A mining research contract report
MAY 1983

DEVELOPMENT OF A CONTINUOUS SHAFT LINING SYSTEM

VOLUME I

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BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

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N O T I C E

This report was completed under a contract to the U.S. Department of Energy (DOE). Responsibility for the program to which the report relates has recently been transferred to the Bureau of Mines, U.S. Department of the Interior, and the report is made public under a Bureau cover. Inquiries concerning the report should be directed to the Bureau.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U.S. Government.

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7. Author(s) Robert Torbin, Tom Brunsing, Douglas Ounanian, Ray Henderson, Jonathan Kelly, George Kirby

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

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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.

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Throughout the execution of this contract, Foster-Miller has been aided by Dravo Engineers, Inc. of Pittsburgh, Pa.; acting as Foster-Miller's technical and construction consultant. Dravo Engineers has played a major role in the design and development of the prototype continuous shaft lining system. In particular, Foster-Miller wishes to recognize the contributions of the following Dravo personnel:

Mr. John M. Sweeney - Program Manager

Mr. Charles D. Dobson - Construction Consultant

Mr. William Gilman - Structural Engineer

These individuals provided the needed expertise to help meet the technical design and prototype testing requirements of the program, and for that effort we are grateful.

In addition, we would like to acknowledge the contributions of Mr. Kenneth Saucier of the Corps of Engineers from the Waterways Experimental Station, and his valuable assistance in the area of concrete technology.

Furthermore, we would be remiss if we failed to recognize the outstanding efforts of our own Foster-Miller staff. Although it is difficult to place a value on each individuals efforts, it is safe to say that the following people gave more than the job required:

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George Kirby

Duke Lewis

Carol Repole

Robert Cardenas

No program of this scale (in terms of technical scope and industry impact) can operate without a credible reviewing committee. We are grateful to the Institute of Shaft Drilling Technology (ISDT) for providing us with a platform from which to present to and discuss with the shaft sinking industry, the development of the shaft lining system. In particular, we wish to thank the following ISDT members who actively participated on the CSL Industry Steering Committee and provided valuable feedback on the CSL system:

Robert Evans	U.S. Department of Energy/ U.S. Bureau of Mines
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Bruce Kemper/William Nash	Frontier Kemper Constructors
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Gunther Matthes	Thyssen Mining Construction

Respectfully submitted,

Robert Torbin, Program Manager

EXECUTIVE SUMMARY

1. PROGRAM OBJECTIVES

The objective of this research and development program, documented in this report, was to develop a rapid shaft lining system which would be compatible with the excavation advance rates achievable by manned and unmanned boring/drilling equipment. In order to be compatible with the various available mechanized shaft sinking equipment, the innovative shaft lining system must be capable of the following functions:

- Achieve a rate of advance of up to 5 ft/hr
- Ability to place a lining concurrently with the shaft sinking operation
- Capability to operate both continuously as well as under frequent stop/start situations
- Ability to maintain a minimum amount of unsupported ground between the lining system and any operating personnel in the shaft.

A research and development program was funded by U.S. Department of Energy to investigate the feasibility of the Continuous Shaft Lining (CSL) System concept. Foster-Miller Inc. and their major subcontractor Dravo Engineers undertook a three task R&D effort to meet the Government's goals. Task I involved the engineering study and laboratory testing of the basic operating principles of the CSL concept. This included concrete mix design, concrete distribution, inverted slipforming and shaft sealing. Task I was culminated in the successful testing of a full scale 15 ft dia CSL system in an above ground simulation facility. Tasks II and III have been subsequently cancelled by the Government

2. TECHNICAL BACKGROUND

The fundamental operating concept of the Continuous Shaft Lining System is one of continuous inverted slipforming, under pressurized conditions, from the shaft collar downward. In order to slipform a concrete lining from the top of the shaft downward, the concrete must be placed through the bottom of a closed form. This requires pumping the concrete, and maintaining sufficient pressure on the concrete lining to keep the young concrete in a compressive state until it has cured enough to be self-supporting. The ability to achieve rapid rates of advance is obtained through the use of a special concrete mix. The special mix will allow time for easy placement, while developing strength quickly to allow for rapid slipforming.

The CSL system is comprised of four main components and include:

- Slipform - The slipform acts as the mold around which the concrete lining is formed and extruded.
- Curb ring - The curb ring is a moving pressure boundary between the slipform and shaft wall. It supports the young concrete and maintains the internal pressure while the concrete cures.
- Jack ring - The jack ring acts as a moving reference table on which the curb ring and slipform are mounted. It provides a reaction point for all the major forces acting on the CSL.
- Work stage - The work stage is the moving platform which contains the various mechanical and electrical support systems required by the CSL, and carries the necessary CSL operators.

The operation of the CSL is, by design, very flexible compared to conventional step forming systems. The CSL can operate in three different modes. The primary mode is continuous slipforming. This mode allows the CSL to be compatible with the relatively rapid excavation rates expected from manned boring machines. During periods when rapid slipforming is not required, the CSL can be operated similar to a conventional step form. In bad ground zones, the CSL can be operated as a jump form, to negotiate and line over large slough zones.

3. LABORATORY FEATURE STUDIES

As part of the overall research program, four features of the CSL concept were selected for evaluation by conducting laboratory experiments. These four features were:

- Concrete distribution
- Concrete slipforming
- Concrete sealing
- Concrete mix design.

A special test rig was constructed to investigate the process by which concrete is placed and distributed behind the form through a downward moving, pressurized curb ring. The effects of concrete pressure, number of inlet ports, port spacing, vibration, concrete mix design, and curb advance rate were evaluated. The concrete slipforming phenomenon was studied in a separate test rig to investigate the effects of advance rate, form taper and concrete pressure on the feasibility of slipforming vertically downward. Concrete sealing was studied in a third test rig to develop a flexible seal capable of maintaining pressurized conditions behind the curb ring. The seal must be capable of extending into slough zones without concrete blow-by.

The concrete mix design work was performed in Foster-Miller's concrete lab. A unique mix design was developed to meet the strict requirements of the CSL concrete specification. This specification required the following mix characteristics:

Good workability for 30 minutes

Initial slump of 6 to 8 inches

Rapid strength gain 25 to 50 psi in 2½ hours

Ultimate strength >3000 psi

A Portland type III cement mix was ultimately develop which allowed proof of concept testing and achieved an advance rate of 3 to 4 ft/hr.

4. FULL SCALE SIMULATION TESTS

A full scale above ground simulation test facility was constructed and a 15 ft diameter CSL system was tested and evaluated. The CSL was fully operational and instrumented to allow collection of performance data. Ten performance tests were conducted and the following features were demonstrated:

- Excellent concrete distribution and good quality of the concrete lining were attained
- Ability to slipform vertically downward up to 3 ft/hr
- Viability of prototype concrete seal to hold pressurized conditions up to 30 psi

- The mechanized step forming and jump forming modes of operation are viable
- Viability of Portland type III concrete mix in meeting operational requirements
- Ability to control the CSL through the placement of concrete and use of the hydraulic power systems.

The data from the tests have led to the establishment of empirical relationships between the various operational variables including concrete pressure, slipform drag, seal drag, slipform effective length and turning moments. These relationships formed the bases for the second generation design.

5. SECOND GENERATION DESIGN

Based on the results of the laboratory and full scale test programs, a second generation CSL system has been designed. The more significant changes to the prototype design include:

- Use of a 3 point cable suspension system to replace the 4 point steel rod arrangement
- Incorporation of an active slipform guidance system to maintain plumbness and concentricity in the shaft.
- Structural improvements in the curb ring shape, curb ring seals, and other curb ring attachments
- Upgrading of the overall CSL instrumentation and control package.

Cost estimates for the second generation design have been prepared. The cost per foot of lining placement using the CSL is competitive with conventional concrete lining systems, and is estimated to cost between $300 to $350/ft of lining.

The cost of a complete CSL system could exceed $400,000. The main cost advantage of the CSL is its ability to complete the entire shaft project earlier than a conventional lining system, and thus help reduce the overall project costs. The primary cost factors involved with shaft lining are the materials cost, the labor, the cost of embedments, and the depreciation of the hardware.

6. RECOMMENDATIONS

The CSL research and development program has been terminated prior to completion of the scope of work originally stipulated in the program contract. The work that has been terminated included the underground testing and demonstration. Without this knowledge, there remains several unanswered questions concerning the operation and performance of the CSL system. This situation leads to the following list of recommendations for additional research.

- Evaluation of system compliance when the CSL is suspended from the surface on wire ropes, in effect, evaluate the "stick-slip" phenomenon associated with slipforming
- Evaluation of the impact of water inflows on the quality of the concrete lining and its impact on the slipforming process
- Further development of the outer concrete seal to improve performance and lower cost
- Further improvement in short-and long-term behavior of the concrete mix
- Demonstration of CSL guidance system and investigation into simplifying its functions.

7. CONCLUSIONS

The Continuous Shaft Lining System development program has successfully demonstrated the concept of inverted concrete slipforming under pressurized conditions, from the shaft collar downward. A full size CSL was fabricated and tested. The results have been used to establish operating limits and achievable advance rates; and provided important input to the second generation design. A second generation CSL has been engineered based on the results from the entire testing program. Further hardware development remains to be performed in translating the results of these tests into a viable underground worthy commercial product. However, major groundwork has been completed toward this goal as a result of this program.

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Meaning	New Symbol
Concrete Pressure at Curb	P_V
Vertical (Hydraulic) Forces on Curb	F_{CV}
Area of Curb	A_C
Width of Curb	B
Inner Curb Seal Drag on Slipform	D_i
Outer Curb Seal Drag on Wall	D_O
Slipform Drag on Concrete	D_S
Vertical (Hydraulic) Forces on Slipform	F_{SV}
Horizontal (Hydraulic) Forces on Slipform	F_{SH}
Torsion on Slipform	T_S
Weight of Slipform	W_S
Concrete Horizontal Pressure on Slipform and Shaft Wall	P_H
Concrete Vertical Adhesion to Shaft Wall	τ_W
Weight of Slug of Concrete	W_C
Pressure on Lining Due to Ground Load	P_{HR}
Guide Pads Horizontal Load on Shaft Wall	F_H
Vertical Loads on Cable Support	F_V
Coefficient of Friction of Seal	μ_S
Coefficient of Friction of Concrete on slipform (pressure independent)	μ_O
Coefficient of Friction of Concrete on slipform (pressure dependent)	μ_1
Distance from Shaft Centerline to Centerline of Slipform Cylinders	L_1
Diameter of Slipform	d
Radial Depth of Slough Zone	s
Unit Weight of Concrete	ρ
Peak Slipform Drag Force	$D_{S_{peak}}$
Shaft Diameter	D

1. INTRODUCTION

1.1 Program Background

There have been several recognizable trends in recent years in the shaft construction industry. There is the general trend of going to larger diameter shafts to meet the expanding needs of existing and new mines. There is also a trend toward using mechanized shaft drilling/boring equipment. Some of the reasons for these trends are as follows:

a. Diminishing labor pool of trained construction personnel for conventional sinking techniques

b. Increasing cost of labor (conventional shaft sinking is very labor intensive)

c. Trend toward larger shaft diameters to minimize the required number of new shafts

d. Desire for improved safety during construction

e. High cost of borrowed money and, therefore, desire for minimum construction time.

Most modern shaft excavations are lined by concrete, shotcrete or steel. Shaft linings have multi-purpose functions. The various uses are as follows:

a. Waterproofing - A lining will retard or control water inflows.

b. Ground Support - The stability of the ground, particularly that found in coal fields, will deteriorate with exposure to air and water. Therefore, a lining is needed to maintain the shaft cross section.

c. Air Flow - A lined shaft provides a more efficient passage of air.

d. Anchorage System - Many shaft equipment installations require a lining to provide an efficient anchoring medium.

Inherent in mechanized shaft sinking is the potential capability of relatively high excavation advance rates (up to 1.5 m/hr) as compared to conventional manual shaft sinking techniques (3 to 5 m/day). In order for any manned mechanized shaft sinking equipment, such as a blind shaft boring machine (1), to attain its maximum production potential, a complementary rapid shaft lining technique must be available.

Current Mining Safety and Health Adminstration (MSHA) regulations require that shaft sinking methods shall be selected to minimize hazards to those employed in the development of the shaft (2). These regulations generally require that a shaft lining be placed as the shaft is being developed. Furthermore, MSHA also restricts the amount of unsupported ground allowed above the work deck of the shaft sinking equipment. In the case of the Robbins Blind Shaft Borer, this distance was set at 25 feet. This distance is not rigidly fixed at one value, but is based on the site conditions, the equipment involved, and the judgement of the MSHA officials.

In actual practice, "continuous" mining equiment is constrained by unscheduled stoppages. Such interruptions can be attributed to occasional equipment failures; the discontinuous nature of some of the support systems (such as hoisting systems and service extensions); scheduled maintenance on equipment; or poor shaft conditions (unstable ground or excessive water inflow). What is needed, then, is a hybrid system capable of routine, continuous progress when conditions permit, as well as the ability to handle simple stop and start situations. Therefore, the lining system should have similar flexibility, compared to conventional jump forming systems, to handle difficult ground conditions.

In summary, the innovative lining system must exhibit the following operational characteristics:

a. Achieve a rapid rate of advance (up to 1.5 m/hr)

b. Ability to place a lining concurrently with the shaft sinking operation

c. Ability to place lining within a limited distance from the boring machine

d. Capability to operate continuously, as well as under frequent stop/start situations.

The United States Department of Energy (DOE) has sponsored various research programs in the past aimed at identifying the most cost effective approach to this problem. Some concepts which have been studied include precast concrete lining segments (3), an under-mud upward slipforming system (4), and an improved mechanized step forming system (5). In the final analysis DOE selected an innovative downward slipforming technique, developed by Rapidex, Inc. (6) as the system for further research and development. A preliminary conceptual study was performed and a report was issued in October 1978. The report recommended that the concept be reduced to practice through a series of laboratory and full scale tests. Ultimately, DOE awarded a contract to Foster-Miller, Inc. to develop and test a concrete lining system based on an inverted, pressurized slipforming concept.

This program was originally intended to proceed in three phases. Phase I included testing critical aspects of the concept in the laboratory, demonstrating the concept in a full scale simulated shaft, and designing an underground prototype CSL for field evaluation. The specific objectives of Phase I included:

- Developing a suitable concrete mix design to enable a slipforming rate of 5 ft/hr to be obtained
- Determining concrete distribution requirements a effect of slipforming on young concrete
- Developing suitable shaft wall sealing and wall preparation capabilities to enable the system to function in actual underground conditions.
- Demonstrating the system in a full scale simulated shaft
- Designing an underground worthy prototype for field tests in a machine sunk shaft.

Phases II and III, which have been cancelled, were intend to take the system underground for field test and an industry demonstration in an abandoned shaft and a production shaft operation, respectively.

This report only reflects the efforts under Task I of the program and summarizes the results of the Continuous Shaft Lining (CSL) System research and development program. Volume 1 describes the basic CSL concept, the design and operation of a prototype unit, and estimates of cost. Volume 2 summarizes the results of the laboratory and full scale tests conducted during

Task I of the program. The appendix contains related information on these laboratory tests and test facilities.

1.2 State-of-the-Art Lining Systems

1.2.1 Introduction

Excavation for the purpose of generating a permanent underground access or opening requires three distinct operations: excavation, material transport and ground support. These operations impact each other, and therefore must be reviewed as a system. Ground support is categorized as either temporary or permanent. The excavation technique and need for temporary support directly impacts the choice of the permanent support systems or the lining systems. Both tunneling and shaft sinking disciplines have this interrelationship in common. For this reason, historically, operations of excavation, material transport and ground support from one of these disciplines have been adopted to the other. An overview of the state-of-the-art of lining systems for both shaft sinking and tunneling, with reference to their technical status, field of application and system limitations, is summarized in Table 1.

A brief description of innovative lining systems applicable to mechanically excavated shafts follows this introduction in order to place CSL in context with alternate directions of the advancement in the state-of-the-art. Finally, more detailed descriptions are given of cast-in-place concrete shaft lining and slipforming from the bottom up shaft lining. An understanding of these "reduced to practice" systems will provide meaningful insight into the CSL design and operation, and to the steps required in making the transition from conventional to the fully mechanized operation of the CSL system.

1.2.2 Novel Lining Systems

Extruded Tunnel Lining System (ETLS)

An automated slipform concrete lining system has been developed for installing a lining some distance behind a full face tunnel boring machine advancing in competent rock (7). The system pumps very high early strength concrete through a bulkhead moving between an independently advancing slipform and the tunnel wall. A full scale simulation system was tested, and is limited to ground which is stable for several diameters behind the face with only minimal temporary support. A conceptual design of an ETLS system has been developed for lining immediately behind the cutter head, thus expanding the systems application to less stable ground conditions.

TABLE 1. - Summary of state-of-the-art lining systems

Classification	Lining system	State of the art	Present application	Limitation
Conventional	Cast-in-place concrete	Commonly practiced in shafts	Drill and blast Machine and excavated shafts	Not capable of immediate temporary support
	Shotcrete on wire mesh	Commonly used in tunnels, occasionally in shafts	Principally used in drill & blast shafts	Thicker linings not cost effective because of rebound
	Liner plates	Well established practice particularly in unstable ground	Unstable ground conditions/soft-ground	Used either as temporary support with final concrete lining or as final liner used for more extreme ground control conditions
Partially mechanized	Jump form cast-in-place	Commonly used in tunnels	Principally in machine bored tunnels/long tunnels	Longer tunnels required to justify hardware expense
	Slipform Upward	Practiced by specialty contractors in shafts	As final lining following shaft completion with other temporary support	Temporary support must eliminate sloughing potential for bottom up slipforming
	Sectional precast	Common practice in European tunnels. Conceptually developed for shafts	Machine bored tunnels	Partially reinforced concrete for handling purposes

TABLE 1. - Summary of state-of-the-art lining systems continued

Classification	Lining system	State of the art	Present application	Limitation
Partially mechanized (continued)	Steel ring beams	Commonly used in tunnels	Machine bored and drill & blast tunnels for temporary ground support	Generally required final lining; not used in soft ground
Fully mechanized	CSL	Demonstrated in above ground simulation facility	Mechanically excavated shafts	Non-reinforced concrete
	Extruded Tunnel Lining System	Demonstrated in above ground simulation facilities	Machine bored tunnels	Non-reinforced concrete
	Pressure injected jump form	Demonstrated in European/Soviet tunnels	Machine bored tunnels	Non-reinforced concrete
Remotely operated	Welded steel casing	Practiced in U.S.A.	Big hole drilled shafts	Shaft must be filled with drilling mud
	Remotely operated shotcrete	Demonstrated in U.S.A. & Mexico	Small shafts, raise bored	Thin unreinforced lining - must be applied after shaft sinking complete
	Stacked pre-cast shaft lining	Conceptual design	Big hole drilled shafts	Thick reinforced lining; shaft must be filled with drilling mud

TABLE 1. - Summary of state-of-the-art lining systems continued

Classification	Lining system	State of the art	Present application	Limitation
Remotely operated (continued)	Tremie concrete shaft lining	Conceptually designed & laboratory tested	Big hole drilled shafts	Reliability judged insufficient in deeper shafts
	Pipe jacking	Commonly produced in limited length tunnels. Extensively used in Japan	Utility tunnels in soft ground; culverts	Rock loads during installation limit jacking distance
	Progressive pipe jacking	Demonstrated	Utility tunnels in soft ground	Cannot sustain concentrated rock loads during installation

Pressure Injected Jump Form

An automated jump form concrete lining system has been developed for installing a lining immediately behind the shield of a slurry supported soft ground tunneling machine. The system pumps fiber reinforced concrete through a bulkhead moving between the shield tail and stationary jump form. The bulkhead is used to react the shield advance thrust. Since the bulkhead transfers the thrust to the fluid concrete, only limited thrusts are achievable. This type of system has been developed in both the U.S.S.R. and Germany (8).

Remotely Operated Shotcrete System

An automated lining system for placing a thin shotcrete lining on small diameter shafts has been developed and demonstrated in the United States (9). The system is operated from an above ground control station with closed circuit television observation of the downhole system. The system can apply shotcrete at relatively high advance rates in dry ground. The application is limited to thin linings due to excessive material costs resulting from shotcrete rebound, and a high cement content mix design. Water inflows can drastically impede progress and increase sloughing or rebound. This system is best suited to small raise bored shafts in reasonably dry ground requiring a non-structural lining to inhibit weathering.

Precast Lining for Blind Drilled Shafts

A remotely installed precast concrete lining system has been conceptually designed for application in slurry filled blind drilled shafts (10). The lining is designed for full hydrostatic head. Full round precast segments are remotely lowered into the shaft and stacked from the shaft bottom up. The segments are grouted to the shaft wall intermittently during the lining processes to limit cumulative vertical loads. The system is best suited to severe groundwater conditions. Under less severe conditions the excessively thick walled segments would not be cost competitive with other lining systems.

1.2.3 Conventional Lining Systems

Cast In-Place Concrete Linings

Cast in-place is the lining system used in traditional shaft sinking operations. The process requires a collapsible form, curb ring and work stage which progress from the shaft collar down in discrete steps. Typically each cycle of the operation places 20 ft of circular concrete lining. The cycle starts by setting the curb ring from hanging rods and positioning scribing by hand to seal the curb against the shaft wall. A fast setting short (typically 3 ft) lift (continuous single placement of concrete) is then cast in the curb ring form. The second step in the cycle is to lower the remaining form into position to span the distance from the curb ring to the set concrete of the previous cycle (typically 17 ft). Non-accelerated concrete is normally placed in this lift. Once the accelerated short life has gained sufficient strength, the curb ring is then lowered to commence the next cycle. Advance rates of 1 cycle per day are normal, but 2 cycles per day have been achieved with multiple shifts. The concrete is supplied by skip or slick line to the work platform during the placing operations. The hanging rods which level and support the curb ring are embedded in the concrete but add relatively little strength as reinforcement to the lining. Steel reinforcing may be added prior to placing concrete, but often is deemed an unnecessary extra expense by the lining designer. Water control, including grouting and water panning, are often necessary as wall preparation prior to concrete lining. Some water may continue to leak into the shaft at cold joints after lining placement. If necessary, dry wall conditions can be obtained by additional pressure grouting behind the lining, although care must be taken not to over pressurize the curing concrete.

Shaft Linings Slipformed from the Bottom Up

Shafts requiring extensive temporary support such as ground freezing and steel liner plates will require a final permanent lining typically of either reinforced or non-reinforced concrete. Such extensive temporary lining systems offer sufficient safety or insurance against rock falls to allow placement of the permanent lining to proceed from the bottom up. Conventional slipforming has been used in such circumstances. The conventional slipform is a continuously moving tapered form open at the top end. Concrete is gravity fed from the shaft collar via a 6 to 8 in. slick line to an energy absorber at the slipforming elevation. It is then distributed, by gravity uniformly over the top lip of the form, dispensing from a chute attached to a central swivel (11). Mobile probe type vibrators are used to ensure complete distribution behind the form.

The form advance rate is adjusted to maintain a steady initial set level behind the form. The initial set point is determined by measuring the "hard" by probing the concrete from the open top end of the form with a rod. The "hard" is the depth of concrete behind the form through which the rod cannot be hand pressed. The "hard" is typically maintained between

1 and 2 ft depending on the set rate of the particular concrete mix design. Advance rates are normally 12 to 18 in. per hour, but advance rates as high as 30 in. per hour have been achieved with accelerated mixes (11). The heat of hydration of the setting concrete, coupled with the typical moist condition in the shaft, create a hot humid atmosphere which is conducive to concrete curing.

2. CONTINUOUS SHAFT LINING CONCEPT

2.1 Introduction

The fundamental operating concept of the continuous shaft lining (CSL) system is one of continuous inverted slipforming, under pressurized conditions, from the shaft collar downward. Slipforming involves the placement of concrete behind a form which is moved either continuously or incrementally (with the time increment being small) to prevent the concrete from bonding to the form. The motion of the form is controlled to prevent bonding, and the timing of the motion is such, as to provide a finished lining that is sufficiently cured to retain its shape in the presence of imposed loads.

Slipforming of concrete provides two significant advantages over concrete placed with fixed forms. These advantages are:

a. Increased speed of placement

b. Elimination of "cold joints" in the finished concrete product.

The elimination of cold joints in a concrete shaft lining is important as cold joints provide easy paths for ground water leakage. The CSL is designed to place an unreinforced concrete lining of uniform thickness with a minimum of cold joints between concrete pours.

This is not to say that slipforming is new. Indeed, slipforming has been done both horizontally and vertically. Horizontal slipforming has been used since the turn of the century and its usage is continually increasing. It is currently used to construct roadways, curbs and gutters, median barriers, irrigation ditches, cattle feed troughs, and cast-in-place drainage or irrigation pipe. Vertical slipforming has been used extensively over the past two decades, but is presently only performed working upward. It has been used to construct shaft linings, building cores, chimneys, cooling towers, bridge piers, communication towers, water towers, grain silos, apartment houses, and off-shore drilling platforms.

However, the CSL system is designed to slipform concrete working downward from the top of the shaft. This involves an advance in the state of the art in vertical slipforming. In order to slipform concrete from the top downward, the concrete must be placed at the bottom of a closed form. This involves pumping the concrete, with the pumping pressure maintained at a level that will counteract the gravitational forces on the fluid concrete. It also requires a special concrete mix which will allow easy placement, and yet develop strength quickly to allow for rapid slipforming.

2.2 Basic Hardware

The CSL system which will be discussed throughout Volume 1, represents the culmination of 3 years of developmental effort. The underground, second generation design is based on an original operational concept developed by Foster Miller which has undergone several design improvements as results of the laboratory and full scale tests became known. The second generation design represents the best technology known to Foster-Miller and Dravo Engineers, which can be substantiated based on technical knowledge, professional experience and the results of the testing programs. The general arrangement of the basic CSL hardware is shown in Figure 1. The CSL is comprised of three main components:

a. Slipform - The slipform is a 10 ft high, cylindrical concrete form of steel construction. The form is tapered radially inward from the leading (lower) to the trailing (upper) edge. The form incorporates a wedging system which allows it to be collapsed in case of accidental jamming or planned step forming. The slipform is supported on six hydraulic cylinders which allow the slipform to be guided down the shaft in order to maintain reasonable plumbness and concentricity with the center of the bored shaft.

b. Curb Ring - The curb ring is a structural steel, box-shaped circular beam. The curb ring width corresponds to the thickness of concrete lining. The curb ring contains the concrete seals which bridge the gaps between itself and the shaft wall, and between itself and the slipform. In addition, concrete entry ports, vibrators and instrumentation are mounted on the curb ring. The curb ring is mounted on four hydraulic cylinders, which allow independent positioning of the curb relative to the slipform. The curb ring provides the moving pressure boundary for the concrete slipforming process, and allows the fluid concrete to be kept under a controlled pressure as it sets up.

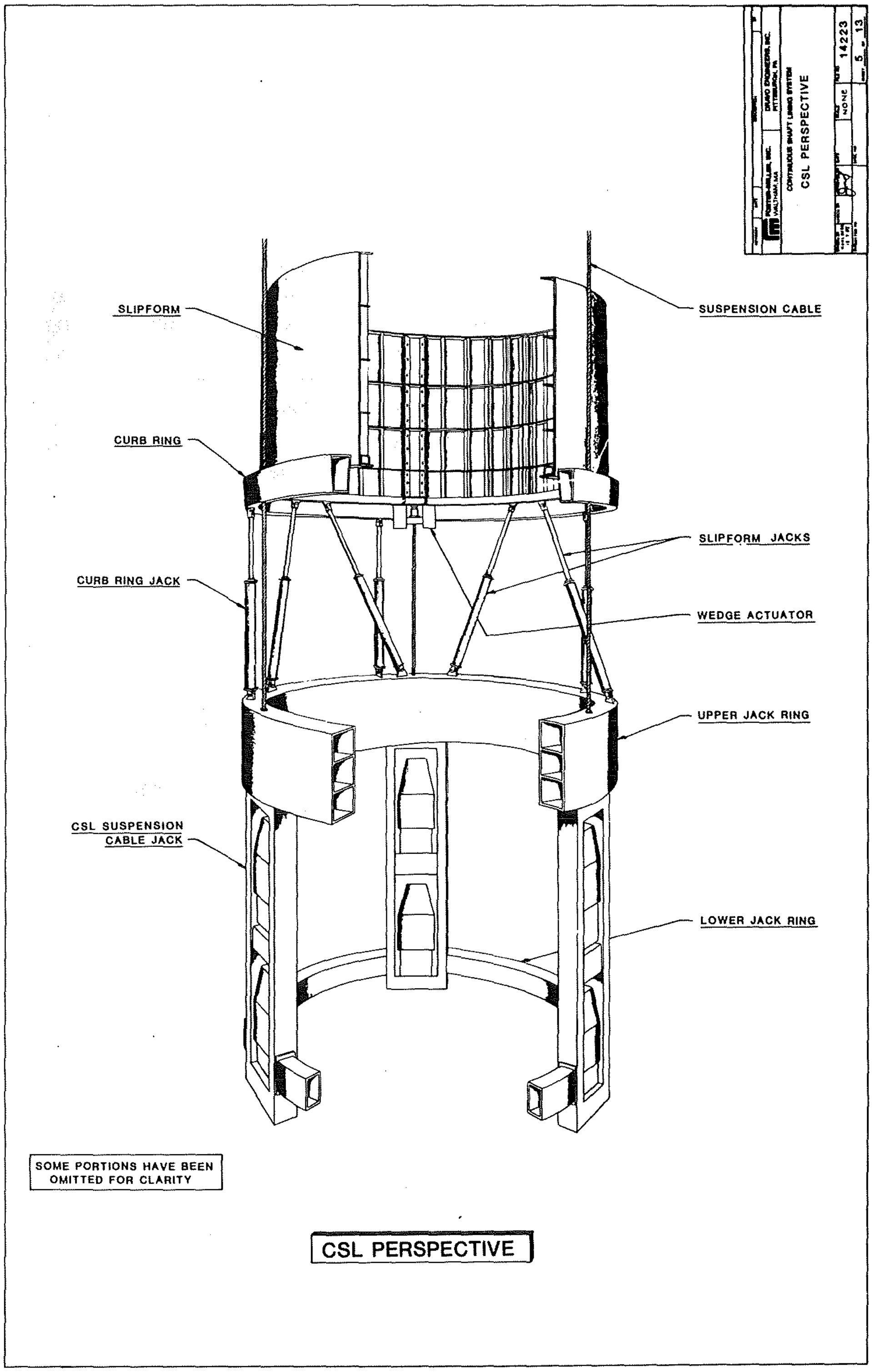


FIGURE 1. - General arrangement of the 2nd generation CSL.

c. Jack Ring - The jack ring is a structural steel platform which supports the slipform and curb ring. The jack ring is lowered down the shaft on a three point cable suspension system which uses hydraulic climbing units to control the descent. The jack ring also provides the means of transferring the moments and loads, induced by the slipform guidance system, from the CSL to the shaft wall.

Not shown in Figure 1 is all the support equipment, which will be discussed in detail later in this report. This equipment includes a work stage or galloway on which are mounted a concrete remix hopper and pump, a four port slide valve for directing the concrete to each of the curb ring ports, the hydraulic power supply and instrumentation and control console for operating the system. In addition to the galloway mounted equipment, there is a complete concrete batch plant at the shaft collar and concrete slick line/service line extension system following the CSL.

2.3 Modes of Operation

The CSL has been designed to have a unique combination of operational modes. It is capable of continuous slipforming, as well as functioning in a similar manner to a conventional step form system. The CSL has the ability to quickly change its rate of advance to match the rate of advance of the shaft excavation. The CSL has been designed to deal with large slough zones by providing it with a jump form mode. This operational flexibility makes the CSL a valuable tool to the construction contractor, who must often deal with changing ground conditions throughout the life of a shaft construction project.

The CSL can be operated in three distinctly different modes. These include continuous slipforming, mechanized step forming, and jump forming.

2.3.1 Continuous Slipforming

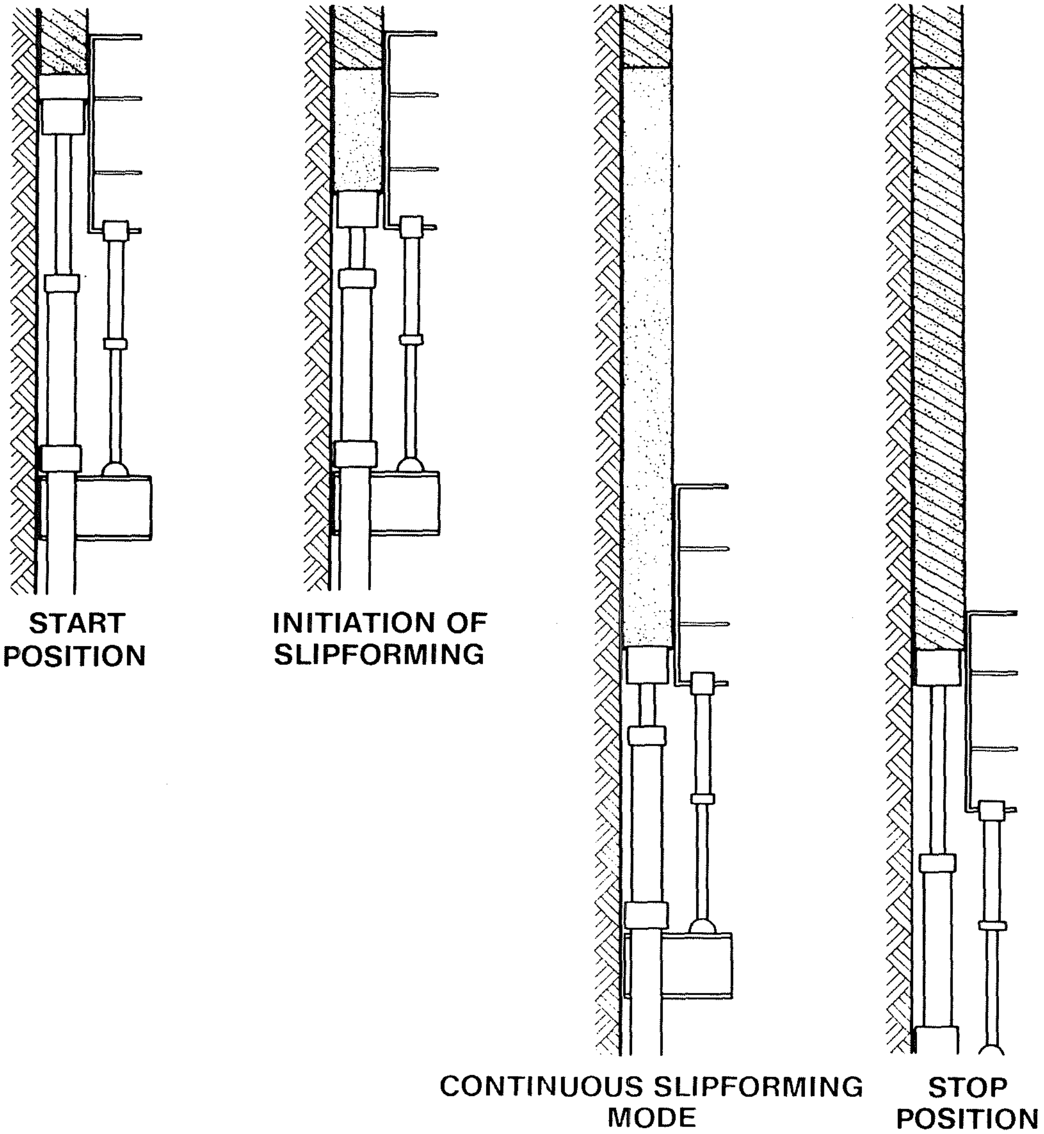
This is a primary mode of operation. Concrete is placed through the multiple curb ring ports (individually and sequentially) at a volumetric rate equivalent to the CSL rate of advance desired. The CSL suspension system is also independently advanced at this rate to synchronize the three main components of the CSL. Continuous operation will proceed in accordance with the excavation rate of the shaft sinking machine. The rate of advance is variable. Construction may stop each day or may continue 24 hours per day.

Concrete is initially placed in a small void between the top of the curb ring and the previously cast lining. (Refer to Figure 2.) After the void is filled and pressurized, the concrete pressure will eventually overcome a pre-set back pressure in the curb ring hydraulic actuators, and allow the curb ring to advance downward. The slipform is stationary until the curb ring advances to a point near the leading edge. At this point, both the curb ring and slipform will advance down the shaft at the same rate. This is accomplished by activating the CSL suspension system which lowers the jack ring, slipform and curb ring simultaneously. There is some speed matching required between the curb ring and suspension system in order to maintain a constant relative position between the crub ring and slipform.

After concrete placement ceases, the curb ring is stopped, and the slipform is allowed to advance until all the concrete is exposed. As the slipform is advanced, the curb ring position is maintained by the four independent hydraulic actuators, which extend to compensate for the jack ring position.

2.3.2 Mechanized Step Forming

In the situation where the excavation rate slows down, due to geological conditions or non-lining equipment related problems, to a point where continuous slipforming is impractical, then a mechanized step form mode can be utilized. Typically, operation under this mode requires the form to be inserted into and set against the previously cast lining, and the curb ring placed in the start position (same as continuous slipforming mode; see Figure 3). Concrete is placed in the void, pressuring the void, and then advances the curb downward. When the curb advances to the leading edge of the slipform, concrete placement is terminated, and the CSL system shut down. Once the concrete has cured sufficiently, the slipform is collapsed, the jack ring advanced to a new start position, and the slipform reset. The rate of concrete placement can be significantly increased during the step forming mode, as slipforming is not performed. Slipforming requires sufficient concrete residence time behind the form for the concrete to attain a certain strength before exposure. There is, in effect, a uniform gradient of concrete age behind the form. In step forming, a uniform concrete age is desirable for the entire pour. In this way, the slipform can be removed as quickly as possible without fear of a partial collapse of the lining.



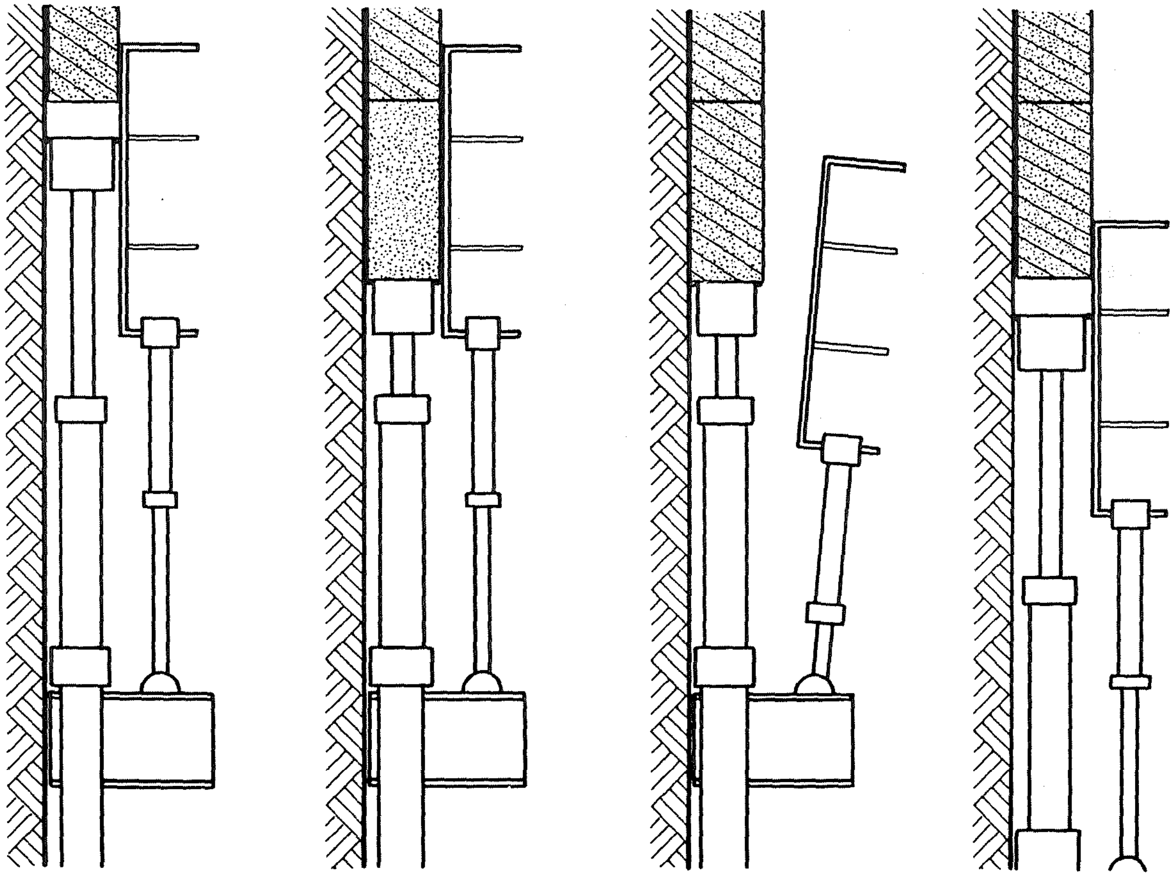
START POSITION

INITIATION OF SLIPFORMING

CONTINUOUS SLIPFORMING MODE

STOP POSITION

FIGURE 2. - Continuous slipforming mode of operation.



START POSITION

STOP POSITION

SLIPFORM COLLAPSE

START POSITION

FIGURE 3. - Mechanized step forming mode of operation.

2.3.3 Jump Forming

Jump forming is required when slough zones are encountered which exceed the sealing capabilities of the outer curb ring seal. In this circumstance, the slipform is inserted into and set against the previously cast lining, and the curb ring is advanced beyond the slough zone as shown in Figure 4. The void is filled and pressurized as rapidly as possible, and then the concrete is allowed to cure. If the slipform cannot be moved after the concrete has set, then it must be collapsed and reset to a new start position.

2.3.4 Crew Size and Job Descriptions

The CSL system is designed to be operated with a three man, full time crew underground plus a three man surface crew. The six man crew includes the CSL operator; concrete remix and pump operator; wall preparation and support system operator; two concrete batch plant operators and surface support supervisor.

The CSL operator is in charge of the three man underground crew. He is stationed at the CSL operator's control panel, located on the second deck of the galloway. He is in voice communication with all other stations and he makes decisions regarding the CSL operating techniques. His regular job tasks include the following:

a. Controlling curb ring level and pressure

b. Controlling slipform advance rate and guidance

c. Checking quality of exposed lining

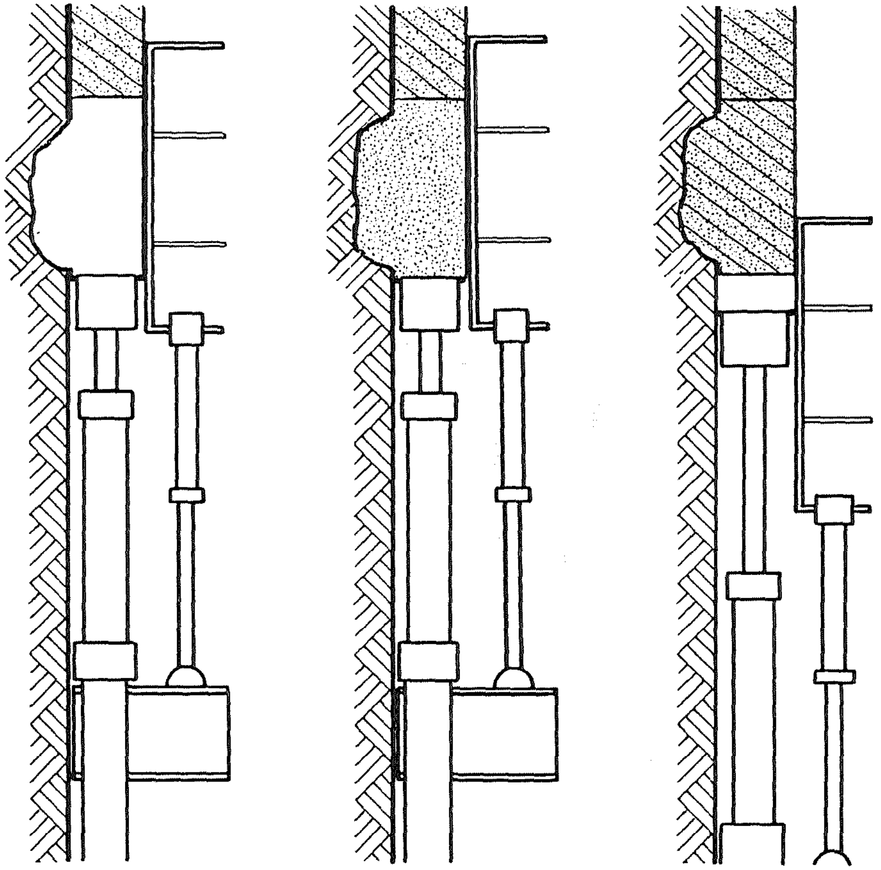
d. Monitoring system performance instrumentation for potential problems.

The concrete remix and pump operator controls all the concrete delivery system equipment on the galloway and CSL. He is responsible for:

a. Maintaining proper concrete level in the remix hopper by communication with concrete plant operator

b. Maintaining proper operation of the multi-port valve

c. Maintaining proper operation of the vibrators



START POSITION

VOID FILLED SLIPFORM MOVED OR COLLAPSED

START POSITION FOR SLIPFORMING

FIGURE 4. - Jump forming mode of operation.

d. Control of the concrete pump operation

e. Clean out of concrete system components upon a shutdown.

The support system operator is responsible to monitor the operation of the three CSL suspension jacks and cable feed system. He must communicate with the CSL operator to alert him of potential problems. In addition, he must prepare the shaft wall if oversized slough zones are encountered. As an additional responsibility, he aids the pump operator during clean-up operations. A fourth person dedicated to wall preparation may be required if severe slough zones or water in flows are encountered.

Because the CSL is a continuous process, the three man surface crew is also full time. The concrete plant operators must maintain the levels inside the various materials bins and chemical holding tanks, monitor the mixing of the concrete materials and admixtures, as well as check the temperature and slump of the final concrete before it enters the slick line. They are responsible for quality control of the concrete, and must be able to quickly adjust the plant output if there is a need to change the CSL advance rate. The surface support supervisor is in contact with the CSL operator and together they determine the curb ring advance rate by setting the appropriate concrete production rate. He ensures that the galloway suspension system and the extension of services function without problem. He is also in charge of the concrete plant. A site hoist operator is required to operate the man hoist, the galloway, and service line extension, but is not considered a part of the CSL crew.

2.3.5 Routine Operations

In the continuous slipforming mode, the work tasks are straightforward. The CSL advance rate is chosen to match that of the boring machine and is set by the delivery rate of the concrete plant and pump. If no change in advance rate is required, then the concrete pump and plant will not need adjustments. If, on the other hand, the CSL must speed up or slow down, the CSL operator alerts the surface supervisor, who in turn orders a change in the output of the concrete plant. The plant is stopped, adjustments are dialed in, and then the plant is restarted. The concrete pump operator also adjusts the output of the pump. The CSL is back in operation in less than 60 seconds at a new adjusted rate of advance. This procedure has been performed many times during the CSL testing program without difficulty.

The CSL operator is constantly monitoring the concrete lining emerging from behind the slipform. The operator is looking for defects in the lining which would dictate remedial action. For example, if the lining is cracked or showing large gaps, then an increase in curb pressure is required. If the lining is bulging, then too much curb pressure is being applied and/or the slipform advance rate must be slowed down. The CSL operator is constantly controlling curb level, slipform alignment and jack frame level. All the above tasks can be monitored and controlled from the CSL operator's control panel.

Should the boring machine shut down for more than two hours, then the CSL system should also be shut down. The CSL operator directs the surface supervisor to stop making concrete. The concrete pump operator and helper purge the remix hopper and the pump of residual concrete. The concrete dash pot and slick line are cleaned out. Once pumping has ceased, the concrete spade shut-off valves on each curb ring nozzle are engaged. The multi-port valve and downstream and upstream piping are cleaned and washed out. The concrete, removed from these components, is directed to a muck skip rather than over the galloway side, to prevent harm to the boring machine personnel.

The final step in the cleanup is to remove the concrete nozzles. This action must await the initial set of the concrete to prevent loss of pressure on the curb ring. Should the nozzles be removed too soon, concrete may flow out from the curb creating a void or causing large cracks in the lining. When removed, the nozzles must be cleaned out or replaced. The system is now ready to be reconnected and prepared for start-up.

2.3.6 Maintenance Requirements

The maintenance requirements for the CSL are no different from present underground practices for similar equipment. The most critical components are in the concrete delivery system. Careless cleanup and maintenance will eventually lead to unacceptably large concrete build-up on components and loss of cross section in hoses and slick line. The concrete remix hopper and pump must be carefully cleaned after each use. Frequency washing of this equipment during operation is also recommended. Proper lubrication and greasing also aids in keeping the rotating components free of cement grout.

The other major maintenance area is the hydraulic control system. Fluid levels and temperatures in the reservoirs must be frequently checked. Hydraulic filters must be periodically cleaned. All hydraulic and pneumatic actuators must be kept clean, as well as the hydraulic valve manifolds. Frequent washing with water is one method of preventing future problems.

Other normal maintenance items include:

a. Greasing of rotating and sliding parts such as cable reel bearings, slipform wedges, and multiport valve.

b. Cleaning concrete grout from outer seals and replacement of damged leaves

c. Checking the proper functioning of the vibrators and the vibrator mounts.

2.4 Concrete Behavior

2.4.1 Phases of Concrete Behavior

In order to dictate the required behavioral properties of concrete used for slipforming, a general understanding of how the concrete changes from a fully plastic, workable material into a hardened, rigid structure must be provided. The various phases of behavior are important to track since they directly affect the force balance developing during slipforming. This section provides a general description of these behavioral phases. Section 2.5 describes the influence on slipforming directly.

In general, concrete has two major phases - a very brief period of plasticity which occurs just after mixing followed by a permanent (in practical terms) hardened state. Since the period of most concern to slipforming covers only a small fraction at the beginning of the concrete life span, it is important to take a closer look at the changes in behavior during this period.

For this closer examination, the concrete can be considered to have four phases during the transition from a liquid to a solid. These can be defined as:

a. Phase I - Fully plastic state when the concrete has measurable slump and behaves as a Bingham fluid

b. Phase II - Period when concrete is still plastic but has no slump

c. Phase III - Concrete is semi-rigid and reaches an initial set

d. Phase IV - Concrete has gone through a final set, is rigid and considered to have useable strength.

