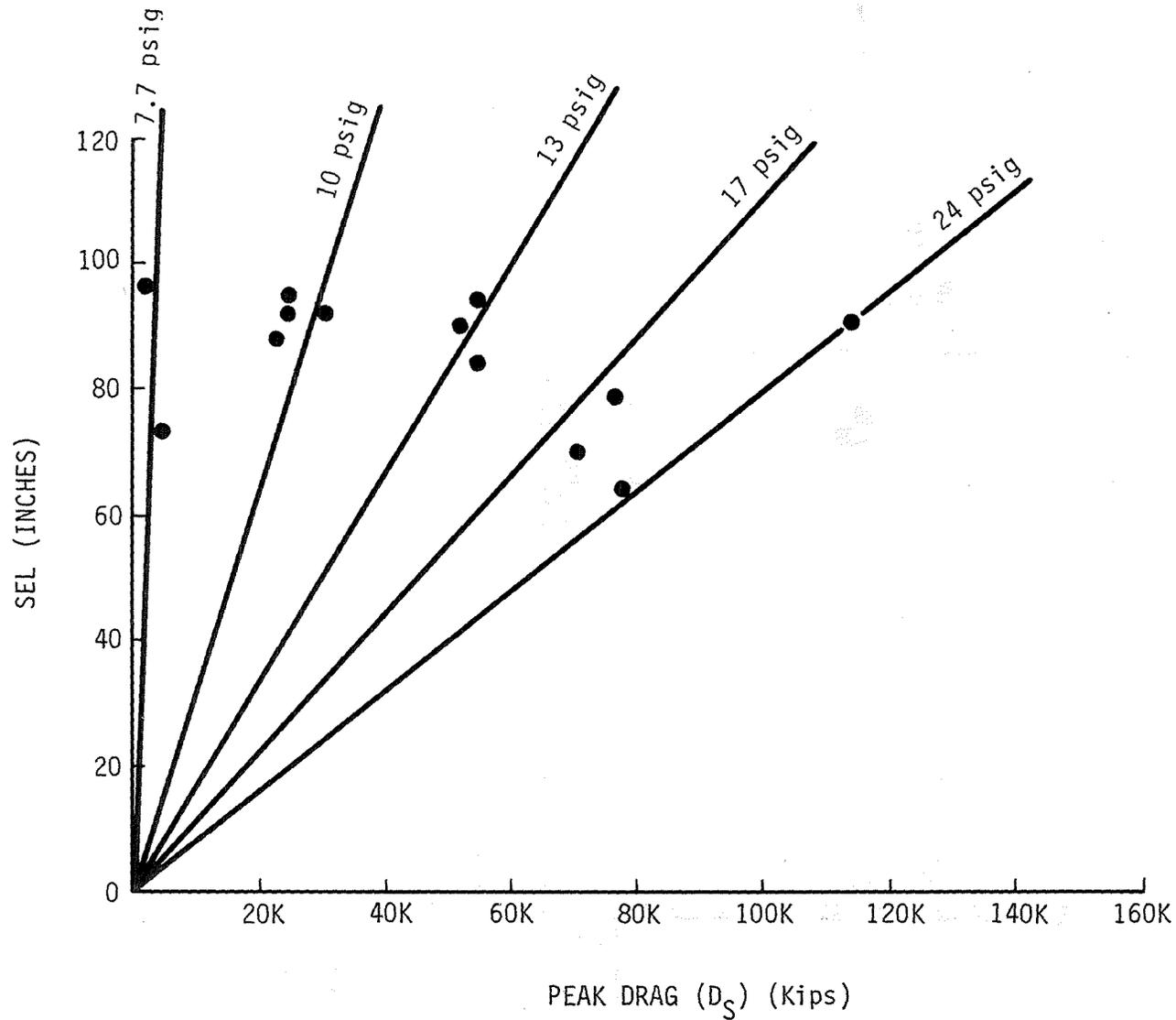
FIGURE 33. - Best-fit curve drag = πd x SEL x (2.2 x log $(\overline{P}_V)$ - 4.408) plotted as SEL versus drag.

SLUG OF
CONCRETE

WALL

SLIPFORM

CURB

CONCRETE PRESSURE ≡ 0
AT SLIPFORM TRAILING EDGE

WALL
DRAG ≡ 0

UNIT
SLIPFORM
DRAG
$(D_{s_{peak}}$ /CIRCUMFERENCE)

WEIGHT

AVERAGE CONCRETE
CURB PRESSURE
x WIDTH OF CURB
$(P_v B)$

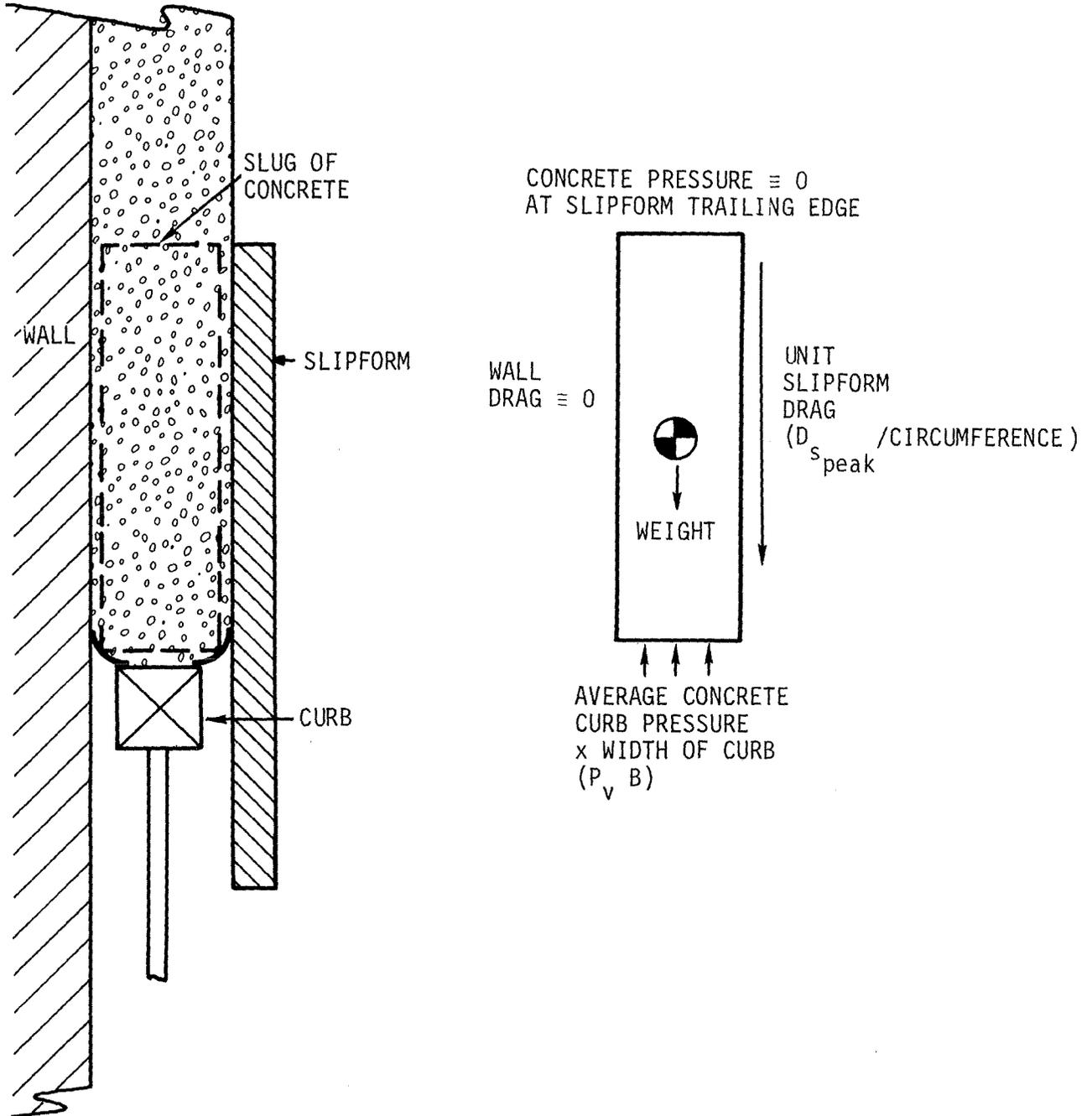FIGURE 34. - Free body diagram of slug of concrete
behind slipform.

$$(\bar{P}_V)(B) = \rho \, (SEL)(B) + drag/unit \; circumference \quad (8)$$

where

$$SEL = slipform \; effective \; length \; (in.)$$

$$\rho = density \; of \; concrete \; (0.0856 \; lb/in.^3)$$

$$B = width \; of \; curb \; (in.)$$

$$drag = as \; measured \; for \; the \; CSL \; form \; of \\ 490 \; in. \; circumference$$

$$= 490 \times SEL \times (2.2 \times \log(\bar{P}_V) - 4.408)$$

$$drag/unit \; circumference = drag/490$$

so

$$\bar{P}_V \, B = \rho \, SEL \, (B) + SEL \, (2.2 \log(\bar{P}_V) - 4.408) \quad (9)$$

or

$$\bar{P}_V \, B = SEL \, (\rho B + (2.2 \log \bar{P}_V - 4.408))$$

so

$$SEL = \frac{\bar{P}_V}{\rho + \frac{1}{B} (2.2 \times \log(\bar{P}_V) - 4.408)} \quad (10)$$