Phase I - Fully Plastic

During the first phase, the concrete is fully plastic and can be transported for placement. Its workability is generally measured by the slump test. A slump greater than 4 in. is considered high workability. The concrete can be pumped and behaves as a Bingham fluid. Concrete remains in this state until it has stiffened to a point where slump has reached zero.

Phase II - Plastic with No Slump

During this period the concrete can still be vibrated but it cannot be pumped. It cannot resist any external loads but may be free standing, depending on its cross sectional shape. The surface may still be wet. This phase may last up to several hours for ordinary concretes.

Phase III - Initial Set

This phase marks the transition from plastic to the hardened state. At this point the concrete can no longer be vibrated. Concretes generally exhibit some useable strength during this phase, but have little tensile resistance and form only a slight bond to the surrounding strata.

Phase IV - Final Set

Concrete begins to develop strength. Rate of strength gain is dependent on cement type, but it will not show much strength gain before final set begins. The concrete acts as a rigid body and will adhere to surrounding strata.

2.4.2 Concrete Performance Specifications

The concrete used for the CSL must meet specific behavioral requirements to ensure successful slipforming. The concrete must remain plastic while it is being pumped and consolidated within the form. Once in place, it must lose its plasticity and begin to stiffen and harden so that when it emerges from trailing edge of the form, it will be self-supporting.

In conventional slipforming practice, advance rates are relatively slow (1 to 2 ft/hr) so that normal Portland Type I cement concretes are adequate for use. In conventional slipforming, exposure time is generally in excess of 6 hrs when using unaccelerated concrete. In the CSL system, the advance rate and form length used require self-supporting strength as soon as 2-1/2 hrs after concrete mixing. This requires the concrete to change quickly from a workable, plastic material into a stiffened, rigid lining.

The concrete performance specification for the CSL system is as follows:

Short-Term Performance

a. Initial slump of 6 to 8 in.

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

c. Strength gain rate of about 25 to 50 psi (compressive strength) in 2-1/2 hr and 100 psi in 4 hr

d. Measured air content 4 to 6 percent.

Long-Term Performance

a. Final strength: 3000 psi minimum

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

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

d. Adequate freeze-thaw resistance.

Concrete used for the CSL simulation testing had to, at least, meet the short-term requirements to allow proof-of-concept testing of the CSL system. The long-term properties are important for the final application, however, meeting the short-term performance was more important during the testing stage. Once slipforming at rapid rates was proven successful, work would be performed on adjusting the mix to improve long-term properties if required.

2.4.3 Short-Term Behavior

In the short-term, the concrete for the CSL must accommodate two requirements. First, the concrete must remain plastic during the period when it is being handled. This includes the time during:

a. Concrete mixing

b. Transporting to the remix hopper

c. Pumping through all of the supply lines and valves

d. Moving within the annulus between the slipform and shaft wall above the curb ring.

No rapid slump loss can be allowed to occur until the concrete has reached its final position.

Secondly, the concrete must stiffen and gain strength as fast as possible after placement. Since the concrete will be exposed and, therefore, unsupported as early as 2-1/2 hrs after mixing, the concrete must gain strength much faster than in normal construction applications. The minimum strength requirement at exposure is difficult to pinpoint. In conventional horizontal slipforming of highway median barriers, hardly any measureable strength (3 to 5 psi) is required since the sections being generated are only 3 to 4 ft high. In vertical slipforming in the downward direction, however, a greater number of feet of recently placed concrete must be held up without lateral support once the concrete emerges from the form. The section just emerging from the form must support all the concrete above that has not transferred its weight through a mechanical shear bond to the surrounding rock wall. The transfer of load to the rock wall proceeds as the concrete gains strength. The faster the concrete gains strength, the sooner transfer will occur.

In addition to this pressure applied by the concrete above, the concrete must be strong enough to resist bulging induced by the concrete pumping pressure. Concrete distribution in a closed form is achieved by using pumping pressure and vibration. The pumping pressure required for proper CSL operation is dependent on the inlet port spacing, the workability or slump of the mix, and the drag force induced by the moving slipform. The summation of all these forces, including the static weight of the unbonded concrete lining, must be less than the compressive strength of the emerging concrete.

From the results of laboratory scale testing performed during Task I, a compressive strength of 25 to 50 psi is required to prevent bulging of the concrete lining above the slipform. To guarantee that a minimum acceptable shear bond develops with the shaft wall within a reasonable distance from the slipform, a minimum compressive strength of 100 psi at 4 hrs is required. This equates to a shear bond strength which exceeds 5 psi, (based on an estimated ratio of 20:1 between compressive strength and shear bond strength).

A measured fresh concrete air content of 4 to 6 percent is specified for freeze-thaw resistance and, therefore, the use of an air entraining agent is required. Although freeze-thaw resistance is a long-term property, air content directly affects two important short-term properties: slump behavior and early strength gain.

2.4.4 Long-Term Properties

A final or ultimate strength of 3000 psi is specified. This is a common requirement for most shaft linings constructed in the United States. Rapid early strength requirements cited for short-term behavior will govern the concrete mix design. To meet this requirement, a high cement content is used in the concrete mix. This will produce a concrete with an ultimate strength far in excess of 3000 psi.

Excessive shrinkage must be avoided in concrete used for the CSL. High shrinkage will lead to two major problems. First, excessive and uncontrolled cracking will occur due to the lack of reinforcement. These cracks may fill with water allowing high seepage which will cause damage if freezing occurs. Secondly, high shrinkage values will cause the lining to debond from the supporting rock, creating uneven lining loading and may allow water to collect behind the lining. This water if frozen, will exert large loads over extensive areas of the lining.

The groundwater in many soils and rock strata throughout the U.S. contain sulfates. These sulfates will react with chemical compounds in some concretes and will cause long-term expansion resulting in some loss of strength. The concrete used for the CSL should be formulated for moderate sulfate resistance so that excessive expansion will not occur. Early strength development is usually dependent (in most portland cement concretes) on the formation of tricalcium aluminate (C_3A)* which is highly reactive to groundwater sulfates. In this respect, a certain amount of sulfate reaction will be expected and tolerated for this type of concrete. A limit of 800 μin./in. (0.08 percent) expansion has been specified. This level of expansion is acceptable since the concrete will have an ultimate strength well in excess of that required for structural integrity.

*C_3A is a civil engineering designation for ($3CaO \cdot Al_2O_3$)

Air entrainment is commonly specified for concrete that will be exposed to freezing and thawing cycles. Although shafts are placed in ground that maintains about 55°F temperature year round, those used for down cast ventilation are exposed to the ambient temperature extremes.

2.4.5 Final Concrete Mix Design

The concrete used for the CSL simulation was developed from extensive laboratory testing. The research and testing performed is discussed in Volume II, subsection 1.2. The resulting mix design is shown in Table 2. All values are per cubic yard of concrete.

Typical fresh properties of the concrete are as stated in Table 3.

2.4.6 Concrete Mix Design Development

During the early part of the CSL program, various concrete mix designs, using several cement types, were investigated. The goal was to develop a concrete that would meet the performance specifications defined in subsection 2.4.2.

TABLE 2. - CSL concrete mix design

752 lbs Portland Type III Cement

1225 lbs Sand

1500 lbs 3/4-in. maximum sized stone

11.3 lbs Mighty 150® Superplasticizer
(1.5 percent by weight of cement)

22.6 lbs calcium chloride (3 percent by weight of cement)

11.3 fl. oz. Daravair® Air Entraining Agent
(1.5 fl. oz. per 100 lbs cement)

0.42 water cement ratio (316 lbs water, including water in admixtures)

TABLE 3. - Fresh properties of CSL concrete

Initial Slump	5 min. Slump	30 min. Slump	Air Content
6 to 8 in.	4 to 6 in.	3 to 4 in.	4 to 6 percent

In the short-term, the concrete mix was to remain pumpable for at least 45 min after mixing and develop strength as soon as possible after placement. Forty-five minutes was chosen as the minimum practical time period required for pumping, placing and consolidating the concrete in the form. A shorter period would not have been practical and would have created the risk of ruining equipment and pump lines in the event of an unexpected shutdown.

It was desirable to obtain the fastest rate of strength gain once the concrete had been placed. Originally a strength gain of 50 to 100 psi in 2 hr was set as the goal. After surveying the latest developments in mix design technology using standard materials, it appeared that this requirement was ambitious. Before CSL testing began, the strength gain requirement was reduced to 50 to 100 psi at 2-1/2 hr after mixing.

Concretes used for conventional placement techniques provided a point of departure for the mix design development. Portland Type I cement concretes, the most common concrete, remains workable for 2 to 3 hr after mixing and will not develop any strength for at least 6 hr after placement. Portland Type III mixes generally stiffen faster than Type I mixes, but still provide no strength for at least 4 hr.

The major emphasis of the mix development was to take a conventional mix (either a Type I, II, or III) and reduce its set time without adversely affecting its slump history. That is, produce a mix that would begin to set about 1 to 2 hr after mixing, yet remain workable for at least 45 min.

The aid of a number of admixture suppliers was enlisted. None could provide a formulation that would allow the concrete to meet the behavioral requirements, but many provided useful starting points and admixture samples.

A variety of cement types, cement contents, accelerators and water reducers were used in an attempt to formulate a concrete to meet the desired short-term properties. These constituents are listed in Table 4. Although the long-term behavior was important for final field applications, it was used only as a secondary consideration in selecting a mix. The only exception was that air entraining agent was used in all mixes.

A total of 127 mix combinations were tried. A majority of the mixes showed little better performance than unaccelerated Portland Type III. A complete description of the concrete mix design studies is provided in Volume II, subsection 1.2. A summary of the mix design work is provided in Table 5. It provides the cement type used, admixtures used (if any), the range in cement content, water cement ratio used, and the general results.

It was clear from the testing, that none of the mixes could meet the short-term strength requirement of 50 to 100 psi in 2-1/2 hr. The combinations that worked the best were the accelerated Type III mixes. The accelerated expansive cement mixes showed some promise, but problems controlling the slump and air content, coupled with the high cost of this material, precluded further consideration.

The candidate mix was formulated with 752 lb of Type III cement with 3 percent calcium chloride and 1.5 percent Mighty 150 superplasticizer, both by weight of cement. The chloride was used to shorten set time. The plasticizer facilitated the use of a low water cement ratio while maintaining adequate mix workability. The Type III cement used had a high tricalcium aluminate (C_3A) content. Although this mix combination provided proper slump behavior and the best strength development potential, it was anticipated that two long-term properties would be sacrificed. First, a mix made with high calcium chloride and high cement content would be expected to show large shrinkage potential. Second, a concrete formulated with a cement having a high C_3A content will provide poor resistance to sulfate attack. Test performed to measure these two long-term properties (discussed in Volume II, subsection 1.2) confirmed these expectations.

One other mix design was considered for use for the CSL demonstration tests. This mix was design for a horizontal slipforming application (7) and is formulated with very high early cement (VHEC). VHEC is a modified Portland cement that sets and hardens much faster than any of the cements shown in Table 5. A mix design formulated with VHEC will far exceed all of the CSL concrete behavioral requirements. However, there are

TABLE 4. - CSL mix cement and admixture candidates

Cements	Accelerators
Portland Type II	Darex Set Accelerator (DSA)
Portland Type III - 2 brands	Darex Corrosion Inhibitor (DCI)
Expansive Type K	Lithium Carbonate
Aluminous - 2 brands	LL880

Water Reducers and Superplasticizers
Lomar D
Mighty 150
Plastiment
Mighty RD2
Pozzolith 122R
Pozzolith 100 XR
Pozzolith 300N
Pozzolith 122 HE
WRDA HYCOL

a number of drawbacks to using VHEC for the CSL demonstration. VHEC is not readily available in all parts of the United States. Shipping charges may increase the total cement cost to as high as three times the cost of Portland Type III. In addition, VHEC cement is best used for applications where high strength (500 to 1000 psi) is required very soon (1 to 2 hr) after mixing, such as in patching or horizontal slipforming applications. Retarding the mix to CSL specifications may not be practical nor economical.

TABLE 5. - Summary of mix design development

Cement	Cement Content lbs/cu yd	Water/ Cement Ratio	Accelerator Type	Water Reducer (Plasticizer)	Comments
Portland Type II	564-658	0.39-0.43	4% DSA	None	Too slow - no strength up to 4 hr.
Portland Type III Martin Marietta	564-752	0.35-0.50	6% DSA 3-4% $CaCl_2$	● Mighty 150 ● Pozzolith 122R ● Pozzolith 100 XR ● Mighty RD2 ● Plastiment	Good strength - poor slump Good slump - no strength up to 4 hr.
Portland Type III Iron Clad	752	0.34-0.42	2-3 $CaCl_2$ 6% DCI 5% LL 880	● Mighty 150 ● Lomar D ● Pozzolith 122 HE ● Pozzolith 300N ● WRDA HYCOL	3% $CaCl_2$ worked best with 1.5% Mighty - slump good but strength only 10 psi in 3 hr; 30-40 psi in 4 hr
Type K Expansive	564-658	0.35-0.50	3-6% DSA	● Mighty RD2 ● Pozzolith 122R ● Mighty 150	Air content uncontrollable. Slump loss rapid (6 in.-30 min) But strength gain good 1 hr - 10 psi 3 hr - 50-60 psi
Aluminous Fondu	752	0.35	Lithium Carbonate	● Plastiment ● Lomar D	All stiffened to no slump in 15 min. Strength development erratic
Aluminous Lumnite	752	0.35	Lithium Carbonate	● Plastiment ● Lomar D	All stiffened to no slump in 15 min. Strength development erratic.

Although there were a number of deficiencies in the Portland Type III mix, it allowed demonstration of the CSL concept. The Type III mix was chosen for use during testing while some additional attempts to improve mix performance were considered. In addition to work performed in-house, a short study was conducted by Waterways Experimental Station (WES) in Vickburg, MS to improve the short-term behavior of the Type III mix design. Full details of the study are provided in the Appendix F. WES considered a number of cement combinations including the use of VHEC as a partial replacement for some of the Type III in the mix. From the results of the study, WES concluded that the final Type III mix design (Table 2) exhibited the best behavior of the mix combinations considered.

2.5 Force Balance

2.5.1 Description of Forces

An acceptable slipforming operational mode must insure that the concrete is kept in an undisturbed state following distribution. The young concrete must be supported for a sufficient period of time to allow adequate strength gain in the lining to carry ground induced loads. The concrete aging process occurs continually as the CSL advances down the shaft, and can be thought of in terms of zones of concrete age. This multi-zoned transition can best be understood by describing the balance between internal stresses in the concrete and external forces imposed by the CSL and surrounding rock. The mechanism for reacting these forces can then be illustrated by describing the external force balance on the CSL. Finally, the interaction between the CSL components can be illustrated by describing the internal force balance.

The major external force generators impacting the concrete shown in Figure 5 are as follows:

- Curb ring confinement pressure P_V
- Slipform and shaft wall confinement pressure P_H
- Total slipform drag D_S
- Shaft wall adhesion τ_W
- Ground induced loads P_W.

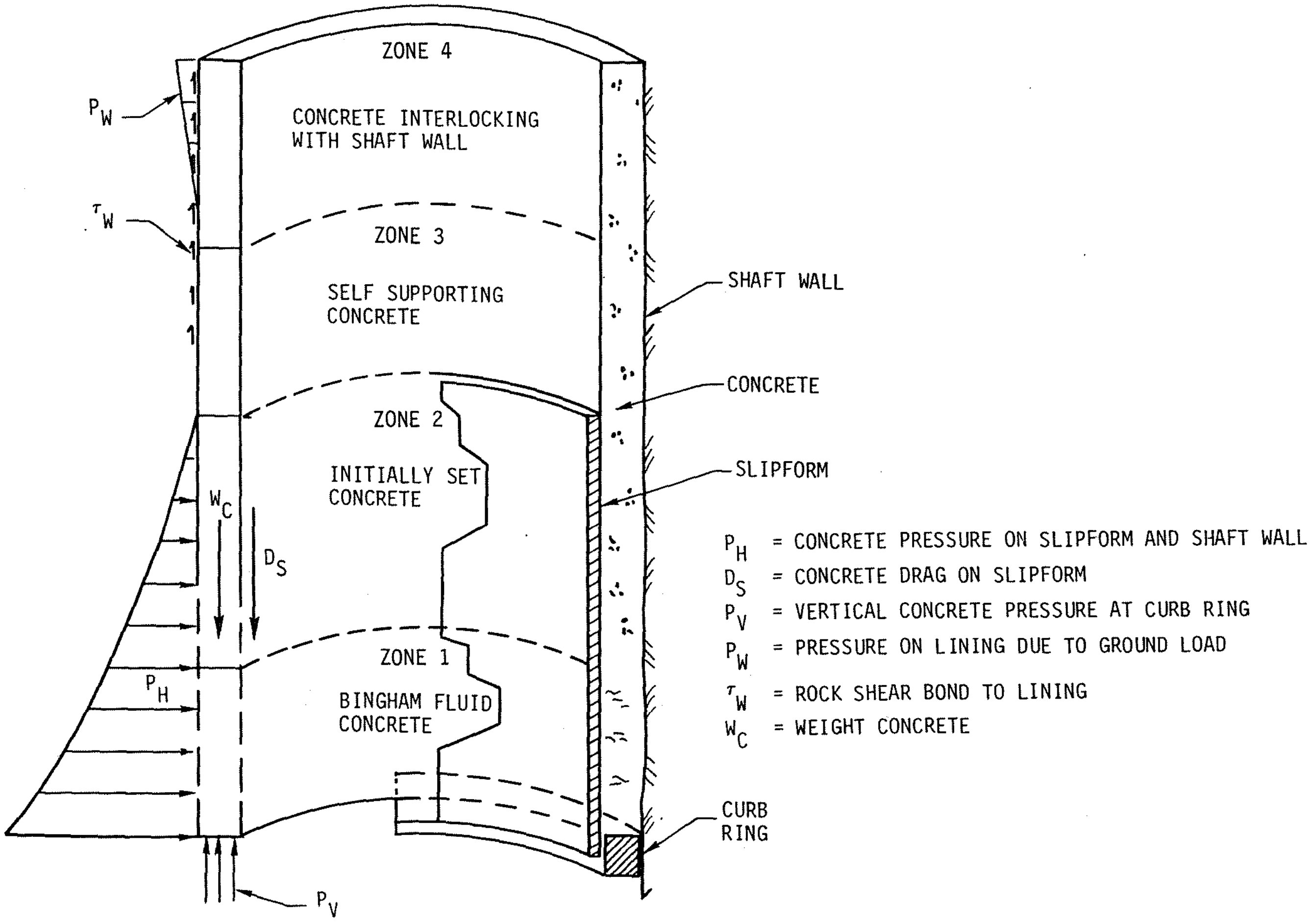


FIGURE 5. - Concrete force balance.

Throughout the multi-zoned transition, the concrete must be kept in a compressive state of stress to avoid cracking the lining. The initially placed concrete is in a Bingham fluid state in zone 1, transmitting curb ring induced pressure as a fluid and developing some drag force with respect to the slipform. Once the concrete has reached a state of initial set in zone 2, it begins to act as a solid imparting pressure dependent drag forces to the slipform. Upon exiting the slipform in zone 3 the concrete must emerge in a self-supporting state of limited vertical compressive stress.

The maximum allowable vertical compressive stress in the concrete emerging from behind the form is dependent on concrete strength. If the vertical stress in the emerging concrete exceeds its uniaxial compressive strength, the lining will bulge. The minimum allowable vertical compressive stress in the emerging concrete is dependent on the height of zone 3 concrete above the trailing edge of the slipform. Zone 3 concrete is being supported by the emerging concrete as it has not developed sufficient shear strength to carry its own weight by bonding to the shaft wall. If the compressive strength in the emerging concrete is not sufficient to counteract the weight of zone 3 concrete, the lining will crack.

The envelope of permissible vertical stress, between the maximum and minimum allowable, defines a corresponding operating pressure range for the initially placed Bingham Phase I concrete.

The concrete developes shear strength as well as compressive strength with age, although the relationship between the two is not well defined in young concrete. In zone 4, the concrete has attained sufficient shear strength to transfer its weight to the adjacent rock wall by means of interlocking asperities. The point of transition to zone 4 is dependent on concrete set rate and slipform advance rate, and may be very close to the point of transition from zone 2 to zone 3.

Ground induced loads, including ground water pressure, will develop in zone 4 with time. The continuously placed lining will experience the same long term ground loading as that imposed on a conventional step-formed lining. In general, distributed ground induced loads from a 20 ft diameter shaft will not impose a hoop stress exceeding 40 psi in a 12 inch lining. Ground induced loading is described in more detail in section 5.2.1.2. Concrete linings have sufficient compliance to inhibit cracking due to concentrated loads which might be imposed by blocky ground conditions. The lining operation should be located an appropriate distance above the sinking operation to allow the optimum ground relaxation, thus minimizing the support requirement of the lining. This relaxation occurs for a period of time which is substantially longer than that required for the concrete to gain 40 psi compressive strength. The CSL is designed to allow for a small amount of concrete deformation to accommodate ground relaxation during this early strength gain period.

The external force generators acting on the CSL shown in Figure 6 are as follows:

- Concrete pressure on curb ring, P_V
- Concrete pressure on slipform, P_H
- Unit concrete drag on slipform, D'_S
- Support cable loads on jack ring, F_V
- Rock loads on jack ring guide pads, F_H
- Unit wall drag on outer curb ring seals, D'_O

The concrete pressure on the curb ring P_V, is operator controlled by setting the hydraulic relief pressure to the curb ring actuators. The concrete pressure varies along the surface of the curb ring which is depicted in Figure 6 by the variation in P_V ($P_{V1} \neq P_{V3}$). The unit outer seal drag force D'_O also varies about the curb circumference due to variation in the shaft wall surface and variation in the concrete pressure pressing the seal against the wall.

The unit concrete drag on the slipform D'_S also varies about the slipform circumference due to its dependency on concrete pressure against the slipform, P_H. The drag force is small in the lower reaches of the slipform due to the fluid state (Bingham state) of the concrete. However, following initial set in the upper reaches of the slipform, significant drag forces develop, and then subside as the concrete gains strength and begins to hold its shape.

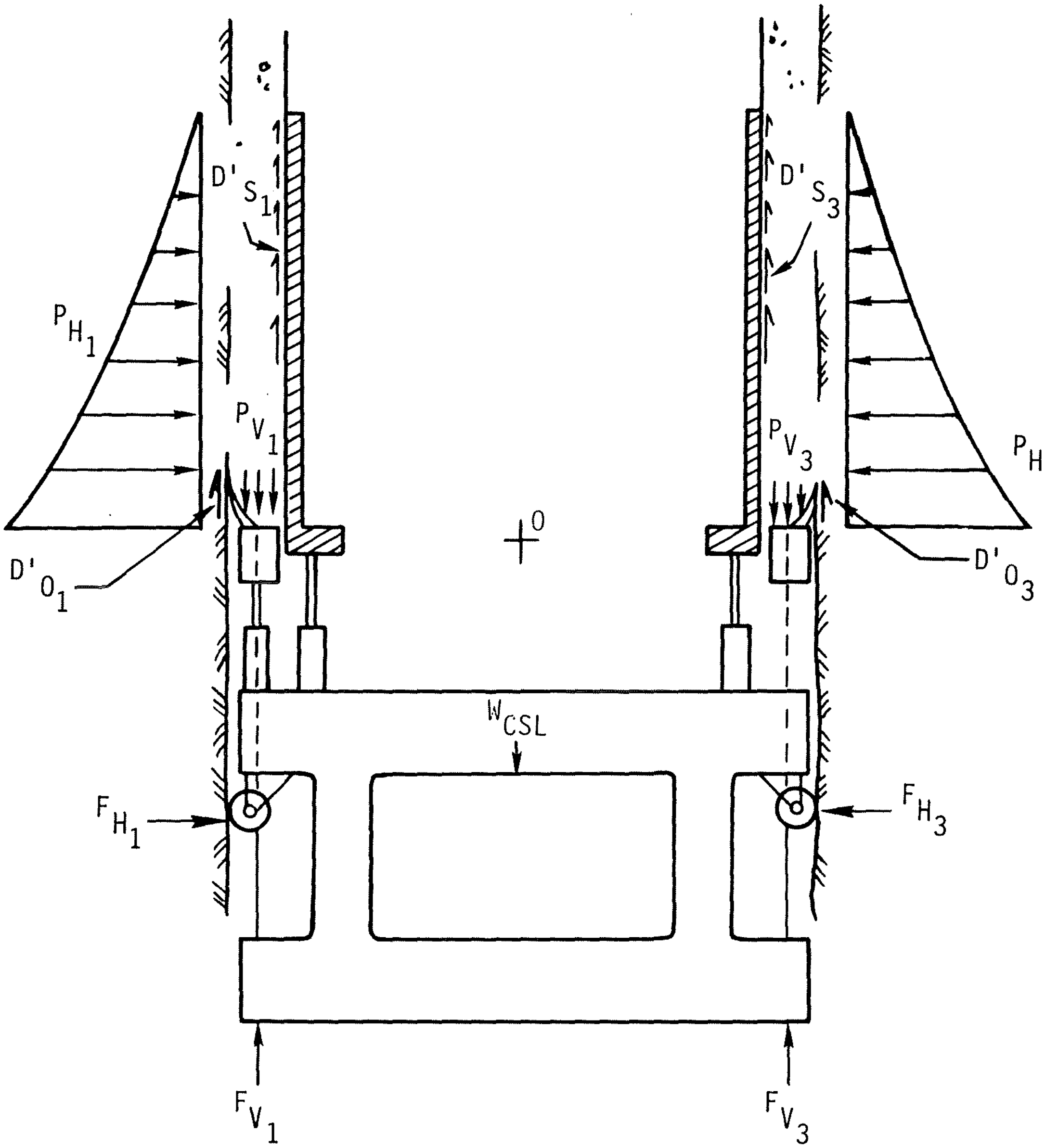


FIGURE 6. - External forces acting on the CSL.

The concrete pressure against the slipform, P_H is equal to the vertical concrete pressure P_V in the lower reaches of the slipform and is reduced in a nonlinear fashion to zero at the trailing edge of the slipform. This pressure reduction is attributed to the decrease in vertical stress and to relaxation of confinement as the tapered form pulls free from the selfsupporting concrete. The concrete pressure against the slipform varies about the slipform circumference predominately due to form tilting and translation induced in the process of steering the slipform as it travels down the shaft.

Support cables, embedded into the concrete lining, carry the downward load F_V of the CSL resulting from the combination of the average vertical concrete pressure ($\bar{P}_V$) over the area of the curb ring; slipform and external seal drag forces; and the weight of the CSL (W_{CSL}).

$$\Sigma F_V = \bar{P}_V A_c - D_S - D_O + W_{CSL} \qquad (1)$$

Force couples induced by variation in these combined vertical forces are counteracted by variation in the support cable loads (F_V) on the jack ring depicted in Figure 6 as F_V ($F_{V1} \neq F_{V3}$). Differential loading on guide wheels attached to the jack ring, F_H, react the resultant lateral force due to variation in concrete pressure on the slipform, P_H. These guide wheels are part of a hydraulically actuated system, and center the CSL in the shaft.

The internal forces acting on the three major CSL components shown in Figure 7 are as follows:

- Vertical load transfers between curb ring and jack ring, (F_{CV})
- Vertical load transfers between slipform and jack ring (F_{SV})
- Horizontal load transfers between slipform and jack ring (F_{SH})
- Drag force between inner curb ring seal and slipform (D_i)
- Torsional transfer from slipform to curb ring and jack ring (T_S).

The vertical load transferred from the curb ring and jack ring F_{CV} is equivalent to the product of the concrete pressure P_V over the surface area of the curb ring (A_C) plus the internal and external seal drag D_i and D_o. The hydraulic pressure to the curb ring actuators is normally uniform but may occasionally be biased as a tilt control mechanism to compensate for lack in symmetry of loads about the curb ring. The actuators transferring the curb load act as a buffer, allowing independent curb ring and jack ring movement.

Vertical load transfers between the slipform and jack ring, F_{SV}, is generated by slipform drag force, D_S, and the weight of the slipform. Steering and movement buffering requirements necessitate operator biasing of both vertical (F_{SV}) and horizontal (F_{SH}) load transfer mechanisms between the slipform and jack ring. Drag forces between the inner curb ring seal and the slipform (Di) are self cancelling in the jack ring, but can induce bias in the curb ring and slipform load transfer mechanisms.

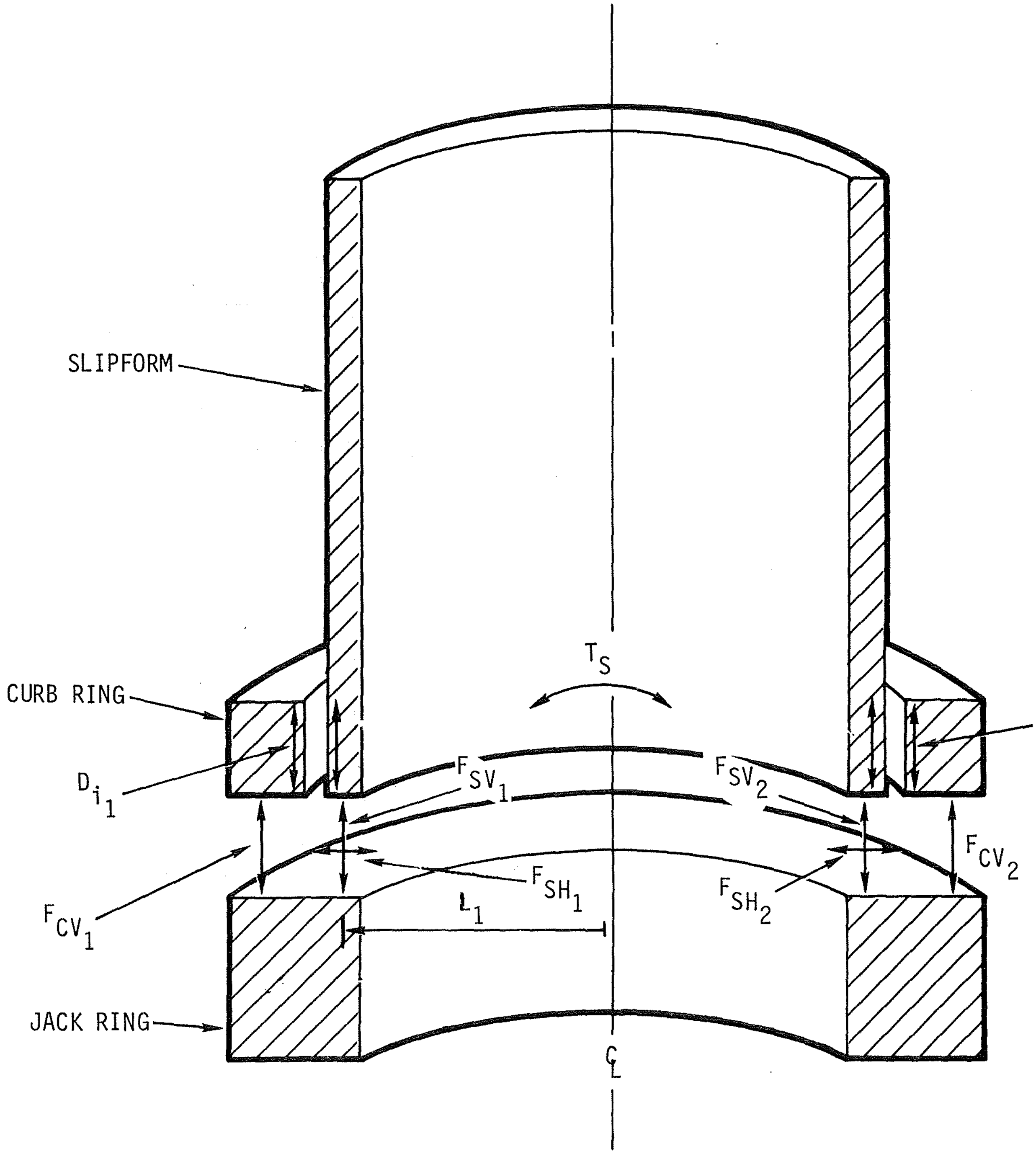
2.5.2 Concrete Force Balance

A major factor which determines limitations on the feasibility and ultimate advance rate potential of the CSL is the behavior of drag forces generated between the concrete and slipform. The magnitude of, and the parameters effecting, the drag force substantially impact the underground CSL design. To maintain integrity in the placed concrete lining, the combined weight of concrete and peak drag force must not exceed the upward support induced by the curb ring. The complete concrete force balance requires the average curb ring pressure, $\overline{P}_V$, on the concrete times the curb ring area, A_C, to equal, as a minimum, the weight of concrete behind the form plus the peak slipform drag force.

$$\overline{P}_V \times A_C \geqslant \rho\, \pi\, (\mathrm{SEL}) \left(\frac{2dB + B^2}{4} \right) + D_{S_{peak}} \qquad (2)$$

where ρ is the unit weight of concrete; d is the slipform diameter; B is the width of the curb ring; and (SEL) is the slipform effective length.

The simulation tests indicated that the drag force exhibits a stick-slip phenomenon which is attributed to a combination of hardware compliance and reduction in coefficient of friction with slipform movement. Test data indicate that the peak drag force, $D_{S_{peak}}$, is dependent on concrete pressure at the curb (P_V) and the slipform effective length (SEL). The relationship obtained



D_i = INNER CURB RING SEAL DRAG
F_{CV} = FORCE VERTICALLY ON CURB
F_{SH} = FORCE HORIZONTALLY ON SLIPFORM
F_{SV} = FORCE VERTICALLY ON SLIPFORM
T_S = TORSION ON SLIPFORM

FIGURE 7. - Internal forces on the CSL.

holds for the design mix concrete placed at a 3 ft/hr advance rate. It must be interpreted cautiously in estimating behavior of concrete having different set and placement rates.

The curb pressure (P_V) drag relationship is indicated in Figure 8 for the design mix placed 3 ft/hr. The concrete was slipformed with a 12 in. wide curb ring and a slipform having a taper ratio of 1 to 240 (radial change to slipform length). This graph indicates a marked drag dependence on both SEL and concrete curb pressure.

Based on observation of the trends in Figure 8, the same data was normalized by SEL to establish the curb pressure dependence relationship, independent of SEL as indicated in Figure 9. The degree of curve fit in Figure 9 indicates that an empirical linear relationship exists between drag force and the surface area of the slipform. This indicates the propensity of the concrete in the SEL region to be in zone 2, Figure 5, and that the zone 2 concrete exhibits a similar curb pressure dependent drag force everywhere in this region. Statistical curve fitting using the least squares method generated a logarithmic curb pressure drag relationship with a correlation coefficient of 0.98.

The pressure distribution along the slipform length has been derived based on a theoretical drag model which best fits the data obtained during simulation testing. This data is plotted on Figure 10. The model assumes a pressure dependent drag using a constant coefficient of friction (μ_1).

The complete empirical relationship between drag, pressure, and SEL is as follows for the simulation test data:

$$D_{S_{peak}} = 490 \text{ x SEL x } (2.2 \text{ x } \mathrm{Log}(\overline{P}_V) - 4.408) \qquad (3)$$

for $D_{S_{peak}}$ = (lbf)

SEL = (in.)

$\overline{P}_V$ = (psig)

[It should be noted that $A_c = 6333$ in.^{2} and d = 156 in. for simulation tests.]

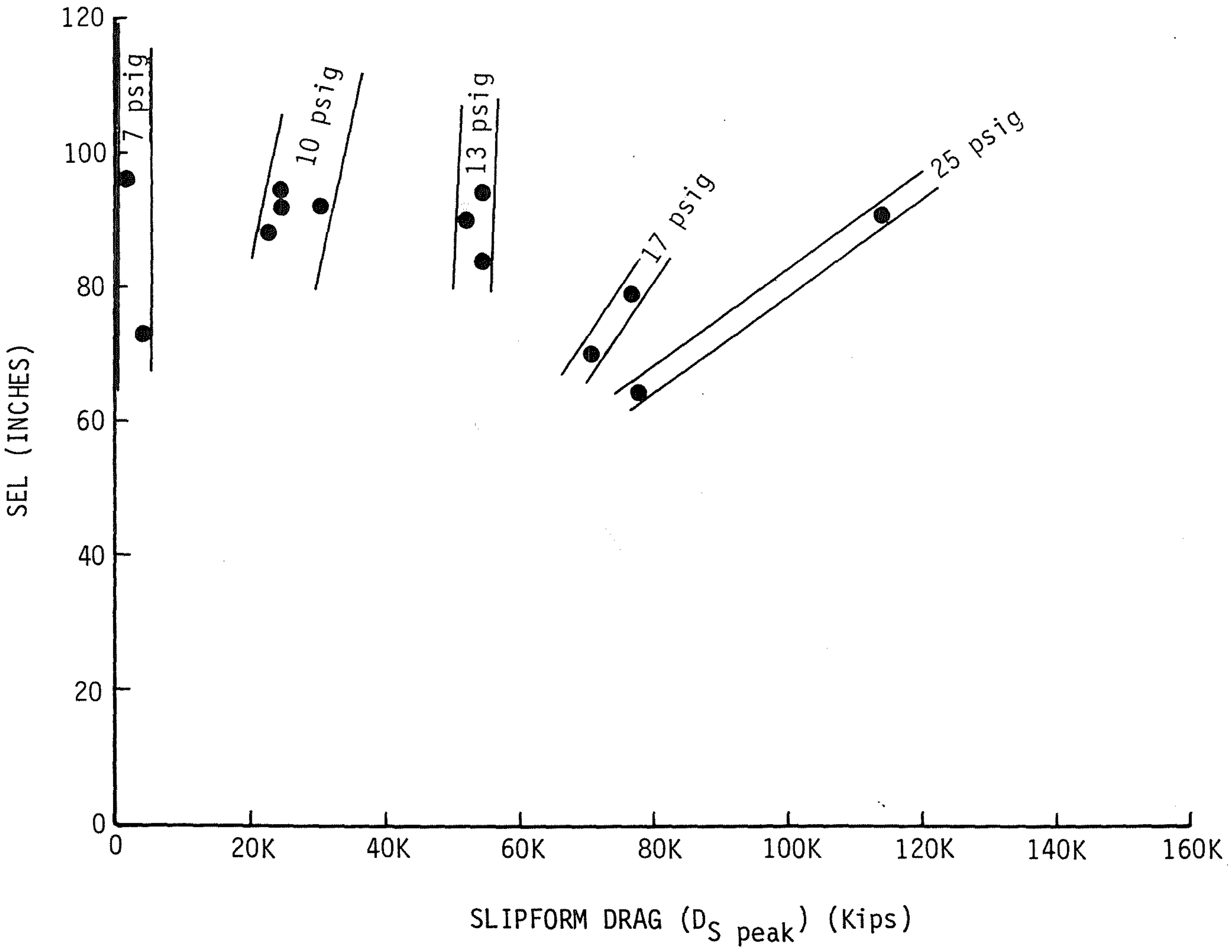


FIGURE 8. - Peak slipform drag versus SEL for various concrete curb pressures.

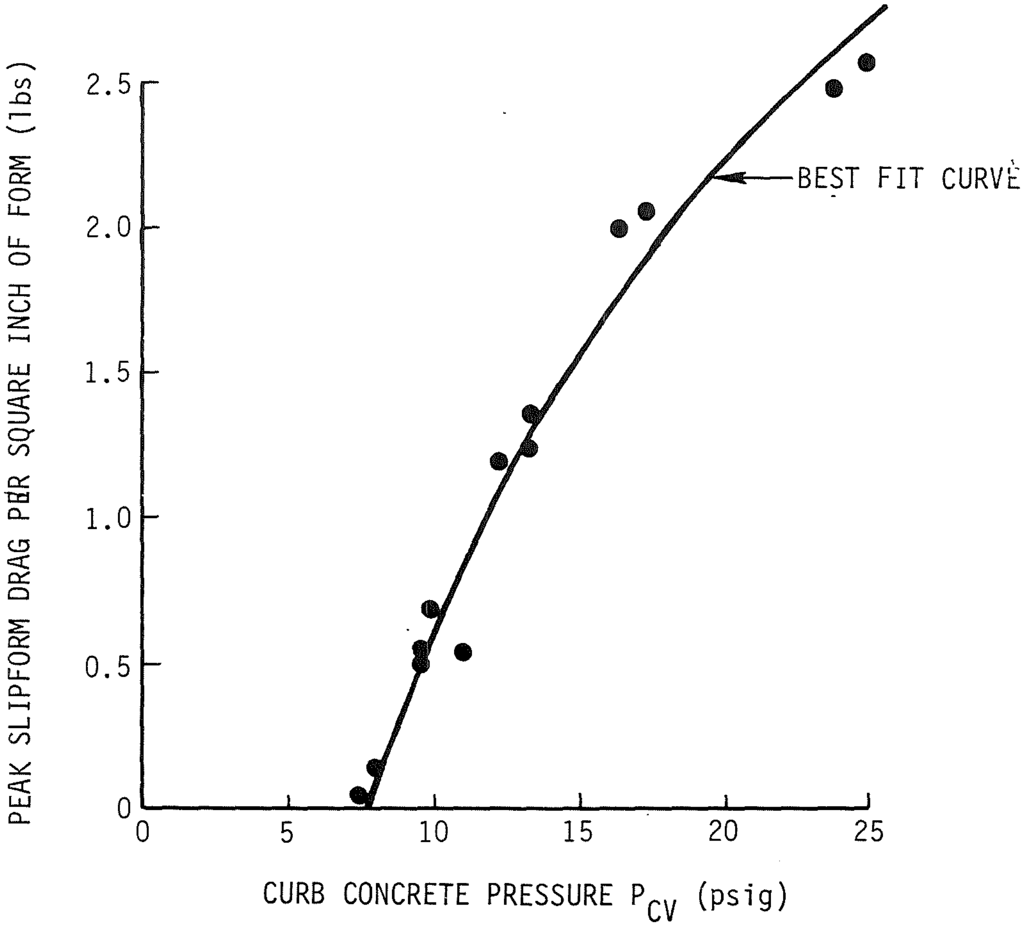


FIGURE 9. - Peak slipform drag normalized by SEL versus concrete pressure at curb ring.

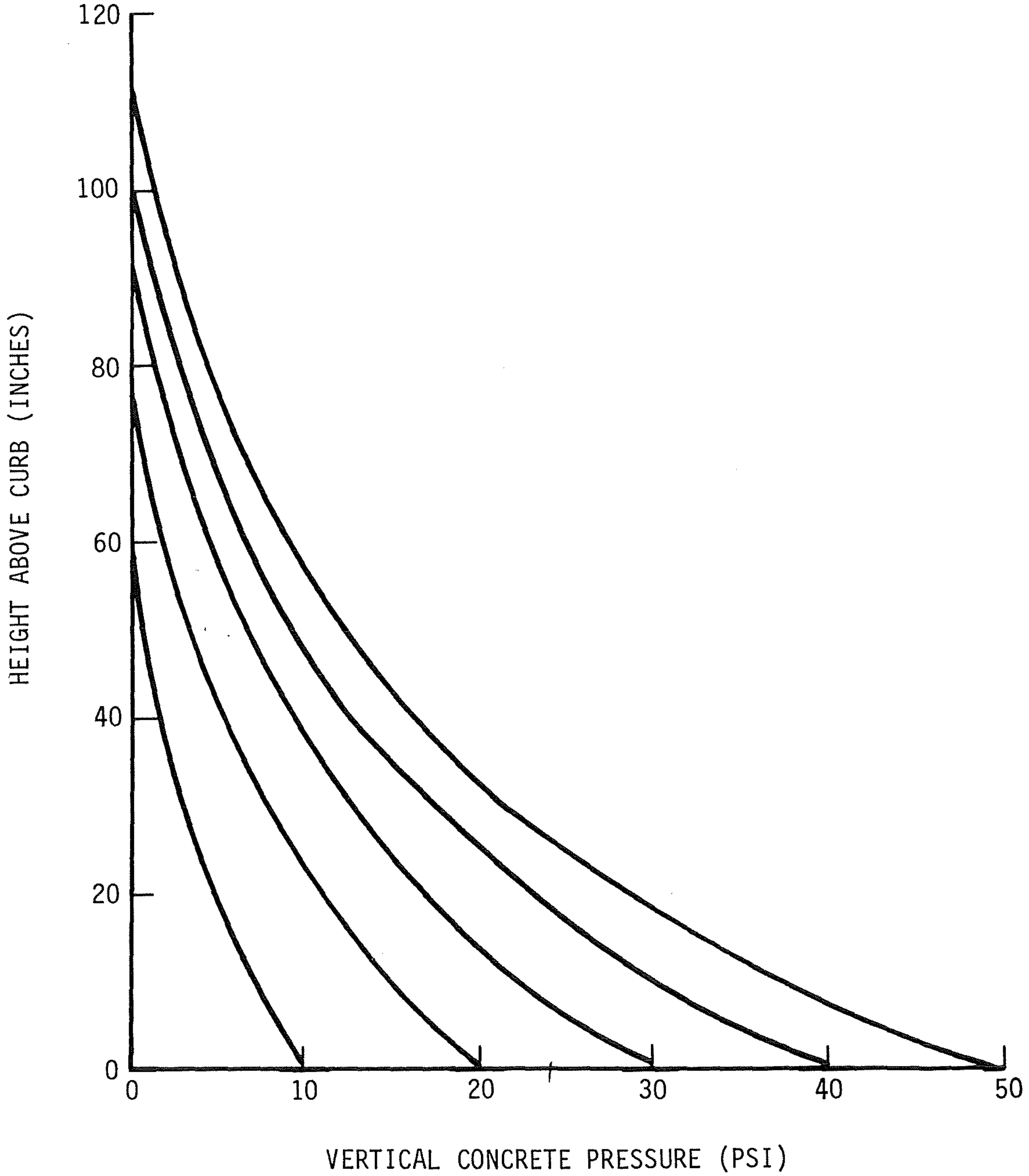


FIGURE 10. - Concrete pressure distribution along the slipform for $\mu = 0.3$.

Combining this empirical equation (3) with the force balance requirement in equation (2) yields the general equation (4).

$$\mathrm{SEL} = \frac{\overline{P}_V}{\rho + \frac{1}{B} \times (2.2 \times \mathrm{Log}(\overline{P}_V) - 4.408)} \qquad (4)$$

for SEL = (in.)

$\overline{P}_V$ = (psig)

B = cross-sectional width of curb (in.)

ρ = unit weight of concrete (≅ .085 lb./cu. in.)

This equation is plotted in Figure 11, and can be used as a design aid for establishing the minimum concrete curb pressure required for various combinations of curb width and SEL. It should be noted that this data is conservative, as it assumes no shear strength or tensile strength has developed in the concrete prior to emerging from the slipform. Using Figure 11 as a design tool for the simulation test hardware, the present 12 in. curb width and nominal lining thickness, with a maximum allowable concrete pressure of 40 psi, suggests the SEL cannot exceed 104 in. without inducing cracking in the lining. For the downhole design CSL, a 9 in. lining is desired. Using the present concrete mix design and placement rate, this would constrain the SEL to 80 in. However, the drag could be reduced by coating the slipform and by improved slipform guidance control. Assuming a 50 percent reduction in drag, the limitations on SEL are drastically reduced as shown in Figure 12.

During the course of simulation testing, the CSL was operated at pressures below the minimum predicted by equation (4) as necessary to keep the concrete in compression. The data points are plotted in Figure 13 along with the curve from equation (4). During the tests, some cracking was noted in the lining, but major crack openings did not occur when operating below the calculated minimum pressure for SEL. This was due to the conservative predictive nature of equation (4) as mentioned earlier.

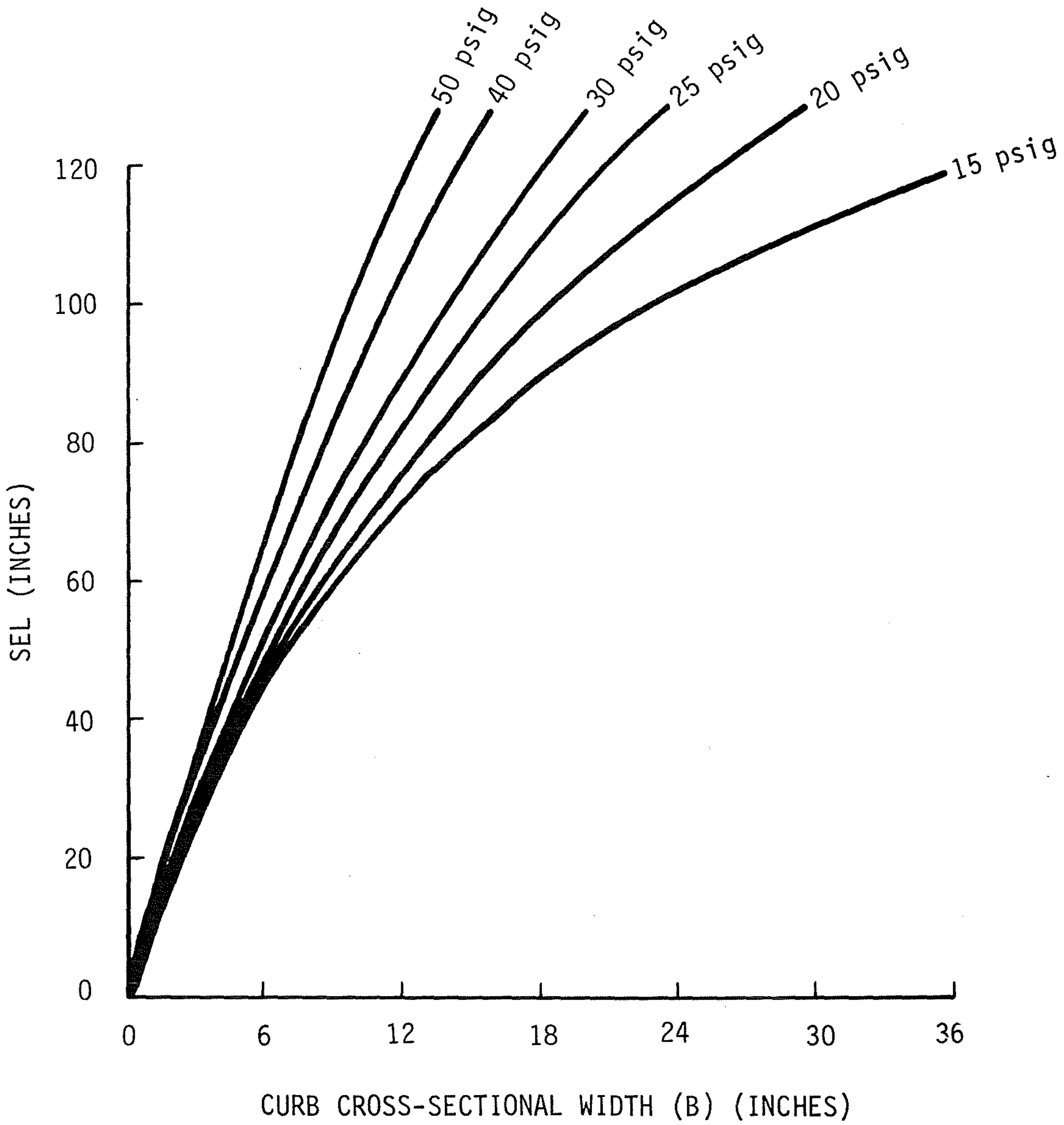


FIGURE 11. - Theoretical minimum concrete curb pressures required to keep concrete in compression.