Choosing a curb width B for the concrete lining thickness desired, this equation allows an estimate of the maximum SEL allowable for any chosen concrete curb pressure without cracking the lining (by keeping it in compression). The equation is plotted in Figure 35.
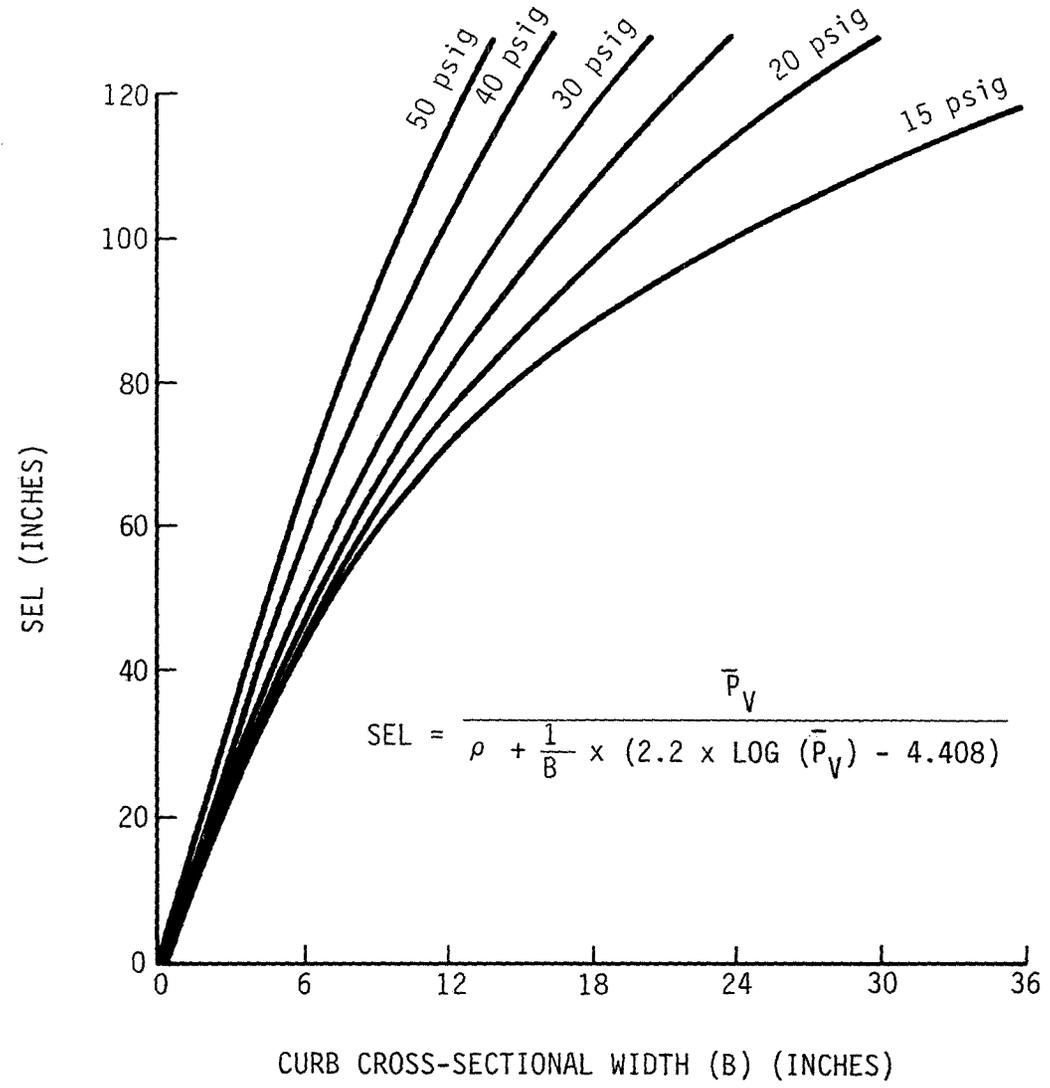
FIGURE 35. — Theoretical minimum concrete curb pressures
required to keep concrete in compression.

2.4.5 Qualitative Assessment of Test Results

2.4.5.1 Introduction

As with many research and development programs, many of the test results are difficult to quantify. The CSL simulation tests are no exception. Qualitative assessments are by their nature subjective. However, many consistent patterns were obseved during the CSL tests that allow one to draw some reasonably sound conclusions. The areas of the test program where qualitative assessments have been made include the following:

- Quality of concrete lining

- Performance of curb seal in slough zones

- Impact of water inflows

- Quality of cold joints

Each area is discussed separately in the following subsections.

2.4.5.2 Quality of Concrete Lining

Throughout the entire test program, the CSL consistently placed a high quality concrete lining provided curb ring pressure and level were maintained within acceptable limits. The quality of the lining was evaluated based on the following characteristics:

- Distribution of coarse and fine aggregates throughout the cross-section

- Presence or absence of voids, especially around the square Heede rods

- Presence or absence of surface cracks

- Concrete strength as measured by tests of concrete specimens

During several tests, colored dyes were added to the concrete to help establish some gross indication of flow lines. Figure 36 is a typical dye distribution pattern and this rainbow pattern was repeated several times throughout the test program. This distribution compares well with the patterns produced during the laboratory concrete distribution tests (see Appendix B). Also note the complete formation of the lining, without
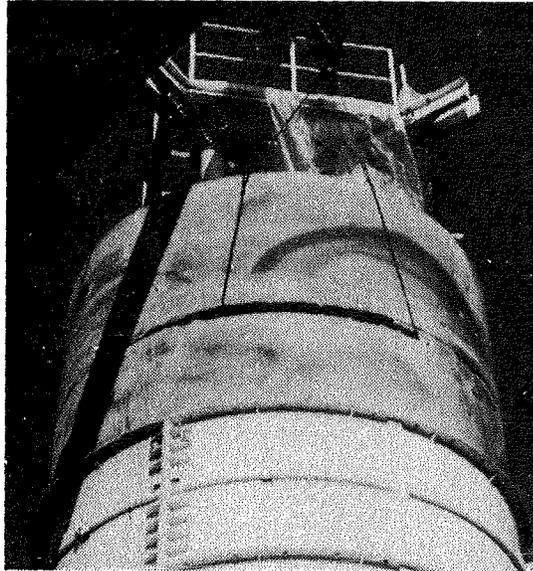
FIGURE 36. - Concrete lining with dye distribution pattern.

voids or gaps. Figure 37 shows a typical lining cross-section
near a Heede rod location. From this photograph, it is obvious
that the aggregate is well distributed; and that no voids have
occurred around the rod. Note the dye streak which is also
indicative of good distribution, and confirming the fact that
"old" concrete will depart from the curb when displaced by "new"
concrete.

Figure 38 depicts the typical cracking that occurs when
curb pressure is not maintained. The small cracks in the center
of the photograph are typically formed when the young concrete
is placed in tension before the development of adequate internal
compressive strength.

2.4.5.3 Performance of the Curb Seal in Slough Zones

During the simulation tests, two different slough zone
configurations were used. Figure 39 shows the more difficult
configuration of the two used, and represents a 3½ in. deep
slough, of rectangular shape with steeply ramped edges. The
curb seal passed through this slough zone, and the other as well,
without any discernable problems or evidence of concrete
blow-by. Figure 40 shows the concrete lining produced inside
the slough zone and represents the mirror image of Figure 39.
Figure 41 is a cross-section of the same concrete lining, and
shows the good concrete distribution, and the lack of voids
around the Heede rod (note the square impression of the rod
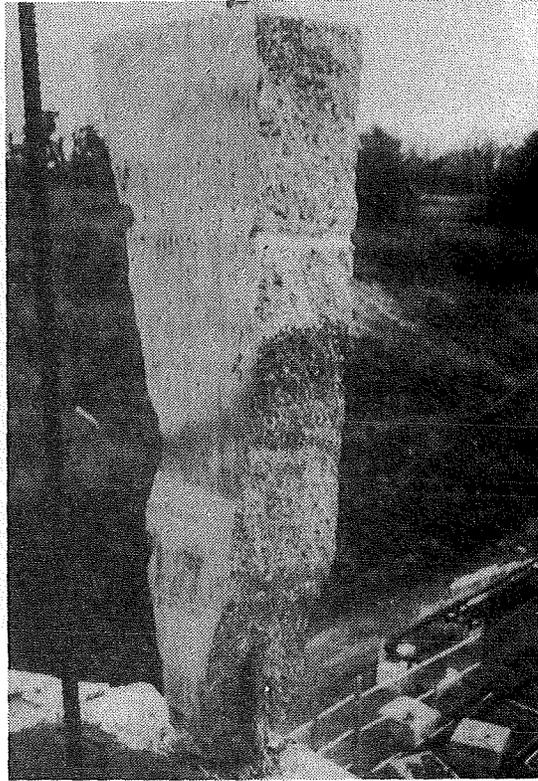running vertically through the cross-section).

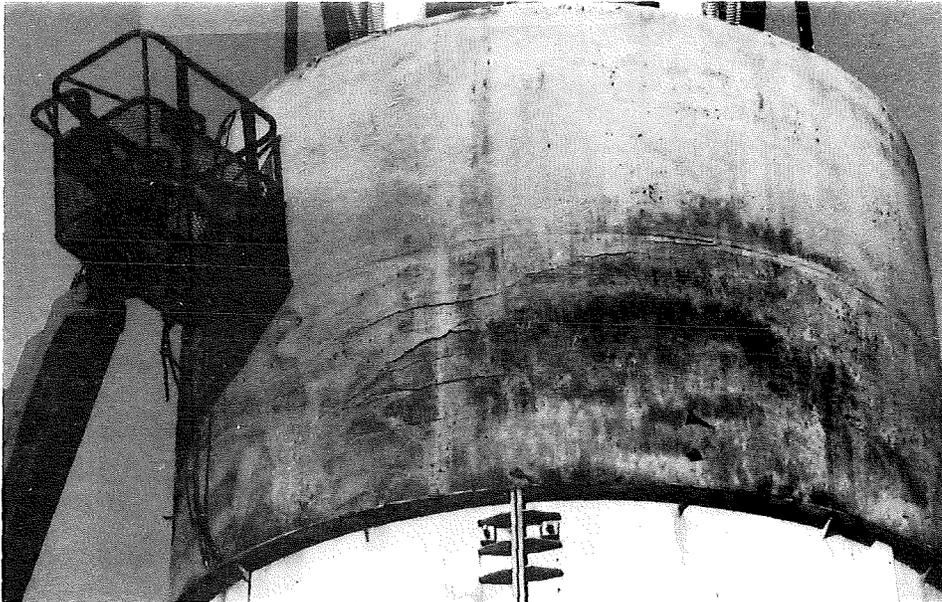FIGURE 37. - Typical lining cross section near Heede rod.

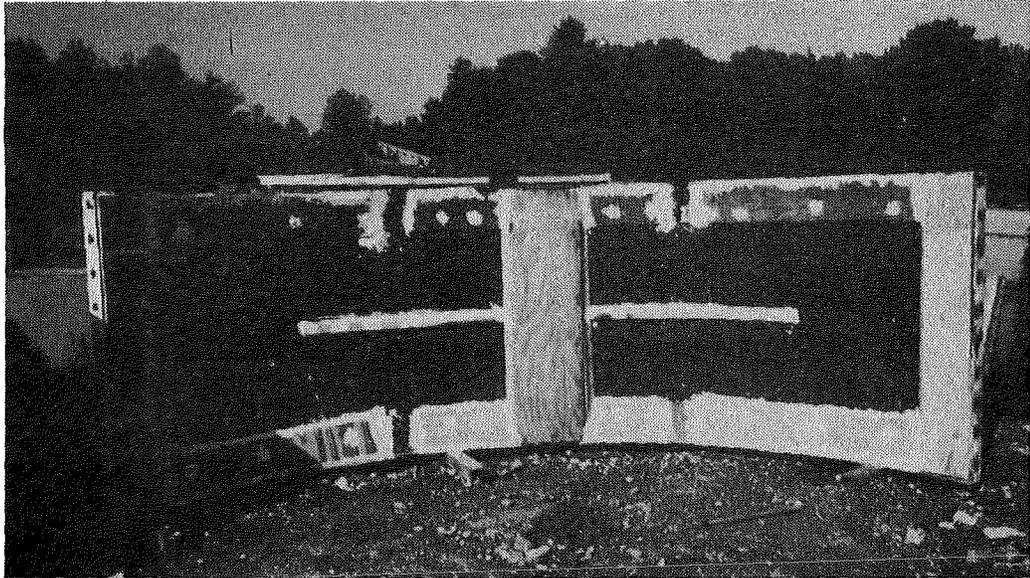FIGURE 38. - Crack formation in lining due to low curb pressure.