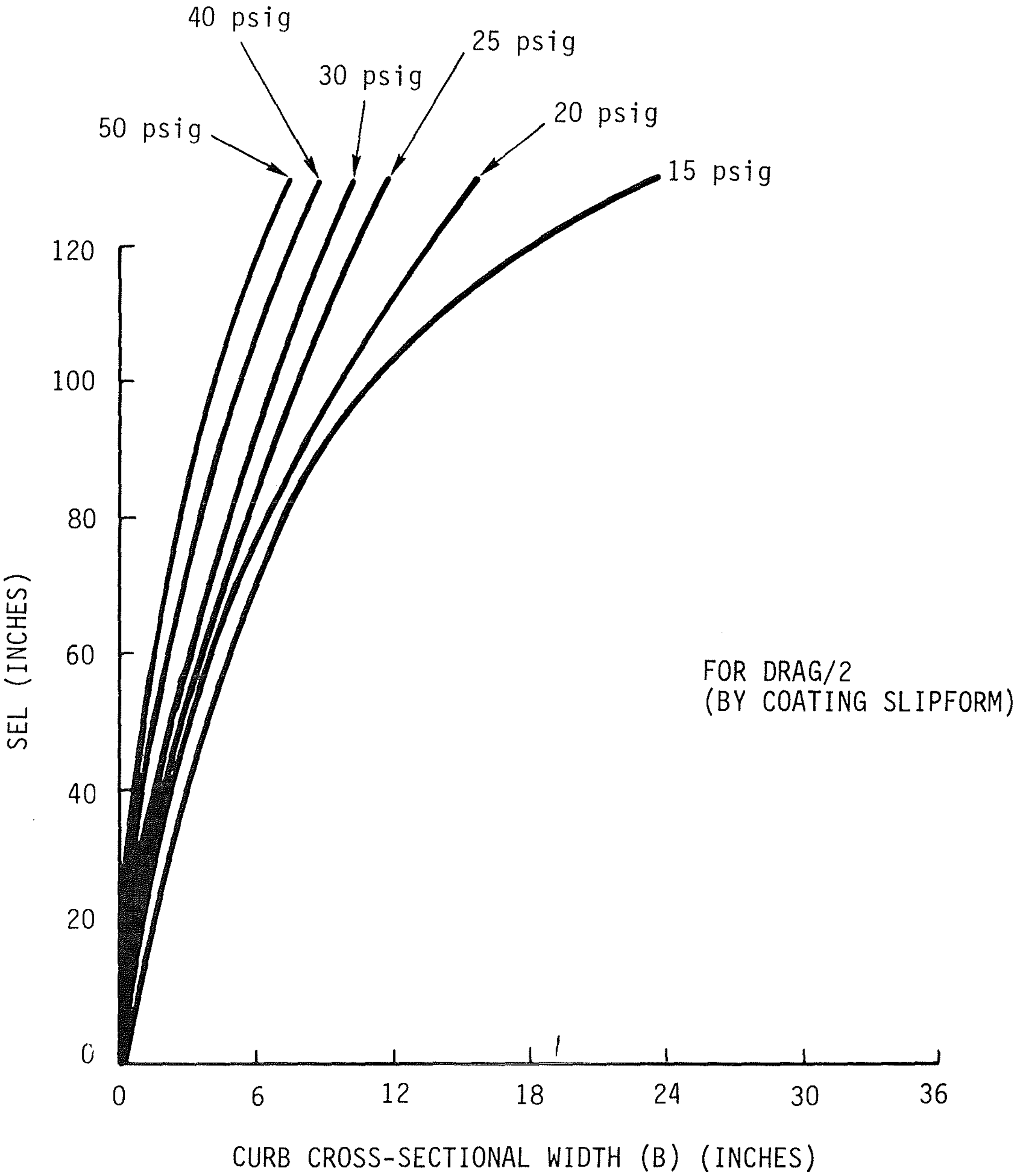


FIGURE 12. - Theoretical minimum concrete curb pressures required to keep concrete in compression.

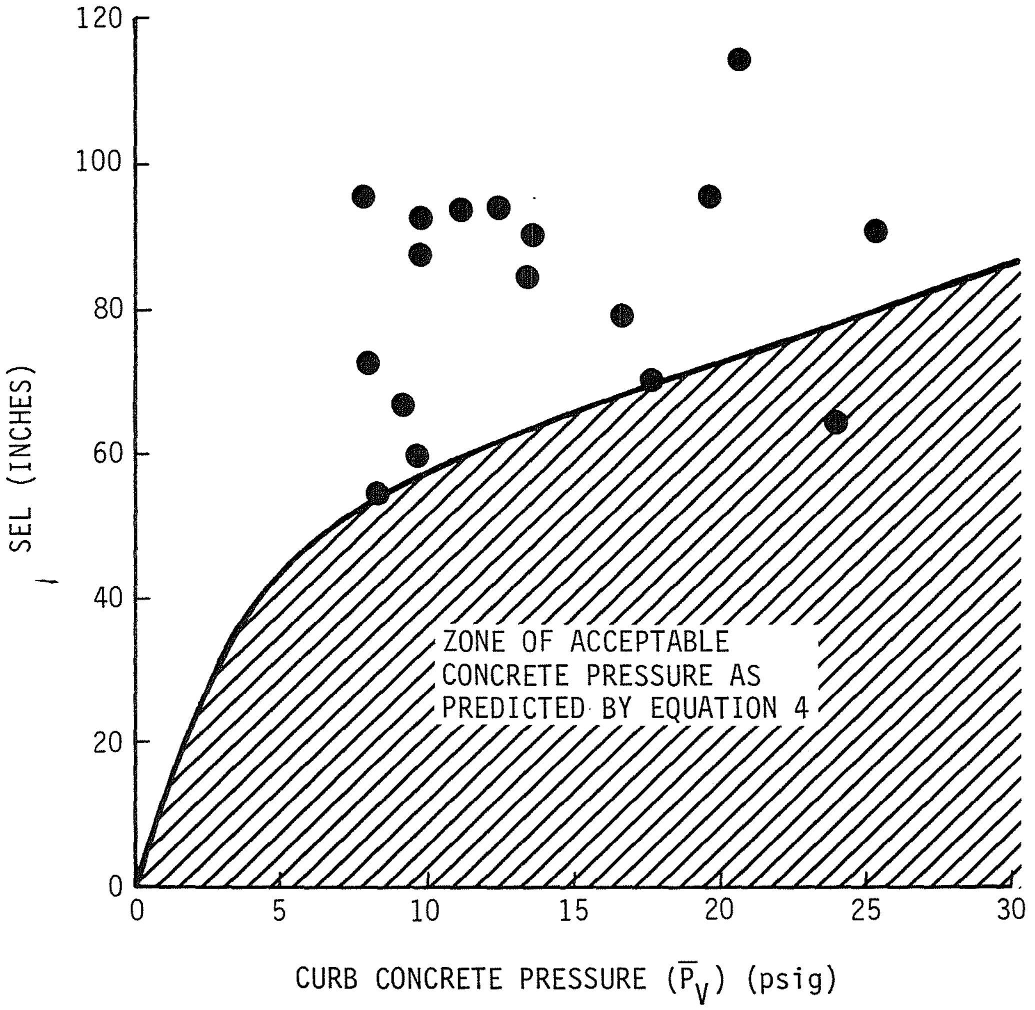


FIGURE 13. - Concrete pressure vs. SEL recorded during simulation testing.

2.5.3 External Force Balance on CSL

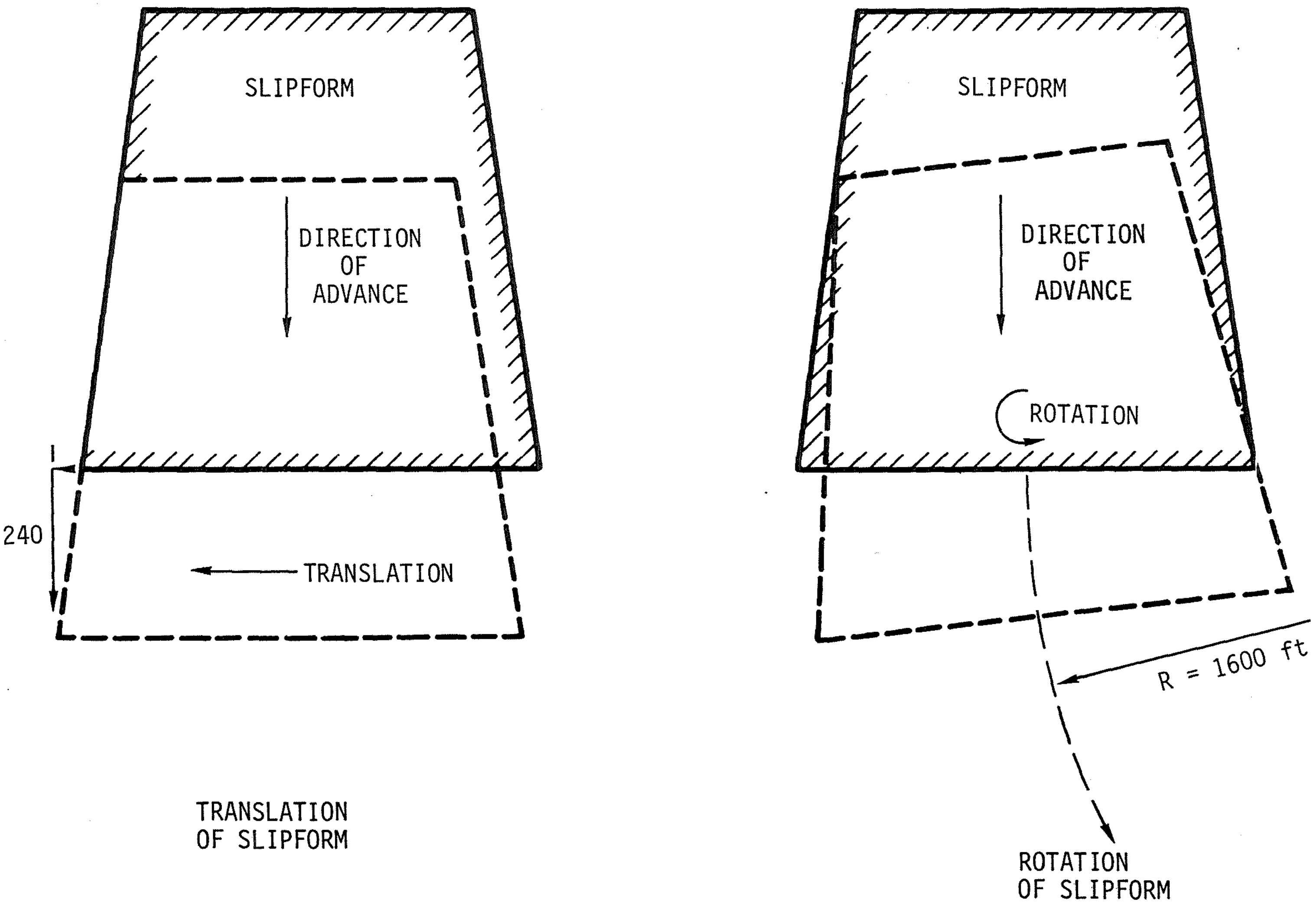
The external forces on the CSL hardware illustrated in Figure 6 are influenced by the active operation of the system for guidance control and by the cyclic nature of concrete placement. In the process of advancing down the shaft, the slipform must maintain axial alignment within the shaft in order to avoid jamming the system. The curb ring must oscillate down the shaft as concrete is pumped from port to port, but must not accumulate misalignment in so doing.

Maintaining CSL alignment requires constant guidance or steering of the slipform. In the process of steering, however, the slipform must not be forced to excessively distort the concrete placed, as high drag forces and possible damage to the lining or hardware may result. Steering the slipform is accomplished by a combination of slipform lateral translation, and slipform rotation about the horizontal axis as shown in Figure 14. In general, the leading end of the slipform, which is in contact with freshly pumped concrete, can move about the shaft more freely than the trailing edge which is in contact with set concrete. Damage and high drag forces are more likely to result from excessive movement at the trailing edge.

The slipform taper enables both a limited rotation and translation with slipform advance without requiring significant loading or deformation of the placed concrete as illustrated in Figure 14. The simulation test slipform could rotate about a radius of curvature of 1600 ft or translate at 0.4 percent of its advance rate without violating the placed concrete.

Tighter turning radii and higher translation rates can be achieved by inducing a combination of lateral forces and force couples into the slipform. Empirical data was collected during simulation testing to correlate a laterally induced force couple to the radius of curvature of rotation, as shown in Figure 15. This force couple was counteracted by an equal force couple transmitted through jack frame guide pads to the test tower. In a downhole CSL design, this counter force couple must be transmitted through differential loading in the jack ring support system F_V (Figure 6).

The magnitude of the force couple required for CSL guidance control of the slipform is dependent on the rate of rotational correction with advance required (radius of curvature). The minimum required radius of curvature as shown in Figure 16 is dependent on two factors. One, the resolution of the instrumentation and controls correcting rotational and lateral



TRANSLATION OF SLIPFORM

ROTATION OF SLIPFORM

FIGURE 14. - Geometric constraints on slipform alignment adjustments.

alignment; and two, the lateral misalignment tolerances (total gap) of the CSL in the mine shaft. Reasonable rotational control (tilt control) can be maintained within 0.5 deg of vertical. The CSL design has allocated 1/2 in. of the total radial gap between the curb ring and shaft wall for slipform steering corrections. This is reasonable taking into account sealing considerations and curb ring structural tolerances. This yields a minimum radius of curvature requirement of 800 ft (Figure 16). The corresponding guidance force couple requirement is 75,000 ft-lb, from Figure 15, for a 20 ft diam slipform (SEL = 100 in. with 0.04 percent radial taper). This corresponds to a required differential in vertical load, ΔF_V, of 5000 lbs between opposing load transfer mechanisms spaced 15 ft apart (see Figure 7 for L_1)

Maintaining curb ring alignment is principally accomplished by pumping a greater volume of concrete to the port which is lagging behind. Locally, pressure increases temporarily in the vicinity of the port to which concrete is being pumped. When passing through slough zones, local increases in the effective curb ring width combined with local reductions in outer seal drag can induce eccentric vertical loading in the CSL. This force couple is counterbalanced by the variation in support cable loads against the jack ring as indicated in Figure 6. The CSL is designed to pass through slough zones as large as 3 in. in excess of the nominal shaft radius. Assuming a slough extending around one-half the circumference of the shaft, this yields a combined increase in concrete load and reduction in seal drag (in lb) given by equation 5 (based on a seal drag coefficient of friction of 0.6).

$$\Delta\text{load} = 1.6\ (S)\ \overline{P}_V\ (D) \qquad (5)$$

where S is radial gap (in.) and D is shaft diameter (in.).

2.5.4 Internal Force Balance in CSL Components

There is a need for active guidance control for both the curb ring and slipform. The need combined with the need to buffer jack ring movement from the curb ring and slipform movement, necessitates controlling the relative motion between these three components. Under normal operating conditions, the curb ring translates vertically relative to the jack ring and oscillates downward to accommodate the cyclic nature of concrete placement. Normally, the vertical load transfer between the curb ring and jack ring is symmetrical about the CSL and shaft axis. However, occasionally the load is eccentric as indicated in Figure 7. Both curb ring and jack ring must be structurally capable of taking the curb induced eccentric loads.

The active slipform guidance control requires a slipform to jack ring load transfer mechanism which can accommodate relative tilt and translation between the two components. This mechanism must induce both lateral and vertical (F_{SV} and F_{SH}, Figure 7) loads as well as vertical force couples ($\Sigma L_1 F_{SV}$, Figure 7), but inhibit rotation of the slipform about the shaft axis (T_S, Figure 7). Both slipform and jack ring must be structurally capable of taking these combined loads at the discrete locations of the transfer mechanisms.

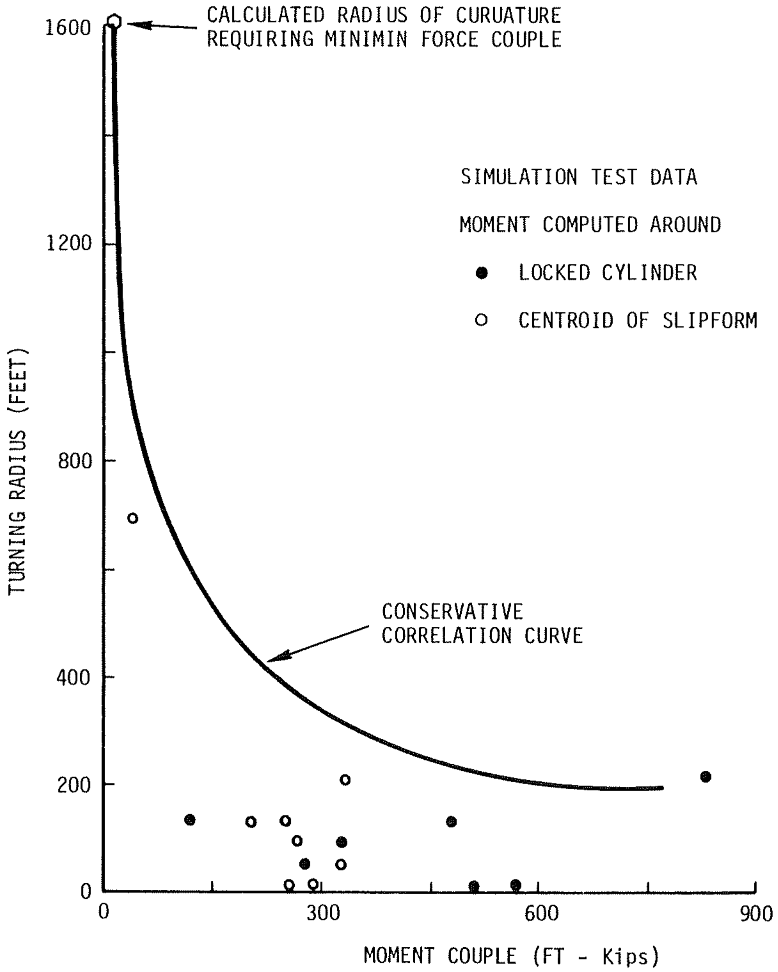


FIGURE 15. - Correlation between radius of curvature and force couple on slipform.

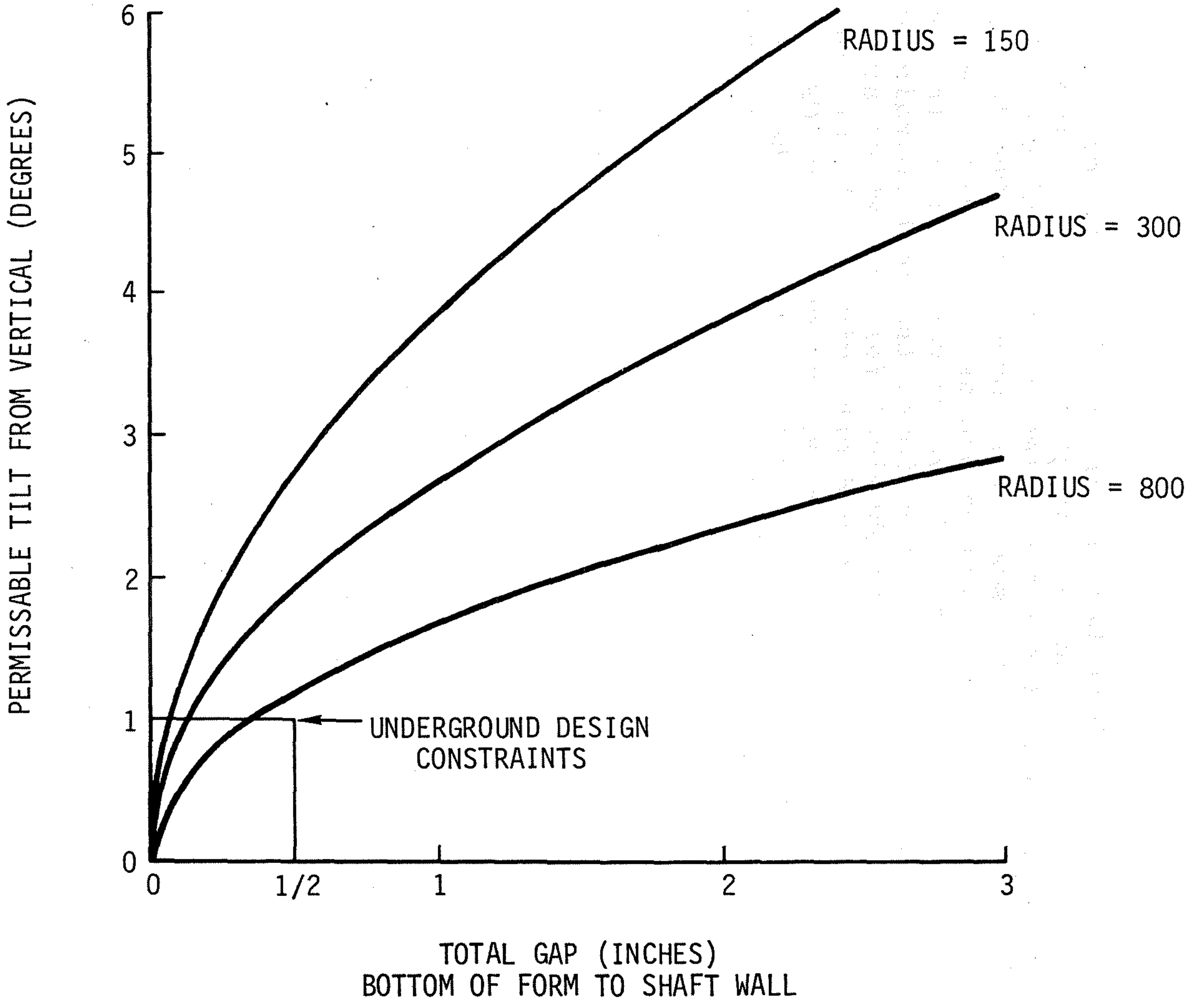


FIGURE 16. - Interrelation between allocated steering gap and guidance requirements.

3. UNDERGROUND CSL PERFORMANCE SPECIFICATIONS

3.1 Introduction

Specifications have been established for the performance, design configuration, and instrumentation of a prototype CSL unit. These specifications are based on the results of the Task I laboratory and full scale test programs. The design of the prototype CSL has been approached as a laboratory test apparatus, as it will require performance verification testing in an underground environment. Therefore, the unit contains certain operational flexibilities and physical features which are conducive to testing, but which would otherwise not be provided on a "commercial" unit. However, the second generation CSL does represent a closer version of a "commercial" unit than the initial laboratory CSL unit. Figure 17 depicts a general arrangement drawing of the second generation prototype CSL.

3.2 Performance Requirements

3.2.1 Types of Applicable Shaft Sinking Techniques

3.2.1.1 Blind Hole Drilled Shafts

The blind drilled shafts are presently sunk using modified oil field type drilling rigs with a large diameter drilling head. The lining would be most efficiently installed after the drilling operation is completed. If drilling mud is present, the lining process would require pumping out the mud just ahead of the CSL.

3.2.1.2 Downhole Bored Shafts

The state-of-the-art downhole boring machines are manned and require protection from material falling from the shaft walls. This protection for personnel and machine is provided by a shaft lining which is installed simultaneously as the borer advances downward. The Wirth V-mole and the DOE/Robbins borer are examples of downhole boring machines.

3.2.1.3 Raise Drilled Shafts

The raise drill method is an efficient method of excavating large diameter shafts. The raise drill concept mandates that the lining be installed after the shaft has been completely excavated.

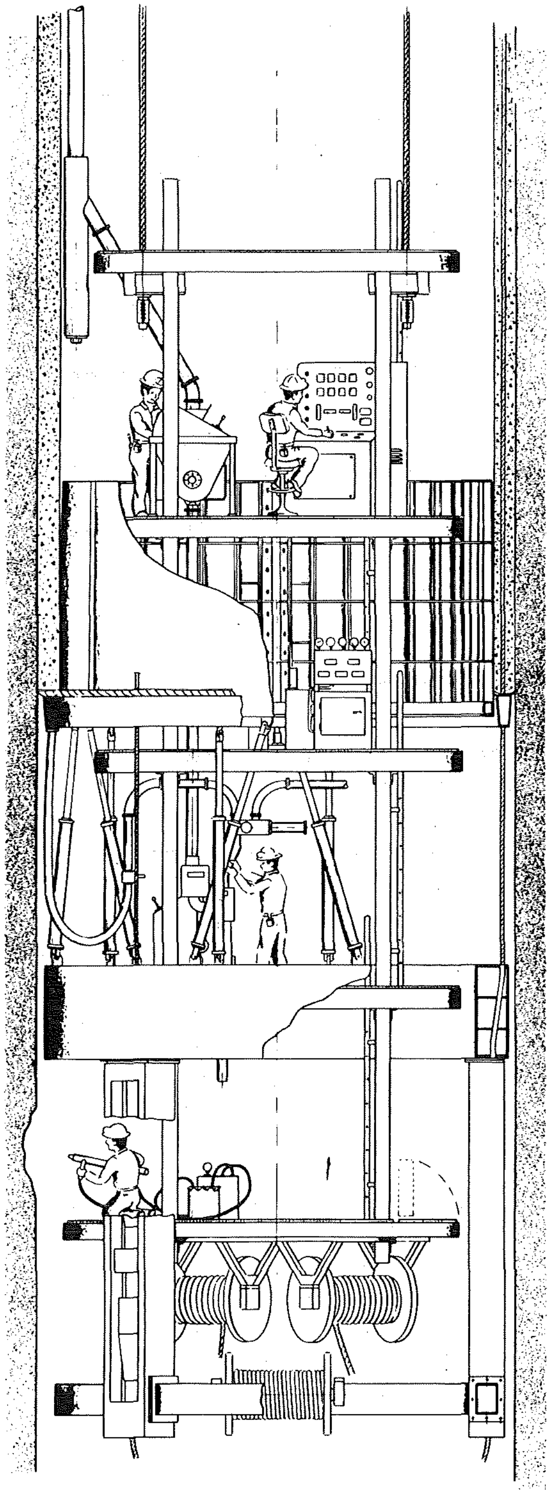


FIGURE 17. - General arrangement of continuous shaft liner.

The mechanically excavated shafts normally have walls which are relatively smooth. However, helical striations are produced by the gauge cutters, and range in depth from very slight up to ±3/4 in. In a conventionally sunk shaft (drill, shoot and muck), the overbreak creates surfaces which are usually far too irregular for the CSL outer seal to accommodate in the continually advancing mode. Furthermore, advance rates in conventionally sunk shafts are usually too slow to justify a continuously operated lining system.

3.2.2 Diameter Range of Unlined Shafts

The CSL requires an essentially round shaft to perform effectively. The curb ring is sized to allow a nominal 1-3/8 in. gap between the outer edge of the curb ring and the shaft wall. The CSL can operate efficiently in shafts which have diameters no smaller than 14 ft. Although there is no technical limit on how large a shaft diameter the CSL can be applied to, in practice, a 30 ft limit is as large as is considered feasible at this time. The prototype will be designed for a shaft diameter of 20 ft, 3 in.

3.2.3 Depth of Shafts

Economics indicate that the shaft depth be not less than 400 ft. There is no technical limit on how deep the CSL can proceed; however, there are practical limits on the related support systems. The prototype system will be designed for a shaft depth of 2000 ft.

3.2.4 Concrete Properties

A very important requirement of the concrete, for successful slipforming, is to gain strength at a controlled and fast rate. The concrete mix must remain plastic and pumpable while it is being transported through the slick line, pump, hoses, valves, nozzles, and into the region above the curb. Once it has arrived at its final position, it must start gaining strength at a rate which will attain 25 psi to 50 psi at age 2-1/2 hr (timing begins when the water is added to the cement and aggregate mixture). Tests have proved that the concrete emerging from the top of the slipform will be self-supporting if its strength exceeds 25 psi. From an availability point of view, it is desirable to use a Portland type of cement. However, other types of cement are available, and are compatible with the CSL system.

The initial slump range of 6 to 8 in. is used as a measure of pumpability and not the total water content of the mix. Slump loss must not exceed 4 in. in 30 min to allow for ample residence time in the delivery system prior to placement behind the slipform.

The required minimum compressive strength of 3000 psi at age 28 days will be far exceeded by any mix that achieves 25 psi in 2-1/2 hr. The 3000 psi strength was selected as minimum because of its familiarity and acceptance by the shaft sinking industry. Concrete linings having an ultimate compressive strength of 3000 psi have historically performed their intended functions in mine shafts.

It is necessary for successful consolidation of the concrete behind the slipform to maintain 15 psi to 25 psi pressure in the fluid concrete. Failure to maintain this pressure will result in a cracked concrete lining. In the slipform mode, pressure greater than the dead load pressure of the fluid concrete should be applied to assure that the concrete will remain in compression.

3.2.5 Lining Thicknesses

The minimum thickness of the concrete is limited by the requirements of the curb. Consideration of the space required by the concrete nozzles, torsional rigidity of the curb, and clearances from both the slipform and the shaft wall suggests a minimum concrete thickness of 9 in.

The maximum thickness of 18 in. was selected because it is the upper limit of thicknesses commonly used in industry. The system can place thicker linings, if required.

3.2.6 Advancement

The rate of advancement of the CSL is a function of the setting time of the concrete. The concrete specified above, pumped into a nominal 10 ft long form, can line a shaft at rate of 1 to 4 ft/hr. At this rate, it is possible to line up to 96 linear ft in 24 hr of continuous operation. A faster rate of advance would be achievable with a faster setting concrete mix or with a longer slipform (assuming drag forces are not too great).

3.2.7 Alignment

The fixed width of the curb and limited capability of the curb seals dictate that the CSL follow the path of the boring machine or drilled shaft. The CSL has the ability to smooth out minor abrupt shifts in shaft alignment. In order to maintain efficient CSL operation and uniform lining thickness, the slipform must be guided to maintain its concentricity within the shaft.

3.2.8 Slough Zones

The outer lip seal which has been developed, will permit the CSL to pass any type slough zone which ranges in depth up to 3-1/2 in.

Sloughs which are too deep for the seal to traverse in the continuous mode without permitting a "blow-by" will be pretreated. The lowest deck of the galloway will be used to fill and pretreat slough zones. The fill material can be blown foam, pneumatically applied cementations material or a combination thereof.

The compressive strength of the applied material does not have to be high because the CSL system will only apply a light load, in the range of 25 psi. It is necessary for the slough zones to be repaired quickly so that the advancement of the CSL is not hindered.

3.2.9 Water Handling Capabilities

The CSL system can tolerate water intrusion with no greater inconvenience than conventional concrete lining methods. The lip seal will pass over conventional water panning material without hindrance. If and when a water ring is required, the CSL system can stop above the ring and begin again below the ring. The curb and form may also be used during the construction of the water ring itself. All cold joints will be capable of accepting a water sealing gasket to minimize the inflow of water at the joint. The joint will be completely cast against the previous lining, with no voids or cracks.

3.3 Design Configuration

3.3.1 Jack Rings

3.3.1.1 Upper Jack Ring

The upper jack ring will be nominally 16 in. wide and 48 in. deep and be constructed from plate steel. The outside diameter will be 2 in. smaller than the diameter of the shaft bored with maximum gauge cutter wear. All external corners will be rounded or chamfered. Sleeves will be used to guide the three suspension ropes through the ring. Splices will develop the full strength of the final cross section.

3.3.1.2 Lower Jack ring

The lower jack ring is primarily intended to brace the lower end of the wire rope climbers. The nominal width will be 12 in. and nominal depth 16 in. to 24 in., as required. The outside diameter will be 4 in. smaller than the upper jack ring. All external corners will be rounded or chamfered. Special sleeves, inserts, and attachments will be added as required.

3.3.2 Curb Ring

The curb ring will be nominally 9 in. wide (including seals) and 16 in. deep and be constructed from plate steel. The width will vary from approximately 7-1/2 in. at the top to 6-1/2 in. at the bottom. The outside diameter will be 1 in. smaller than the diameter of the shaft bored with maximum gauge cutter wear. All external corners will be rounded or chamfered. Sleeves, inserts and attachments will be added as required. Splices will develop the full strength of the final cross section.

The mounting arrangement for the inner and outer concrete seals will be flush with the top curb surface. The mounting arrangement will be designed to allow easy seal replacement.

3.3.3 Slipform

The steel slipform will be 10 ft 0 in. long and will be 1 in. smaller in diameter at the top than at the bottom. The top edge will be rounded or beveled to help prevent tearing the concrete which is emerging from the top. The form will be coated. The slipform will consist of three 120 deg segments.

The form will contain three wedge-shaped units to facilitate stripping. The form will contract 1 to 2 in. in diameter when collapsed. The slipform segments and wedges will be connected with a "quick" release mechanism. The form will be supported by six hydraulic cylinders, one pair located at the midpoint of each leaf. Guides will be strategically located to guide the curb ring when it is being inserted up behind the form. The design will use a "stiff" slipform concept.

3.3.4 Concrete Seals

The outer and inner seals must be able to maintain internal concrete pressures up to 40 psi without significant blow-by. The inner seal may be of a j-seal design, or some other acceptable lip seal design. The outer seal is multi-leaf lip seal design capable of withstanding the shaft wall conditions without wide-scale failure of the seal to cutting, abrasion or tearing. A polyurethane material will be used for the seal.

The outer seal must be capable of maintaining internal concrete pressures while negotiating any slough zone up to 3-1/2 in. in depth, measured radially from the nominal shaft diameter. The outer seal must be designed to negotiate any slough zone configuration. Therefore, the seal must have radial, circumferential and axial flexibilities consistent with the other requirements of this section.

3.3.5 Support Systems

3.3.5.1 Jack Ring Support

The jack ring will be supported on three wire rope climbers. Each climber will be hydraulically actuated, capable of supporting a 110 kip working load, and have a design safety factor of three against failure. Each climber will consist of two sets of rope grippers and two traveling hydraulic cylinders (7 in. diam bore, 4 in. diam rod, 60 in. stroke). The wire rope specified for the prototype CSL is Bridon American IHT - 1-3/4 in. diam having a breaking strength of 332 kips. The wire rope will penetrate the curb ring through 2 in. diam sleeves, each located 120 deg apart.

3.3.5.2 Curb Support

The curb ring will be supported by four hydraulically actuated cylinders. The cylinders will have a 7 in. diam bore with a 4-1/2 in. push rod having a 54 in. stroke and a 11 in. stop tube. The cylinders may be series ER-3000, Model 84B supplied by Miller Fluid Power or equivalent. The curb support system shall be designed to accommodate a curb tilt of 5 in. without hindrance of curb operation.

3.5.5.3 Slipform Support

The slipform will be supported by three pairs of hydraulically actuated cylinders similar to those provided for the curb. The cylinders will have a 6 in. diam bore with a 4 in. push rod with 48 in. of stroke, and a 10 in. stop tube.

3.3.6 Concrete Delivery System

3.3.6.1 Concrete Pump

The concrete pump will be a double cylinder, positive displacement type. The pump will be able to pump continuously at a variable rate of between 1 to 20 cy/hr and provide up to 500 psi of concrete pressure. The concrete pump will be hydraulically operated, and the hydraulic system will be electrically powered.

3.3.6.2 Concrete Hoses

The concrete hoses will be 4 in. diam flexible rubber hoses with Victaulic snap joint couplings. Rigid 4 in. diam pipe will also be used, where practical. An 8 in. diam slick line will feed concrete to the remix hopper of the concrete pump.

3.3.6.3 Multi-Port Slide Valve

A multi-port hydraulically actuated slide valve will be used to direct the flow of concrete to the proper curb port. The valve will have the capability of being operated automatically or manually. The slide valve ports will be 4 in. in diameter and designed to accept the Victaulic coupling.

3.3.6.4 Nozzles

The number of concrete inlet nozzles required is dependent on the shaft diameter. The nozzles will be 4 in. diam, will be provided with manual spade shutoff valves, and will be easily removed and cleaned. Nozzles will be inserted through the curb ring from the bottom. Four nozzles are needed for this CSL.

3.3.7 Guidance

The slipform must be guided so as to maintain its concentricity within the shaft at all times. A slipform guidance system will be comprised of six hydraulic cylinders paired into a three point support system. These cylinders will actively control horizontal, vertical and rotational movements of the slipform relative to the shaft.

The upper jack ring will be centered in the shaft by six hydraulically loaded pistons with rubber wheels or rollers.

3.3.8 Vibration

Hydraulically operated vibrators will be located in the curb. The duration, timing, and sequence of operation will be adjustable. The vibrators will be installed so as to vibrate the concrete only, will be isolated from directly vibrating the curb, and will only vibrate over a small percentage of the total curb surface.

3.4 Controls and Instrumentation

3.4.1 CSL Control System

3.4.1.1 Hydraulic Power Unit

One or two hydraulic power units will operate all hydraulically actuated devices on the CSL and work stage. These devices include the curb ring and slipform cylinders; guide wheel cylinders; the multi-port valve; the suspension system; the concrete pump; and vibrators. Major hydraulic subsystems will be supplied from independent pumps. Maximum design pressure will be 3000 psi. An oil base fluid will be used unless fire-resistant fluids are mandated. The power unit(s) shall be air cooled with sufficient reservoir capacity to keep the operating fluid temperature below 160F. The power unit(s) will be located on the work stage and all hose connections from it to the CSL will be of quick disconnect design. The power unit(s) will be operated at 240 Vac; however, all related electrical components of the hydraulic system on the CSL will be operated at 24 Vdc.

3.4.1.2 Operator's Control Station

All controls necessary to operate the CSL and monitor its performance shall be located at a single control station mounted on the work stage. Controls and instruments associated with the actual placement of concrete and advancement of the CSL shall be combined in a single panel within reach of a seated operator. Other controls and instruments shall be within 6 ft of the operator's position.

3.4.2 Jack Ring

3.4.2.1 Depth Indicator

Jack ring position from the shaft collar down the shaft shall be measured and indicated to the operator. Depth measurement accuracy shall be within 1 percent of true depth.

3.4.2.2 Level Indicators

Jack ring level relative to a plane normal to plumb shall be measured and indicated to the operator. Level measurement accuracy shall be within 0.12 deg of true level (1/2 in. over the 20 ft shaft diameter).

3.4.3 Curb Ring

3.4.3.1 Pressure Transducers

Pressure transducers shall be provided on the curb ring surface adjacent to each concrete inlet port. The transducers will be of a diaphragm design (hydraulically isolated from the concrete) in the range of 0 to 50 psi. The accuracy of the pressure measurements shall be within 1 percent of full-scale reading. Pressure readings at each port will be indicated to the operator.

3.4.3.2 Level Indicators

Curb ring level relative to a plane normal to plumb shall be measured on two axes. The tilt of the curb ring shall be displayed to the operator. Position measurements shall be made relative to the upper jack ring and shall be accurate to within 1/2 in. of true position. The position of the curb ring relative to the slipform (slipform effective length (SEL)) shall be determined and displayed. An alarm will be provided for excessive curb tilt relative to the slipform (greater than 3 in. in either X or Y axis).

3.4.3.3 Advance Rate Indicator

The average advance rate of the curb ring shall be calculated and displayed to the operator. The information will be updated every 60 sec.

3.4.4 Slipform

3.4.4.1 Level Indicators

Slipform level relative to the natural horizon shall be measured on three axes and displayed to the operator.

3.4.4.2 Position Indicators

The slipform effective length (SEL) shall be determined from curb ring position indicators. Slipform position measurements shall be made relative to the upper jack ring and shall be accurate to within 1/2 in. of the position. The concentricity of the slipform to the shaft wall shall also be determined and displayed.

3.4.4.3 Advance Rate Indicator

The average advance rate of the slipform shall be calculated and displayed to the operator. The information will be recalculated and redisplayed every 60 sec.

3.4.5 Wire Rope Spools

3.4.5.1 Tension Alarm

An audible and visual (light) alarm will be provided to alert the operator of excessive tension in any one of the three suspension system cables.

3.4.5.2 Slack Alarm

An audible and visual (light) alarm will be provided to alert the operator of incipient loss of tension in any one of the three suspension system cables.

3.4.5.3 Directional Status

The operational direction of each cable gripping unit (grip moving up or grip moving down) shall be displayed to the operator.

3.4.6 Concrete System

3.4.6.1 Pressure Indicator

Concrete line pressure at the multi-port valve will be measured and indicated to the operator. The range of pressures will be 0 to 300 psi. The accuracy of the pressure measurement shall be within 1 percent of full-scale.

3.4.6.2 Multi-Port Valve

The multi-port valve shall be operated from the operator's control panel. The valve shall be capable of being switched from manual to automatic operation. Automatic operation shall be controlled through an adjustable timer. The range of the timer will be 0 to 60 sec for each position. The position of the multi-port valve will be displayed to the operator.

3.4.6.3 Concrete Pumping Indication

During operations, the instrumentation will display whether the concrete system is in the forward or reverse operational mode, and whether or not concrete is actively being pumped.

3.4.6.4 Batch Plant On-Off Operations

A signal light shall be provided to indicate active operation of the concrete batch plant.

3.4.6.5 Concrete Remix Hopper Level Alarm

An alarm (audible or light) shall indicate to the operator both low and high concrete levels in the remix hopper.

4. UNDERGROUND CSL CONCEPTUAL DESIGN

4.1 Introduction

The description of the CSL system will be divided into two specific areas to facilitate understanding the hardware. These areas will be described in the following order:

a. Lining Equipment

   1. Main CSL structural components
   2. CSL suspension system
   3. CSL hydraulic control and instrumentation system

b. Nonlining Equipment

   1. Galloway
   2. Galloway suspension system
   3. Concrete plant and delivery system
   4. Extension of services system.

4.2 Lining Equipment

4.2.1 Main CSL Structural Components

As described in Section 2, the CSL is comprised of three main structural components which include the slipform, curb ring and jack ring. Each will be described in detail in the following subsections.

4.2.1.1 Slipform

The slipform acts as the mold around which the concrete lining is formed and extruded. It is designed to be stiff in the axial direction to withstand the tendency to "hour-glass" under the hydrostatic loads induced by the pressurized fluid concrete. The slipform form length of 10 ft is designed to provide sufficient residence time for the concrete to obtain self-supporting strength before it leaves the slipform. The factors which influence the choice of slipform length include the strength gain characteristics of the CSL concrete, and the maximum desired rate of advance. The form is tapered radially inward at the trailing edge to:

a. Reduce form drag forces which impede slipforming as well as,

b. Aid in reinserting the slipform into previously cast lining.

The form is also coated for protection and to reduce form drag.

The form is constructed of structural steel elements and 1/2 in. thick steel plate. Figure 18 shows the basic configuration of the slipform which is comprised of three segments. The slipform is reinforced with axially aligned structural steel and stiffened radially with cut steel plates, at the top, bottom and three equally spaced lengths in between. The bottom section has additional stiffening, in the form of rectangular steel tubing, to withstand the higher hydrostatic loading and the induced loading from the hydraulic actuators.

The slipform is segmented to allow for collapsing the form should the situation arise, accidentally or intentionally, where the form is bonded to the concrete lining. The form collapsing is accomplished through the use of three wedges which also serve as the connecting pieces for the three assembled slipform pieces. Figure 19 details the wedges and collapsing system. The wedges are wider at their base than at their top. Thus, when the wedges are bolted to each side of the slipform segments, this dimensional discrepancy causes the taper to appear in the slipform.

The slipform collapsing system works as follows: the wedge connecting bolts (16 bolts, 1-1/4 in. diam) are removed from both sides of the wedge. The remaining 8 bolts are shoulder bolts (see detail) located in slots machined into the slipform edges. These bolts are not tight in these slots. The wedge action actuator (manually operated with hand pump) is extended, forcing the wedge to be pushed inward. A complete extension of the three wedges would induce a 1 to 2 in. decrease in the slipform diameter. To re-expand the slipform, the wedge action actuator is retracted, forcing the wedge outward. If this procedure does not fully expand the form due to wedge friction or other restraints, then the form can be "coaxed" into position using two lateral spreading bars. The threaded bars are placed across each wedge (one wedge at a time) by inserting them into the "jack clip angles" shown on Figure 18.

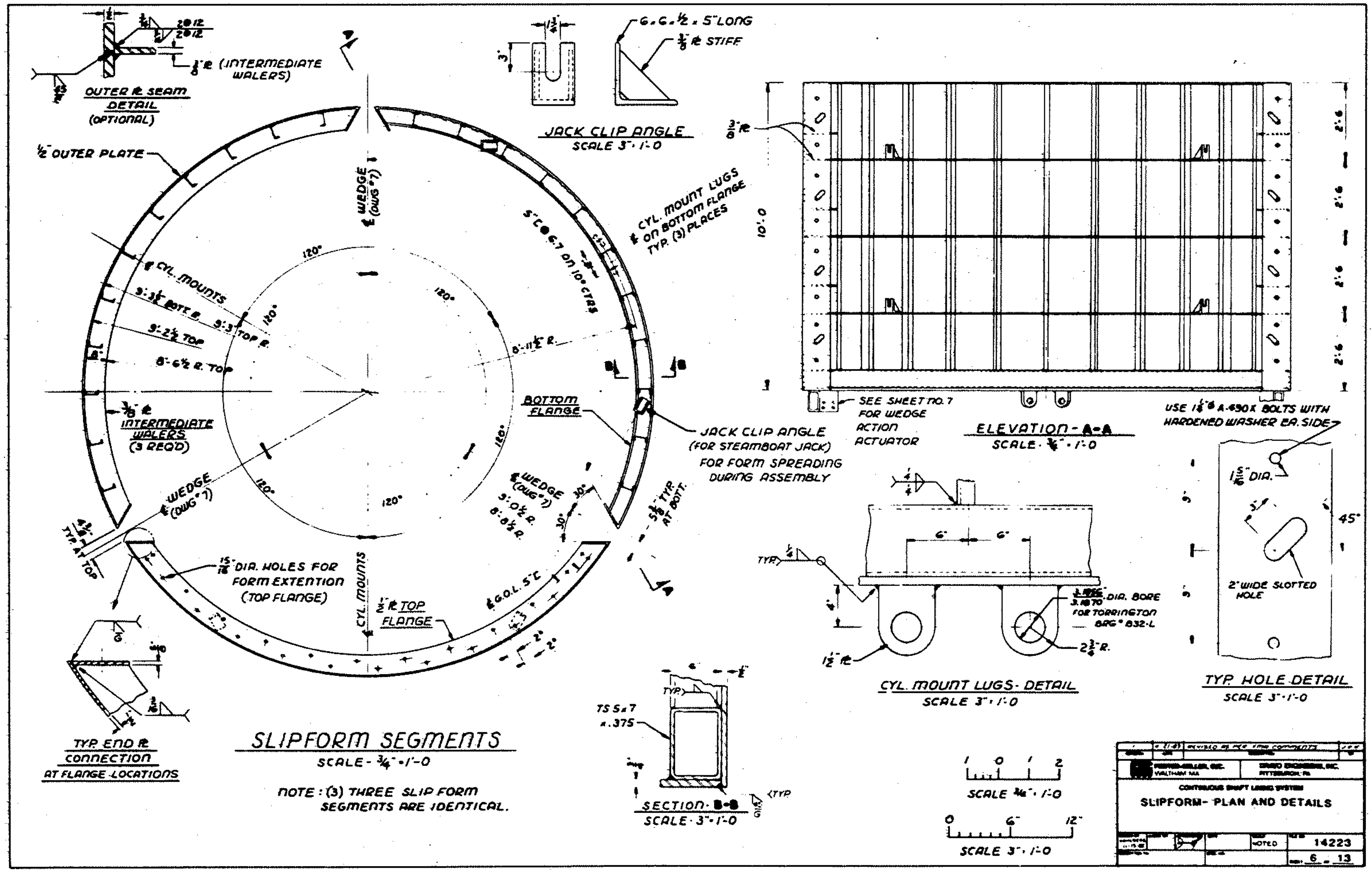


FIGURE 18. - Slipform - plan and details.

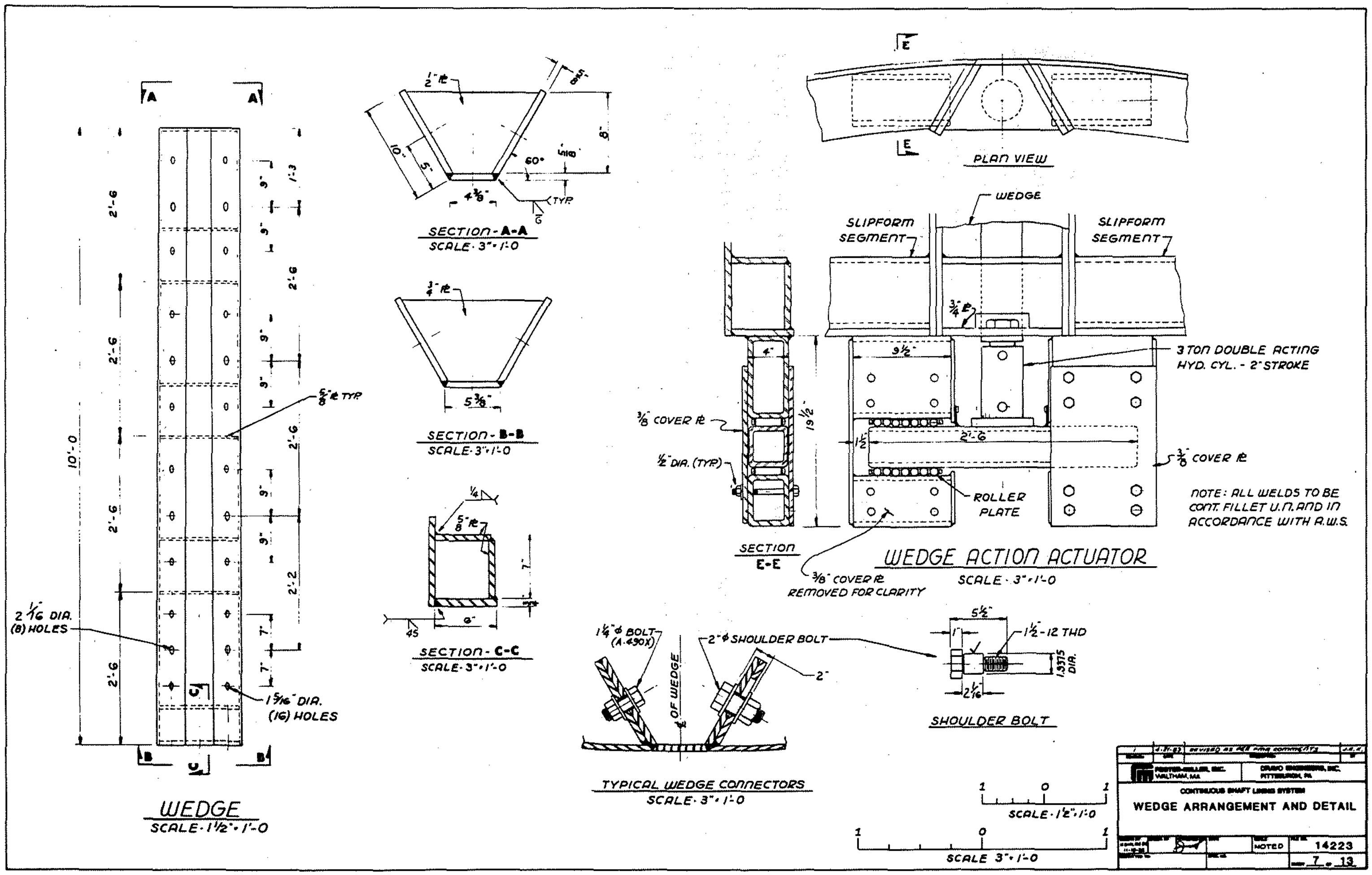


FIGURE 19. - Wedge arrangement and detail.

The slipform is mounted on six hydraulic cylinders which are mounted to the jack ring. These cylinders provide for vertical, lateral and torsional motion of the slipform as part of the slipform guidance and alignment system. This system is discussed in detail in subsection 4.2.3.

4.2.1.2 Curb Ring

The curb ring design is one of the critical areas in the CSL system design. The curb ring must create and maintain pressurized conditions behind the slipform to support the uncured portion of the concrete above it. The curb ring must be sufficiently rigid to retain an accurate circular shape while under the influence of large vertical loads. This requirement is complicated due to the many penetrations of the curb ring, its narrow width, and the desire to maintain full operational capabilities in an extreme out of level condition. This last requirement prevents the curb ring from being excessively deep as the means of providing the required rigidity.

The curb ring is a structural steel box beam design. Figures 20 and 21 show the plan and various cross sections of the curb ring. Although not shown, the curb ring is fabricated in multiple segments and bolted together. The curb ring is tapered with all edges beveled or rounded. This design allows for maximum curb tilt without contacting the slipform, and prevents inadvertent hang-ups of sharp edges on shaft wall protrusions. The many penetrations of the curb ring are for various purposes as listed here:

a. Four concrete inlet nozzles

b. Three suspension system wire ropes

c. Six concrete vibrators

d. Four concrete pressure transducers.

The curb ring is mounted on four hydraulic cylinders which are mounted on the jack ring. These cylinders provide for vertical motion of the curb ring. This arrangement is discussed in detail in subsection 4.2.3.

Each penetration of the curb ring has a specific insert design. The concrete nozzle and vibrator inserts are described in detail in subsection 4.3.3. The inserts for the pressure transducers are described in subsection 4.2.3. The wire ropes pass

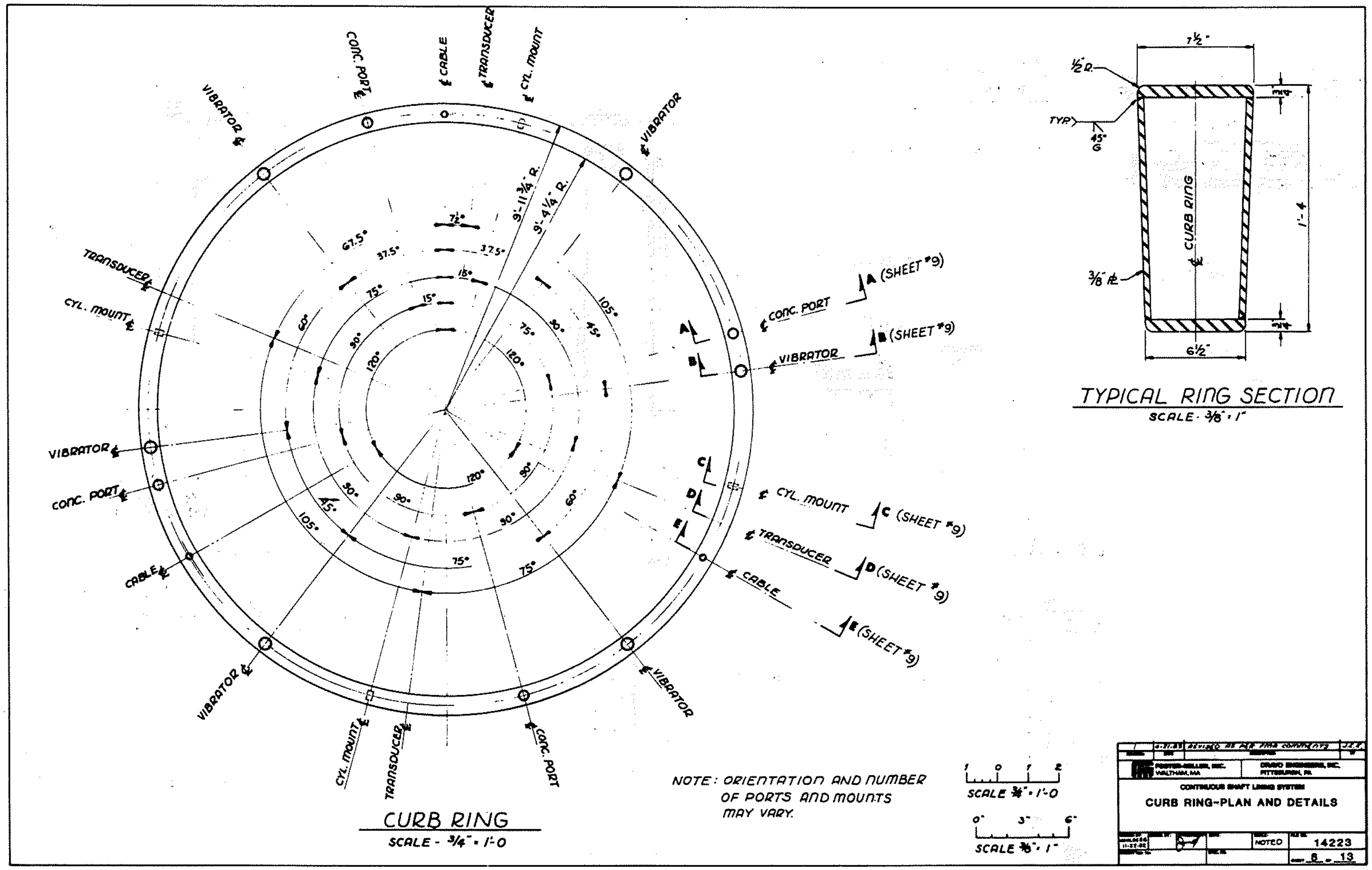


FIGURE 20. - Curb ring - plan and details.

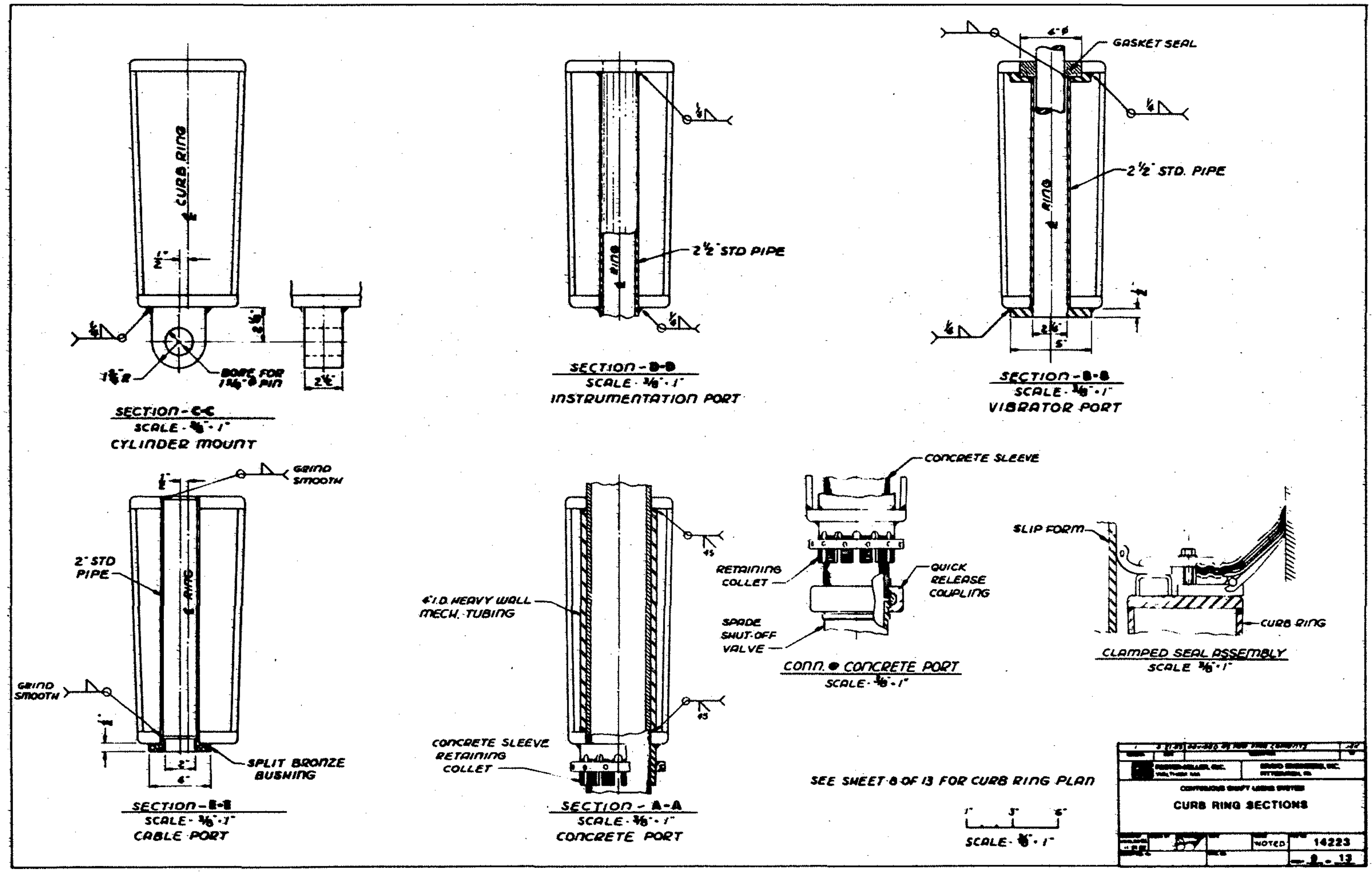


FIGURE 21. - Curb ring sections.

through bronze bushings which are detailed in Figure 21 (Section E-E). This bushing is close fitting, preventing any loss of fresh concrete. The sleeve is continually cleaned as the greased rope slides over it during the lining process, and effectively carries out the cement paste that might have fallen into the insert.

Of most interest in the curb design is the design and mounting of the inner and outer curb ring seals. Figure 22 depicts the arrangements of these seals. The inner seal is a standard J-type bulb seal which essentially rubs against the slipform surface. This seal demonstrated enormous capability for rough treatment and bi-directional flexibility during the CSL simulation tests. Both the inner and outer seal are secured to the curb ring with the same steel cover plate which is bolted to the top of the curb ring. The basis of the outer seal design is discussed in Volume II, Section 4. The seal was successfully tested during the CSL simulation test program, and from its performance, a second generation seal has been developed.

The outer seal is basically of the same design as that tested during simulation tests. It is a multi-layered, polyurethane seal of overlapping shingled leafs. The leafs are supported by multiple steel hinges which provide axial stiffness in deep slough zones. The inner and outer segments are of high durometer material (for stiffness), and the inner three layers are of low durometer (for flexibility). The clamping angle has been flattened to prevent concrete from migrating between the seal layers. The seals have ridged ends which mate up with ridges in the mounting brackets. This is to help provide resistance to pull-out when the curb ring is freed from set concrete after an extended period of shutdown.

4.2.1.3 Jack Ring

The upper jack ring acts as the moving reference table on which the CSL is mounted. It provides a reaction point for all the major forces acting on the CSL. The slipform and curb ring are connected to it by hydraulic cylinders. The CSL suspension system is also connected to it from below. The lower jack ring is merely provided as a stabilizing structure for the suspension jacks and is not required to react any CSL loads.

Both upper and lower jack rings are structural steel beams. For reasons discussed above, the upper jack ring section must be substantial to handle the CSL loads. Figure 23 depicts the plan and section of the upper jack ring and Figure 24 does the same for the lower jack ring. Besides the hydraulic actuators mentioned above, six jack ring roller guides are also mounted on the upper

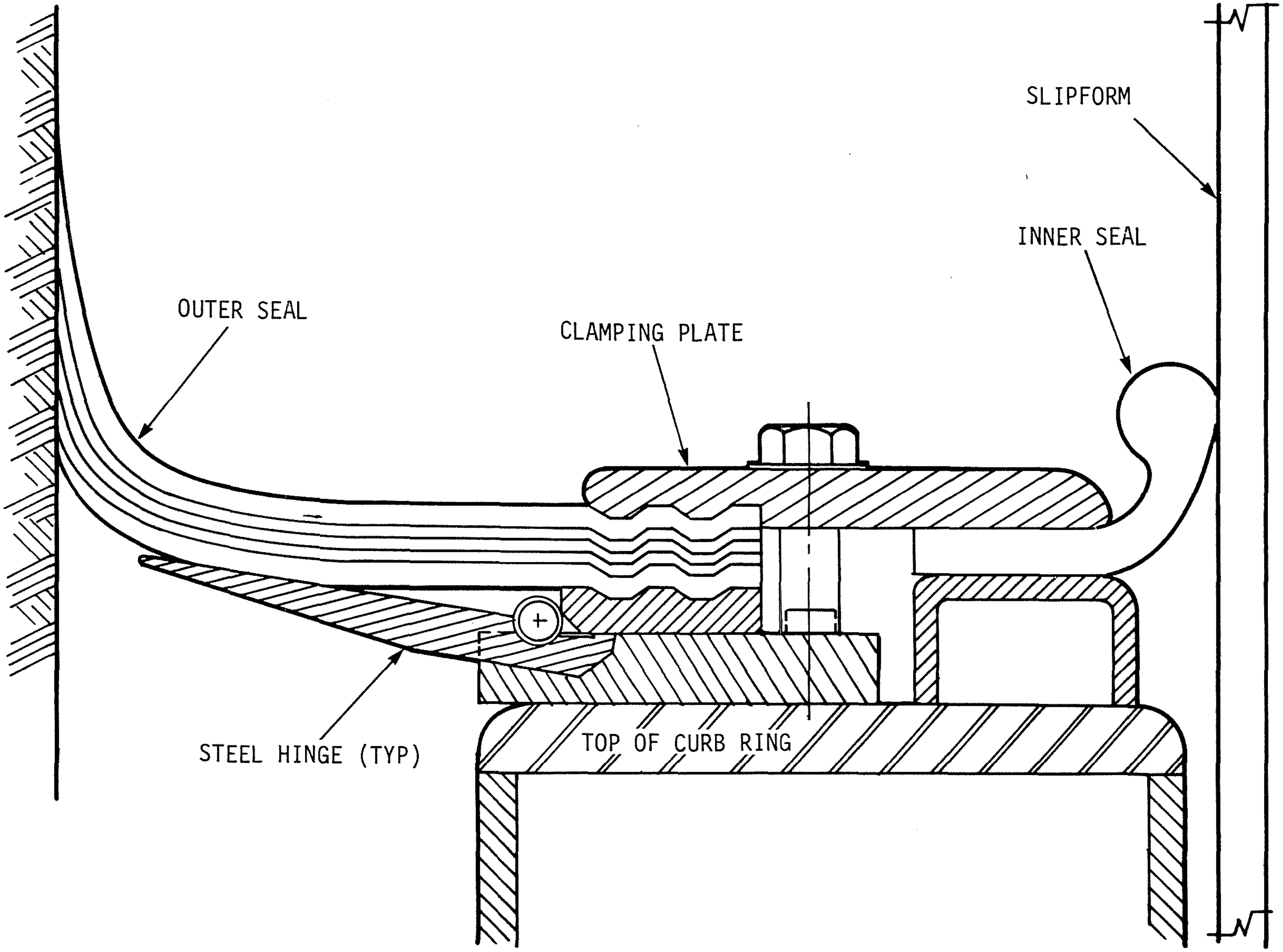


FIGURE 22. - Curb ring seals.

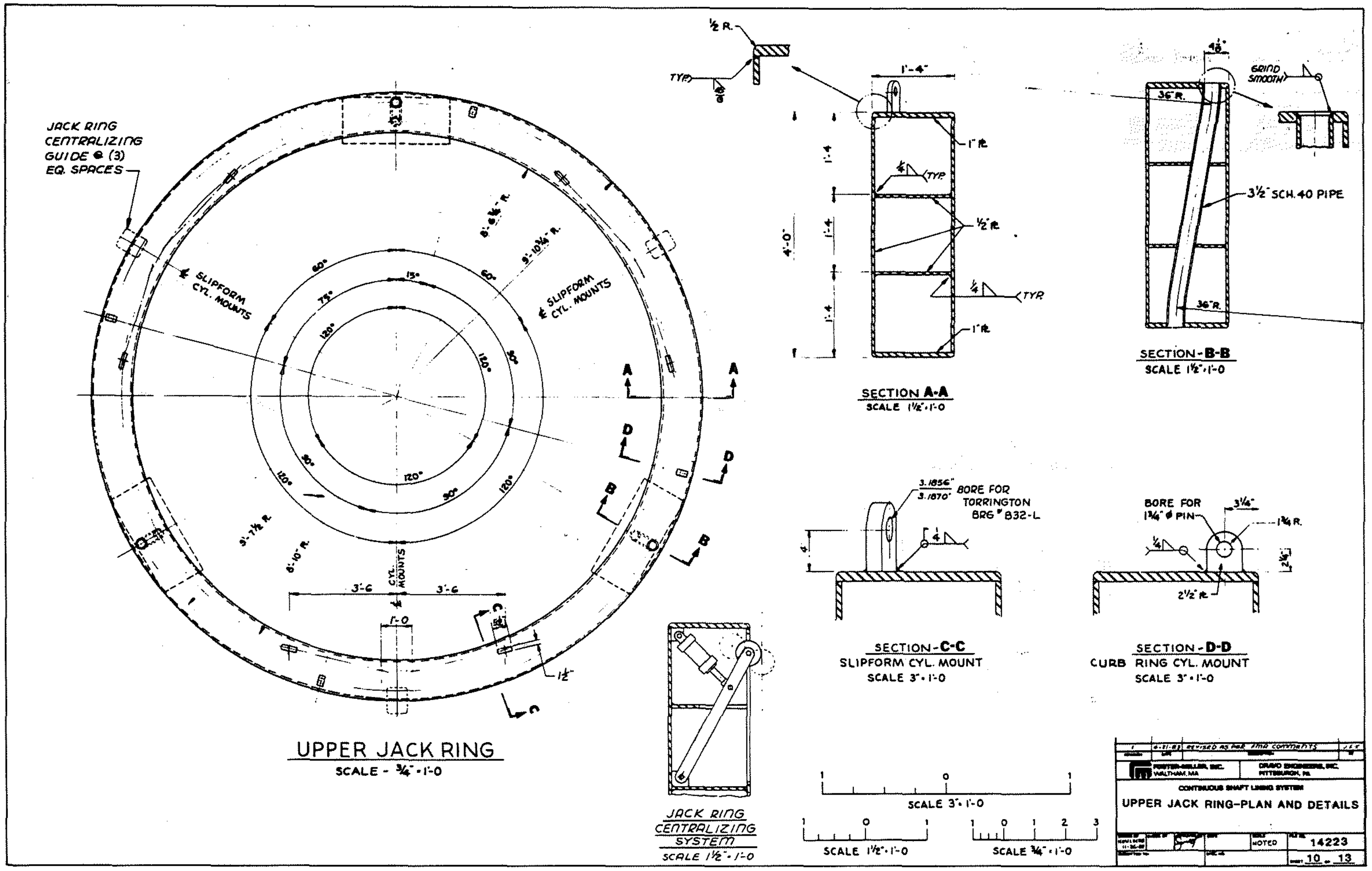


FIGURE 23. - Upper jack ring - plan and details.

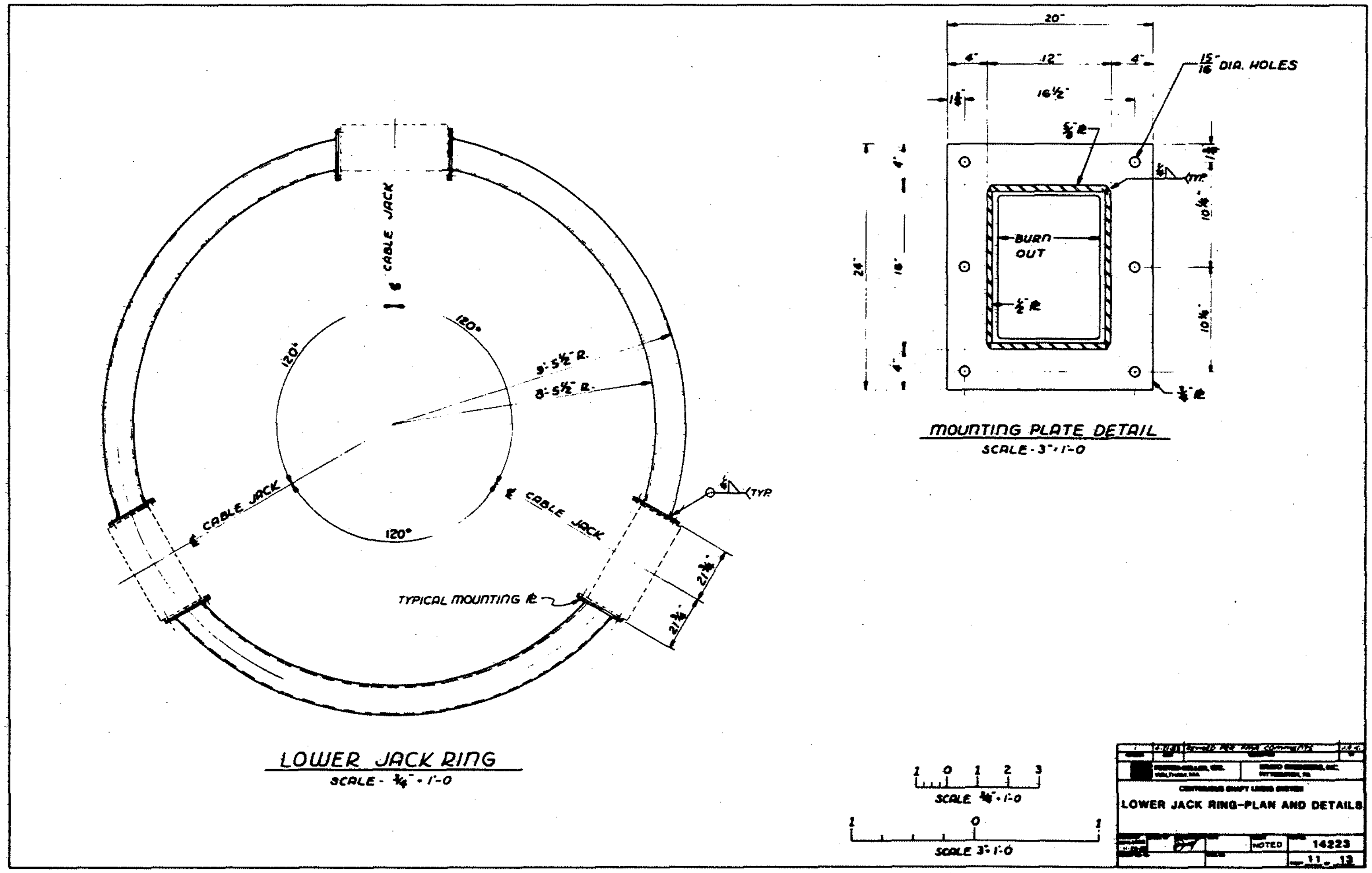


FIGURE 24. - Lower jack ring - plan and details.

jack ring. The upper jack ring, therefore, requires both axial and radial stiffness to react the expected forces on it. Radial stiffness is provided by two internal steel diaphragms which run the entire diameter of the beam. The upper jack ring also has a relatively high width to height ratio to provide torsional stiffness.

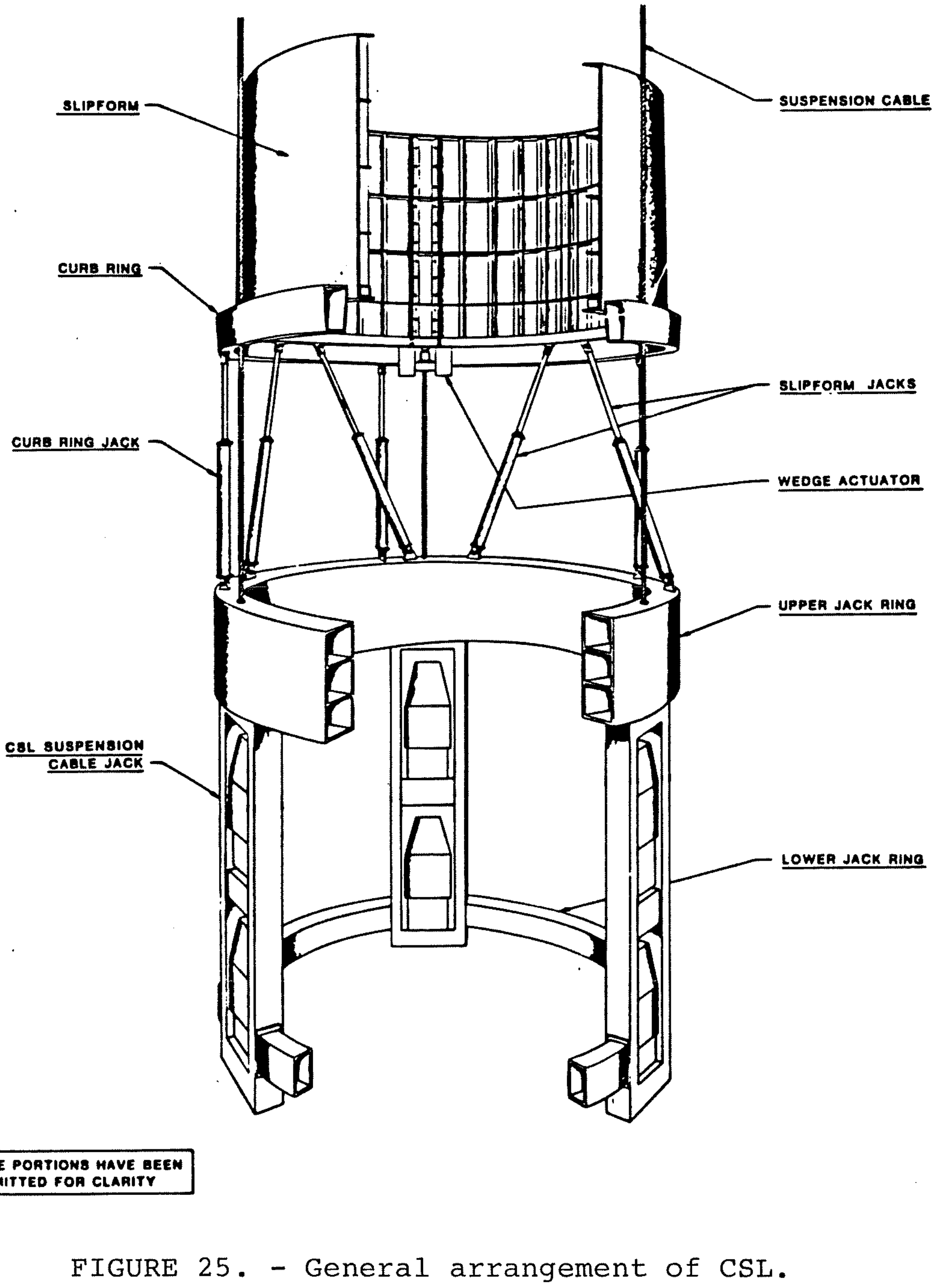
Because the cable climber is not symmetrical about its centerline, the location of the wire rope insert had to be offset. Section BB on Figure 23 shows the offset required in the wire rope insert through the upper jack ring. This offset insert compensates for the misalignment between the centerlines of the cable climber unit and the curb ring sleeve.

4.2.2 CSL Suspension System

The CSL is designed as a self-supporting downhole piece of construction equipment. It does not rely on several embedded hanging rods which is the typical manner in which conventional lining systems are supported. The CSL is, rather, suspended on three wire ropes which are embedded in the finished concrete lining. Figure 25 clearly depicts the CSL suspension system. The capability of continuously feeding cable without the need for splicing makes this system very attractive. The suspension system is able to operate automatically, without constant surveillance, thus minimizing the crew labor needed in comparison to conventional stepforming systems. The suspension system lowers the jack ring at a controlled rate aproximately matching the slipform advance rate. This smooth descent is interrupted for a short period at 5 ft intervals to allow for a cable regrip cycle.

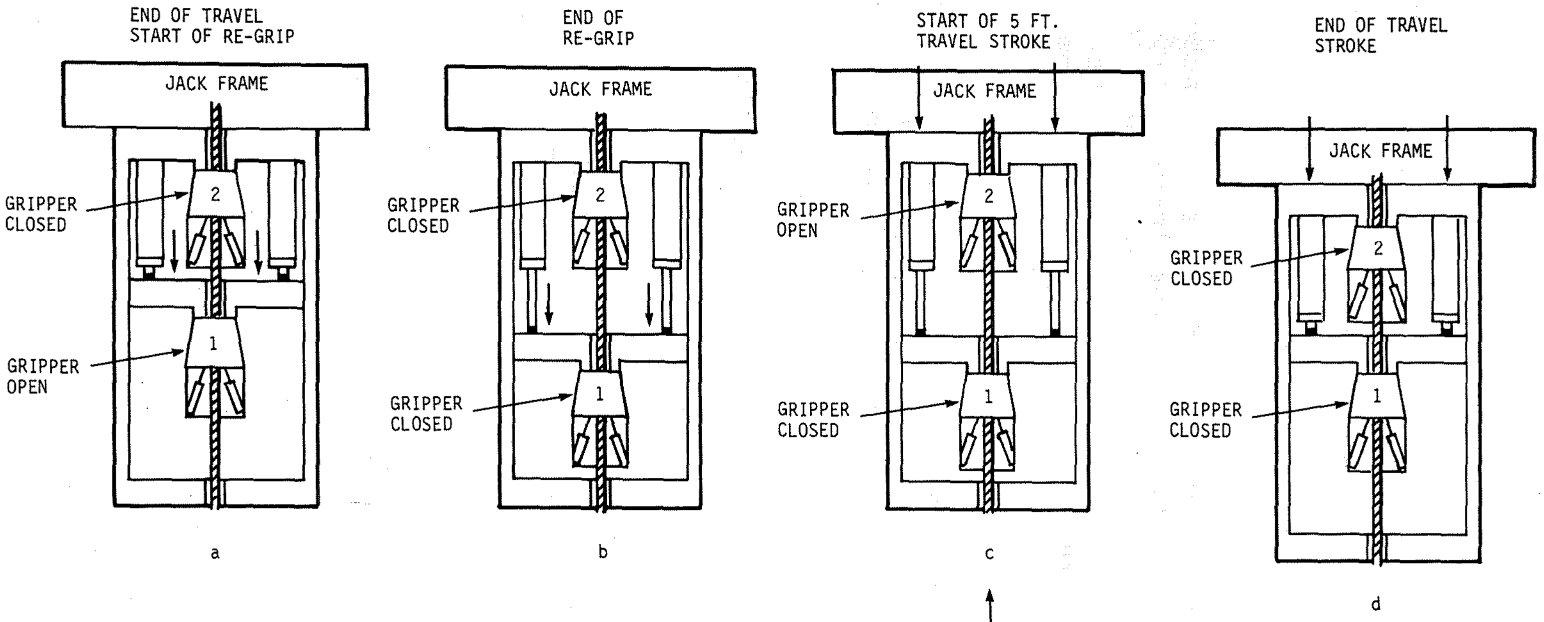
As shown in Figure 25, the three suspension cable jacking units are equally spaced around the circumference of the upper jack ring. The lower jack ring is provided for stabilization purposes only. Each jacking unit is comprised of two cable grippers, either pneumatic or hydraulically actuated, and two traveling cylinders all mounted inside a structural steel frame. The arrangement of these components and their operation as a unit can be better understood with the aid of Figure 26.

The jacking units are wire rope climbers that lift or lower a load in a hand-over-hand fashion. One of the two cable grippers is movable and is used to raise or lower the load. The other gripper is fixed and holds the unit on the cable while the movable gripper regrips. The two grippers are coupled in a fail-safe fashion such that neither gripper can release the load until the other gripper picks up the load.



SOME PORTIONS HAVE BEEN OMITTED FOR CLARITY

FIGURE 25. - General arrangement of CSL.



GRIPPER ASSEMBLY ❷ , ATTACHED TO THE STATIONARY CROSS HEAD, IS CLOSED FIRMLY HOLDING THE CABLE. MOVING GRIPPER ASSEMBLY ❶ IS OPEN TO ALLOW WIRE ROPE TO PASS FREELY. THE HYDRAULIC RAMS START TO EXTEND GRIPPER ASSEMBLY. ❶

AT THE END OF THE RAM CYCLE, GRIPPER ASSEMBLY ❶ CLOSES AND HOLDS THE ROPE AND LOAD FIRMLY. GRIPPER ASSEMBLY ❷ OPENS.

GRIPPER ASSEMBLY ❷ IS OPEN AND RAMS RETRACT CARRYING THE JACK FRAME. THE LOAD IS HELD BY GRIPPER ❶ DURING THIS SEQUENCE.

WHEN RAMS ARE FULLY RETRACTED, GRIPPER ASSEMBLY ❷ CLOSES ON THE WIRE ROPE AS GRIPPER ASSEMBLY ❶ OPENS. NOW THE SEQUENCE BEGINS AGAIN.

THE UNIT CAN BE STOPPED AND WILL HOLD FIRMLY AT ANY POINT IN THE CYCLE AND BE RE-STARTED AT ANY TIME.

FIGURE 26. - CSL suspension cable jacking unit.

Each of the cable jacking units has a rated capacity of 50 tons. The wire rope specified as typical for the prototype CSL is Bridon American IHT 1-3/4 in. in diameter. The rope has a breaking strength of 332 kips. The CSL suspension system is designed with a safety factor of three. This safety factor is considered reasonable due, in part, to the CSL being unmanned during slipforming operations. All manual operations are carried out from the independently suspended galloway system. Tension only and not bending plus tension (such as hoist ropes bent over sheaves) is the design condition used for these ropes.

Each of the three wire ropes is drawn from a separate cable storage reel mounted to the bottom of the lowest galloway deck. The wire rope is in single purchase, passes through the grippers, jack ring and curb ring, and is, thereafter, embedded in the concrete lining. The dead end of the wire rope is terminated at the shaft collar in anchored arrangement as shown on Figure 27.

The jacking units are commercially available for purchase or lease. The prototype CSL design assumes a leasing arrangement; thus, the manufacturer's supplied control panel and power unit are used in conjunction with the CSL's control panel. This is discussed in more detail in subsection 4.2.3.

4.2.3 The CSL Hydraulic Control and Instrumentation System

4.2.3.1 Instrumentation and Feedback

The physical size of the equipment dictates a narrow work envelope inside the shaft and, therefore, requires close operational tolerances. Relatively small amounts of misalignment of the curb ring, slipform or jack ring will result in one of these components contacting another or the shaft wall. For example, the allowable tolerance on tilt of the curb ring is 1.5 deg. The allowable tolerance on tilt of the slipform is less than 1.0 deg. Misalignment of these components must be kept under 1.0 in. Maintaining these tight tolerances will require reliable, accurate instrumentation.

The electrical supply to the instrumentation will be voltage protected. This protection will provide a stabilized voltage supply that will compensate for surges in the supply voltage. These surges are the large variations in electrical loads as machinery is operated. All instrumentation cables will be shielded to protect them from stray electrical fields and to provide physical protection from the harsh environment expected in a mine shaft. All transducer signals will be relatively high

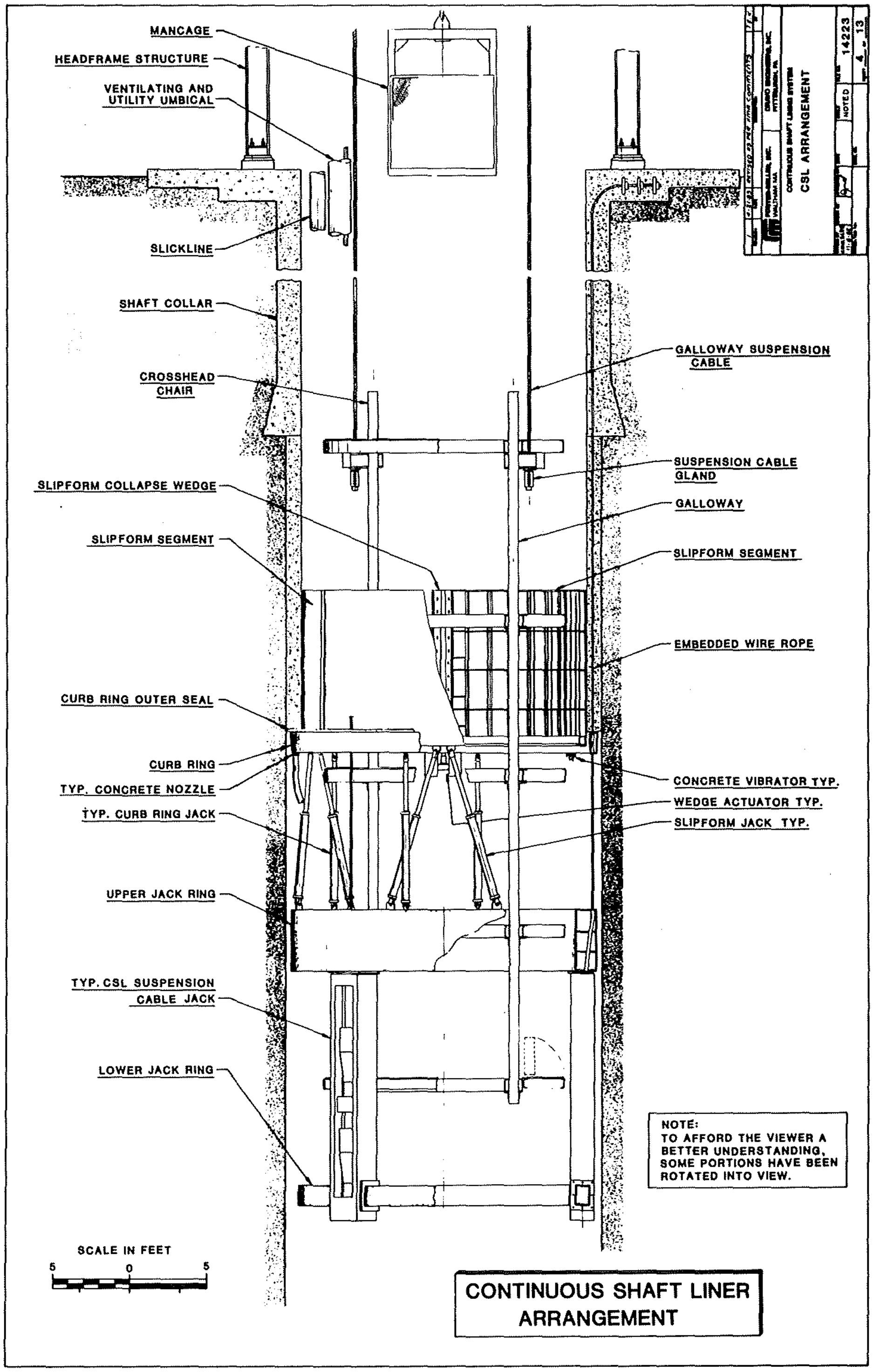


FIGURE 27. - CSL arrangement.

powered. Where necessary, signal amplification at the transducers will be utilized. The need to provide high transducer outputs is dictated by the need to reduce the sensitivity of electrical signals to transient effects and to minimize losses in connectors and long signal cables.

The information generated by the transducers will be directly utilized for control purposes. All relevant information will be recorded by a data logger system which is considered a part of the instrumentation package. This system will include a minicomputer whose prime function will be data processing and storage. All the information gathered will be relayed to the surface.

4.2.3.2 Hydraulic Control of the CSL

The many hydraulic functions required by the CSL hardware will be controlled and powered by two hydraulic systems. One system will be supplied by the cable gripper vendor, as the power source for the activation of the cable climber system. The system will have only one function which is to control the position of the jack ring. The hydraulic supply to each of these three suspension cable jacking units will be controlled by a tilt meter which will ensure that the jack ring remains level. The second hydraulic package is a multifunctional unit which provides hydraulic power for slipform and curb ring, and position control and power-takeoffs for other functions.

The power pack performing the multifunctional role powers the following devices:

a. Four curb ring cylinders

b. Six slipform cylinders

c. Concrete pump

d. Multiport valve

e. Hydraulic vibrators.

The hydraulic pump will be a high capacity pressure compensated axial piston pump. The system pressure will be 3000 psi and each subcircuit is equipped with its own pressure reducing valve so that each can function as separate circuits. In the case of the curb cylinders, the pressure reducing valves will be electrically modulated from the control panel.

The reservoir will be designed to accept either a mineral based oil or a fire resistant fluid. The capacity of the tank shall be sized such that during the operating cycle, when the oil level is at a minimum, the volume remaining is five times that of the capacity of the pump. The tank will be fitted with level gauges and thermometers that are clearly visible. Other protection devices will include a low level switch and an electrically operated temperature gauge. Both these items will be electrically interlocked with the electric pump motor to shut down the unit if unacceptable operating conditions occur. The pump will be mounted on the reservoir together with all the necessary filters and valves. All piping should be external so that any component changes can be efficiently performed.

Filtration of the oil will be performed by an inlet indicating filter rated at 100 mesh. The return line filter will be rated at 10 micron. both filters will be equipped with an internal bypass valve, a mechanical visual indicator and an electrical indicator which will illuminate a warning light on the control panel in the event of excessive clogging.

The environment temperatures in which the CSL will be expected to operate span a broad range. The hydraulic power unit is also designed to cope with a range of conditions. The return line will be fitted with an air-type oil cooler that is thermostatically controlled. The axial piston pump was chosen because when there are no flow conditions, its output reduces to almost zero, thus preventing heating of the oil as it passes over the relief valve. The tank will be equipped with a reservoir plug to accommodate a thermostatically controlled immersion heater. The operational temperature of the fluid will be dependent on the type of fluid chosen and the environmental temperature. However to enable rapid start-up without cavitation the minimum temperature will be 45°F. Running temperature will be restricted to a maximum of 150°F to ensure protection of the hydraulic equipment and a long fluid life.

Having described briefly the basic design of the reservoir, reference should be made to Figure 28, the hydraulic control circuit diagram.

Curb Ring Cylinders

During normal operation, the curb ring cylinders are in the extend position to pressurize the fresh concrete that is being placed on the curb ring. At a concrete pressure of 25 psi, a thrust of 72,000 pounds of force is transmitted to the curb. Using data generated in CSL simulation tests, this force translates into a cylinder pressure of 1785 psi. Design changes have

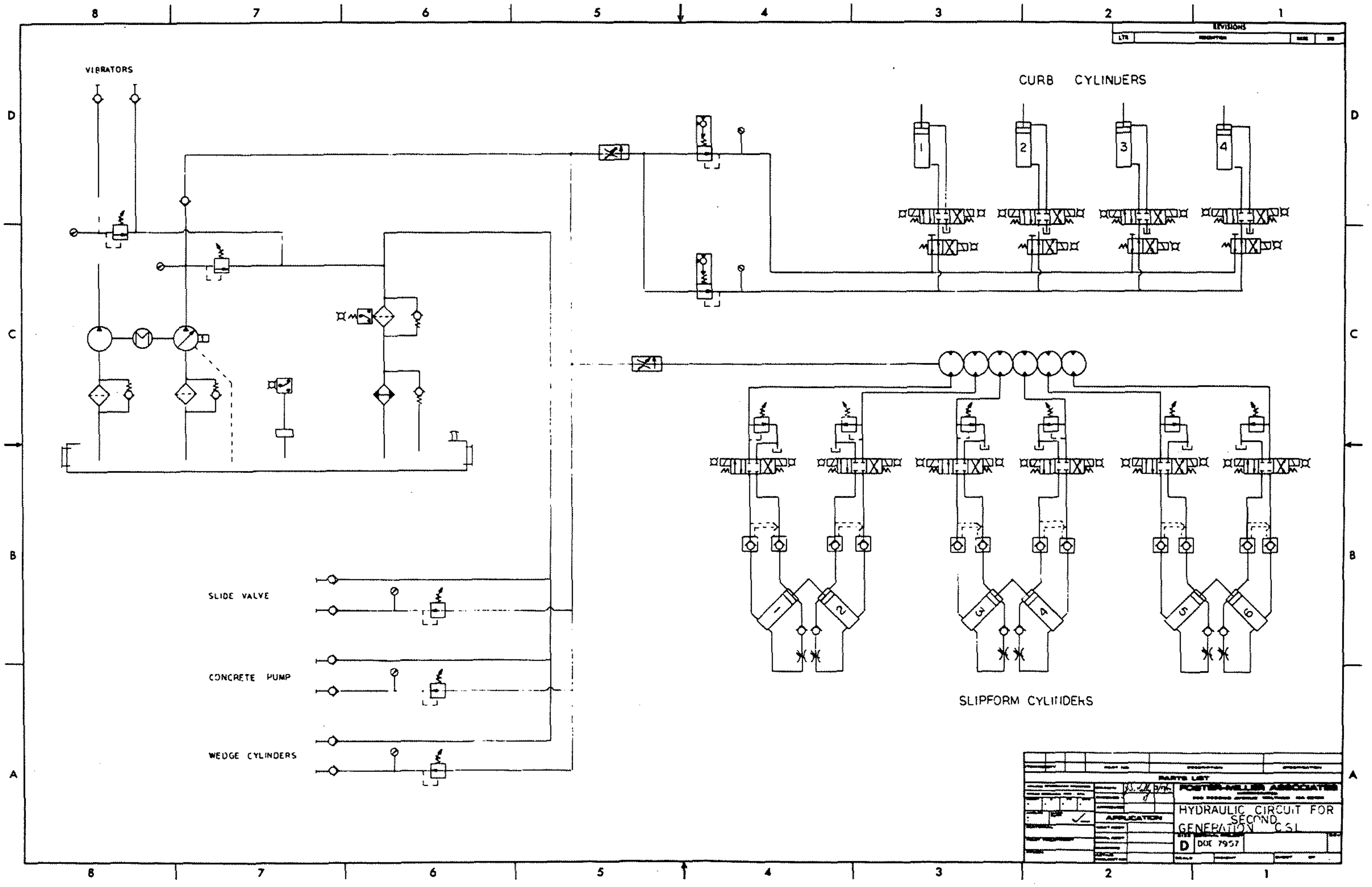


FIGURE 28. - Hydraulic control circuit diagram.

been incorporated in the curb since the experimental testing was completed. To incorporate sufficient latitude in the design in order to accommodate these improvements, the curb cylinders shall be specified for a 3000 psi operational pressure.

The pressure to the curb ring cylinders is controlled by two electrically modulated pressure reducing valves which are activated by individual potentiometers on the control panel. One pressure reducing valve is used in normal operation to control the pressure on the new concrete. The second valve controls a high boost pressure which can be provided to the relevant cylinders if the curb becomes out of level when encountering a slough zone. A pressure compensated flow control valve is incorporated in the circuit prior to the pressure reducing valves to dampen cylinder response. Each individual curb cylinder is controlled by two valves. The three way, four port, double solenoid valves control the motion of the cylinder. The two way, four port, single solenoid valves select the pressure to the curb cylinders.

Slipform Cylinders

The slipform cylinders operate in pairs and provide both vertical and lateral movement of the slipform. To obtain vertical movement, cylinder pairs 1 and 2, 3 and 4, 5 and 6 operate together. To obtain lateral movement, cylinder pairs 6 and 1, 2 and 3, 4 and 5 operate together. If adequate alignment and level control are maintained by the jack ring, the slipform cylinders will operate in a fully extended condition. Corrections for tilt or lateral misalignment are made by the electrical control system which responds by retracting the appropriate pair of cylinders from the fully extended condition. Flow to each pair of cylinders is metered by flow dividers to ensure that both cylinders maintain equal stroke. The system requires relief valves on the cylinder side of the flow dividers. Pressure relief is required when a cylinder is fully stroked out. This arrangement compensates for the difference in stroke by permitting the fast cylinder to stroke out and the fluid to be relieved while the second cylinder catches up. When the second cylinder is also stroked out, both cylinders become synchronized again. The slipform cylinders cannot be electrically controlled as individuals from the control panel. However, to permit this function during initial setting up, a manual override system is incorporated in the circuit. Mounted on the cylinders, a needle valve provides a bleed from the rod end to the piston end. The needle valve continuously bleeds a small quantity of fluid back to the piston end to keep the cylinders in a stroked out condition. All circuits are protect by pilot operated non-return valves to isolate the hydraulic lines so there is no hydraulic feedback between operations.