FIGURE 39. - Slough zone outer form panel.
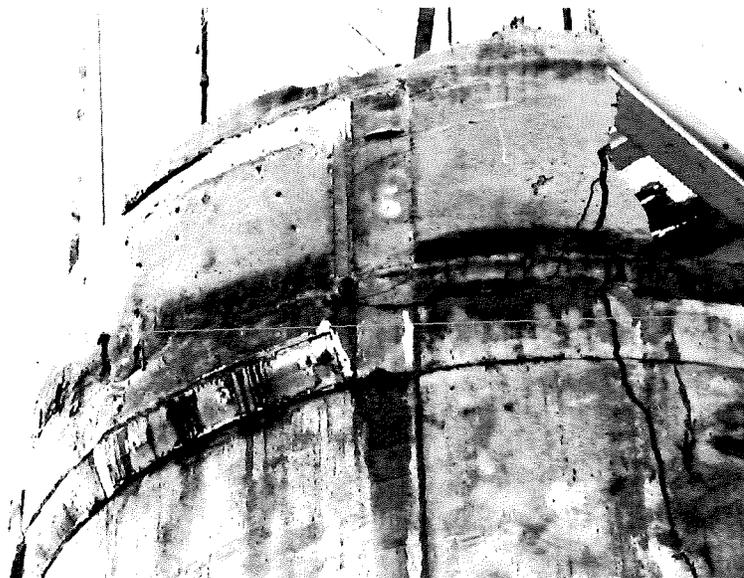
FIGURE 40. - Concrete lining from slough zone panel.
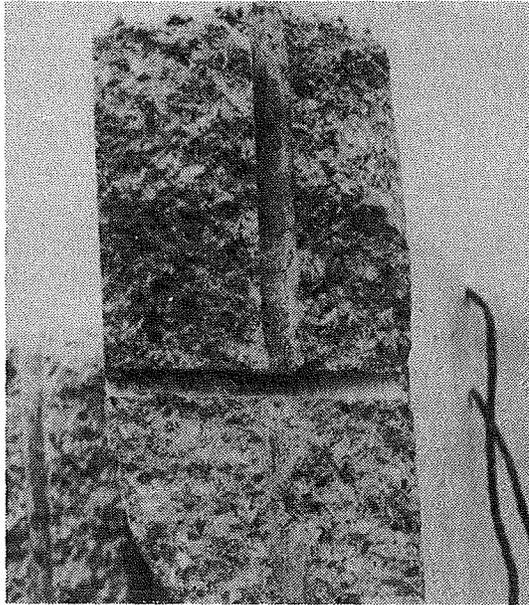
FIGURE 41. - Lining cross section in slough zone.

2.4.5.4 Impact of Water Inflow

The water inflow test was conducted once during the last simulation test. Unfortunately, the results are very inconclusive, although certain general conclusions can be drawn. It is important to point out, however, that there has been no claim that the CSL could handle or deal with water inflows any better or differently than conventional step forming systems. What the test demonstrated was that large point source inflows (> 5 gpm) must be shut off before lining can proceed, otherwise the quality of lining may be jeopardized. The CSL may be able to handle low point source flows (< 1 gpm) without too much difficulty. It appeared that low flows would superficially channel down the lining interface with the shaft wall and relieve any potential short-term pressure build up. Once the concrete strength had reached 25 to 50 psi (2 to 3 hours), the flow would be closed off. Assuming the strength gain of the lining exceeds the build up of hydro static head, the water would remain in a no-flow condition.

What was demonstrated was the ability of the prototype curb seal to pass over water panning without any hindrance to the lining process. Corrugated steel sheet is typically used for panning and a section of sheeting was placed in the simulated

slough zone panel. Figure 42 shows the results of lining over the panning, and a small triangular shaped slough zone. The panning will normally be placed on the wall from the lower decks of the galloway, and would be attached to the shaft wall before the arrival of the curb ring.

2.4.5.5 Quality of Cold Joints

The making of a complete cold joint is important to the quality of the overall shaft lining job because the cold joint represents a potential water inflow site. Throughout the entire test program, many cold joints were made. In those cases where curb ring pressure and position were maintained, the cold joints were complete and of acceptable quality. There is apparently no possibility of air voids forming due to the fact that all the air escapes through gaps between the lining and slipform. Since the lining process is pressurized, there is no chance that small air pockets can remain underneath the previous lining. All air is blown out and a complete casting (void-free) is created.
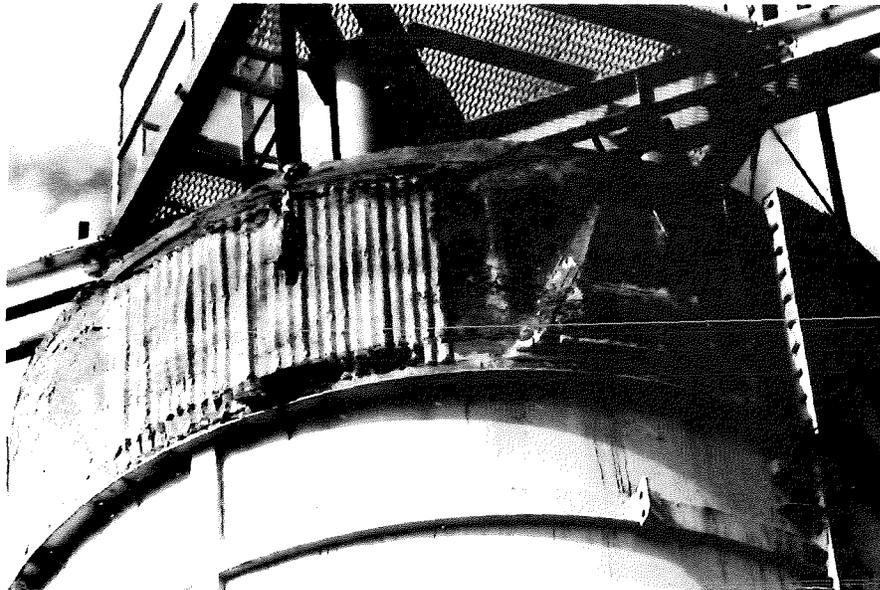

FIGURE 42. - Concrete lining over water panning.