Power Takeoffs

The auxiliary functions provided by the power unit are the activation of the multi-port valve for concrete placement; power for the concrete pump to provide energy for both pumping and sequencing of the unit, and pressure and flow required for the activation of the curb vibrators.

4.2.3.3 Jack Ring Control System

The hydraulic pump used to power the suspension cable jacking units is a variable swashplate axial piston pump. The pump will provide an infinitely variable speed capability for the climbing cylinders up to the pumps maximum flow capacity. The variable output will be controlled by a potentiometer on the control desk which is wired to an electrically modulated flow control valve on the pump. The pump is powered by a 25 hp electric motor. The flow metering, which is required to ensure that all cylinders take equal steps, is achieved by connecting the three pairs of climbing cylinders individually to the outputs from each piston of this multipiston pump. The system supplied by the manufacturer is for manual operation and provides the following modes of operation.

a. Climb/lower all cylinder pairs

b. Climb/lower individual cylinder pairs

c. Climb/lower all grippers

d. Climb/lower individual grippers.

The system, as supplied, has no instrumentation or control system for monitoring and correcting for jack ring tilt. Upon receiving the system, a control package will be added.

The jack ring, which is supported by the three suspension cable jacking units, is a critical component since the whole CSL is mounted on it. Any misalignment or tilt of the jack ring will require compensation for the curb ring and slipform. To minimize this correction requirement, the jack ring has its own tilt control and centralizing system.

Tilt Control

The tilt of the jack ring will be monitored by three tilt meters. Tilt meters (inclinometers) were chosen because information on the tilt trend is required by the control system, rather than the go/no go information provided by level switches. Each instrument will be mounted on the jack ring on the same axis as the set of jacks it is controlling. The control circuit will correct only for a jack in a low condition by deactivating a solenoid valve. The closure of the valve would cause the hyrdaulic fluid to that set of cylinders to pass through a relief valve and back to the tank. The tilt meters would be continuously monitoring and correcting the jack ring tilt while in the automatic mode of operation.

A typical tilt transducer recommended is as follows:

a. Robinson-Halpern inclinometer
   Range ±0 to 6 deg
   Power input 12 to 30 Vdc unregulated
   Output ±1.0 Vdc into not less than 50K ohms

b. Output amplifier required for inclinometer.

These devices have been used in adverse environments in both the oil and construction industries, and will be expected to perform adequately in a shaft environment.

Centralizing System

Guidance is required to centralize the jack ring as it is lowered down the shaft. The centralizing system consists of three pairs of hydraulically activated wheels. Figure 29 depicts a system arrangement. Each pair is located on the jack ring on either side of each suspension cable jacking unit. The position of the wheel is adjusted by a mechanical stop. During normal operation the wheel will run just clear of the shaft wall. The wheels are mounted on trailing arms that are hydraulically activated. Any misalignment will bring the wheel into contact with the shaft wall and the hydraulic cylinder will push the jack frame to centralize it. The hydraulic cylinders act as springs and the force is modulated by hydraulic pressure. No active control system will be used to monitor the wheels.

Typical components for this system include:

a. Langley, 6 in. diam, 4 in. width wheel with 1 in. bearing and high capacity polyurethane tire bonded to a steel base. Model No. OG24161616

b. Miller ER3000 cylinder, fitted with rear clevis and piston rod clevis; 2-1/2 in. diam bore, 5 in. stroke, 1 in. diam rod. Maximum thrust at 3000 psi is 14,500 lbf.

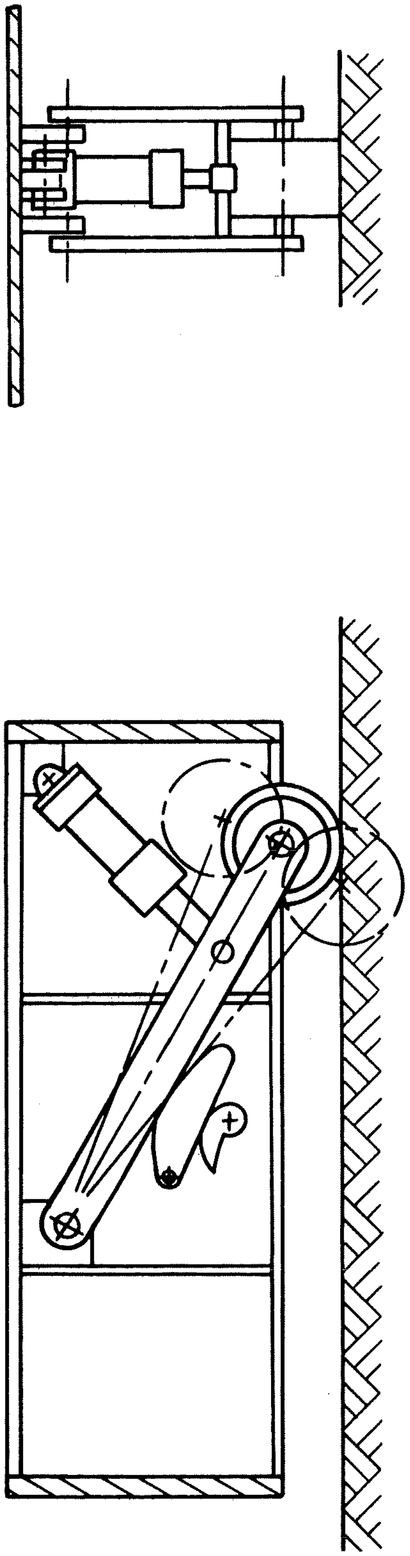


FIGURE 29. - Jack ring centralizing system.

4.2.3.4 Slipform Control System

The slipform is supported on six hydraulic cylinders as illustrated in Figure 27. The blind end of the cylinders is attached to the jack ring and the rod end to the slipform. The cylinders are mounted in pairs to form a triangle. The blind ends of the cylinders are spaced apart on the jack ring and the rod ends are located at the same point on the slipform. All location points on the jack ring and slipform are designed to accept spherical bearings. The slipform cylinders always operate in pairs. By selecting the appropriate pair of cylinders, the required lateral and vertical motion can be achieved. Under automatic control, the motion desired is always achieved by retracting the cylinders. The guidance of the slipform is critical. Since the unit is 10 ft high, any prolonged misalignment will result in the slipform trapping the curb ring against the shaft wall. To steer the slipform successfully, three transducers are required:

a. Lateral transducer

b. Tilt transducer

c. Position transducer.

The first two control the actuation of the hydraulic cylinders. The lateral and tilt transducers have automatic feedback control for positioning the slipform cylinders.

Lateral Transducer

The lateral transducers control the slipform to keep it concentric with the shaft. The activation of the hydraulic cylinders control the position of the base of the slipform. The top of the slipform cannot be controlled since its location is dictated by the set concrete lining.

The slipform requires three lateral transducers mounted midway between each pair of inclined slipform cylinders. The transducers consist of a four point linkage attached between a rigid support from the slipform and a guide shoe that slides against the shaft wall (see Figure 30). The four-bar linkage ensures that there is parallel motion between the slipform and the guide shoe. The shoe is beveled at either end to enable it to negotiate variations in the shaft wall. The shoe and linkage can be folded up into its support channel where it can be locked so that the curb ring can be lowered for maintenance.

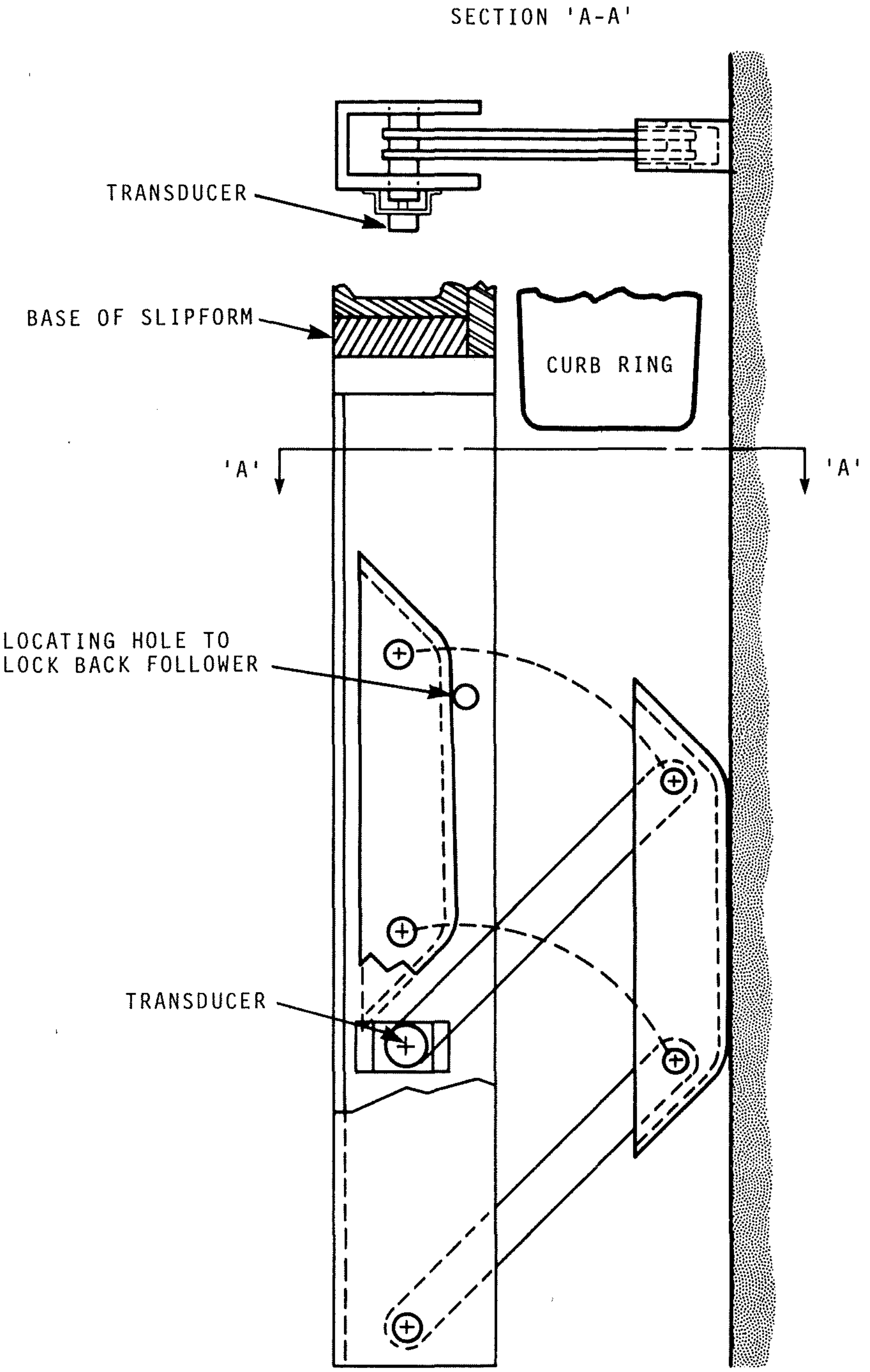


FIGURE 30. - Slipform lateral position indicator.

The change in angle of the linkage is measured by a linear rotary single-turn potentiometer on the linkage spindle. The angular displacement of the arm relative to the horizontal location of the shoe is shown in Figure 31, for a 15-in. arm length. The change in horizontal displacement of the guide shoe has an approximately linear relationship with the change in the angular displacement of the linkage. Therefore, the guide shoe displacement generates a corresponding linear change in the resistance of the potentiometer. It is not considered necessary to correct for any deviation from linearity since the control circuit is correcting to a null condition. The electrical control circuit is shown in Figure 32. The reference distance which the transducer should attempt to maintain is preset by the ten-turn potentiometer. Provided the output from the single potentiometer remains at or below a certain level, the power transistor will not be energized. However, above the predetermined level the power transistor will be activated and it will activate the appropriate hydraulic solenoid to centralize the slipform by retracting a pair of slipform cylinders.

The activation of the appropriate cylinders provides movement in the 60, 180, and 300 deg axes. The Electrical Control Circuit, Figure 33, shows the integration of the transducers into the control circuit. The transducers activate relays CR10, CR12, and CR14 which, in turn, activate hydraulic valve solenoids. The transducer signals are fed to the control panel where the lateral displacement is displayed for each transducer.

Tilt Transducer

Three tilt transducers mounted on the bottom edge of the slipform (Figure 34) are required. The transducers are located on the tilt axis of each pair of cylinders, Figure 35. The transducer signal has two functions. It is fed to the control panel where its value is displayed on a LCD analog panel meter, and the tilt is controlled by activating hydraulic cylinders. The control circuit is shown in Figure 36. Once the meter signal exceeds a predetermined level set by the reference potentiometer, it activates the hydraulic solenoid control valves. In the Electrical Control Circuit (Figure 33) the signal activation of relays CR4, CR6 and CR8 will energize the appropriate soienoids.

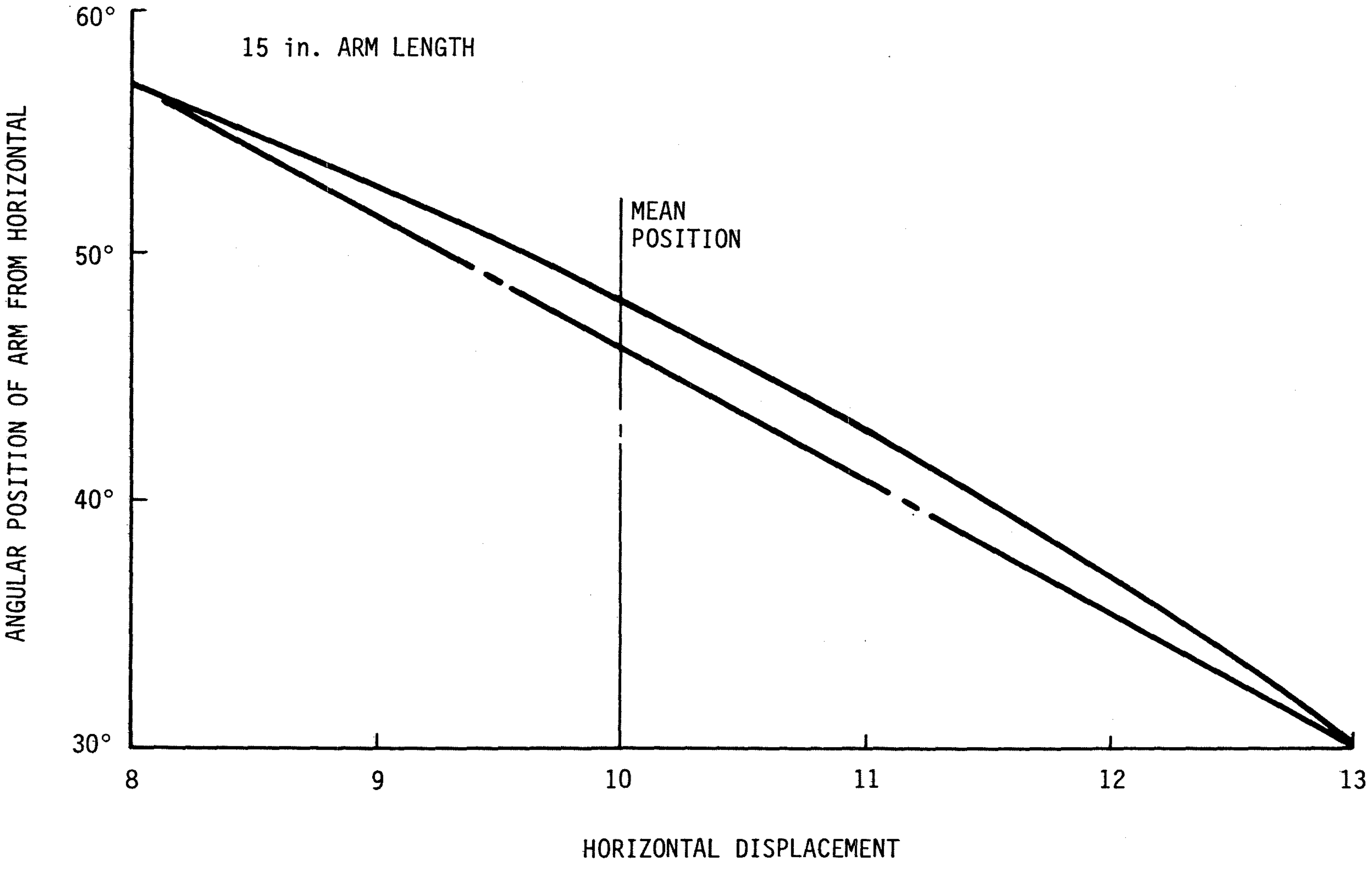


FIGURE 31. - Linearity of position indicator.

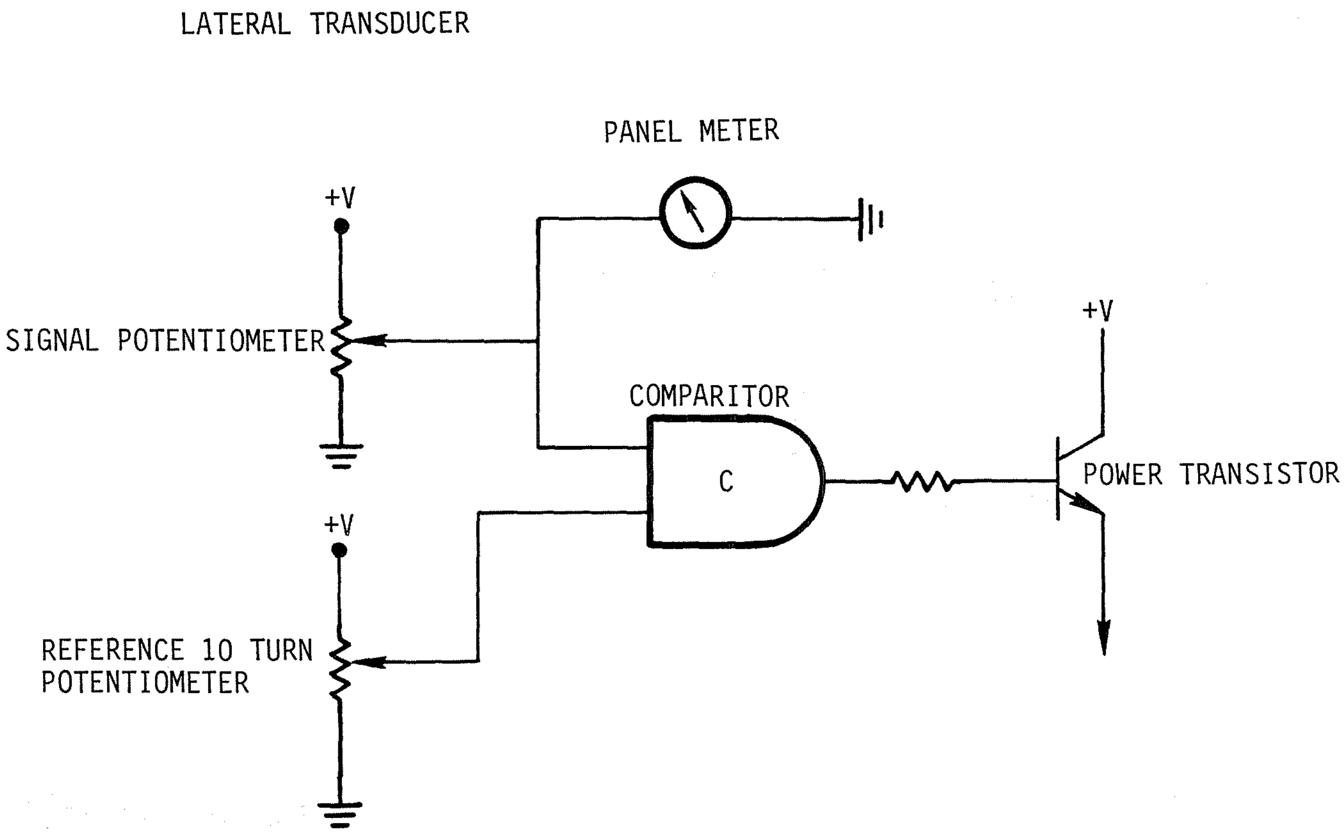


FIGURE 32. - Slipform alignment control circuit.

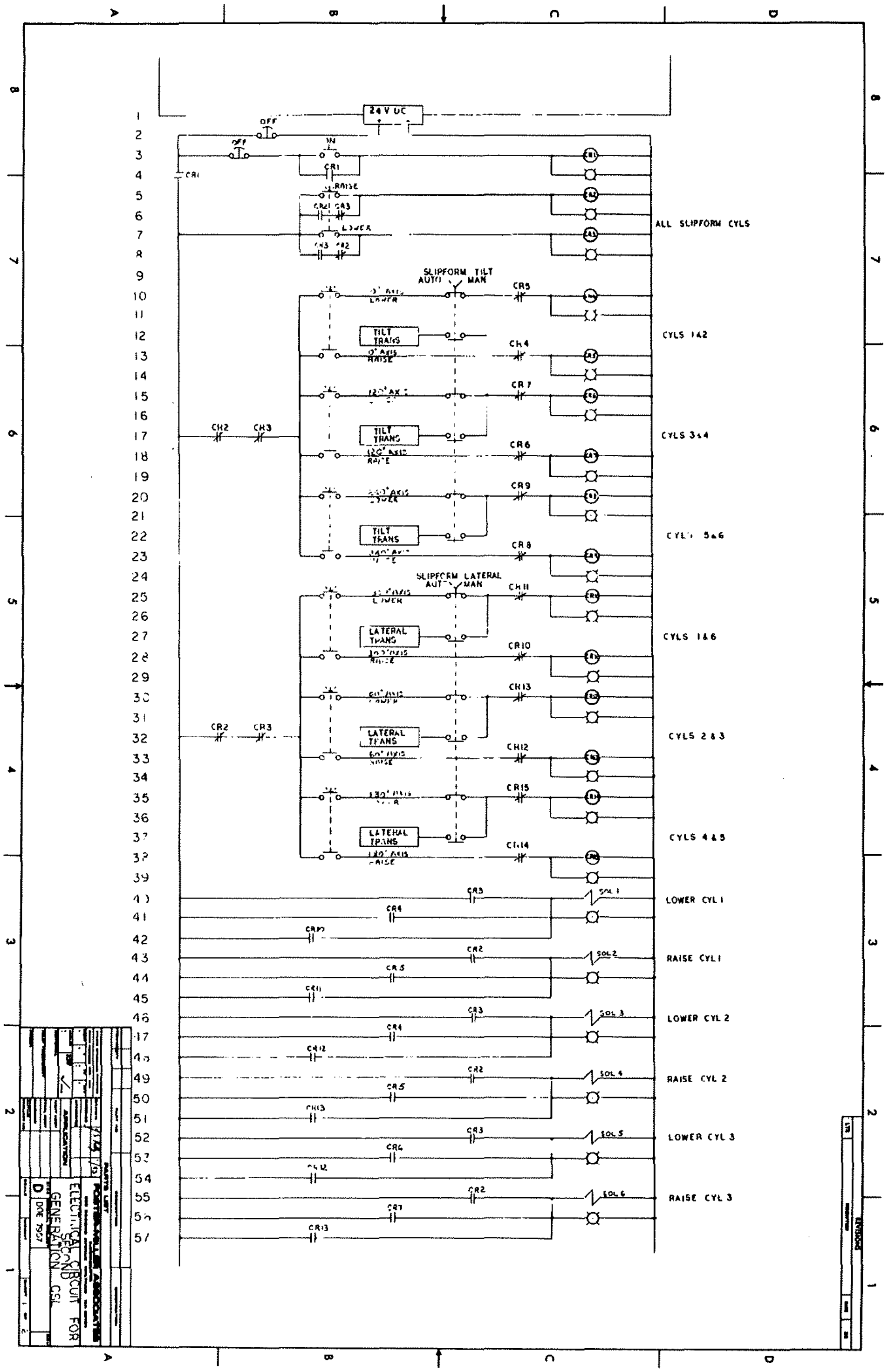


FIGURE 33a. - CSL electric control circuit.

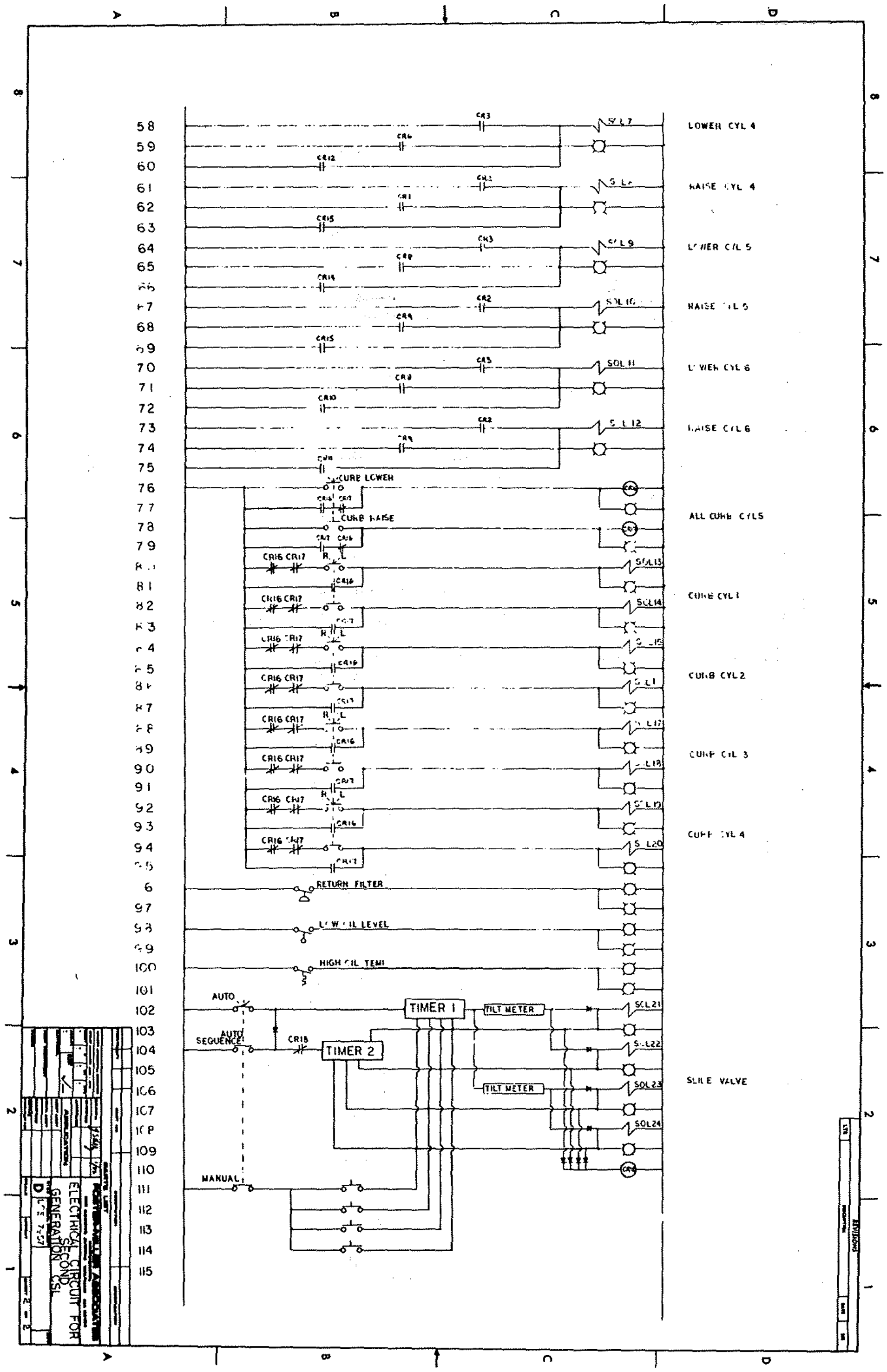


FIGURE 33b. - CSL electric control circuit.

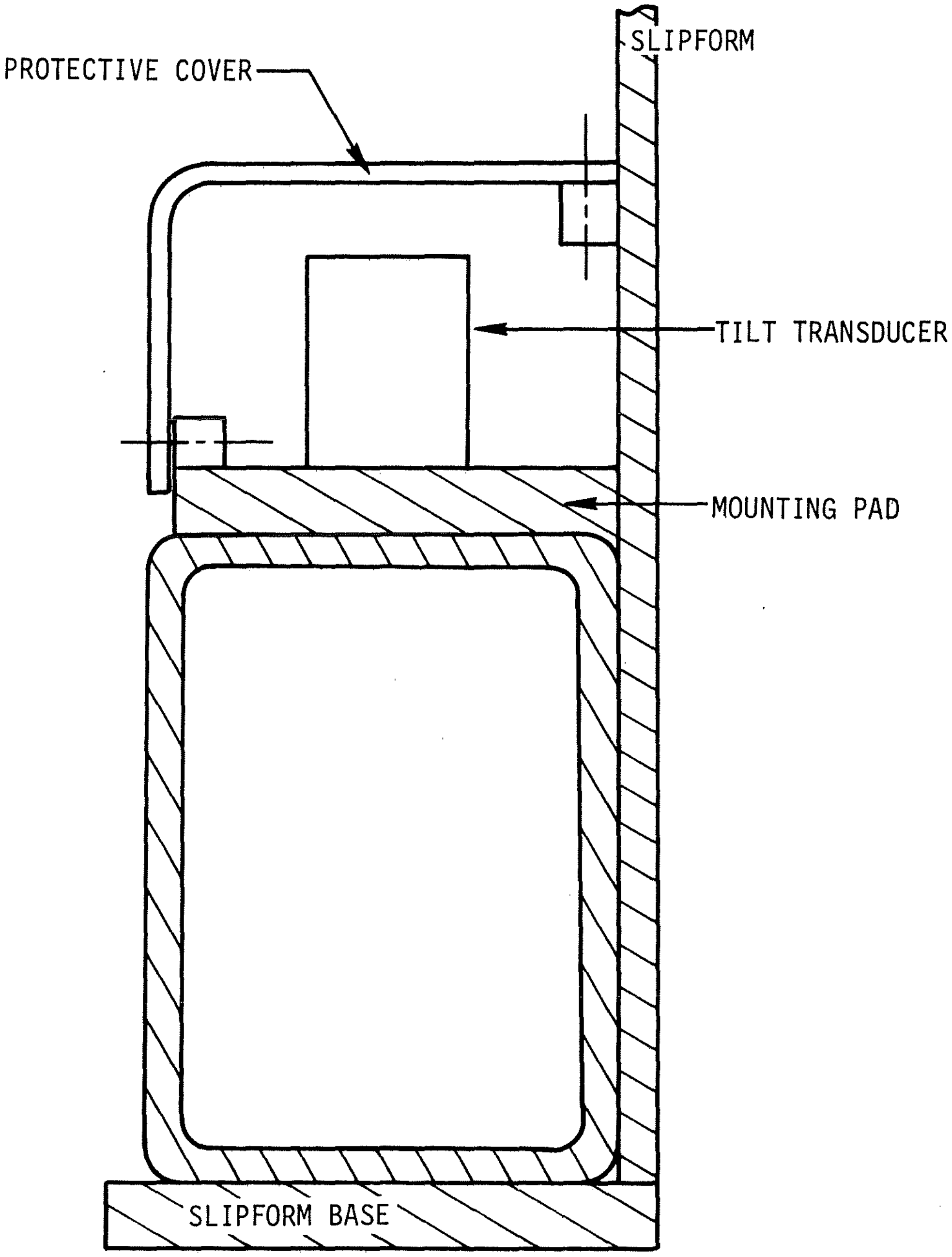


FIGURE 34. - Slipform tilt transducer mounting.

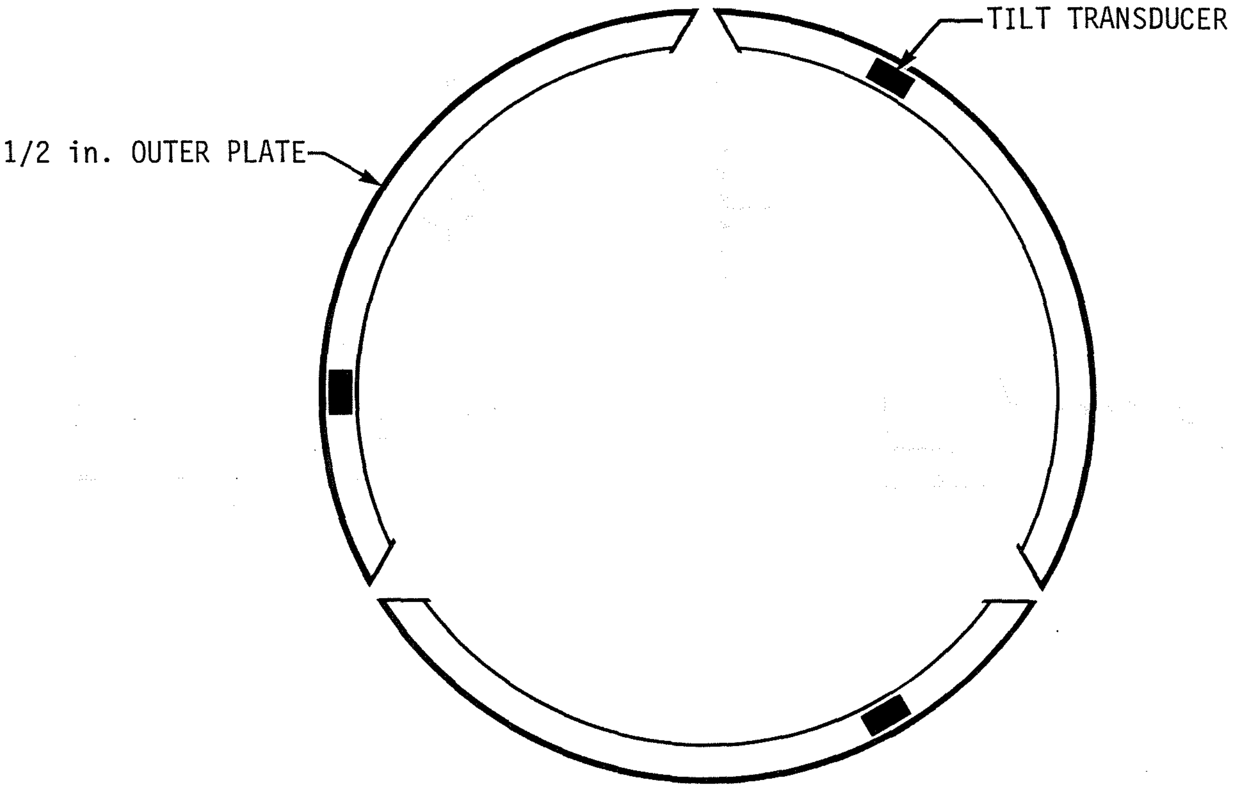


FIGURE 35. - Location of tilt transducers on slipform.

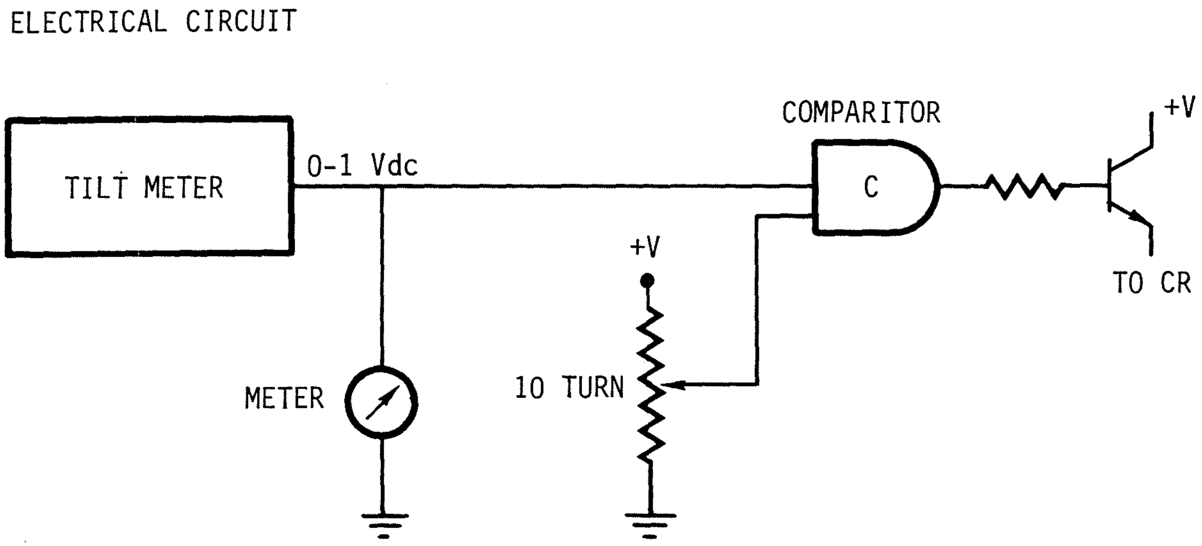


FIGURE 36. - Slipform tilt control circuit.

Typical components are:

a. Robinson-Halpern inclinometer
Range ±6 deg
Power input 12 to 30 Vdc unregulated
Output ±1.0 Vdc into not less than 50K ohms

b. Output signal amplifier

c. Bowmar solid-state liquid crystal bargraph analog Panel Meter. Accuracy ±1 percent typical.

Position Transducer

The slipform position is manipulated by the six cylinders mounted on the jack ring. All lateral and tilt misalignment is corrected by retracting the appropriate pairs of cylinders. It is conceivable that, should the transducers be correcting over a long period of time, the cylinders will be operating in a partially retracted condition. To help prevent this situation, the cylinders are bled back to tank through a needle valve. However, if a partially retracted condition is encountered, then the operator should be aware since the mechanical stiffness of the system is reduced which is undesirable. The distance between the jack frame and the slipform will be measured by a potentiometric cable displacement transducer (string pot). Previous experimental testing highlighted the susceptibility of the string pot to damage. In the prototype CSL design, the string will be protected by placing it inside two telescoping tubes. The string pot will be a ruggedized version for extreme environments. The signal will be displayed on the control panel on a digital panel meter.

Typical components are:

a. Colesco Position Transducer
Ruggedized version Model PT-101RX
Typical accuracy 0.1 percent

b. Datel LCD 3-1/2 digit, digital panel meter; 0.75 in. high numerals. Model DM-LX3
Typical accuracy ±0.1 percent, FSR, ±1 count.

4.2.3.5 Curb Ring Control System

Instrumentation of the curb ring is required for control and feedback circuits. The following types of transducers are mounted on the curb ring:

a. Tilt transducer
b. Position transducer
c. Concrete pressure transducer.

The following subsections describe the function of each transducer in detail.

Tilt transducer

The curb ring is controlled by the hydraulic cylinders in the vertical plane, but there is some limited freedom of movement in the lateral plane. The curb cylinders have 7 in. diam bore, 4-1/2 in. diam rod and 54 in. stroke, and are mounted in the true vertical position with the rod end attached to the curb. The electrical control circuit will permit cylinders to be operated individually or simultaneously under manual control. In the automatic mode the tilt meters will identify and correct for the curb tilt on a continuous basis by placement of concrete to the port in the highest position. The transducer signals control the multi-port concrete valve which selects the concrete line to be connected to the concrete pump. Under normal operating conditions, the cylinders function in the raised mode pushing against the new concrete. The cylinders are hydraulically connected to a common supply pressure. The desired concrete pressure above the curb is hydraulically controlled by a pressure relief valve. Under normal operating conditions, the cylinders are free to float. Their position and the tilt of the curb ring will be controlled by concrete placement. The monitoring and control of the tilt will be achieved using two inclinometers. The transducers are mounted on pads on the curb at right angles to the cylinders they control as shown in Figure 37.

The output signal from the inclinometer is fed directly to a LCD analog panel meter. The output from the inclinometer is also fed to a comparator circuit which provides a "go/no go" signal to operate the concrete slide valve. The comparator circuit, shown in Figure 38 is similar to the circuit used to control the slipform in a level position. The comparator circuit is designed to examine two diametrically opposite cylinders and signal the slide valve to place concrete at the high port. Otherwise, no signal is generated for level and low conditions.

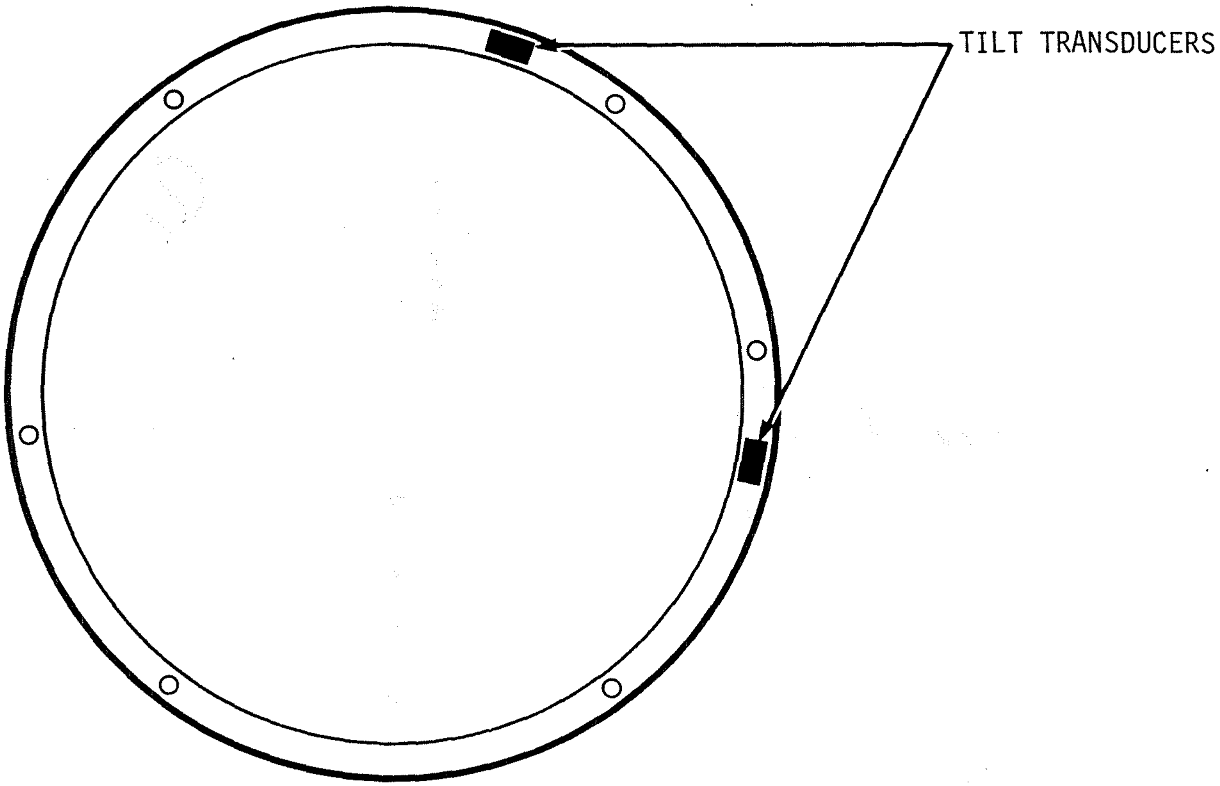


FIGURE 37. - Location of tilt transducers on curb ring.

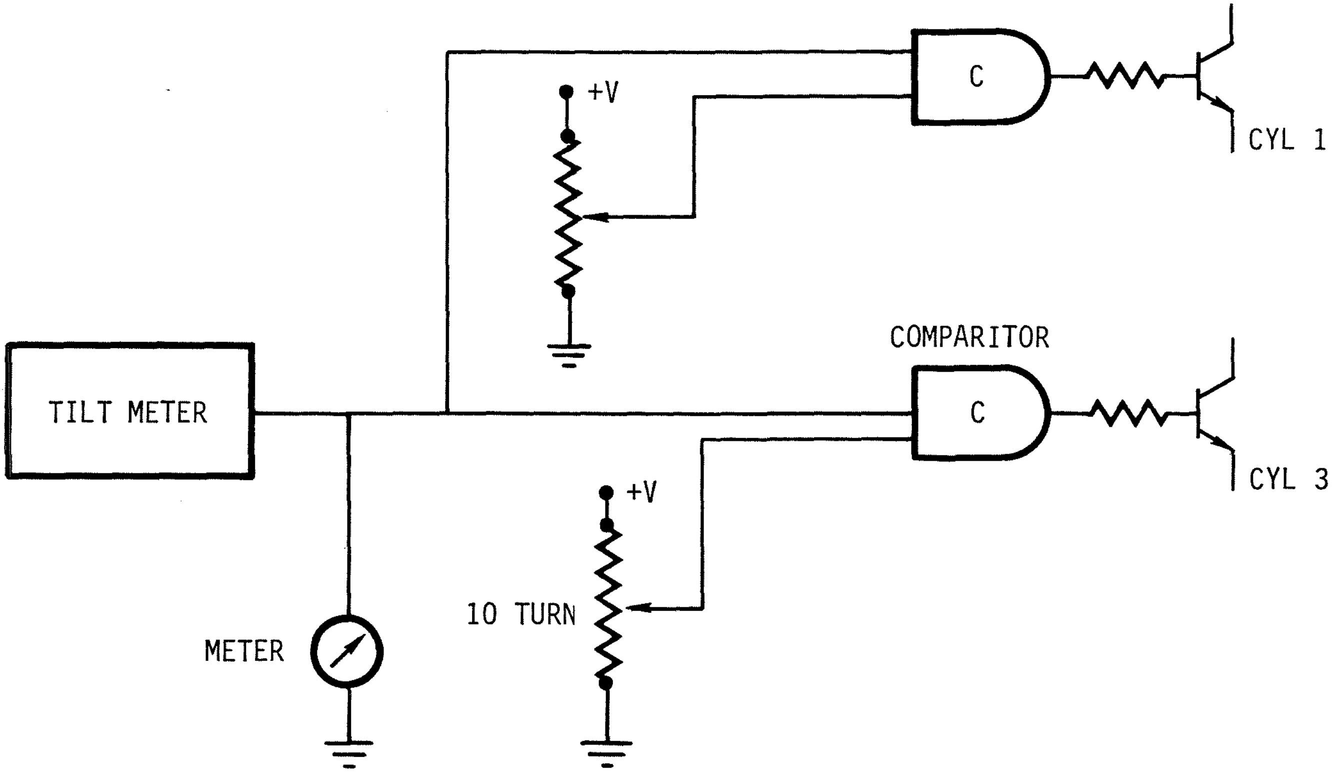


FIGURE 38. - Curb ring tilt meter circuit.

Typical instrumentation selection are:

a. Robinson-Halpern inclinometer
   Range ±6 deg
   Power input 12 to 30 Vdc unregulated
   Output ±1.0 Vdc into not less than 50K ohms

b. Output signal amplifier

c. Bowmar solid-state liquid crystal bargraph analog
   Panel meters
   Accuracy ±1 percent typical.

Slide Valve Control

The slide valve is a multi-port device that directs the concrete from the concrete pump to any one of the lines connected to the concrete nozzles mounted in the curb ring. The slide valve design used for the second generation CSL has four ports, and is activated by two hydraulic cylinders which position an upper and lower slide plate. The upper slide plate contains a single inlet nozzle, while the lower slide plate has four outlet nozzles. The slide valve is used as a key device in the concrete placement operation. The primary function is to respond to the tilt meters and keep the curb ring level. The second function is to regularly direct concrete to all lines to keep it moving in order to prevent unacceptably long residence time for the concrete.

In the earler experiments, an electrical-mechanical timer was used to control the sequencing of the slide valve which, in turn, placed equal amounts of concrete at each port. The system proved inadequate because it could not distinguish operational problems with the curb tilt. To overcome this problem a new control circuit was designed and is illustrated in Figure 33. Timer No. 1 has five outputs. The first output is to activate the tilt meters and allow them to perform the leveling exercise on the curb automatically. The four solenoids (Solenoids 21 through 24) operate hydraulic directional valves to activate the slide valve hydraulic cylinders. The remaining four outputs are sequentially timed to systematically place concrete to the four ports for 30 sec intervals.

A second timer comes into operation only if both tilt meters have a level condition. During automatic cycling, the tilt meters are correcting for level, and relay CR18 will be activated. However, if a level condition exists for both meters, the slide valve would not activate and would remain at one port. This would throw the curb ring once again out of level. To prevent this occurrence, CR18 is deactivated (curb level) and timer No. 2 comes into operation to equally distribute concrete to each port.

A concrete pressure sensing valve manufactured by the Red Valve Company is located close to the slide valve. The valve is fitted with both a direct readout mechanical pressure gauge and with an electronic pressure transducer. Concrete pressure is displayed on the operator's control panel.

Curb Ring

Position Transducer - The operator is required to know the position of the curb ring relative to the slipform at all times. To achieve this a measuring wheel transducer, which is spring loaded against the slipform, is mounted in the curb. Mounting the transducer in this manner will afford it maximum protection. Only one transducer is required and it can be located at any position on the curb ring circumference. A typical mounting arrangement is shown in Figure 39. Withdrawal of the transducer for inspection and maintenance is facilitated by using an easy release system. The main components are:

a. Spring loaded mounting bracket

b. Rotary shaft encoder

c. Wheel and bi-directional totalizer.

The bracket and the urethane rimmed 12 in. circumference wheel are commercially available. A rotary shaft encoder (quadrature), which is mounted on the bracket, produces a digitized signal to enable the counter to differentiate between a raise and lower mode. The encoder is selected to give 120 output pulses per revolution which enables increments of 1/10 in. to be measured. The signals from the encoder are fed to a bi-directional totalizer which can count up and down. The value is displayed on a digital meter on the control panel.

Typical instrumentation selections are:

a. Durant Series D Linear Counter Bracket Model No. 40460-400

b. Durant Aluminum Measuring Wheel, Urethane Rim, 12 in. circumference, Model No. 20144-300.

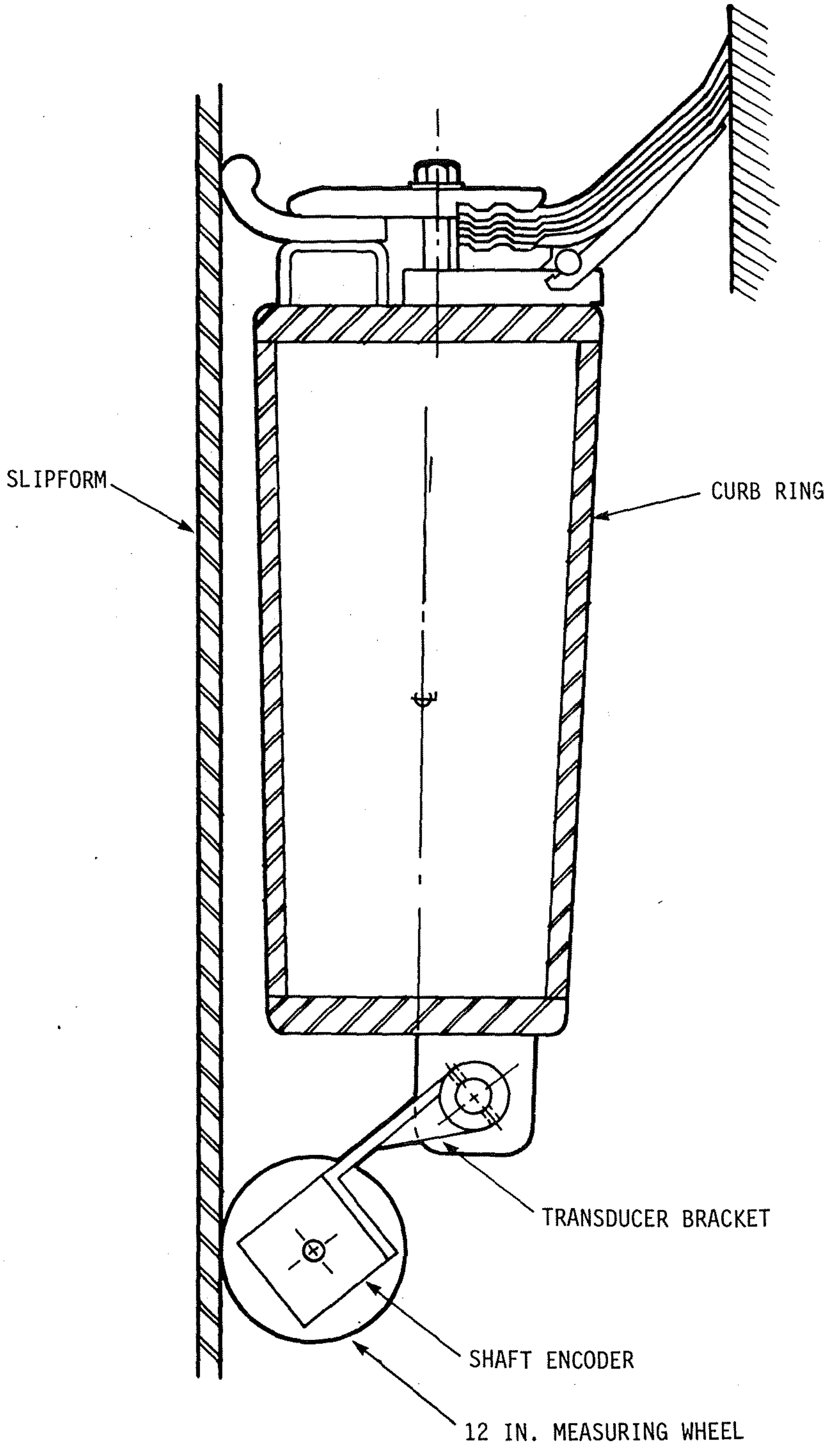


FIGURE 39. - Curb ring mounting for linear transducer.

c. Durant Medium Duty Shaft Encoder (quadrature to suit above measuring wheel Model No. 39702

d. Durant Digital Totalizer Model No. - Series 3500.

Concrete Pressure Transducer - Previous experimental tests were conducted with Data Instruments Model AB pressure transducers mounted directly on the curb. The pressure sensing surface was flush with the top of the curb. Two problems arose from this method of mounting. First, the coarse gravel scratched and dented the surface which locally strained the transducer past its 2:1 overload protection. The second problem that arose was that if a transducer appeared to be inaccurate, it was necessary to remove it for inspection. However, since cement would flow into the clearance gap around the transducer and lock it into the curb ring, any levering performed to free the transducer inevitably would render it useless.

The new design uses a flexible metal diaphragm and an oil interface to protect the transducer as shown in Figure 40. The 2-in. diaphragm is manufactured from nickel-chromium-iron-titanium alloy which has a constant modulus of elasticity over a temperature range of -65 to 200°F. The diaphragm is an electron beam welded onto the main body of the mount which is filled with oil. It is fitted with a Data Instruments Model EA, OEM style ruggedized pressure transducer. The unit could be fitted with the Type AB transducer, but the ruggedized version can withstand more abusive handling. Four equally spaced transducers, which can be removed from below, are mounted on the curb.

Typical component selections are:

a. Kearflex Engineering Co., Mi Span C diaphragm

b. Data Instruments, Model EA ruggedized OEM pressure transducer, range 0 to 50 psi, typical accuracy ±0.05 percent.

4.2.3.6 Electrical Control System

The electrical control system is displayed in ladder diagram format in Figures 33a and b. The diagram illustrates the 24 Vdc control system. No reference will be made to the high voltage starters, etc., which can be considered as auxiliary equipment. The system provides guidance for the:

a. Slipform cylinders

b. Curb ring cylinders

c. Slide valve.

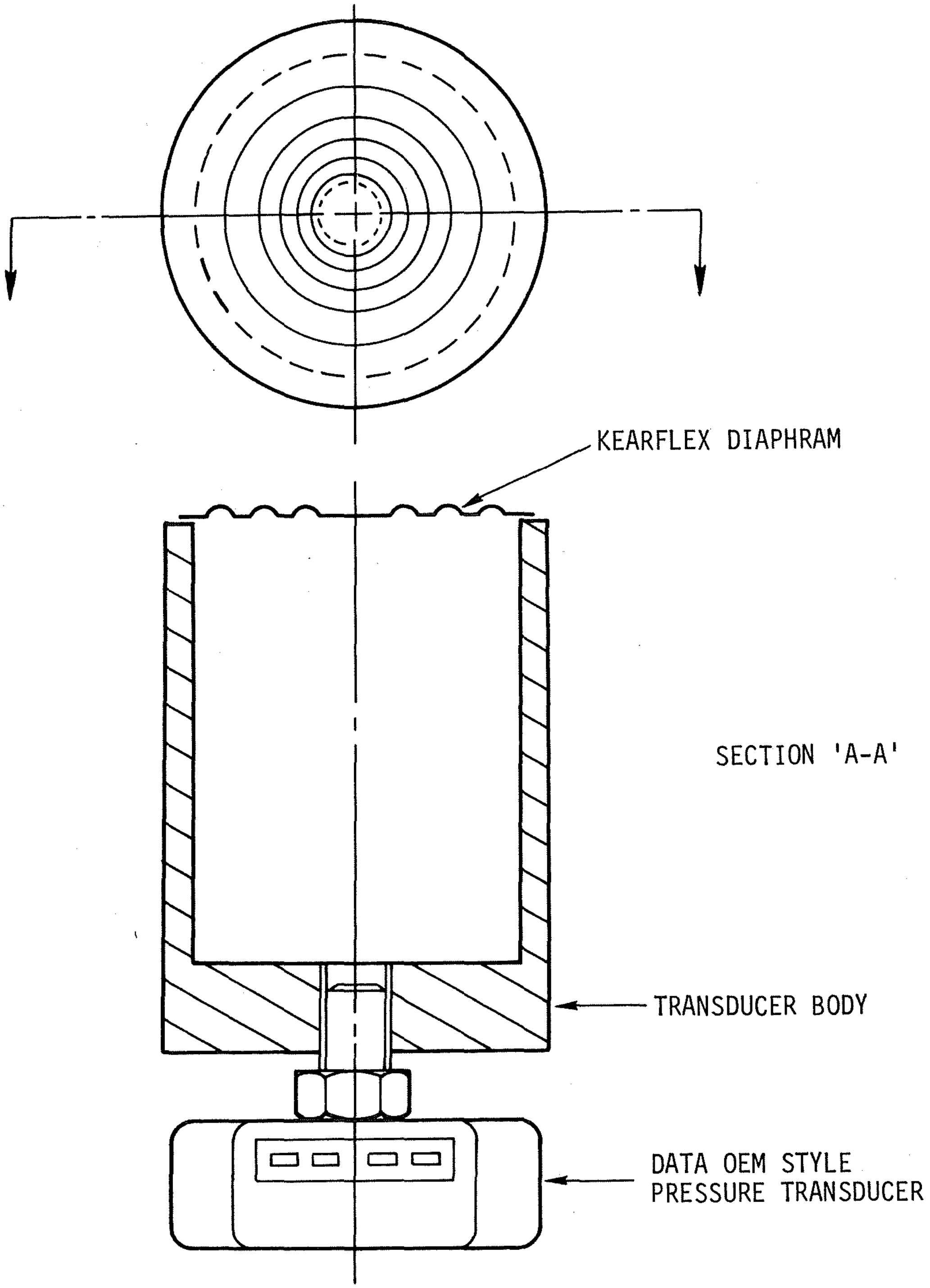


FIGURE 40. - Concrete pressure transducer.

The motions of these devices are governed by solenoid operated hydraulic directional valves. The diagram indicates where the interfaces are with the transducers that are utilized during the automatic modes of operation. Selection of a mode of operation and activation of a hydraulic solenoid is denoted by the illumination of an indicator light. The indicator lights will be mounted on a graphic display illustrating the hydraulic circuit, set off to one side of the operator's control panel (see subsection 4.2.4.4). The functions provided by the control system are described below and are systematically explained, beginning at line 1 on the electrical ladder diagram.

"Stop/Start" of Control System

Line 1 provides a stabilized 24 Vdc power source. Lines 2 and 3 contain emergency stop buttons. Line 3 has a start button which energizes CR1 which closes contacts on Line 4 energizing the control system. CR1 also activates the motor starter for the hydraulic pump, but this has not been shown. Lines 5, 6, 7 and 8 control the raising and lowering of all the slipform cylinders simultaneously by powering either CR2 or CR3. It is not possible to select both functions, activation of either CR2 or CR3 overrides the other operation. Selection of "all raise" or "all lower" opens contacts on Lines 17 and 32 which overrides any automatic or manual operations to control the slipform cylinders in a tilt or lateral motion.

Slipform Control

The solenoids 1 to 12 control the raise and lower operations of the six slipform cylinders. The activation of the relevant solenoids is controlled by the slipform control circuits that activate CR2 to CR15. The operation of the selected solenoid provides:

a. Raise/lower all cylinders simultaneously

b. Manual tilt control in three planes

c. Automatic tilt control

d. Manual lateral control in three planes

e. Automatic lateral control.

Slipform Tilt Control

Lines 10 to 24 incorporate the manual and automatic circuits for control of slipform tilt. In Line 10 there is a three-position switch, raise/off/lower, for manual control of the 0 deg axis (cylinders 1 and 2). Also in Line 10 is a two-position switch for selecting either the manual or automatic operation. The switch is depicted in the manual condition which permits the three-position switch to select either CR4 or CR5 to raise or lower cylinders 1 and 2. In the auto position, the tilt transducer on Line 12 is switched into the circuit and controls CR4 which activates the lower mode of cylinders 1 and 2. The set of contacts located prior to each relay prevent the selection of raise and lower modes simultaneously. The raise mode on Line 13 is controlled by the three-position manual switch on Line 10. Closing the contacts on Line 13 activates CR5 which energizes solenoids 2 and 4 (Lines 44 and 47) which raises cylinders 1 and 2. The tilt control of the 120 deg axis and 240 deg axis is achieved in a similar manner.

Slipform Lateral Control

The lateral movement of the slipform is controlled by Lines 25 to 39. The circuit provides for manual operation of lateral motion in three individual axes and for automatic operation which modulates the cylinders on command of the transducers.

Line 25 has a manual three-position switch, raise/off/lower which generates motion on the 300 deg axis. The switch is linked to a second set of contacts on Line 28. The auto/manual switch is in the manual position. If it were in the auto mode, the set of contacts on Line 27 would be closed and CR10 would be activated by the lateral transducer on Line 27. The set of normally closed contacts on Line 24 prevent simultaneous selection of raise and lower. CR10 closes contacts that activate solenoids 1 and 11 which initiate a lower mode for cylinders 6 and 1. Line 28 controls the raise mode for cylinders 6 and 1 by providing power to relay CR11. The lateral motion generated on the 60 and 180 deg axis is achieved in a similar manner.

Curb Ring Control

The curb ring control circuit permits the raising or lowering of all cylinders simultaneously or by individual operation. In the slipforming operational mode, all four cylinders are in the raise condition pushing up against the new concrete. The pressure to that circuit is determined by a pressure reducing valve that has a remote electrical control. All the cylinders are commonly connected to the same pressure source and are free to float.

The control of the curb ring begins on Line 76 of the ladder diagram. A three-position switch (raise/off/lower) on Line 76 permits manual operation of all the curb cylinders. It is depicted in the off position. If lower were selected, the contacts on Line 76 would close and CR16 would be energized. Should raise be selected, the contacts on Line 78 would close and CR17 would be activated. The sets of contacts from CR16 and CR17 on Lines 77 and 79 prevent both modes from being selected simultaneously. Contacts from CR16 and CR17 on Lines 80, 82, 84, 86, 88, 90, 92 and 94 de-energized all the individual manual (raise/off/lower) switches. The manual three-position switch on Line 80 controls solenoids 13 and 14. All the remaining curb cylinders are operated in a similar manner.

Hydraulic Protection Circuits

Lines 96 to 101 provide warning lights on the control panel to highlight return filter blockage, low oil level and high oil temperature.

Slide Valve Control

The slide valve directs the placement of concrete to the curb ring. The sliding plates are positioned to open the correct port by two hydraulic control cylinders. These cylinders are controlled by two dual position directional control valves powered by four solenoids. The solenoids in the ladder diagram are solenoids 21 to 24. The timer on Line 102 has five outputs. Four of the outputs are for direct activation of individual solenoids, the fifth is to energize the automatic leveling mode. Timer No. 1 places concrete into each of the four ports for 30 sec intervals by activating the appropriate solenoid. At the end of the four-port sequence, it switches to the automatic mode. Upon completing the automatic mode, Timer No. 1 returns to the beginning of the cycle. Should the system achieve level during the automatic mode, CR18 is de-energized which activates the second timer (Timer No. 2) on Line 104. Timer No. 2 has only four outputs and is programmed to switch every 30 sec to each of the four ports.

An auto-sequencing mode is provided (line 104) to enable the slide valve to cycle sequentially between the 4 ports on a 2 minute cycle time. The sequencing is provided by Timer No. 2. The manual override mode enables the operator to control slide valve port selection.

4.2.4 CSL Operator's Control Panel

The underground CSL operator's control panel design has been human-engineered to display the lining equipment and process status in a quickly scanable and readily understandable fashion. The system display is divided into three main groupings:

a. Curb ring and concrete delivery operations

b. Slipform guidance system operations

c. CSL suspension system operations

The arrangement of the panel is shown in Figure 41. The main panel is mounted on a work desk and curves around at one end to keep the displays and controls within the reach of a single seated operator. Manual controls are located on the desk surface while dual function lighted pushbuttons on the panel serve both as controls and status displays for the less frequently adjusted automated functions. A graphic display panel of the hydraulic circuit diagram containing status indicator lights for system troubleshooting and status checks is located at one end of the desk. The top of the control panel is just below the operator's line of sight, reducing job fatigue and allowing for a visual survey of the shaft lining. Additionally, sufficient space is available at the desk for a second operator, if required.

The primary type of panel meter display chosen is a combination analog-digital bar graph type for easy readability and maximum reliability. The analog bar graph display permits easy scanning and comparison of several adjacent meters with the highest or lowest reading clearly visible. Pushbutton controls and displays corresponding to each bar graph meter are conveniently located beneath the appropriate meter, allowing access without obstructing view of the meter display.

Color will be used to indicate the functioning of the displays green for an active "go" condition, yellow for a transitory condition and red for a stopped or alarm condition.

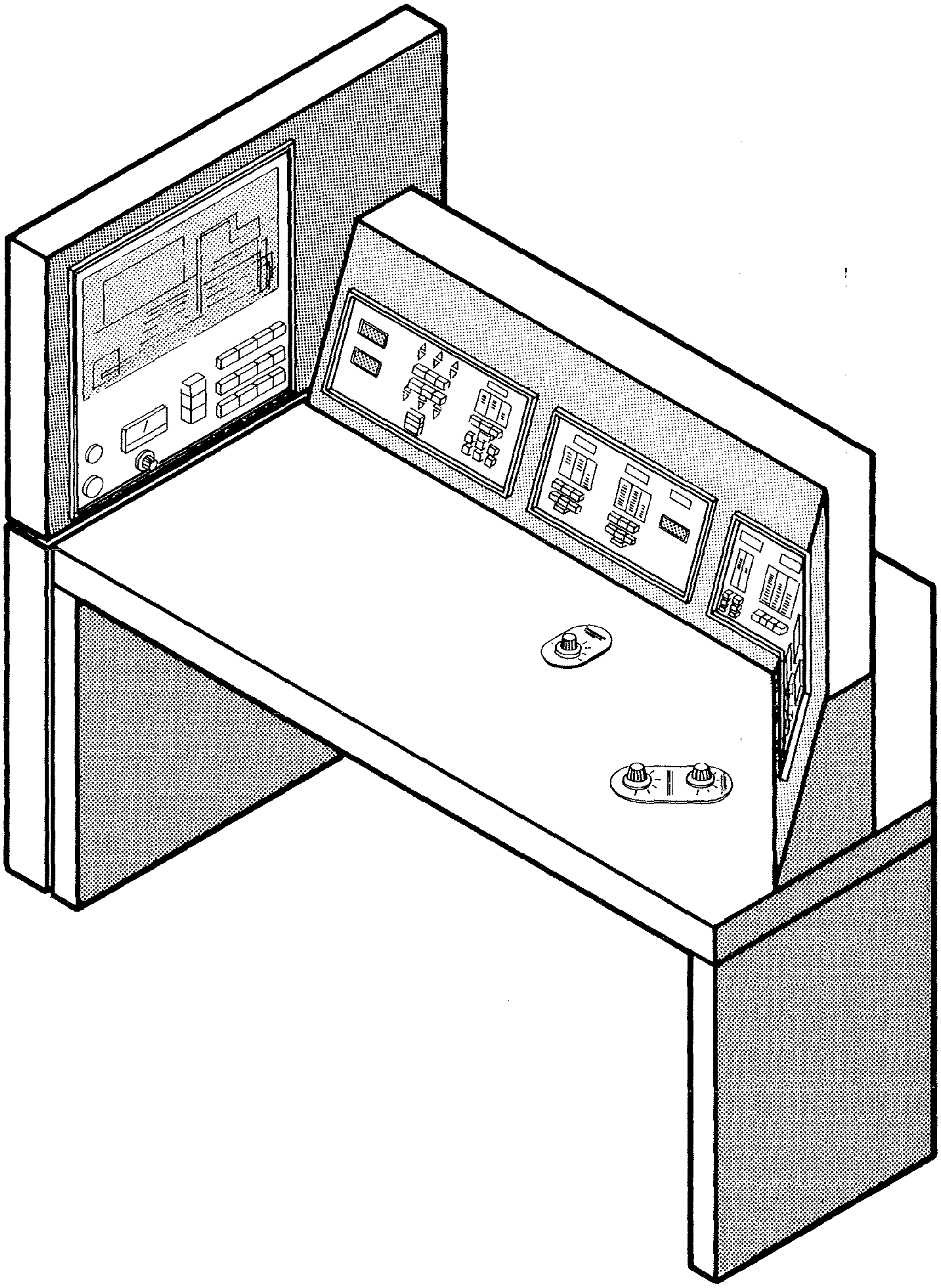


FIGURE 41. - Operator's control console.

4.2.4.1 Curb Ring and Concrete Delivery Operations

Positioned at the right side of the panel is the control and display grouping for the curb ring and concrete delivery operations (Figure 42). From left to right, it encompasses curb tilt and concrete port selection, concrete pressures on the curb, curb cylinder hydraulic pressures and concrete pump status. Although the concrete delivery system is under the control of the concrete pump operator who is at another station, the system status is indicated on the control panel to warn of process problems.

The curb tilt display uses two bargraph meters which are center-zero scale to show the height difference between opposite sides of the curb. The measurement axes run near the concrete ports and the meters indicate the low sides of the curb. The four-position lighted pushbutton group beneath the tilt meters selects and indicates the port receiving concrete. The concrete pumped to that port will gradually push that zone of the curb lower. The orientation of the curb tilt display is consistent with the actuation of the concrete port pushbutton grouping (i.e., selecting port 3 will lead to a tilt display toward position 3). An automatic port cycling function is provided to activate appropriate ports to level the curb. A second automatic function is provided to sequentially pump concrete to all the ports. In case of excessive curb tilt (over a preset limit), the red warning light over the display will begin to flash.

The concrete pressure display consists of four bargraph meters showing concrete pressure on the curb near each of the four concrete ports. These pressures are determined by the amount of upward hydraulic cylinder force applied to the curb, and must be held within a certain range to assure adequate concrete support. Normally, the curb hydraulic cylinders are evenly pressurized and the four concrete pressures will vary by only a few psig, depending on the active concrete port selected. However, when the curb encounters a slough zone on one side of the shaft, the curb seal on that side extends outward to maintain contact with the shaft wall. This causes an effective increase in curb area on that side, spreading the hydraulic force over more concrete and, thus, reducing the local concrete pressure. For example, a 3-in. deep slough zone and a 9-in. curb width could reduce concrete pressure by almost 50 percent. Should the concrete pressure rise above or fall below preset limits, the warning light above the pressure display would begin to flash.

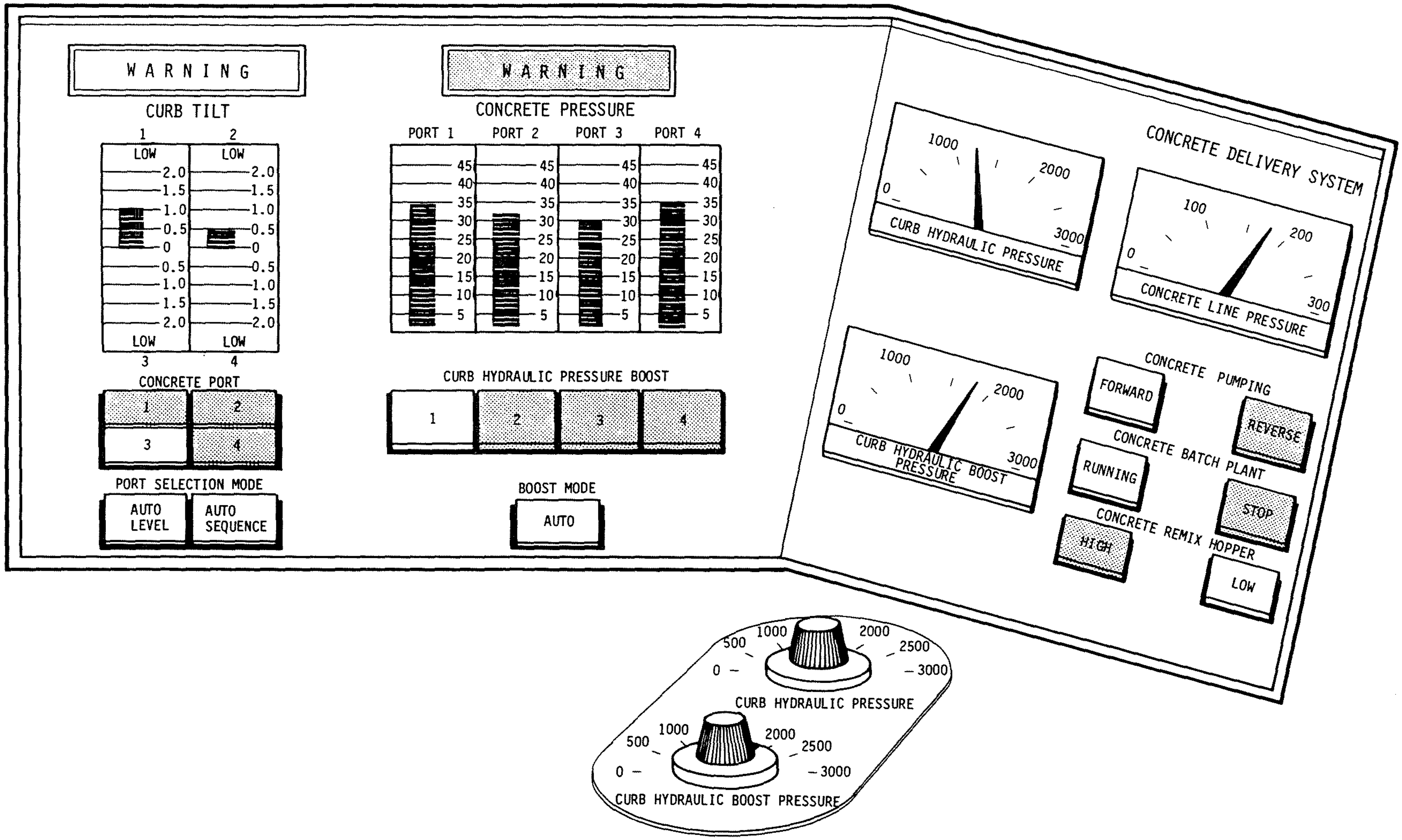


FIGURE 42. - Curb ring and concrete delivery display grouping.

In order to compensate for slough zones, individually boosted hydraulic pressures are available for each of the four curb cylinders. The boosted pressures are engaged by any of the four lighted pushbuttons beneath the concrete pressure display. An automatic function button activates a boosted pressure when it is required by excessive curb tilt or low concrete pressure at a particular location. The magnitudes of both the curb hydraulic pressure and the maximum boosted pressure are displayed on the meters shown in Figure 42, and are set by controls located on the surface of the desk immediately below the meters.

4.2.4.2 Slipform Guidance System Operations

The central panel display grouping (Figure 43) indicates slipform orientation with respect to horizontal tilt, lateral position in the shaft and slipform effective length (SEL). The lateral position display is comprised of three bargraph meters each reading the distance between the lower edge of the slipform and the shaft wall. Three-position transducers are evenly spaced around the circumference of the slipform. The transducers each measure a discrete distance from the slipform to a guide shoe riding on the shaft wall which "averages" out the variations in the shaft wall surface.

It is desirable to keep the slipform centered within the shaft for proper working clearances. Translation of the lower slipform edge to compensate for lateral misalignment is normally accomplished by pulling down on the appropriate pair of cylinders. This function can be automated by activating the "auto" centering mode pushbutton shown in Figure 43, or manually activated by depressing the illuminated "down" pushbuttons corresponding to the meter that reads high. In unusual circumstances where any of the slipform cylinder pairs are too low, they may be extended manually.

The slipform level display is made up of three center-zero scale bargraph meters, which function in a similar fashion to the curb tilt meters. The three meters indicate the slipform level, corresponding to the three pairs of slipform cylinders. Since the level transducers indicate tilt with respect to the horizon, each meter signals whether the slipform at that pair of cylinders is low or high. Although the three level indications are not completely independent, they serve a useful control purpose by easily indicating which pair of slipform cylinders need to be adjusted. The level transducers are located on the

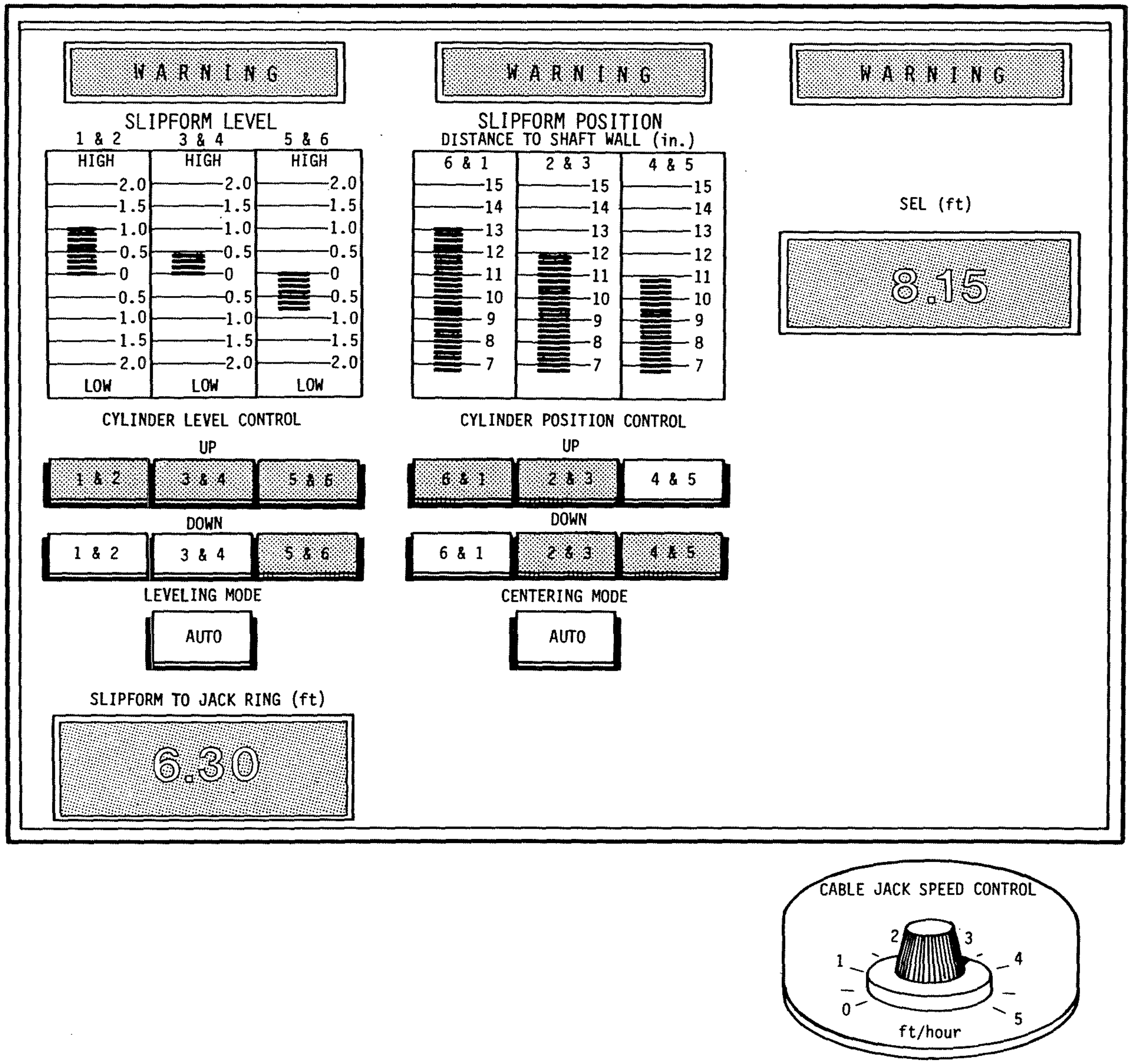


FIGURE 43. - Slipform display grouping.

slipform at the attachments of cylinders 1 and 2, 3 and 4, and 5 and 6. When the meters indicate a high reading on one side (calibrated in terms of inches high or low), the appropriate pair of slipform cylinders is lowered with one of the lighted pushbutton controls located beneath the meters. The "auto" leveling mode function will automatically lower cylinders to adjust the slipform level, and the warning light will flash for overrange tilts.

The slipform effective length (SEL) is digitally displayed on the panel as shown in Figure 43. This is an important operational parameter governing lining quality. The SEL must be held within a certain range to avoid cracking or bulging the concrete. Should the SEL drift out of limits, the panel warning light would begin to flash.

The SEL is determined by the position of the curb relative to the slipform. Since concrete is pumped into the curb at a constant rate, the primary SEL control is via the speed of the cable jack system which lowers the CSL down the shaft. The cable jack speed control is located on the desk directly beneath the SEL meter. Should the SEL become too short, the cable jacks must be slowed down, and vice versa. With a constant concrete pumping rate, the cable jacks will also be set to operate at a constant speed, giving a steady SEL. Any change in curb advance rate or cable jack speed will immediately be reflected in the value of the SEL.

4.2.4.3 CSL Suspension System

The display grouping on the left side of the operator's panel (Figure 44) indicates and controls the orientation and direction of the jack ring and the three cable jacks. The three sets of jacks directly support the jack ring. Their position determines the level of the jack ring which also affects the slipform level. During normal CSL operation, the cable jacks will be walking together down the cables. However, hydraulic and mechanical differences among the three units will cause the jacks to step unevenly, and one will eventually lead the others. Control of the tilt is accomplished by hydraulically pausing the lowest unit until the other units catch up, as indicated by an acceptable tilt of the jack ring. An "auto" leveling mode pushbutton is provided to pause the jacks and hold the tilt within tolerance. A red warning lamp will flash whenever the tilt exceeds the preset limits.

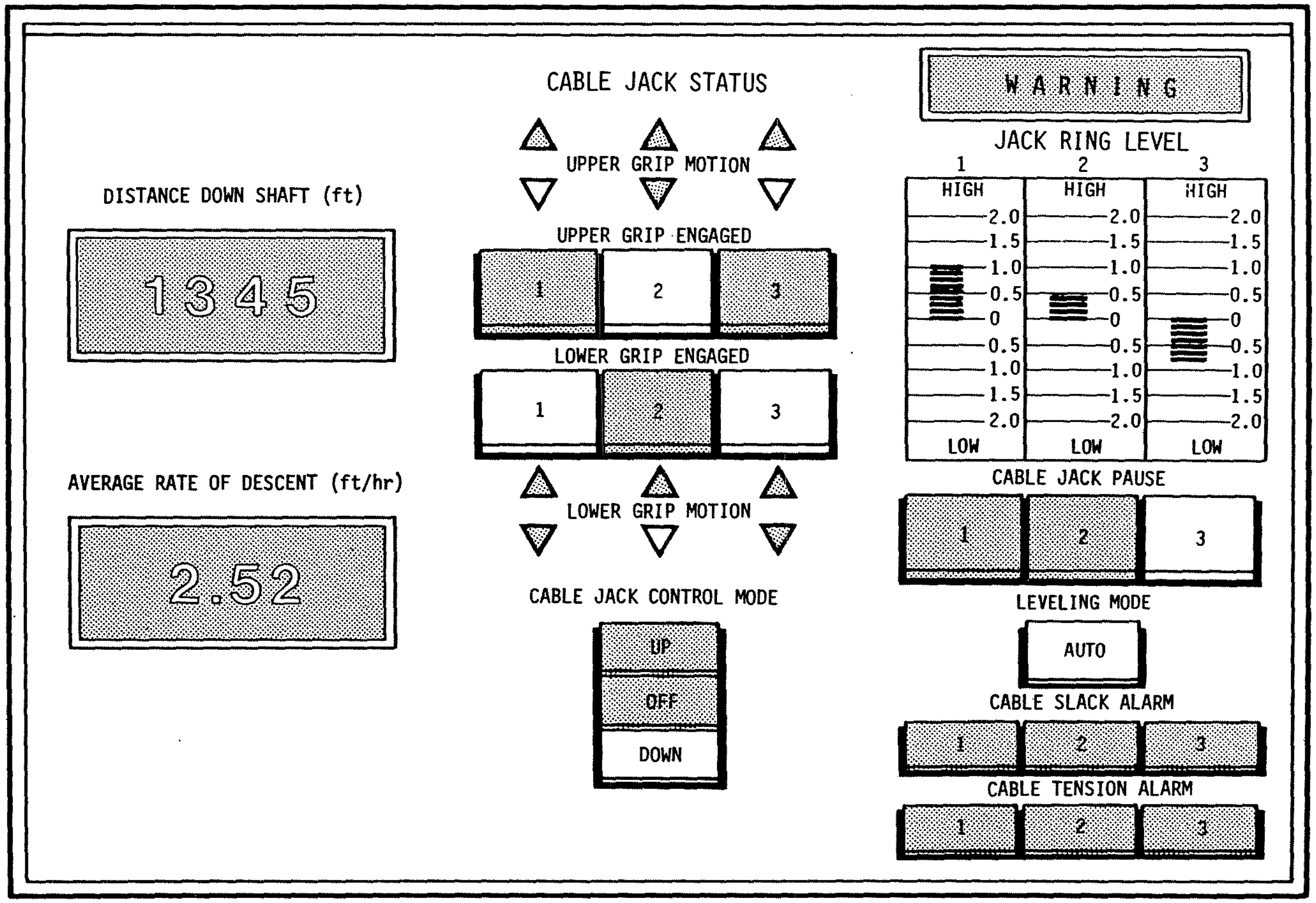


FIGURE 44. - Suspension system display grouping.

The cable tension alarm lamps in Figure 44 warn of impending overloads or slack in the suspension cables due to malfunction in the CSL suspension system. These lamps flash a warning before dangerous levels are reached, enabling corrective action to be taken with the suspension system. If an imminent cable slack situation is encountered, all three cable jack ring units will stop until the situation is corrected.

The movement of the cable jacks is displayed on the status indicator lamps of Figure 44. Each pair of cable jacks is connected by two hydraulic cylinders. The units walk with an alternating hand over hand motion, with one jack gripping while the other reaches for a new position. The block panel lamps indicate whether the upper or lower jack is gripped, and the arrow lamps show the direction of motion of the other jack. The suspension system status is thus clearly displayed, whether the jacks are moving up or down the cable.

The suspension system control mode buttons start/stop all three sets of jacks moving up or down. "Down" would be the normal operating mode, The other modes of operation are useful in a start-up or shutdown sequence. In combination with the jack pause functions, these control modes enable any individual or combination of jack movements to be made (in one direction at a time). Should the suspension system require more attention than directional or speed control, access to the hydraulic power unit is required, which is located on the third deck of the galloway.

The total distance down the shaft and the average rate of descent are read on digital meters shown in Figure 44. An encoder wheel mounted on the traling edge of the slipform rolling on the finished concrete lining, provides digital pulses which are counted and averaged to supply this information.

4.2.4.4 Hydraulic Panel Display

Located on the left side of the operator's control panel, the hydraulic oanel (Figure 45) is a hydraulic circuit diagram of the entire CSL system. Indicator lights on the diagram describe the status of the hydraulic valves and system components. Directional control switches for the individual curb cylinders are provided on the panel for system start-up and shutdown. The panel also includes warning lamps for low oil level, high oil temperature, and clogged filters, the on-off key

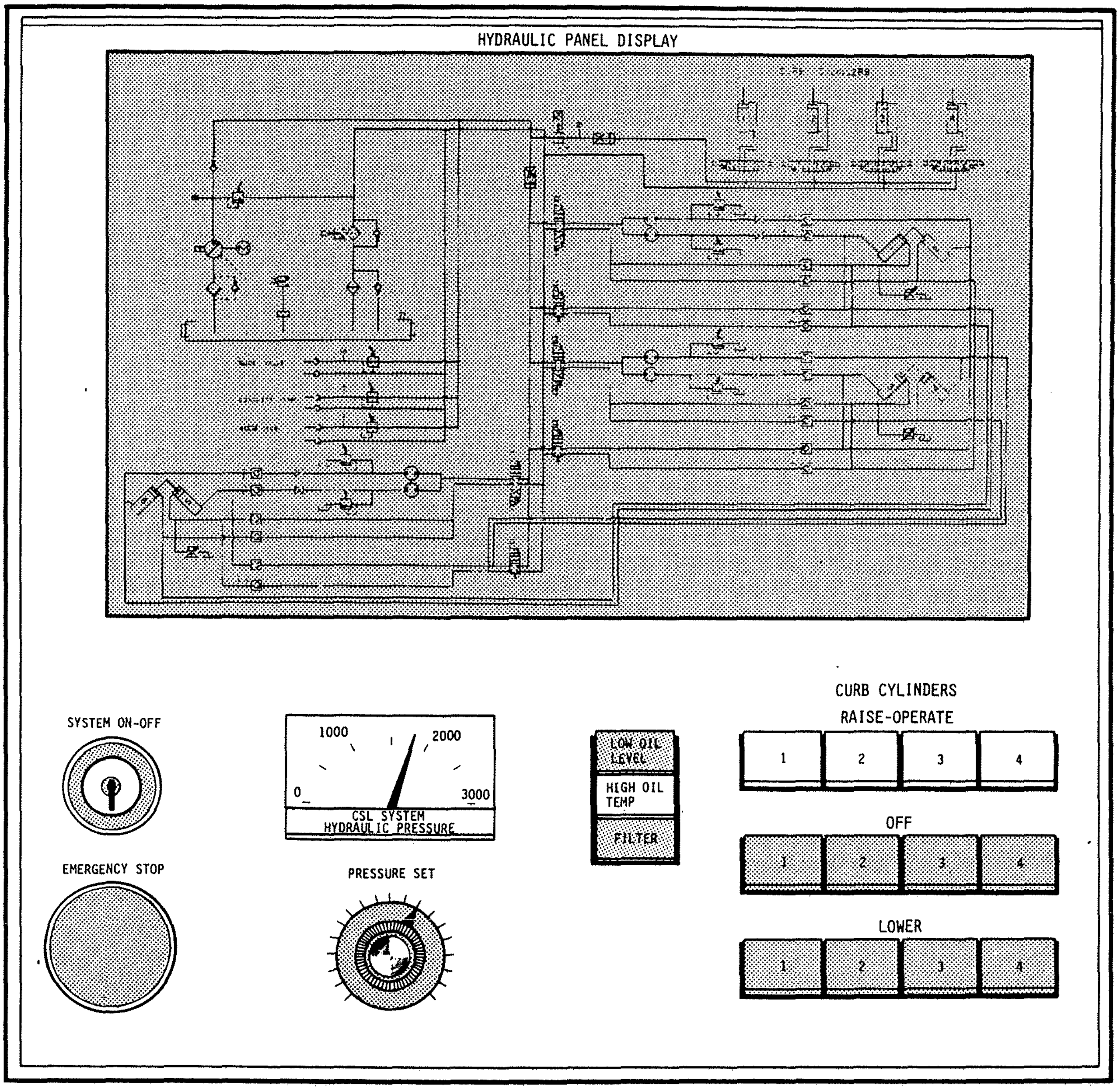


FIGURE 45. - Hydraulic system display grouping.

switch for the entire hydraulic system, a controller and pressure gauge for the hydraulic HPU pump, and an emergency stop button.

The emergency stop function is needed in case of equipment malfunction or hazardous situations. Activation of the button will stop the cable jack system and the concrete delivery system (concrete pumping and batching). However, the hydraulic pump will continue to run, keeping the curb cylinders pressurized and providing hydraulic power for corrective action by the CSL operator.

4.3 Nonlining Equipment

4.3.1 Galloway

The CSL system is designed to work in conjunction with a galloway, which is a multi-deck moving work platform. The galloway carries the necessary support equipment and personnel to operate the CSL. Figure 46 depicts the equipment arrangement on the five deck work stage. Figure 47 shows the relative position of this equipment to the CSL in the shaft. The upper deck of the work stage is provided for protection of the CSL operators from falling objects or shaft debris. The crosshead chair for the man hoist is mounted on this deck.

The CSL operator and pump operator are located on the second level. Also located on this level are the instrumentation and control panel and concrete pump remix hopper. This deck is positioned to allow the CSL operator a clear view of the concrete lining as it is extruded from the slipform. The third deck contains the hydraulic power unit and compressed air manifold for the various CSL operating systems. The third deck also provides the work station for repairs on the curb ring and curb seals.

The concrete pump and multi-port valve are located on the fourth deck. This deck is located relative to the CSL to provide a work platform for inspection and maintenance of the curb ring and slipform cylinders. The support systems operator divides his time between this and the fifth deck. This last stage of the galloway allows for preparing the shaft wall should oversized slough zones be encountered. It also allows for inspection and maintenance of the CSL suspension system grippers. Mounted beneath the fifth deck are the three cable reels for the three CSL suspension jacking units.

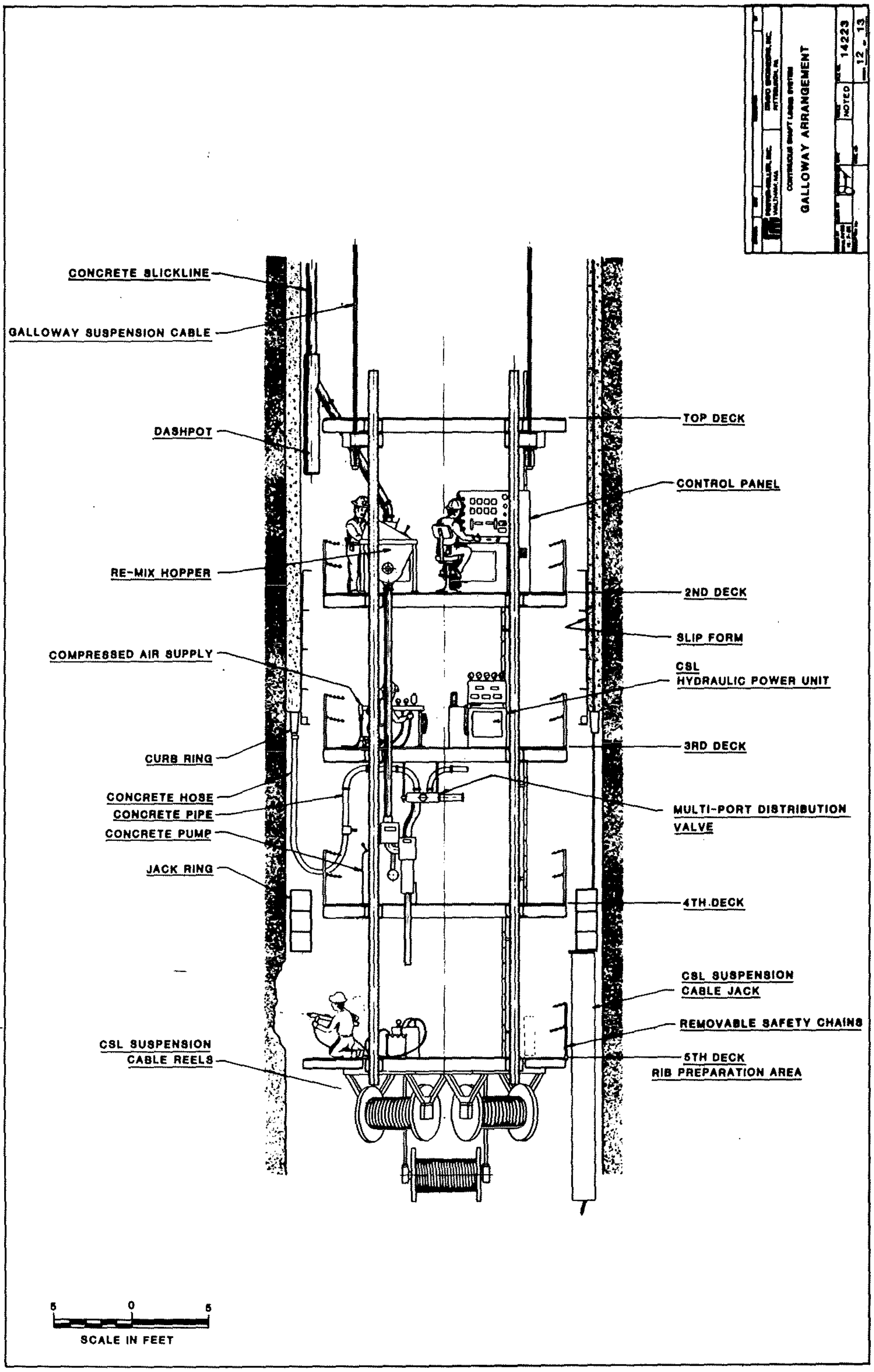


FIGURE 46. - Galloway arrangement.

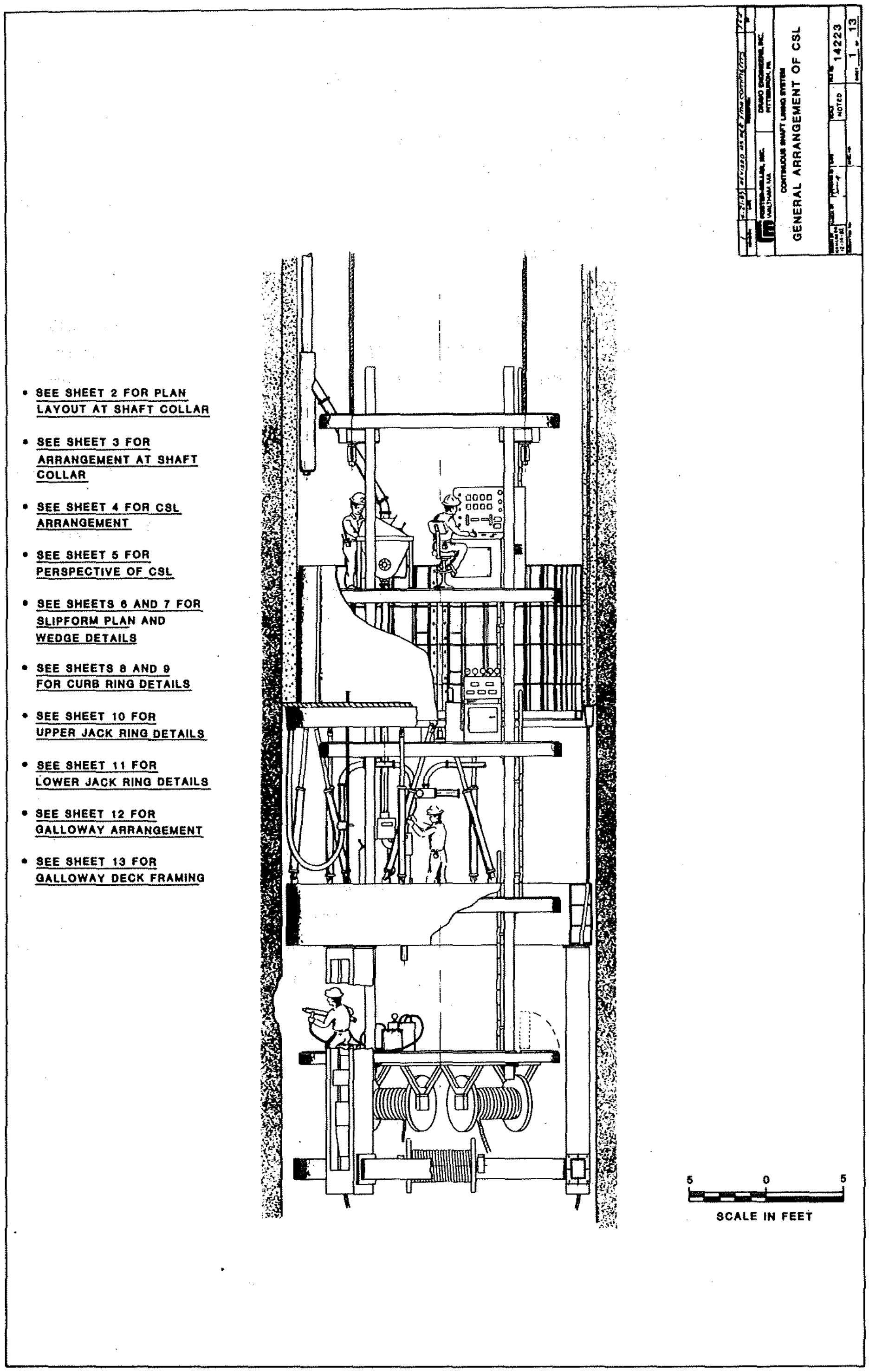


FIGURE 47. - CSL arrangement.