2.5 Impact on Underground Design

2.5.1 Introduction

The CSL simulation test facility not only served as a proving grounds for the theory and operation of the CSL system, it also served as a proving grounds for the individual CSL components. Almost every aspect of the second generation conceptual design was directly impacted, in some way, by information gained during simulation testing. In any design, the equipment used must be suitable for its operating environment. Further, the reliability and complexity of operation accessibility and repairability of components, and initial capital and operating costs of the total system must be considered. Every piece of equipment used during the simulation testing was subject to this review before being incorporated into the second generation underground conceptual design.

2.5.2 CSL Suspension System

During the simulation testing of CSL, the jack frame was supported by four rod climbing Heede jacks. This suspension system suffered from a number of problems. The major problem was the the Heede jacks were not well suited to the operating environment. In fact, even if the jacks had worked perfectly, erroneous design assumptions would still have affected the operation of the CSL. The following discussion outlines the problems with simulation suspension system, and resulting impacts on the underground design:

a. Heede Gripping Jaws - The major short coming of the Heede jack was its inability to perform reliably in a dirty environment. Each jack has two sets of hardened steel jaws that physically bite into a square, mild steel rod. The load is supported by the jaws digging into the rod and not by a clamping force applied by the jaws. It is because of this, that the jaws are very sensitive to dirt. When serrations in the jaws fill in with muck, the jaws can no longer dig into the rod. The design of the Heede jack is such that, one set of jaws must grip before the other set can release. This prevents any catastrophic failure, however, it also, on occasion, prevented normal progress of the CSL. The design of the jacks provided for easy entry of dirt into the jaw area.

b. Heede Jack Stroke - The Heede jacks have a very short
    travel stroke, only three to four inches of movement
    when the jack equalizers are taken into account.
    Because of the gripping problem, and because of the
    increase in control operations per linear foot of
    CSL movement, this short travel stroke impacted
    the reliability of the jacking system in a negative
    way.

c. Equalized Jack Loading Versus Jack Frame Control -
    The simulation jack frame was designed to be supported
    by four Heede jacks. The standard Heede jacking system
    employs a load equalization system that ensures each
    jack holds an equal load. Simulation testing showed
    that equalized load sharing by the jacks is not a
    desirable feature. In fact, it was highly desirable
    to accommodate the unequal loads placed on the jack
    frame by the slipform and curb.

    As a result of this problem, the jack frame was
    difficult to maintain in a level position. From an
    operational point of view, it was desirable to keep
    the jack frame level. A secondary feature of this
    problem was a type of jamming failure. When one
    jack did take a higher load than the other three
    jacks it would jam on the climbing rods. The only
    way to unlock the jack was to temporarily support
    the jack frame on the remaining three jacks. This
    action generated many control problems.

    All these problems serve as reminders of design and equip-
ment short comings of the suspension system to be avoided in
the conceptual underground prototype design. Considering the
problems encountered with the Heede system, it was decided to
use a wire rope climbing jack system in the prototype design.

    The cable climbing system appears to be insensitive to muck.
This is due, in part, to the frictional gripping of the cable as
opposed to the physical biting of the rod. Secondly, the cable
climbers are very large ruggedized units that are better suited
to the dirty environment. With regard to the short stroke of
the Heede jacks, the wire rope climbers can be made to have any
reasonable stroke that is available with standard hydraulic
cylinders. The prototype CSL climbers will be designed with a 5
foot step. Therefore, even at maximum advance rate, the suspen-
sion system will only stop for regripping once an hour. Between
each regrip, the CSL will be operating continuously as the
traveling cylinders retract slowly.

The 5 ft. step will reduce the number of regripping intervals by a factor of 15 to 20. This in turn should greatly increase the systems reliability, and minimize suspension system control problems. The prototype jacks are designed to carry load independently. Each jack will be sized to take 100 percent of the jack frame loads. This should deal with the problem of unequal loading, and eliminate the possibilities of overloading a jack. Additionally, this should greatly aid in the level control functions of the jack ring.

The four point suspension system proved difficult to control because of the inherent redundancy of the fourth point in this arrangment. This arrangment would cause instability in the jack frame unless all four jacks are maintained in the same plane. The use of the four equalizers will, in fact, eliminate this instability. However, practical experience indicated that it was quite possible to have any one of the four jacks "walk" away from the jack frame, thus, inducing the instability. The second generation design utilizes a three points actively controlled suspension system which eliminates the potential problems associated with the four point equalized arrangement.

2.5.3 The Curb Ring

Simulation testing has shed a great deal of knowledge on design improvements for the curb ring. The curb ring is the highest stressed structural member of the CSL, and much of its design is constrained by strength considerations.

One obvious design change has been the removal of all sharp edges and corners from the curb. During the simulation testing a number of problems developed when the curb contacted any of the sharp edges (found at the joints of the outer form panels). To eliminate this problem, the clearances between the curb, slipform, and shaft wall have been greatly increased. The ability to provide greater clearances is due to the performance of the prototype seal, which is capable of sealing gaps in excess of 3 in. The final design refinement in this area is the trapazoidal cross sectional shape of the curb. This shape allows double the amount of the curb tilt, relative to the slipform, before the curb contacts the slipform. All of these design changes should make the curb more suitable for underground applications.

Design improvements have been made on various functions associated with the curb and curb control. They include improvements to the concrete placement and consolidation activities, and the instrumentation and control of the curb.

The curb instrumentation and wiring is highly vulnerable equipment, and must be protected. Provisions have been made to place the majority of the instrumentation and wiring inside the curb.

In simulation testing, the curb was instrumented with four linear displacement transducers, which measured the curb position and tilt. It was learned during simulation testing that tilt was the critical aspect of the curb control. Simulation testing also revealed the solution of how best to measure tilt and from what reference. The curb tilt was referenced off the jack frame, which proved to be inadequate. For the prototype CSL, curb tilt will be measured directly with two tilt meters. This will make the instrumentation gravity referenced. This system should prove adequate without compensation or adjustment in most shafts. Problems would only occur if a shaft deviated excessively from vertical, and this deviation was not accounted for by the CSL control station.

Curb position is far less critical than tilt. The curb position relative to the slipform defines the actual slipform length. In simulation testing the curb position was referenced from the jack frame. This was an adquate means of measuring curb position. To be effective on an underground machine the linear displacement transducers used would have to be greatly ruggedized and protected from damage.

The curb position relative to the slipform could also be measured directly. This could be accomplished by means of a calibrated wheel riding on the slipform from the curb. This has the advantages of being simple and rugged. The one drawback of this system over referencing from the jack frame is, it has to be recalibrated every time the curb is serviced below the slipform. Both systems have been proposed as alternative possibilities in the conceptual design.

During simulation tests, repeated problems occurred with the removal of concrete nozzles. This job could be very difficult, and possibly impossible to do, depending on the final curb position. The prototype concrete nozzle will be easily removable in all curb positions. The nozzle may be designed as disposable units. This should greatly help in reducing CSL downtime. The second change in the concrete delivery system is the curb vibrators. The simulation curb ring used air driven piston type vibrators. These vibrators were excessively loud, and prone to breakdowns. For these reasons, as well as space constraints and installation considerations, hydraulic vibrators will be used.

The mounting method for the inner and outer curb seals has been modified. The mounting bracket used on the outer seal during simulation testing was a retrofitted device, and did not create a flat curb ring surface. The second generation design utilizes a common mounting plate for both inner and outer seals, thus creating the required flat surface. The outer seal clamp remains, in concept, essentially the same as the one evaluated during simulation tests. The new design allows easier and more efficient maintenance as well as easy replacement of both the inner and outer seals.

2.5.4 Slipform Design

Mechanically and structurally the prototype slipform looks very similar to the simulation slipform. Simulation testing revealed the need for several design improvements. As a result, the following changes were recommended and incorporated into the prototype design.

The wedging system functioned very well during the simulation testing. The wedges were easily collapsed, releasing the slipform. In the conceptual underground design, these wedges have been improved to make them easier to use. Permanent shoulder bolts will be added to help in the realignment of the wedges and form. The wedge angle will be reduced to increase the access to the structural bolts. Finally, independent hydraulic actuators will drive the wedges, this should further help in the breaking and repositioning of the wedges.

The slipform will be modified in three ways. One, the outside edge will be beveled inward. This will help align the top of the form as it is repositioned back into previously cast concrete. Secondly, the top flange will be strengthened to accept possible slipform extensions. Thirdly, guides will be added to the lower edge of the slipform, to facilitate reinserting the curb ring following maintenance.

The major change in the slipform will be in the support system. The simulation slipform was built in four sections, and was supported by four hydraulic jacks located directly under the wedges. In the second generation conceptual design, the form is made of three segments, with each segment supported by a pair of hydraulic cylinders attached at the midpoints of each segment. This major support system change came as a design response to known and suspected slipform control problems. This

114

system will form the basis of a control package that will be capable of six degrees of motion of the slipform. That is, it will be able to control translations and rotations about the slipform X, Y and Z axes.

During simulation test, a number of unexpected control problems developed with the slipform. The simulation test equipment had not been designed with sufficient flexibility to accomodate various control scenarios. Originally it was believed the slipform could be passively towed by the jack frame. This may still be a possibility. However, it was learned in simulation that the slipform, curb ring, and jack frame all have effects on each other. The three point paired cylinder support system is a research tool which will allow the slipform to be rigidly attached to the jack frame or completely independent. It provides the maximum operating flexibility for position control and alignment guidance.

The change in the support system for the slipform will mean a change in the slipform instrumentation and controls. Simulation testing gave real insight into instrument accuracy versus control accuracy. In the second conceptual design, the slipform will be kept level and centered in the shaft. To do this, a more sophisticated instrumentation package will be needed when compared to the one used during simulation studies. Three tilt meters will measure the levelness of the slipform. Like the curb, this will reference the level to gravity and not to the jack ring. For the purposes of centering, three drag skis will measure clearances between the slipform and the shaft wall. These two systems will provide all the information necessary to control the slipform. Additional information will be gathered to monitor the relative positions of the curb ring, slipform, and jack ring, but this information is secondary to the slipform control.

2.5.5 Jack Ring

The new conceptual design jack ring is different from the jack frame used in the simulation testing. Although the shapes are completely different, the function of the jack ring is the same as that in simulation testing. The jack ring, as its name implies, supports the hydraulic jacks for the curb, slipform, and the main CSL suspension system. The underground conceptual CSL design has a completely new CSL support system, and the design of the jack ring reflects this. In simulation, a four point jacking rod system was used, as discussed earlier in the section on suspension systems. In the conceptual design, a three point cable climbing jack system will be used.