The galloway described is laid out to operate efficiently in a 20-ft diam raised-bored shaft. The arrangement of the equipment on each deck is shown in Figure 48. However, the arrangement of equipment is strongly dependent on the shaft sinking equipment being utilized. For example, when using a blind shaft boring machine, there would be need for additional services to pass through the galloway. These would include muck removal skips. Larger sized lines for power, ventilation, water and compressed air would be required. Additional pipe lines may be required if a laser guidance system is being utilized.

In smaller diameter shafts, the CSL support equipment will have to compete with space needed for access and maintenance. Additional decks may be needed to satisfy all requirements.

The galloway has been designed as a man-carrying structure. The CSL work crew do not ride on the CSL under normal operating conditions. They will only mount the CSL for routine and emergency maintenance and repairs when these tasks cannot be accomplished safely from the galloway. Fire protection is provided by use of portable fire extinguishers located on each deck. Each working deck contains safety chain guard rails as further protection for the operators.

4.3.2 Galloway Suspension System

Because the CSL is a continuously lowering system, it requires a more sophisticated galloway suspension system than a conventional galloway. Conventional shaft lining is a step function operation. The form and curb are set in position, concrete is poured and allowed to cure, and the form and curb are then independently stripped, lowered and reset. This cyclic process takes anywhere from 6 to 12 hr depending on concrete set time, ground conditions, and desired rate of advance. During this period the galloway is stationary and provides a work deck for concrete placement (through multiple chutes). Once the curb and form are released, the work stage is lowered to the next position by a standard winching system to allow for resetting the curb and form. The typical suspension system is a multiple cable/winch operation (usually a 2 or 3 cable system). This operation does not require that the galloway remain perfectly level as it is lowered.

The CSL's main support systems are mounted on the galloway and include the concrete pump and the hydraulic power supply. These two systems are connected directly to the CSL via flexible hoses. Therefore, the galloway must remain in a relatively

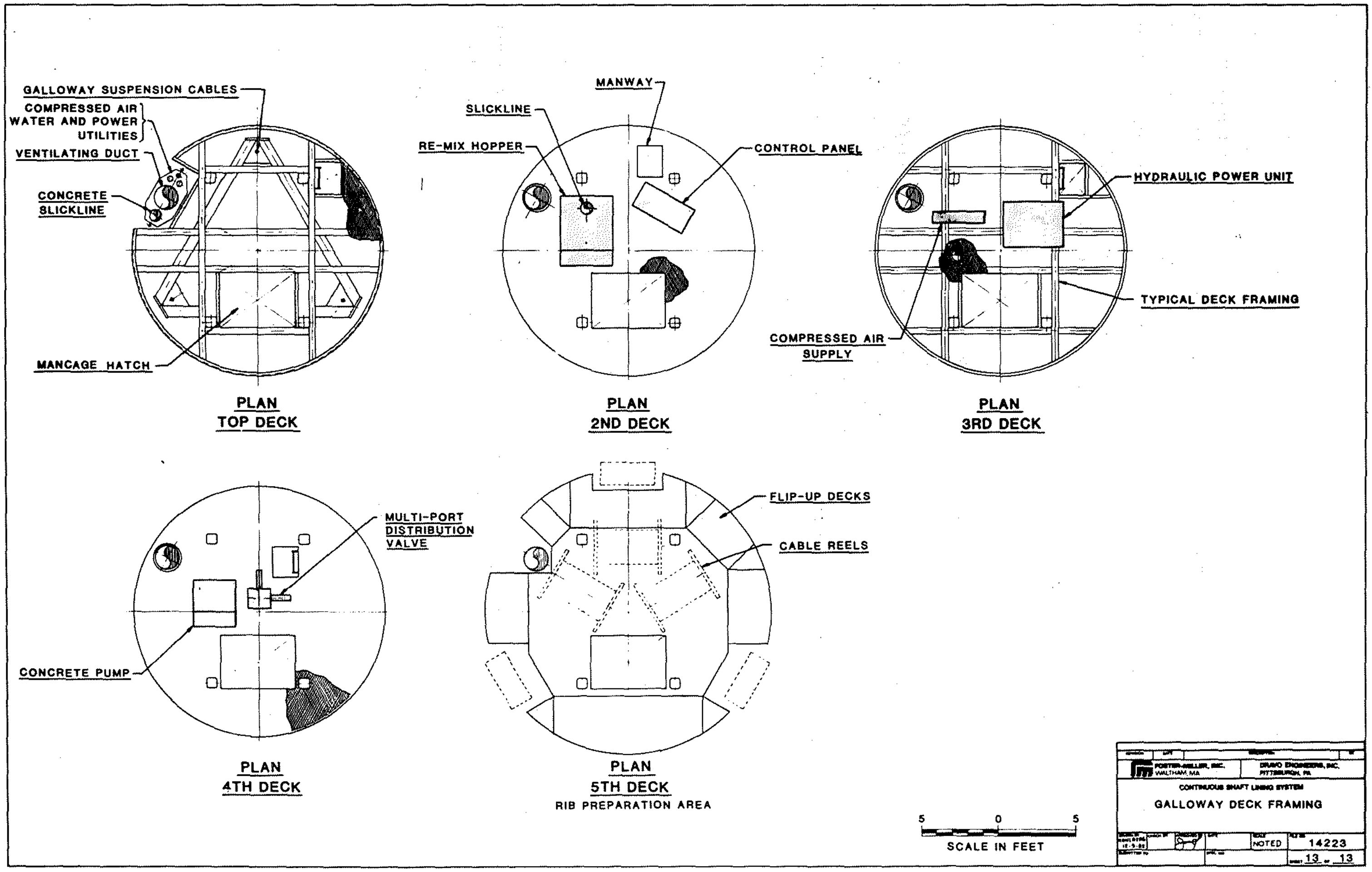


FIGURE 48. - Galloway deck arrangement.

fixed position in relation to the CSL in order not to overstretch these lines. In addition, the CSL operator's position relative to the slipform is crucial to allow for direct observation of the emerging concrete lining. For these reasons, the CSL galloway must be capable of being lowered continuously with the same speed range capabilities as the CSL suspension system. Therefore, a similar three-point cable gripping system has been proposed for the galloway (see subsection 4.2.2 for details on how the grippers operate). However, these gripper units are mounted on the shaft collar steel superstructure (see Figure 49). The safety factor for the galloway ropes is 8, in accordance with MSHA requirements, as this component of the system is manned.

4.3.3 Surface Support

Figure 50 depicts the layout of the surface support systems. These include the collar mounted hoists (galloway, service extension and man cage), cable storage reels, concrete plant, compressor and steel head frame. The following subsections will discuss in detail the concrete plant and delivery system, and the extension of underground services.

4.3.3.1 Concrete Plant and Delivery Systems

The concrete plant and delivery system is the largest subsystem of the CSL, both in terms of physical size and in number of operators. It comprises all the equipment from the loading of aggregates to the vibration of placed concrete above the curb ring. As an integral part of the underground CSL conceptual design, the concrete plant and delivery systems' performance, operation and design must be compatible with the needs of the CSL. The following subsection will serve as a specification for the concrete plant and delivery system. This will include the following components:

a. Concrete plant

b. Admixture skid

c. Concrete pump

d. Concrete drop slick line and dashpot

e. Concrete slide valve and shutoff valves

f. Concrete delivery lines

g. Concrete curb nozzles

h. Concrete vibrators.

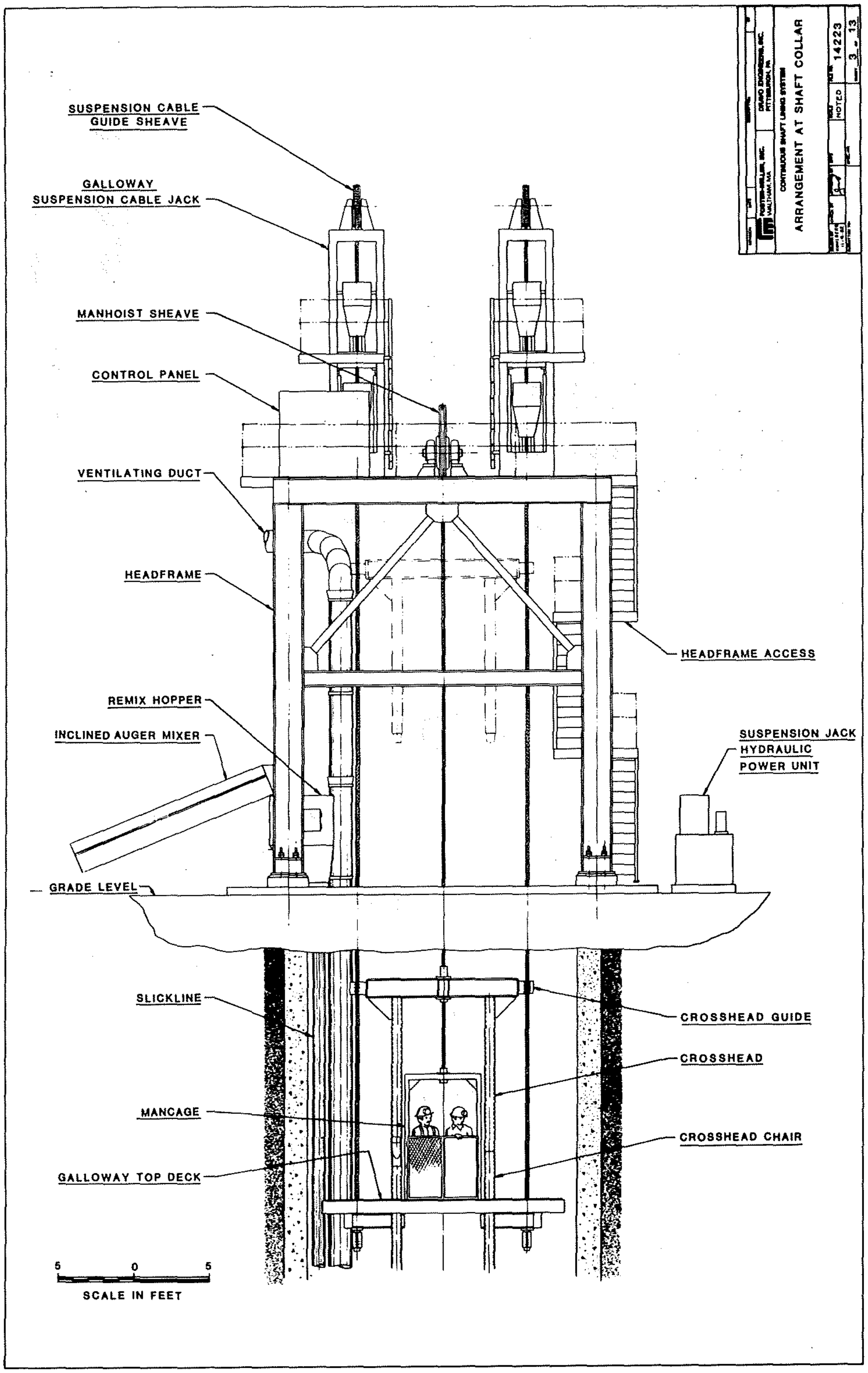


FIGURE 49. - Arrangement at shaft collar.

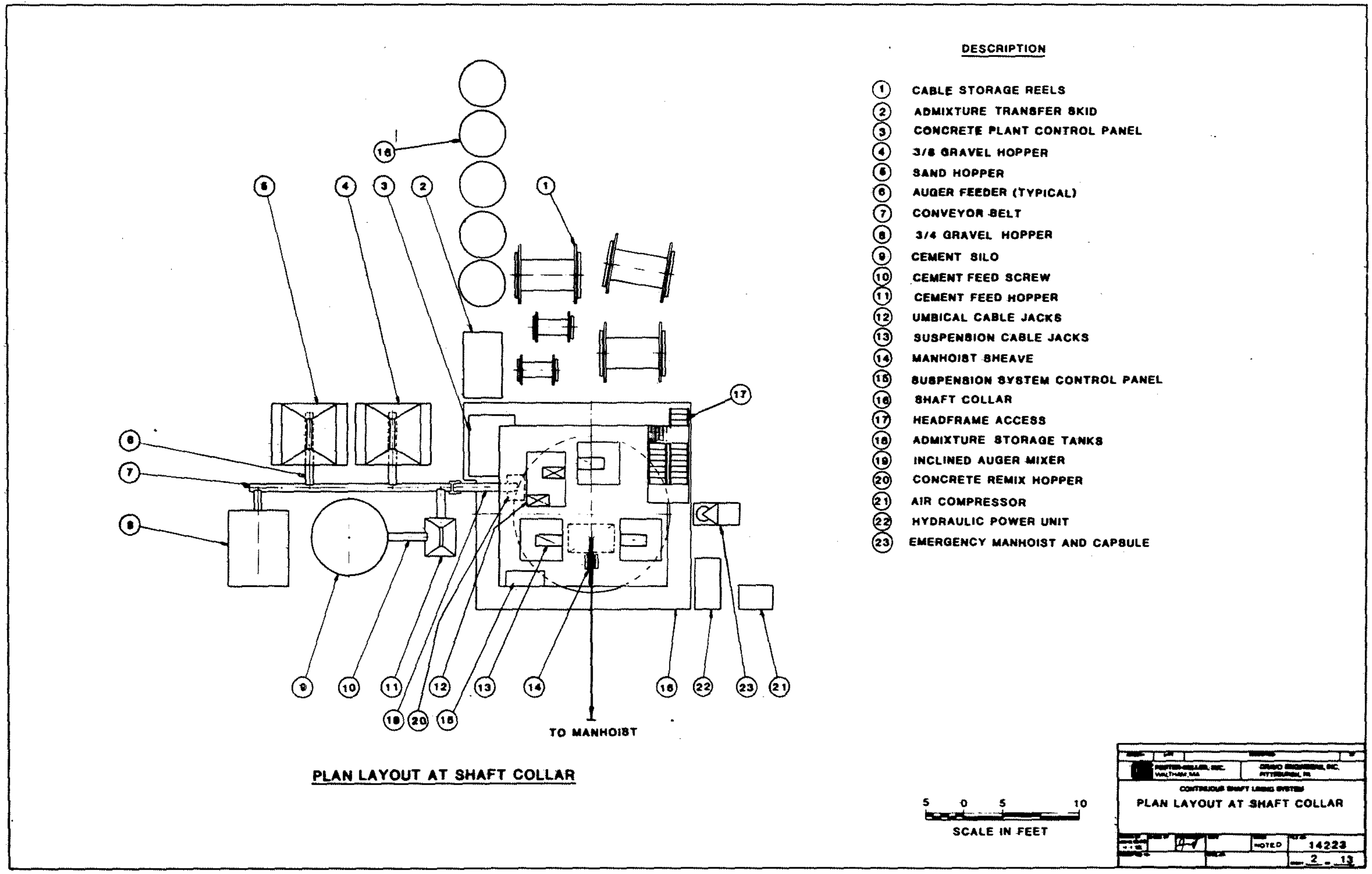


FIGURE 50. - Plan layout at shaft collar.

The concrete process is critical to CSL operations in two important areas. First, the characteristics of the final mix give the concrete the properties that allow for rapid slipforming. Maintaining the accurate proportions of the mix's constituent parts is a prime function of the concrete plant. Secondly, the rate of advance of the CSL down the shaft is determined by the rate of placement of concrete. If changes in the rate of advance are required, then the concrete mix must also be changed to a new production rate, but in the same mix proportions. This change must be accomplished quickly and accurately.

Concrete placed by the CSL must be used as young as possible. Because of the limited time allowed for placement inside the form, and taking into consideration the residence time that the concrete spends in the delivery system prior to placement, it is most desirable to make concrete on-site on a continuous basis. In this way, the age of the concrete entering the slipform can be minimized and is known to the operator. In consideration of the requirements stipulated above, a small, mobile concrete batch plant, capable of continuous, accurate production was selected to provide design mix concrete to the CSL.

The batch plant is located close to the shaft collar. Stockpiled materials can be stored in a convenient location near the batch plant.

General Specifications for the Concrete Plant

a. The concrete plant shall be capable of uniform, continuous output with a production rate adjustable from 2 to 20 yd^3/hr.

b. The plant shall have a bin with a volumetric proportioning auger feeder for each dry bulk concrete component. This includes 3/4 in. gravel, 3/8 in. minus pea stone, sand, and cement. In addition, each auger feeder shall be individually controlled with sufficient accuracy to insure proportioning of the concrete mix within plus or minus 1-1/2 percent of the correct component weight per unit time.

c. For large scale operations, appropriate yard facilities shall be provided in support of the concrete plant. These include a flat, well-drained yard for aggregate storage, a minimum 250 barrel cement silo with an automated cement transfer system for loading the concrete plant cement bin, a level, well-drained yard for the concrete plant and adequate room to operate aggregate loading equipment.

d. The electronic and electrical controls of the concrete plant should be in water-tight enclosures suitable for outdoor use. Further, this equipment should be designed for continuous operation at ambient temperature ranging from 32 to 95°F (0 to 35°C). For operations outside these temperature limits, special preparation and handling of the aggregate and admixtures will be required.

e. The mixer shall be a continuous auger type. This auger mixer must be capable of producing a uniform mix throughout the operating range of the plant.

f. The maximum dry component requirements are:

cement	15,040 lb/hr	180 tons/day
sand	24,500 lb/hr	300 tons/day
stone	30,000 lb/hr	360 tons/day

The stone includes 3/4 in. stone and pea stone.

g. The controls of the concrete plant should be operable by one man. Two operators should be able to perform all necessary functions related to the production of concrete with the plant including loading aggregates, but exclusive of the admixture skid.

General Specifications for the Admixture System

a. The admixture system will be capable of continuous operations at rates necessary to produce 2 to 20 yd^3 of concrete/hr.

b. The admixture system will be capable of processing and controlling four different fluid components individually. They include water, calcium chloride solution (the accelerator), superplasticizer in solution, and an air extrainment fluid in a dilute solution. The individual components will be metered to the correct proportions as specified in the mix design and mix rate. The accuracy will be plus or minus 1-1/2 percent the correct weight per unit time.

c. The admixture system will have a large batching station capable of producing admixture in rates necessary for continuous operations. All admixtures will be by weight-batched with a 1/2 percent accuracy requirement on all weights. In addition, a 100 gal/hr water source shall be provided at the site. If water is to be tanked in, a minimum 12,000 gal storage tank will be required. Storage facilities and handling equipment will also be required for processing of palletized dry chemical and drummed fluid chemical admixtures.

d. The electronic and electric controls of the admixture system should be in water-tight enclosures suitable for outdoor use. This equipment should be designed to work in ambient temperatures from 32 to 95°F.

e. The admixture system will be capable of fully processing the fluid solutions used. This includes pressure control from 6 to 20 psi and temperature control from 32 to 160°F.

f. The maximum fluid admixture requirements are:

Water	8.0 gpm	480 gph
20 percent calcium chloride solution	5.0 gpm	300 gph
Superplasticizer solutions	1.5 gpm	90 gph
Air entrainment solutions	0.54 gpm	30 gph

g. The admixture system will be designed for one man operations with some help from the concrete plant operator.

h. The following is an explanation of the conceptual design admixture system schematic diagram shown in Figure 51:

1. P_1 and P_2: Fluid pumps - these pumps serve as the main and auxiliary mix, remix, and transfer pumps (1 hp, 60 gpm, at 10 psi)

2. P_3, P_4, P_5, P_6: Main solution feed pumps (1 hp, 16 gpm, at 20 psi)

3. T_1, T_2, T_3, T_4 T_5: Main solution storage tanks and mix tanks. T_1, T_2, T_5 - 2000 gal; T_3, T_4 - 1000 gal

4. PCV-1, 2, 3, 4: Pressure control valves - these valves regulate the system pressure between 5 and 20 psi

5. P_7: heat exchanger pump - this pump circulates water between the hot water tank and the heat exchanger

6. MV-1, 2, 3, 4: Mixing valves - these mixing valves take cold tank solutions and hot solutions from the heat exchanger and mix them to the temperature required in the concrete specifications

7. FM-1, 2, 3, 4: Flow meters - these are rotary type flow meters used as a visual check in the operations of the admixture system

8. FCV-1, 2, 3, 4: Flow control valves - these are precision needle valves sized to the flow rates of the solutions and are used to control the flow rates of those solutions.

General Specifications for the Concrete Drop Slick Line and Dashpot

The concrete drop slick line is an 8-in. diam schedule 40 steel pipe which carries the concrete down the shaft to the remix hopper of the concrete pump. The top of the slick line is mounted in a small hopper into which the auger mixer discharges.

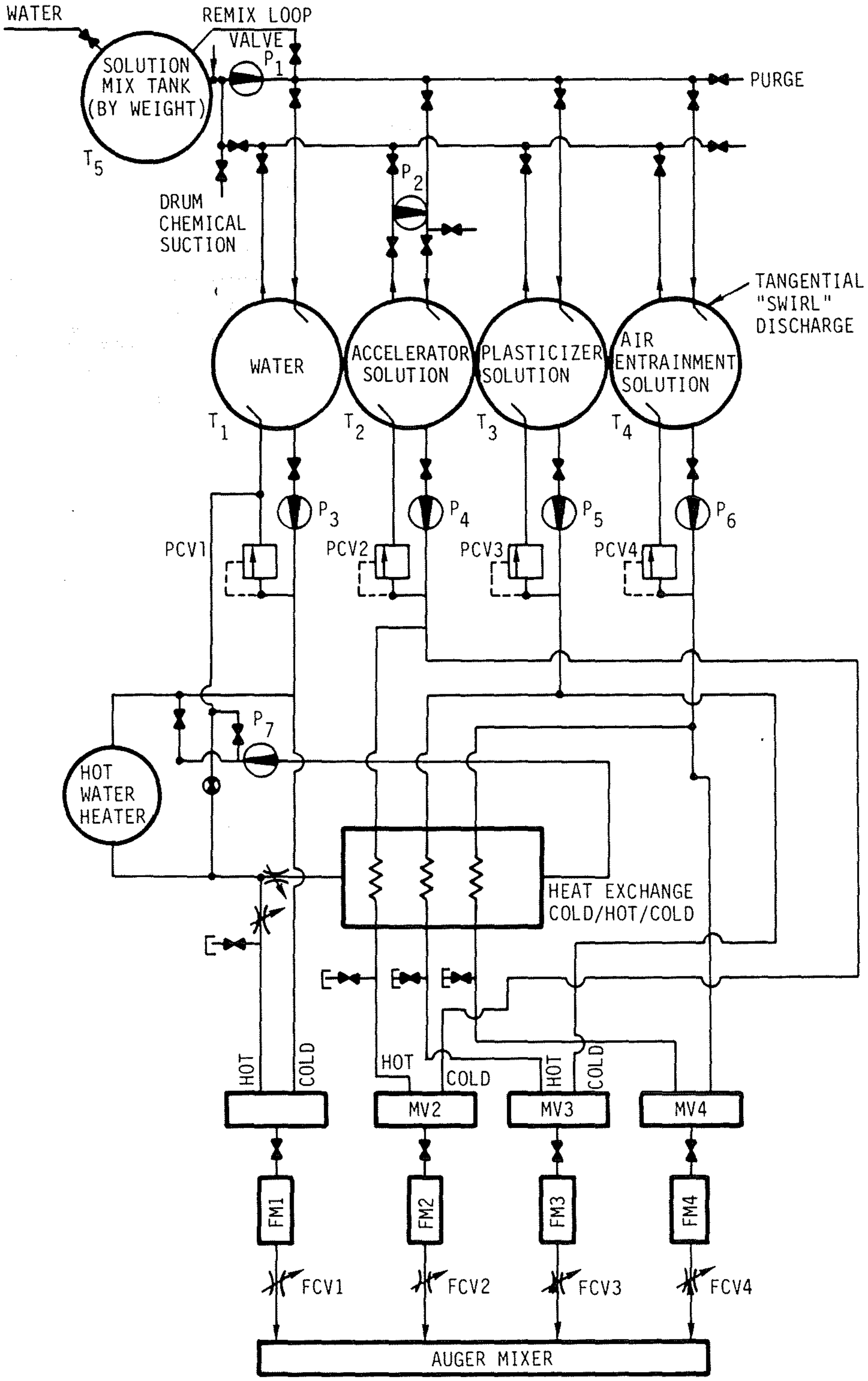


FIGURE 51. - Admixture system schematic.
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The concrete then drops down the line and into the energy absorbing dashpot at the bottom of the line. This is shown in Figure 52. The outlet of the dashpot discharge into the concrete pump remix hopper mounted on the galloway. The dashpot is located near the second deck of the galloway in the shaft.

General Specifications for the Concrete Pump

The concrete pump is the work horse of the CSL system. It is a commercially available positive displacement type unit, mounted on the galloway. The pump supplies the power to place the concrete behind the slipform with enough pressure to overcome the induced back pressure created by the curb ring hydraulic cylinders. In addition, the concrete pressure behind the slipform provides the prime motive force to drive the CSL down the shaft. Because the CSL operates continuously, the pump must be capable of continuous, but variable operation, to allow for changes in the rate of advance.

A detailed analysis and review of the concrete pump used for simulation tests is given in the impact on underground designs, Volume II, Section 2. The specifications are as follows:

a. The concrete pump shall be vertically oriented to take up a minimum of space on the galloway.

b. The pump shall be designed for continuous operation without failure due to cumulative build-up of material.

c. The pump should have a variable pumping rate from 0 to 20 yd^3/hr and be capable of generating concrete pressures in excess of 500 psi.

d. The pump shall be hydraulically operated.

e. The pump shall be of positive displacement design and positive valving, with dual 6 in. diam bore material cylinders.

f. The system shall have a remote hydraulic power supply and be remotely controlled and automatically actuated.

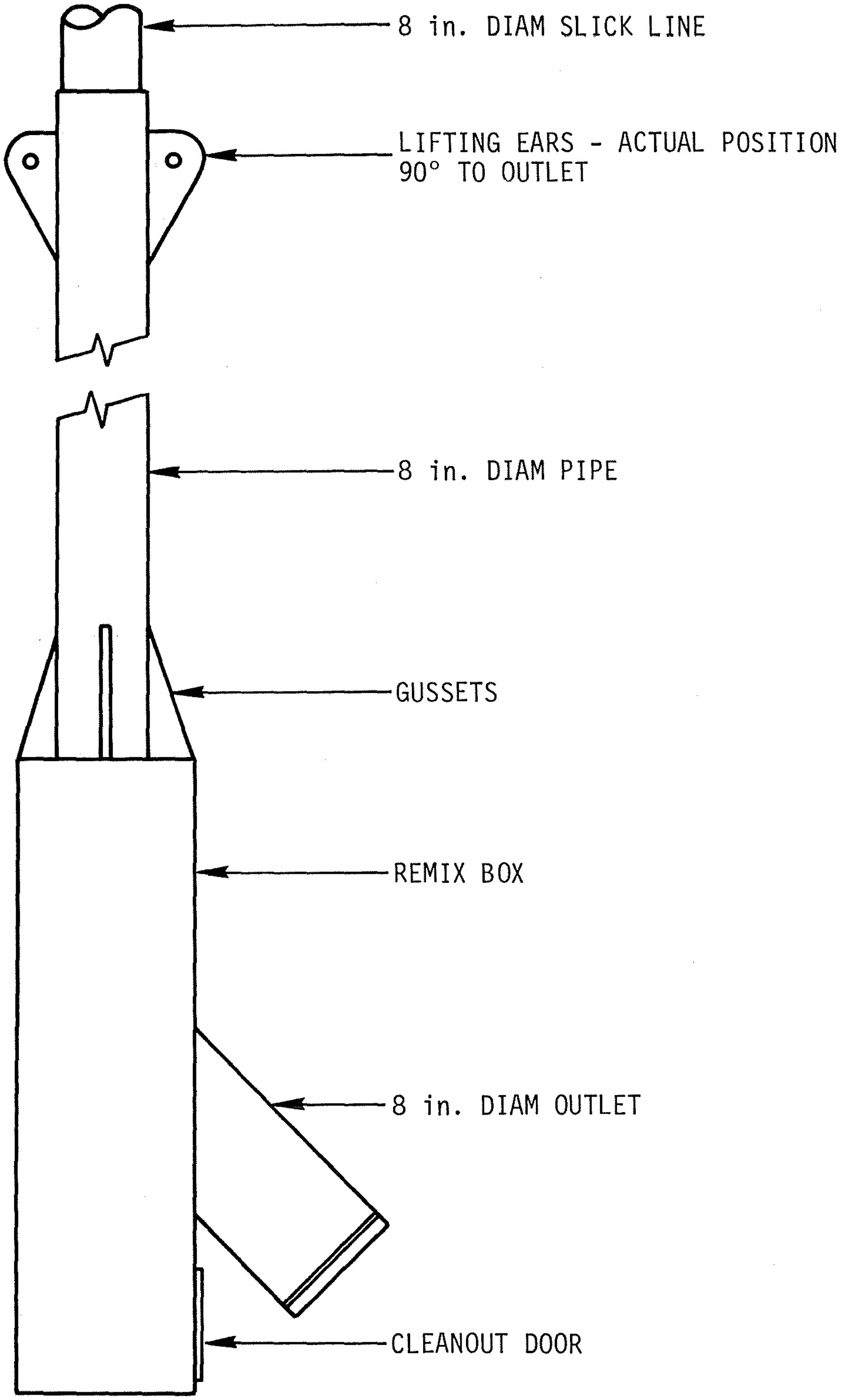


FIGURE 52. - Typical dashpot at the bottom of the concrete slick line.

Multi-Port Slide Valve Requirements

Concrete is discharged from the concrete pump through a single steel slick line. This line feeds immediately into the inlet of the multi-port valve. Here, the flow can be directed to four outlets, each one connected to a port on the curb ring. The flow is not split four ways simultaneously, but rather the total flow is sequentially switched from port to port. Figure 53 shows a four-way slide valve.

a. The valve is hydraulically actuated

b. Remotely controlled

c. Automatically sequenced

d. Sized for 4 in. concrete slick lines with quick disconnect victaulic couplings

e. Designed for 350 psi maximum operating pressure.

Concrete Delivery Lines Requirements

The concrete delivery lines will be:

a. Four-inch diameter steel slick lines or 4 in. rubber flex lines

b. Rated working pressure of 500 psi

c. Heavy duty grooved ends and couplings (see Figure 54)

d. Equipped with nylon safety chains (see Figure 54)

e. No more than 10 ft in length, any one piece

f. Bend radius no smaller than 24 in.

g. Spade type shut-off valves will be used (see Figure 54) to cut-off concrete flow

h. Concrete inlet nozzles will be insert type with grooved ends, designed for quick release from the curb ring. Figure 55 shows a typical concrete nozzle.

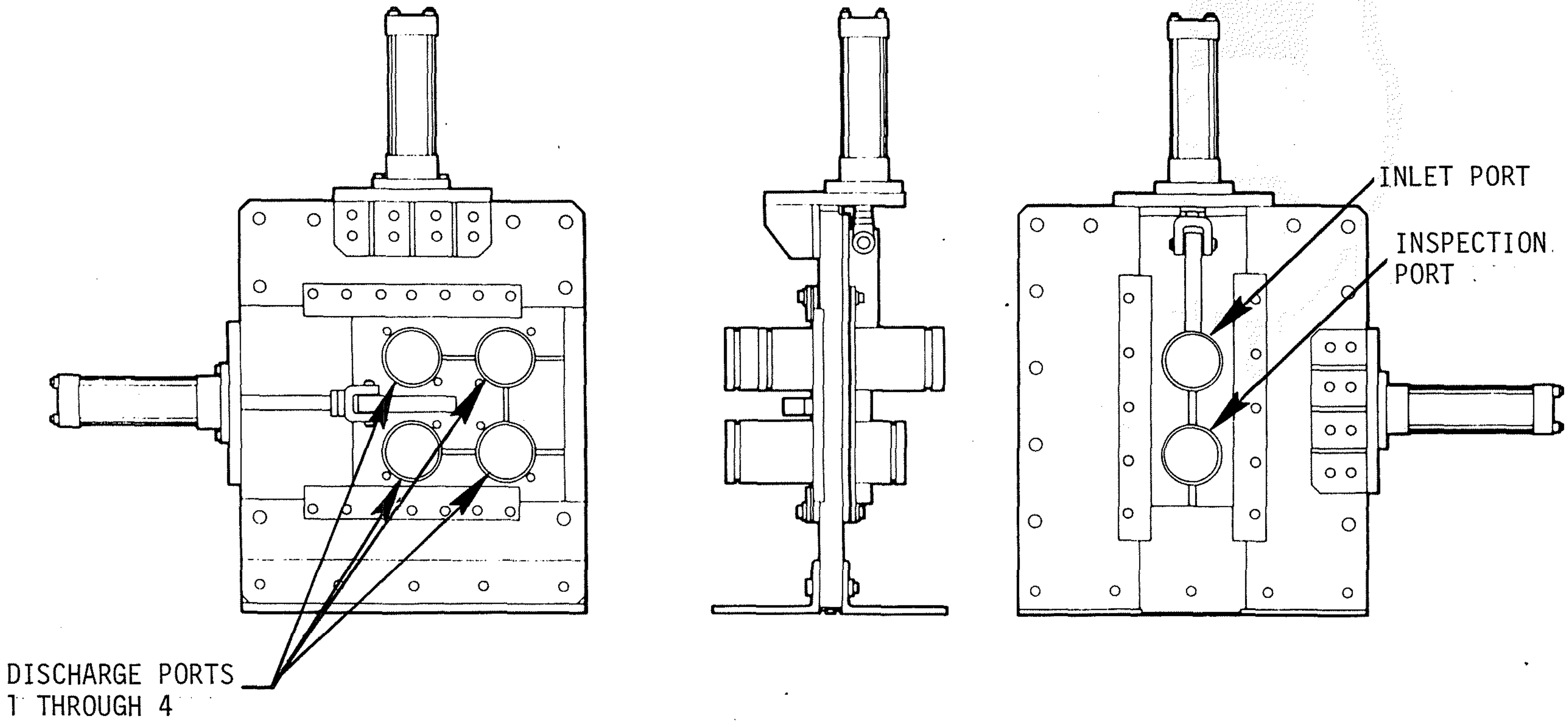


FIGURE 53. - Four-way slide valve.

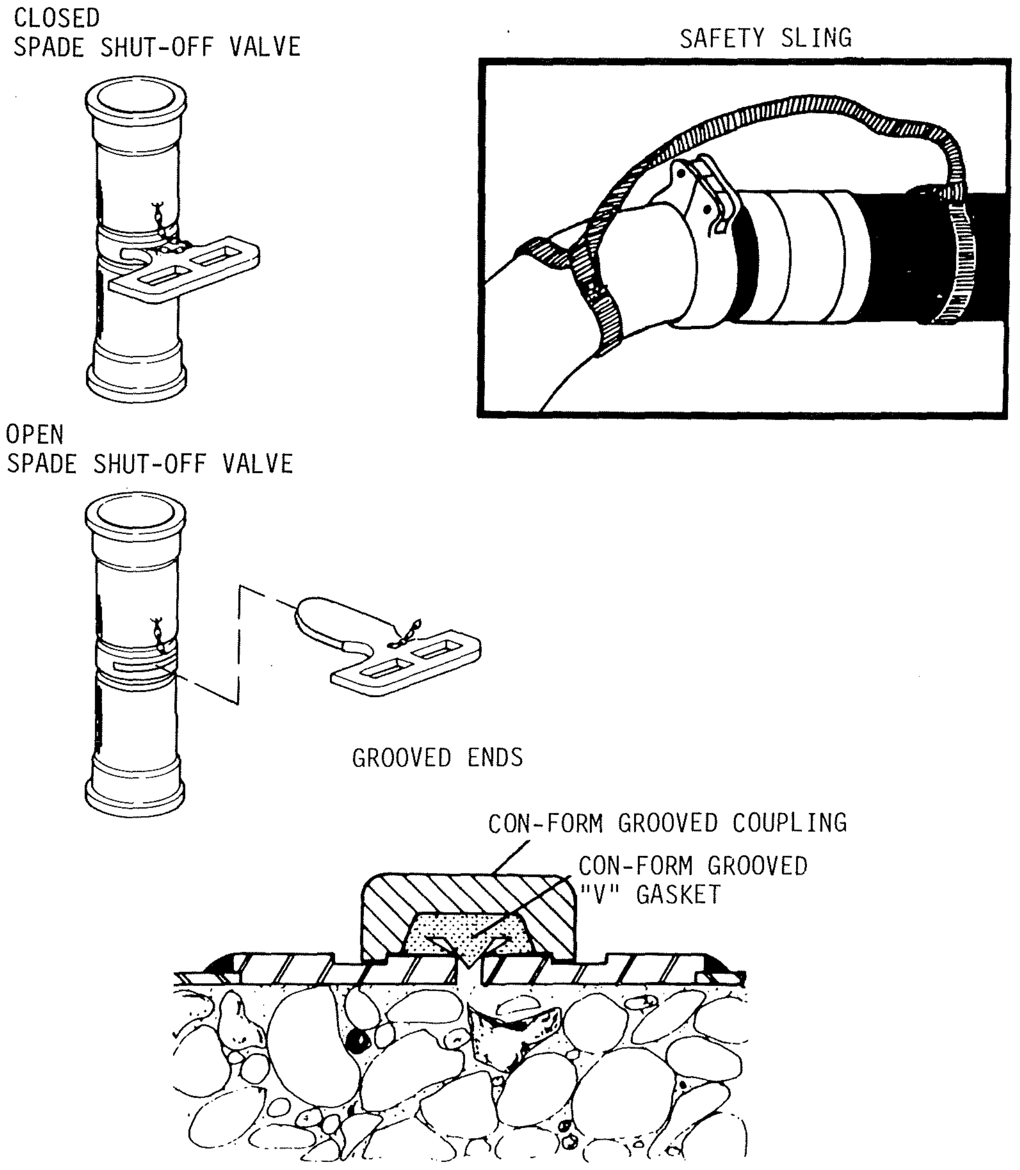


FIGURE 54. - Concrete line shut-off valve and couplings.

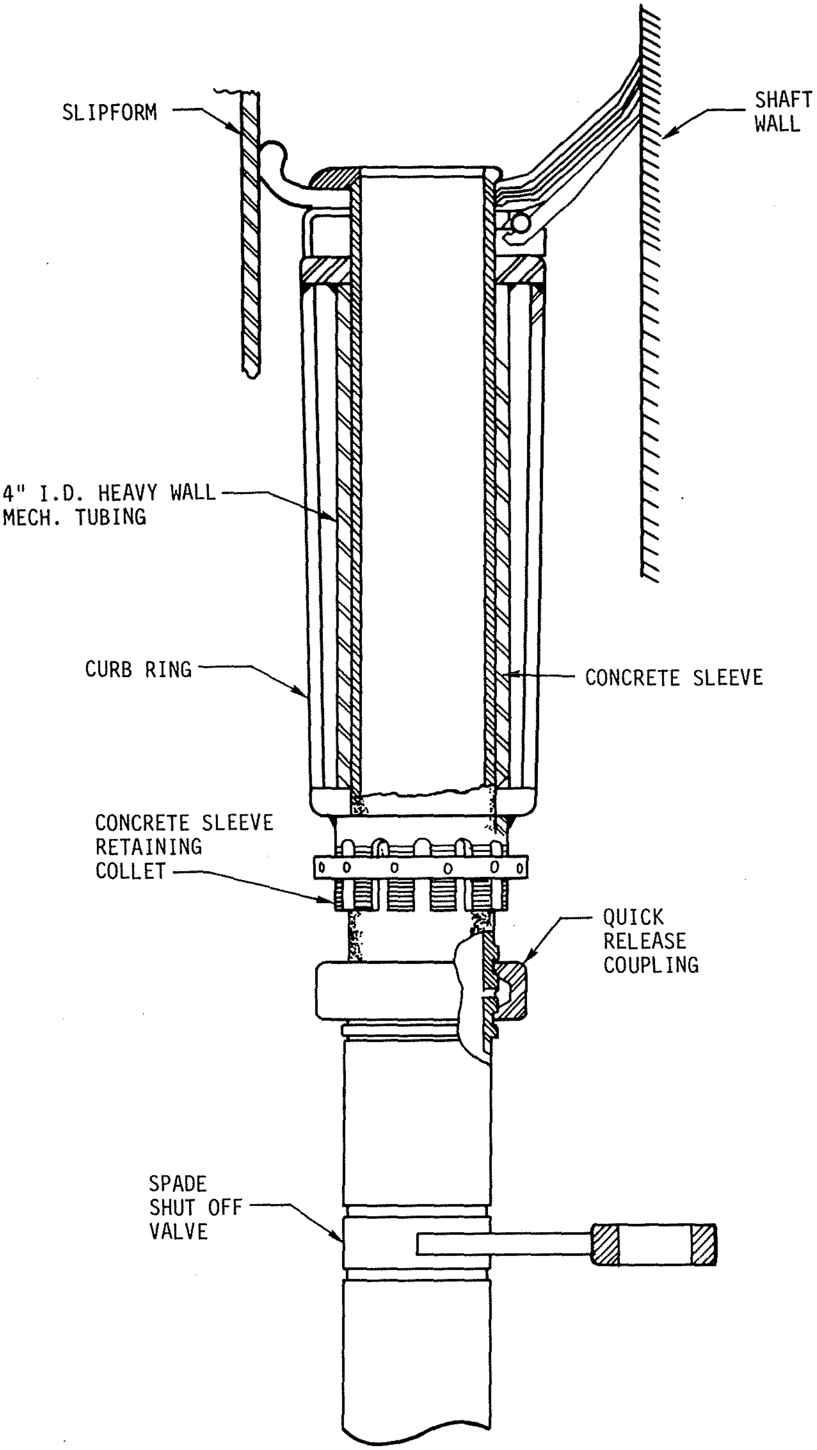


FIGURE 55. - Concrete nozzle.

Concrete Vibrator Requirements

The concrete used in the CSL requires intermittent low amplitude vibration. This will be provided by six independent vibrators as follows:

a. The vibrators will be hydraulically powered with an operating range between 600 and 1000 psi and 7 to 10 gpm flow requirement.

b. The vibrational frequency shall be variable with a range between 3500 to 5300 Hz.

c. The vibrators shall produce between 300 to 600 lbf within their operating range.

d. The vibrators will operate on a 10 to 20 percent duty cycle.

e. All vibrators will operate simultaneously and vibrate independent plates mounted on the top of the curb ring.

Typical vibrator mounting is shown on Figure 56.

4.3.3.2 Service Line Extension System

It is the objective of the service line extension system to provide construction services to the CSL on a continuous basis. The services to be provided include intake ventilation, utility water, compressed air, concrete supply, communication and power cables. Traditional methods of extending these lines involve transporting sections of duct and pipe down the shaft and storing a small inventory of parts on the galloway for fastening sections of pipe and duct together and to the shaft lining. While the lines are being extended, this stops most other operations down hole. A top-assembly system eliminates the traditional problems and permits the service line extension to be completely independent of the lining operation. Extension will be made at the rate demanded by CSL advancement. Under normal operating conditions, the CSL will not have to shut down to extend service lines.

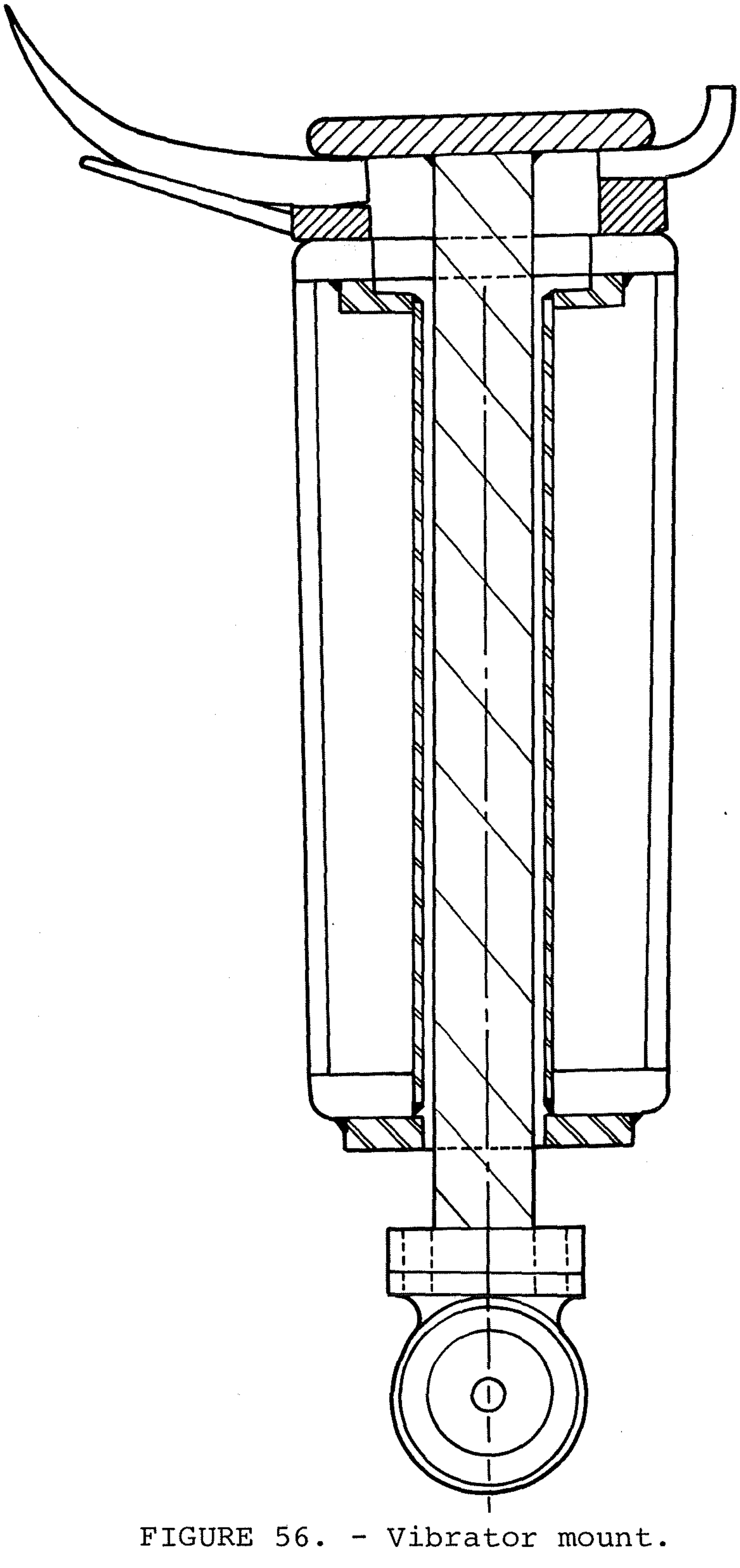


FIGURE 56. - Vibrator mount.

General System Concept

The guidelines which must be followed to design extendability into each of these services will differ. Ventilation ducts are high flow-low pressure systems. This type of flow cannot tolerate the high pressure losses that would occur in tight bends. Therefore, the extension system must be along the axis of the ventilation ducts. In the case of the compressed air and water lines, the pressures are high and the flow moderate. This will allow the use of a limited number of bends. In contrast, the concrete slick line cannot tolerate any bends. The air, water and concrete services can all be interrupted for a short period during the extension cycle. The power and communication systems, however, must maintain continuous operation.

The extension system involves supporting the pipes and the ducts from two steel cables which extend from the headframe at the shaft collar down to the shaft work area. As the shaft is advanced, the cables and the service lines attached to them are lowered by an hydraulic jacking system mounted approximately 25 ft above the shaft collar on the headframe. New lengths of duct or pipe are added in this 25 ft space, as described below and illustrated on Figure 57.

Leading from the air intake fans to the shaft is a stationary air duct which is elevated for convenience. The method for maintaining the connections between the stationary duct and the duct being lowered is similar to vertical slider tubes or telescopes. The stationary duct is approximately 25 ft above the collar at the edge of the shaft. At the shaft, this duct turns 90 deg downward and the vertical portion extends to just below the shaft collar. This vertical portion forms the inner member of the slider tube. The sections of duct to be added to the string are split lengthwise into two halves and hinged along one of the lengthwise joints. This allows the sections to be opened, placed around the slider tube, clamped closed again, and connected to the section below.

Sufficient communications and power cable will be provided on separate cable reels mounted on the headframe above the cable jacks (see Figure 57). These services will be reeled out continuously as the CSL proceeds down the shaft, and will be clamped to the support frames like the other services.