A second change in the jack ring will be its instrumentation and control. Although this may not be as noticeable as the structural changes, these changes are in some ways more significant. During the simulation testing the jack frame was used as an instrumentation reference. This proved to be inadequate because the jack frame alignment could not be controlled with sufficient accuracy. If the underground CSL jack ring can be controlled accurately, it could significantly reduce the curb ring and slipform control problems. To this end, the jack ring will be equipped with three tilt meters which will directly control the suspension jacks. In addition to this, the jack ring will have its own independent guidance system for keeping it centered in the shaft. This will allow much·more accurate control of the jack ring, and will allow simplifications in the other CSL control systems.

2.5.6 Multi-port Valve

The multi-port concrete valve is the valve that controls the distribution of the concrete to the four ports in the curb. As such, it is one of the most important pieces of equipment used. It is the major active element in the control of the curb ring.

The multi-port valve worked quite satisfactorily during simulation. The only design changes recommended for the underground conceptual design are; to make the unit a lower maintenance item, and more rugged in design.

The slide valve ran continuously for up to eight hours during simulation. The prototype CSL will be a twenty-four hour continuous operation, and a low maintenance valve is needed.

The major changes recommended for the valve are:

a. Self alignment and adjusting for wear

b. The valve surfaces should be self wiping, that is, concrete paste should not be allowed to accumulate in areas that, in time, could cause jamming.

2.5.7   The Concrete Pump

Very early in the design work for the CSL, a need was identified for a "downhole" concrete pump, that would meet very tight horizontal space constraints. The concrete pump was also a critical component in the CSL system design, because the concrete pump literally pumps the CSL down the shaft. To meet this need the following general specifications were written:

a.   Vertically oriented concrete pump

b.   1 to 20 yd^3/hr variable pumping rate

c.   0 to 500 psi concrete pressure

d.   Hydraulic operated

e.   Positive displacement

f.   Dual piston 6 in. bore

g.   Remote power supply

h.   Remote control station.

The vertical orientation meant this specification could not be met by any standard off-the-shelf concrete pump. Since this orientation was unproven technology, critical to the performance and operations of the CSL, it was decided to test a prototype concrete pump during the simulation studies.

Reinert Manufacturing Company, custom designed and built an underground worthy, vertically oriented concrete pump. This unit was tested during the spring and summer studies of the simulation test program. In view of this unit's failure to operate up to specifications, serious considerations must be taken in reviewing of the concrete pump requirements and specifications for the conceptual underground design.

The first step in this process, and possibly the most difficult, is determining what caused the failure of the Reinert unit. During testing, a number of component faults developed in the concrete pump, but none of these problems seemed to be the critical fault that prevented the unit from functioning as designed. The concrete batch plant, multi-port slide valve and

placement time can be eliminated as the problem, since they work very well together with a standard horizontal truck-mounted Thompson concrete pump.

There were several problems with the pump hydraulics that were fixed during testing. Valves were improperly sized, sequences were improperly timed, and flow rates were improperly controlled. The automatic valving jammed. The hydraulic power pack overheated and was undersized.

Mechanically, there were several faults, as well. There was a serious concrete backflow problem with the concrete pump slide valve. This problem was remedied somewhat through a modification of the hydraulics and sequence timing. However, it stands out as one of the most important trouble spots. A number of trap doors, cleanouts, paddles, etc. suffered from "poor fit". However, none of the hydro-mechanical problems should have been catastrophic to the operations of the concrete pump. Some proposed theories for the operational problems are listed below:

    a.   Cumulative System Reliability Failure - The simpliest mode of failure is a system reliability and control problem. Nothing is theoretically wrong with the design or controls. However, accumulations of many small problems, each fractionally responsible for a small decrease in performance, add up to a non-functioning system. It should be noted that the operator should always be considered in the design and control of a piece of equipment, and that an operator induced failure is, to some degree, also an equipment induced failure.

    b.   Incomplete Filling or Discharge of Material Cylinders - A second theory on the failure of the concrete pump was, incomplete filling or discharging of concrete from the material cylinders. To test this out, discharge volume measurements were taken. It was found that, against no back pressure the pump fully discharged every stroke. This observation and indirect ones of the remix hopper indicated the material cylinders did completely fill and discharge.

    c.   Cross Flow Conditions in the Concrete Valve - When the concrete pump was first used, a cross flow problem existed with the concrete slide valve. Concrete under pressure from the CSL could back flow into the remix hopper, before the concrete valve was completely cycled. To "fix" this condition, the sequencing operations of the pump were retimed. This seemed to alleviate the problem, but the pump still did not operate in a satisfactory manner.

    d.   Failure Induced by Vertical Orientation - This theory has the most serious impact on CSL. The theory suggests vertical concrete pumps inherently will not work because of its orientation. There is no strong evidence to confirm or refute this theory.

To an extent, some of the problems that occurred with the concrete pump were to be expected. Any new prototype piece of equipment will have a number of minor unexpected problems. It was very disappointing, however, that the issue of the feasibility of vertically oriented concrete pumps was not resolved during simulation testing.

There are several recommendations for the concrete pump designed for the CSL. Like all underground construction equipment, it should be suitable for the working environment, reliable, and repairable. Beyond this, here are a few specific recommendations:

    a.   The very short stroke material cylinders may not theoretically be a problem, however, it is recommended that longer stroke cylinder (24 to 36 in.) be used. This should help to overcome any compliance in the pumping system. Longer stroke cylinders would also reduce wear, by reducing the number of cycles on all assemblies.

    b.   The hydraulic power supplies should be designed well in excess of the concrete pumps theoretical requirements. For the CSL underground pump, it is recommended that a 50 hp hydraulic system be provided.

    c.   The concrete valve in the pump should be designed so that it does not inherently have a cross flow condition.