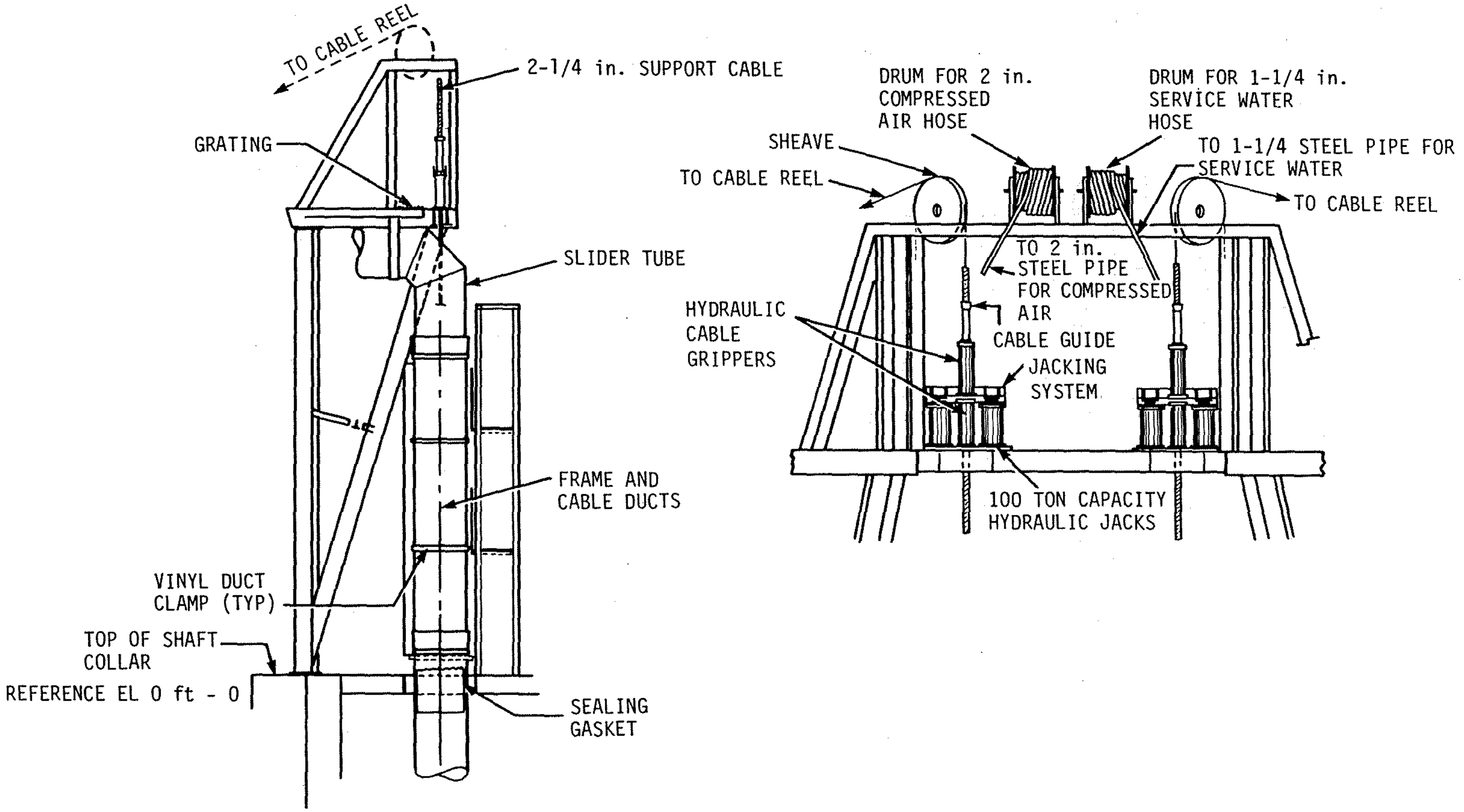


FIGURE 57. - Service line extension system.

The compressed air and water supply pipes are connected at the surface to their respective compressor or pump by flexible hoses. When a new section of pipe is added, the top of the pipe and the hose connection extend 20 ft above the shaft collar. As the service lines are lowered into the shaft, this connection descends, approaching the collar. At this point the flexible connection is broken, a new section of pipe added, and the flexible connection moved up to the top of the new section.

The concrete slick line is connected to a concrete hopper located on the ground level of the shaft collar. The extension of this line cannot, therefore, be handled above the ground in a similar manner to the other services. Therefore, it must be accessed from below ground level in the collar area. Shorter lengths of pipe would be added for ease of handling.

As new sections are added, all lines are lowered down the shaft and support frames are placed around the entire service line bundle. The frames are located at fixed intervals and individual pipes and ducts are fastened to the frames. Each frame is clamped to the support cables. Thus, the service lines are supported from the cables at regular intervals for the entire depth of the shaft.

At the bottom of the shaft, the water and compressed air lines are connected to the CSL by flexible hoses. The fresh air supply duct terminates immediately above the CSL. The concrete slick line is terminated at the energy absorbing dashpot. The power and communication cables continue directly to the main breaker board on the galloway.

Although certain features of the utility lowering system described above are site specific, such as the storage area and headframe, the basic system and its components are applicable to all shafts. Reuse of the materials from one job to another is a cost benefit factor.

Service Line Description

A brief description of each of the service lines is given below including its function, material composition and type of construction.

a. Fresh Air Supply Duct - High volume fans supply fresh air to the shaft interior via a large diameter duct. It is estimated that the CSL system will require 10,000 cfm for breathing air. The duct is constructed of fiberglass reinforced plastic to withstand a positive or negative pressure of 15 in. of water. Each duct segment is cut lengthwise into two halves at the factory. The two halves are then rejoined by flexible, "H" shaped joiner strips. On one side of the duct the joiner strip is permanently fastened to each duct half, thus forming a hinge. At the opposite joint, the strip is fastened to only one duct half at the factory. The duct is clamped into the round configuration by inserting the duct edge into the open end of the "H" joiner strip and clamping vinyl "barrel lid" type clamps around the pipe. It is recommended that the duct be clamped in the round position during handling and left open during shipping and storage to reduce space requirements. This method of fabrication permits extension of the ventilation ducts without interruption of air flow to the CSL.

b. Compressed Air - A 2-in. diam schedule 40 steel pipe supplies compressed air to the shaft lining operations. Pipes shall have grooved ends. The system pressure will be 100 psi at the galloway manifold. The volumetric rate of air supply will depend on its expected useage.

c. Service Water - A 1-1/2-in. diam schedule 40 steel pipe supplies water for the CSL and general clean-up use. Pipes will have grooved ends. Water service pressure should be restricted to 50 psi by use of pressure regulators.

d. Concrete - a 8-in. diam schedule 40 steel pipe delivers concrete to the dashpot located above the remix hopper on the galloway. Pipes shall have grooved ends.

e. Communication and Power - Flexible communications and power cables extend to the galloway. Mining regulations require at least two means of communication to the surface, one of which must be voice. Extra back-up wires from the surface will be provided to meet this requirement. The service voltage to the CSL is expected to be 480V, and the cable sized for a maximum power requirement of 150 hp.

f. Support Frame - The service line support frame is constructed as shown on Figure 58. Its purpose is to bind the various service lines together into a bundle and support them from the steel cables. The frames will be added at fixed intervals as the service lines are lowered into the shaft. The frames are composed of two outer members and two connector members. This arrangement allows the frame to be assembled around the service line bundle after all sections are in place.

Hydraulic Lowering System

The hydraulic lowering system lowers the service line bundle during construction and raises it during demobilization. The system, as shown on Figure 57 consists of two 100 ton jacks and two hydraulic cable grippers for each cable along with an electric powered pumping unit and control console. The jacks have a one foot stroke and are capable of raising or lowering the service lines at a rate of one foot per minute.

The actual lowering speed is automatically controlled to equal that of the CSL. In addition, the hydraulic control system assures that both cables are lowered at an equal rate. Safety switches are provided to warn of any difference in cable loads or lowering rates. In this event, the automatic controls are overriden. The jacks are then synchronized and the automatic controls reactivated. The operating console is located in the headframe area to provide good visibility of the work.

The hydraulic gripping devices are designed so that once actuated, they cannot be released until the load on the cable is removed. Since at least one gripper must be activated to carry the load, there is no possibility of accidentally releasing the cables. If a leak develops in the hydraulic system, the cable would slowly lower through the one foot stroke of the jacks then stop.

The operation of the jacks is similar to the CSL suspension system jacks. To lower the cable, the bottom gripper is activated from a previous cycle and the top gripper is released. The two jacks are extended, raising the top gripper an amount equal to the distance the cable is to be lowered. The top gripper is activated and the jacks are extended a small additional distance to release the load from the bottom gripper so that it may be deactivated. Fluid is then bled from jacks at a controlled rate allowing the service line assembly to lower. As the jacks near the bottom of their stroke, the lower gripper is activated to remove the load from the gripper for release. This cycle is repeated as often as required. In order to raise the service

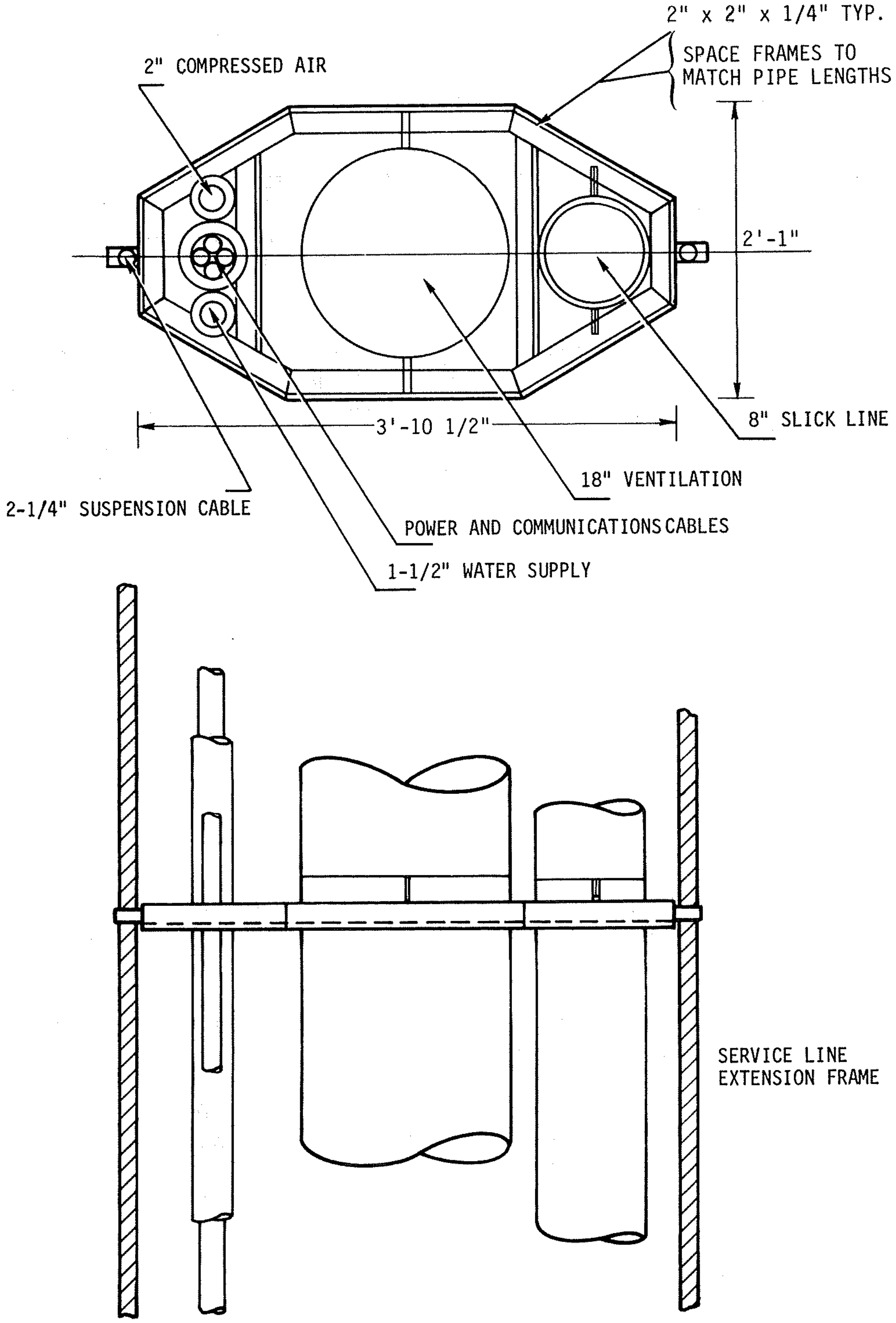


FIGURE 58. - Service line support frame.

line, this procedure is reversed. This lowering system provides a precise, fail-safe control over the location and lowering speed of the service line assembly. All components are removable and are standard, readily available items, if repairs become necessary.

The 2-1/4 inch diam support cables are sufficient to carry the 160 ton service line assembly with a 6:1 factor of safety. The cables pass from hydraulically operated takeup reels, over the 3 foot diam top sheaves, through the lowering jacks and into the shaft.

In the shaft work area, the service line assembly is located to minimize interference with the lining operations. The support cables and frames terminate above the top galloway deck. From this point to the CSL the pipes and ducts carry their own weight and are constructed with no protruding flanges or joints. As a result, personnel on the galloway near the service lines are not subjected to moving protrusions.

4.4 Equipment Costs

4.4.1. Introduction

It is the objective of this subsection to provide a cost estimate of the CSL system and support equipment. There are, however, some underlying assumptions which will affect the total cost. These assumptions include:

a. The CSL is being used in conjunction with a boring machine, and therefore much of the surface support equipment is a shared cost between both pieces of hardware (headframe, hoists, ventilation equipment, etc.).

b. As much equipment as possible is leased or rented to reduce capital investment.

c. Only present day costs are presented since the application of engineering economics analysis can vary widely from contractor to contractor as does the cost of money and the minimum rate of return.

d. The cost presented are for a 20 foot diam shaft; 2000 foot deep, and a 9-inch thick lining.

The cost values presented in this subsection are divided into four areas and include:

a. Surface support equipment
b. CSL and galloway
c. Concrete plant and delivery system
d. CSL operating expenses.

The cost items discussed in this subsection are presented in Table 6. The costs are presented as direct costs for a new CSL system and related hardware. Costs for hardware which are required for both a boring machine and CSL are not included. The use of the ventilation system is shared, as are power, communications, water and compressed air. The headframe is shared, as are the man lift and muck skips (if required). These costs are not charged against the CSL, as they would not be charged against a conventional lining system either. The cost differential between a CSL and a conventional lining system are also shown. A second column on Table 6 reflects the true cost of the CSL when the cost of conventional hardware is subtracted.

4.4.2 Surface Support Equipment

For the most part, the CSL is a self-contained underground unit. However, there are three significant surface support systems which include:

a. Concrete plant (discussed in Section 4.4.4)
b. Galloway suspension system
c. Extension of CSL services system.

4.4.2.1 Galloway Suspension System

It is presumed that any shaft sinking project which would use a CSL would have to be lined conventionally otherwise. Therefore, a galloway would be required as would a galloway suspension system. However, the CSL requires a more sophisticated suspension system and the work stage has greater weight due to more stages and equipment. Although the CSL galloway suspension system will cost more than a conventional work stage, the accurate costing of such a system must reflect a deduction for the cost savings of not procuring or leasing a conventional suspension system.

TABLE 6. - Cost of CSL and related equipment*

Cost item	Direct cost ($1000)	Differential cost to conventional hardware ($1000)
Extension of services for concrete slick line	5.0	0
Slipform and guidance		
• slipform	27.0 (10')	(12.0) (20')
• collapse system	3.0	2.0
• guidance cylinder	9.0	9.0
Curb ring and support		
• curb ring	6.9	0
• inner seal	0.5	0.5
• outer seal	9.5	9.5
• support cylinders	6.0	6.0
• vibrators	0.5	0
CSL suspension support system		
• upper jack ring	20.0	20.0
• lower jack ring	10.0	10.0
• guide wheels	5.0	5.0
• suspension jacks	48.5	48.5
• cable reels	30.0	5.0
Instrumentation control system		
• hydraulic power unit	30.0	30.0
• pressure transducers	1.5	1.5
• position transducers	1.0	1.0
• tilt transducers	2.0	2.0
• control panel	15.0	15.0
Galloway (5 decks)	69.0	23.0
• fire protection system	1.5	0.0
• suspension system	25.5	(35.0)
Concrete plant and delivery system		
• concrete plant	75.0	75.0
• slick line	10.0	0
• concrete pump and controls	18.0	18.0
• multiple port valve	4.0	4.0
• 4 inch hoses and connections	3.0	3.0
Totals	436.4	241.0

*Based on 1983 equipment costs

The cost of the galloway suspension system rope is not included as it is reuseable and common between CSL and conventional lining systems. The cost included in Table 6 is the leased cost of three cable grippers, traveling hydraulic cylinders, metal frames, hydraulic power unit, and control panel.

4.4.2.2 Extension of CSL Services System

As discussed earlier, the CSL services required include power, compressed air, utility water, communications, concrete and ventilation.

The CSL service requirements are fully compatible with the design of the service system for the downhole boring machine. In essence, with the exception of the concrete slick line, the CSL services are tapped off those already going down to the boring machine. As such, the cost of these services and the required suspension system used for extension, are not charged against the CSL. However, the cost of the concrete slick line and, therefore, a part of the present service line system is dedicated to the CSL and should be chargeable. This chargeable part of the service line system is estimated to cost $5,000.

4.4.2.3 Surface Site Preparation

There are direct costs associated with site preparation and construction of the collar. However, these costs are chargeable to the boring machine. The CSL adds little, if any, additional requirements. The CSL is self-contained downhole. The surface support systems including concrete plant are required regardless of the type of lining system used. The assembly area needed to preassemble the large CSL components is the same as is used for the boring machine and, therefore, adds no additional cost to the civil works. The collar requirements include embedment of the CSL suspension cables, however, this cost is too small to consider as a separate item.

4.4.3 CSL and Galloway

The costs of the CSL are straightforward and are itemized in Table 6. The costs are grouped into five areas and include:

a. Slipform and guidance system

b. Curb ring and support system

c. CSL suspension and support system

d. Instrumentation and control systems

e. Galloway.

The following assumptions apply to these cost values:

a. The CSL suspension cable climbers are rented for 6 months including hydraulic power unit.

b. The hydraulic systems include all hoses and end connections.

c. The control systems include all cable runs and end connections.

d. The outer seal cost includes the price of 100 percent replacement seals.

The comparison of the CSL to conventional lining systems can be confusing without some clarification. Figure 59 and Table 7 attempts to clarify the cost values used in Table 6 under "Differential Costs" by itemizing what exactly is included in the cost comparison.

4.4.4 Concrete Plant and Delivery System

Although the concrete plant is assumed to be compatible for both conventional placement of concrete as well as for the CSL, it is only charged against the CSL. The plant is assumed to be purchased and specified to meet the continuous needs of the CSL. This includes the admixture storage and transfer system. Table 6 includes the cost of a specially designed concrete pump. In comparison, the conventional system uses an off-site redi-mix concrete, and a concrete bucket and hoseline to the concrete chutes as a means of placing the concrete. A concrete slick line can also be used on a conventional lining system to deliver the concrete to the work stage.

4.4.5 CSL Operating Expenses

The operating expenses can be itemized. However, costing of each item can be misleading due to outside constraints. The cost of labor varies significantly across the country, especially in cases where union workers must be utilized. The CSL's total operating expenses are very sensitive to the total project time. The CSL's greatest economic promise lies in the fact that it can line a shaft 2 to 3 times faster than conventional system, thus significantly reducing the labor costs. However, the CSL is subject to the operating cycle of the boring machine, unexpected breakdowns of itself or the boring machine, and many other factors which prolong the project's duration. Therefore, we have included the cost items, but have made no attempt at assigning a total dollar value to each.

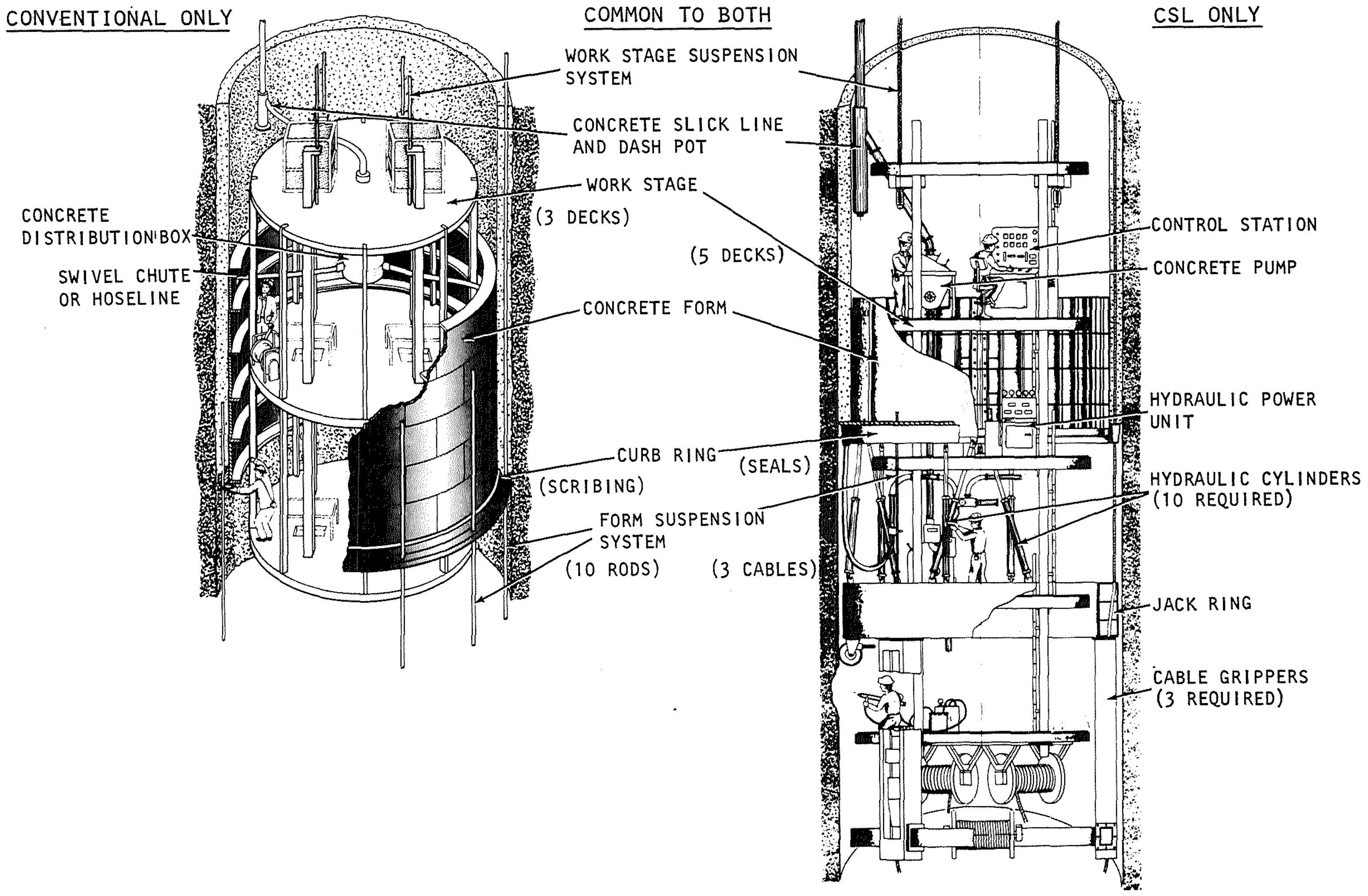


FIGURE 59. - Comparison of conventional and CSL hardware.

TABLE 7. - Equipment comparisons for CSL versus conventional systems

CSL system	Conventional lining system
Slipform and guidance	
● slipform	- essentially the same
● collapse system	- same requirement - different hardware
● guidance cylinders	- no comparable hardware
Curb ring and support system	
● curb ring	- simplified version
● inner seal	- non-required
● outer seal	- scribing used
● support cylinders	- no comparable hardware
● vibrators	- similar requirement
CSL suspension and support system	
● upper and lower jack ring	- no comparable structure
● guide wheels	- no comparable hardware
● suspension jacks	- hung off of galloway and hanging rods
● cable reels	- no comparable hardware
Instrumentation and control	
● HUP, control panel and instrumentation	- no comparable system or requirement
Galloway	
● 5 decks	- 3 decks
● concrete pump with controls, slick line and multi-port valve	- concrete bucket, hoseline and bucket and bucket hoist or slick line

4.4.5.1 Concrete Materials

The CSL is designed to place an unreinforced concrete lining 9 to 18 inches thick. For purposes of discussion, assume a 9-inch thick lining composed of CSL design mix concrete as described in Section 2, subsection 2.4.5. The number of cubic yards of concrete required for a 2000 foot deep shaft is approximately 3600 yd^3 (assuming no slough zones). However, there will be normal losses of material during start-up, during periods when the output of the plant is altered, after normal shutdown and system purging, during periods of unexpected system failures and to fill small slough zones. Therefore, it has been conservatively estimated that a total of 4500 yd^3 of concrete will be required. Based on that value, the volume amount of each major mix constituent can be estimated (see Table 2). The cost of each constituent can then be calculated based on local pricing. In terms of the total project cost, the cost of concrete is essentially the same whether CSL or conventional lining equipment is used. This assumption is based on the use of 5000 psi concrete for the conventional lining system, which is comparable to the ultimate strength of the CSL concrete.

4.4.5.2 Support Cables

The support cables for the CSL are considered as material cost because they are embedded in the finished concrete lining. The 1-3/4 inch diam cable costs approximately $9/foot. The cost of 3 cables per foot of lining is $27. In comparison to a conventional lining system using 8 to 10 hanging rods, the total cost per foot for rods would be approximately $10.

4.4.5.3 Power

The CSL has many electrically powered operational and control components. The major users are the hydraulic power units for the CSL, cable jacks, and concrete pump and for general lighting. The CSL will draw on the power line service for the boring machine and is expected to require no more than 150 horsepower.

4.4.5.4 Rental Costs

Major rental costs associated with the CSL operation include those for the six cable grippers (three on the CSL and three on the galloway); and the use of a crane to assist with the system erection, installation, removal and dismantling.

4.4.5.5 Labor

a. Mobilization: Assembly of the CSL and galloway will occur on site in the same area as the assembly of the boring machine. Major subsystems will be preassembled on the ground and totally assembled in the shaft collar area. Use of match-marked quick disconnect end fittings for both fluid and electrical systems will facilitate the assembly. An estimated total of 2,000 man-hours will be required for mobilization of the CSL, galloway and support system, and get it placed in the shaft. A period of 5 weeks will be required to complete this work.

b. Maintenance: Maintenance and repair costs include those expenditures for cleaning, lubricating, inspecting and maintaining the various CSL systems. It includes the time needed for routine parts replacement, as well as the costs of having spare parts on site. Spare parts are required for the concrete delivery system (including concrete plant); cable suspension system; hydraulic power system, and instrumentation and control systems. It is estimated that the entire maintenance program (including spare parts) will cost approximately $10,000.

c. Routine Operations: As indicated earlier in this report, the routine operation of the CSL system requires six full time workers. In addition, three other personnel are required including a hoist man, top man and standby hydraulic mechanic. This basically breaks down to 72 man-hours per 8 hour work shift. The total labor costs will be determined from site specific conditions and shaft sinking operations. It will include, in some percentage, the following factors:

1. Number of work shifts per day and per week
2. Average rate of advance of CSL and total shaft depth
3. Union or non-union workers and job classifications
4. On-site supervision requirements
5. MSHA requirements.

d. Demobilization: The CSL galloway will be pulled, completely assembled, from the shaft and dismantled on the ground. The CSL must be partially dismantled in the shaft and removed from the shaft on a piecemeal basis. Final dismantling of these large components will be done at the surface. It is estimated that 3 weeks will be required to demobilize the entire CSL system and require 1,000 man-hours to complete.

Table 8 compares the work crew requirements of the CSL system to a conventional lining system. In addition, an estimate is presented on the cost per foot for the placement of the lining , (assuming that work is performed 3 shifts per day, 6 days per week, and that the CSL can place 100 feet/day and a conventional system can place 40 feet/day). The results indicate that although the CSL has a higher initial cost, the cost per foot is less than that for a conventional system.

Figure 60 shows the costs of shaft lining as a function of shaft depth for both conventional lining and CSL systems. The plant set up time and lining time, each in terms of weeks, is shown for each system at three different depths. From this figure, a break even point in favor of the CSL is indicated at 1500 feet of depth excluding the fact that the shaft can be completed earlier.

One of the most costly components of the CSL system is the cost associated with mobilization and demobilization of the CSL equipment. It is reasonable to assume that the set up and tear down crews will become more proficient in these tasks with experience. Therefore, an improvement in time was estimated, each time the CSL was utilized over a five shaft construction project. For purposes of discussion, it is assumed that the crew is 5 percent more proficient in mobilization and demobilization time on the second shaft than the first, 10 percent more proficient on the third; and 15 percent on the fourth and fifth shafts. Based on these assumptions, it can be shown that the total cost of installing the five complete concrete linings is essentially the same for either system. However, the CSL system would complete the five shaft project 3 months faster.

4.5 Conclusions and Recommendation for Future Investigations

All of the contract requirements of Task I of the continuous shaft lining system program have been completed. Neither Task II nor Task III requirements were completed because of their deletion from the program by the Government. As a result of the laboratory

TABLE 8. Operational expenses and labor conventional vs. CSL system

WORK CREW	CONVENTIONAL LINING SYSTEM	CSL SYSTEM
Hoist Man	1	1
Top Man	1	1
Lead Man in Shaft	1	1
Shaft Workers	3	2
Surface Labor	1	1
Surface Equipment Operator	1	1
Hydraulic Mechanic	NR	1
Concrete Plant Operator	NR	1
Total:	8	9
Cost of Lining		
Labor @ 3 shifts per day	(3 x 8 x 8 x $27)*, $5,200/day	(3 x 8 x 9 x $27)*, $5,850/day
Labor per foot of shaft	(40 ft/day), $130/vert ft	(100 ft/day), $58.50/vert ft
Material per foot of shaft	10 hanging rods @ 1/ft $10/vert ft	3 wire ropes @ 9/ft $27/vert ft
	3000 psi redi-mix @ $58/cy $100/vert ft	Special CSL mix @ $65/cy $110/vert ft
Equipment cost (REF 14) over 10,000 ft of shaft	$71/vert ft	$99/vert ft
Operating cost (REF 14)	(373 x 3/40), $28/vert ft	(510 x 3/100), $15/vert ft
	$339/vert ft	$310/vert ft

*Labor cost based on current UMW construction agreement, average wage including taxes, insurance, contract fringes and benefits, workman's comp, plus overhead and profit ($27/hr).

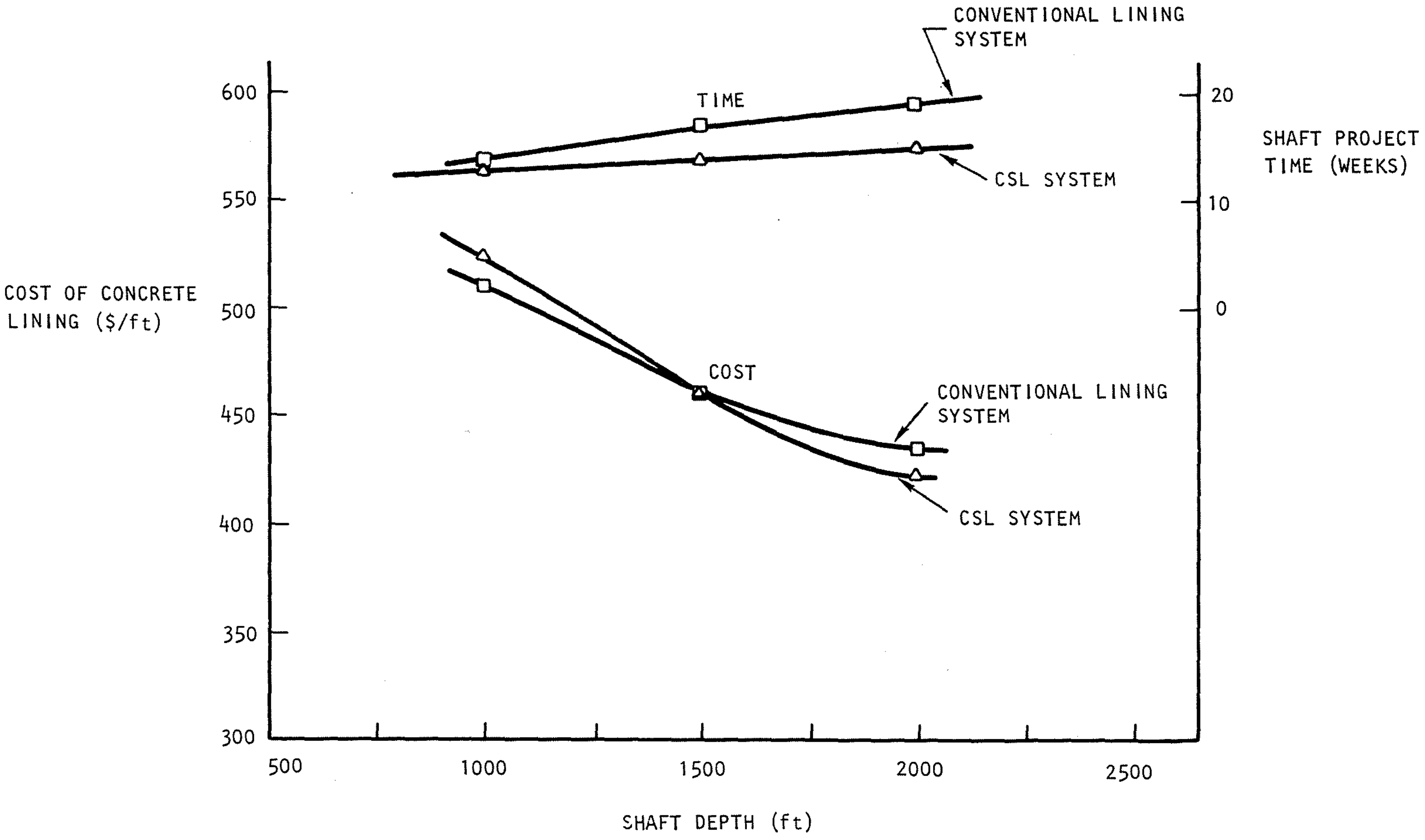


FIGURE 60. - Comparison of lining costs.

and full scale above ground tests, the following general conclusion can be reached:

- The process of pressurized inverted slipforming is viable, and can be reduced to useful hardware for use by the construction industry. The design of the second generation CSL represents the current state-of-the-art for this type of hardware, based on engineering knowledge, professional experience, and the results from the testing programs.

- An accelerated Portland type III concrete mix design was developed which has satisfactory short-term properties. The mix distributes well and enabled the CSL to achieve an advance rate of 4 feet/hour or 80% of the original project goal. The long term shrinkage and sulfate resistance properties of this mix design do not meet normal ACI performance specifications. However, under shaft conditions where high sulfate resistance is not required, this concrete is satisfactory. The excessive shrinkage properties would not normally be a problem as ground relaxation, with time, would compensate for the anticipated 1/4 inch reduction in lining radius. This reduction would keep the lining/ground interface tight and the lining in compression.

- There is an upper limit on slipform effective length and, therefore, on CSL advance rate for a given concrete mix design. The maximum SEL is dictated by slipform drag characteristics and design limitations on concrete pressure at the curb ring. This upper bound or advance rate is 4 feet/hour for the mix developed for this program. Alternate concrete mix designs, using more exotic cements, are available if higher advance rates are desired.

- The concrete seal developed during this program has preformed adequatly during laboratory and simulation testing. The final design of the seal incorporated on the underground prototype should enable the CSL to operate in most machine bored shaft conditions in the continuous slipforming mode.

- The CSL requires active alignment control to keep the slipform and curb ring plumb and centered in the bored shaft. The need for active centering and tilt control was demonstrated during simulation testing. Sufficient data were obtained during these tests to incorporate the needed centering control into the underground prototype design. Because of the difficulties encountered in alignment control during simulation testing, the underground prototype has substantial, and to some degree, redundant alignment control mechanisms engineered into its design. Evaluation of the performance of the underground prototype may ultimately allow for elimination or simplification of some of these mechanisms in a production CSL.

The continuous shaft lining concept can be cost competitive with conventional lining systems under suitable circumstances. The four major lining cost items in order of their significance are concrete materials, labor, embedded rods or cable and equipment depreciation. For a cast in-place lining, the labor component accounts for approximately 35% of these combined costs. Assuming crew sizes for cast-in-place and CSL systems are the same and all material costs are equivalent, the time required to line a shaft becomes the dominant cost variable. A CSL advance rate of 2 feet/hour is comparable to conventional placement of a cast-in-place lining. At a CSL advance rate of 4 feet/hour, the labor cost would be cut in half, thus offering a 17% potential cost reduction. This time saving becomes less significant in shallow shafts as mobilization and demobilization become the dominant time consumers. An additional 10% cost reduction could be realized if embedded cables could be eliminated from the system.

Recommendations for Future Investigations

The Continuous Shaft Lining system test program has demonstrated the viability of the basic CSL operational concepts. There are, however, several key areas which warrant further investigation prior to or in conjunction with an underground test of the CSL. By conducting these further investigations, the practical value of the CSL to the shaft sinking industry will be significantly enhanced.

There are six major areas warranting further investigation:

- Concrete mix designs should be further developed emphasizing improved long term properties such as sulfate and shrinkage resistance.

- Curb ring components exposed to setting concrete such as seals, and placement ports should be evaluated and modified to reduce concrete entrapment and improve stripping.
- Concrete drag force dependence on concrete pressure should be tested at higher (25 to 50 psi) pressures
- The feasibility of lowering the CSL from the shaft collar with non-embedded cables should be evaluated by modeling the effects of cable compliance on the system's operation.
- The slipform guidance system should be evaluated and streamlined to develop a simple and more acceptable operational control system.
- Water inflow effects on early strength gain and the continuity of the lining should be investigated in greater detail to develop a CSL water inflow control specification.

Concrete Mix Design

Although the resulting short-term performance of the CSL mix design used during this program was adequate, the long-term characteristics are clearly deficient. Both sulfate resistance and shrinkage potential exceed ACI specified limits.

There are three main reasons for the poor long-term performance. First the mix contains 752 lbs of cement. Second, the cement composition has a high C_3A content. Finally, 3 percent calcium chloride is used in the mix design. All of these factors serve to maximize the short-term behavior which was of primary concern at the outset of the program. Now that the proof-of-concept testing of the CSL has been completed, some effort should be focused on improving the overall concrete behavior.

The first step would be to use a Type III cement with a lower C_3A content. This will directly improve sulfate resistance and may facilitate the use of less calcium chloride accelerator, which, in turn, will reduce shrinkage. The substitution of a cement with a lower C_3A (and resulting lower calcium chloride content) will only be possible if the strength gain at early ages is not adversely affected. This would have to be assessed through testing.

The addition of flyash to the mix may also improve the sulfate resistance, but may increase water demand which would increase shrinkage. Partial replacement of cement with flyash may work because it will improve long-term behavior. However, replacements in excess of 1 sack of cement per yard may also reduce early strength.

Additional work using Type K (Expansive) cement may be worth considering. Problems with air content and slump may be eliminated if comparable admixtures can be found, and if the sequence of admixture additions can be optimized.

The use of VHEC with different portions of Type III or Type II cement warrants additional study. Because of its limited scope, work initiated by WES did not indicate conclusively that VHEC Portland mixture would not provide the required behavior. Mixes with small amounts (10 to 30 percent of the total cement content) of VHEC should be trial batched.

Any combination of materials that improve long-term performance which through testing, exhibits equal or better short-term behavior, should be tested for sulfate resistance and shrinkage potential. Formulations that show a marked reduction in workability or strength gain will not be suitable regardless of their long-term behavior and should not be pursued.

Curb Ring Component Design

The continuous slipforming operation must be capable of both planned and unexpected shutdown. Immediately following such a shutdown, the concrete pumping and placement system must be cleaned. This task has been routinely carried out during simulation testing and poses no problem for underground operation. However, those curb ring components exposed to fluid concrete downstream from the cut-off valves are subjected to setting concrete and must be capable of being cleanly stripped without major effort or damage to the component. The components which must meet this stripping requirement are the following:

- Curb port cut-off valves
- Curb ring ports
- Curb ring top surface
- Curb ring seals.

Adequate stripping capabilities has either been demonstrated during simulation testing or is common practice in industry for all of these components except for the curb ring seals. It is, therefore, recommended that these seals be subjected to pullout test in set concrete. Based on the results of such tests, the seals and/or seal clamping device may need further refinement in design. In addition, the design options of various concrete port configurations should be assessed and bench scale tests should be conducted to establish the ease of stripping from set concrete.

Slipform Drag Dependence on Concrete Pressure

Concrete drag force behavior was thoroughly documented during simulation testing, as well as by bench scale testing. The empirical results of these tests has been presented as part of this report. However, simulation and bench scale testing were conducted at concrete pressures, at the curb ring, up to 25 psi. Drag force behavior at pressures from 25 to 30 psi are extrapolated from an empirical formula based on the lower pressure data. Both the empirically derived equation and an analytically derived equation (based on behavior of a Bingham fluid calibrated from test data) predict comparable drag forces in the 20 to 50 psi range (Figure 61).

It is anticipated that the underground design CSL will operate at pressures above 25 psi based on this data. A more accurate assessment of drag force dependence at higher pressure is, therefore, necessary to improve the accuracy of predictions of maximum achievable CSL advance rates. Therefore, further bench scale testing should be conducted, monitoring drag force dependence on concrete pressure from 25 to 50 psi. The degree of concrete set should be taken into account in these tests.

Suspension System Design

The CSL suspension system proved troublesome during simulation testing. Based on this experience, a more reliable cable climbing system has been engineered into the CSL underground design. This system replaces the rod climbers with cable climbers and reduces the suspension system from 4 point support to 3 point support. Not as apparent, but of major significance, is the change in jack frame alignment control. The simulation test CSL was originally designed to react force couples induced by the slipform and curb ring through reaction pads contacting the fixed simulation test tower. The underground CSL design

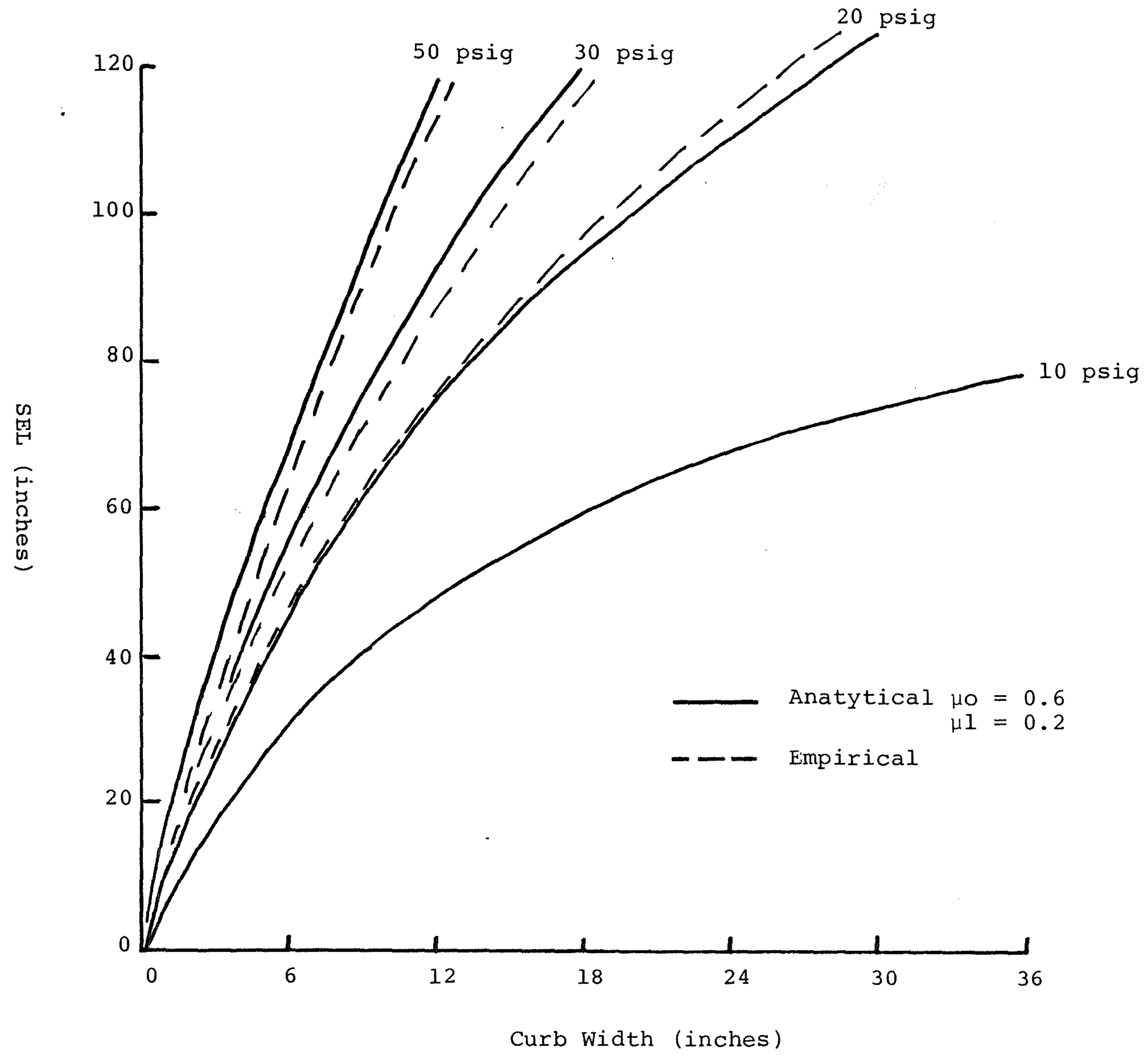


FIGURE 61. - Comparison of analytical to empirical drag force data.

reacts these moments through differential loading in the embedded suspension cables. Because of the anticipated variation in the suspension cable loads due to this alignment mechanism, cable compliance is deemed undesirable.

Cable compliance in external non-embedded cables, hung from the shaft collar to a depth of 2000 ft, would require in excess of one meter of cable take up, at the collar, to compensate for eccentric loading on the CSL. These loads could be caused by a 3 inch deep slough zone of significant circumferential extent. The design of a hydraulic take up mechanism to compensate for this compliance is conceivable, but has not been designed or tested. For this reason, the more conservative embedded cable suspension system was chosen for the underground CSL design. The material cost of cables is between 5 and 10 percent of the total cost of the lining. The options of using either completely non-embedded suspension cables or half size cables in double purchase with one half of the rope embedded and the other half external may significantly improve the cost effectiveness of the CSL. However, before such a system is employed at substantial shaft depths, the compliance effect compensation mechanism must be evaluated with regard to its impact on the lining continuity and operations. Specifically, the compensating process must minimize concrete pressure variation at the curb ring in order to eliminate potential damage to the concrete lining. This problem can be studied using an analog computer model to investigate the response of the CSL to changes in cable stretch, and other variables.

Guidance Control Design

The underground design CSL has been engineered to allow for numerous guidance control options. These systems span a broad range in degree of complexity. The simplest control approach which produces satisfactory performance is the optimum system desired. Guidance problems encountered during simulation testing have dictated that all options be included in the underground system to ensure successful CSL operation. It is hoped that some of these control components can be eliminated by operational refinement in the field.

The ultimate simplistic CSL system would be a passively guided CSL with curb ring and slipform fixed relative to the jack ring. This system combined with non-embedded cable suspension system would be the easiest to operate and would be the most cost effective. Such a system would eliminate the loss of the embedded cables, curb ring and slipform hydraulic actuators, allow for side mounting of concrete ports and virtually eliminate the underground electronic and hydraulic control systems.

The present underground system design is capable of independent movement and alignment monitoring of each of the three major CSL components. The slipform can be actively oriented in all three directions of rotation and all three directions of translation. The curb ring can be oriented in two directions of rotation and one direction of translation. The jack ring can be oriented in two directions of rotation and all three directions of translation. Each of these components has rotation and vertical position control feedback and the slipform has lateral position control feedback as well. The operational flexibility of such a system is extreme, and the control options are complex. We have selected a guidance control scenario based on simulation test results as outlined in this report. Bench scale testing, particularly of the slipform feedback and control system, should be conducted to optimize this system's performance prior to final specification of underground hardware. A sensitivity study should be conducted and an analog model of the entire system should be developed to evaluate the feasibility of simplifying the entire CSL guidance system.

Water Inflow Control Specifications

The effect of ground water inflows on the placed concrete was investigated as part of the simulation tests. The results of these tests indicate that small inflows may not require water control measure such as water panning, prior to concrete placement. The effects of small inflows on concrete set rate, strength dilution and localized lining damage was not quantified during the simulation tests. Further small scale laboratory tests of these phenomenon is needed to develop rigorous specification of water control procedures for underground CSL operation. Such a study would quantify the effect of uncontrolled inflows on advance rate, remedial work required and ultimate lining integrity based on the geometry, rate and anticipated pressure build up of an inflow. This work could best be accomplished in the concrete distribution test rig.

5. TECHNICAL BACKGROUND

5.1 Introduction

Four engineering background study areas have been investigated relating to the design requirements of the lining and lining system. These studies were conducted to further define performance and design specifications of the CSL system. The studies also help establish techniques for system contingency operations. These studies determined:

a. Geotechnical loads on the lining

b. Patching techniques

c. Water control techniques

d. Cold joint techniques.

5.2 System Studies

5.2.1 Geotechnical Study

There are a number of factors which influence the loads induced by the surrounding environment on a shaft lining, including:

a. Local geology (rock properties, in situ stresses)

b. Lining geometry

c. Hydrology

d. Adjacent mining activity

e. Construction technique.

5.2.1.1 Geological Influences

In coal producing regions, the rock formations are of sedimentary origin. Climatic and topographic factors in combination with the lithologic characteristics produce variations of common geologic conditions and also conditions peculiar to the area. These variations in ground conditions can be correlated, in a general fashion, to the properties of the individual rock types and to local structure. Table 9 lists rock type by location and corresponding material properties. Values beyond these ranges occur occasionally.

5.2.1.2 Rock Mass Structure

Characteristics of the rock mass which effect the stability of an underground opening and thus ground induced loading include:

a. Joint spacing and orientation

b. Bedding spacing and orientation in sedimentary deposits

c. Tectonic action including faulting and folding

d. Removal of overburden due to geomorphological processes.

The spacing and orientation of joints in otherwise competent ground can define wedges or blocks of rock which can produce concentrated loads when they intersect a shaft wall in certain orientations.

The spacing and orientation of bedding planes in sedimentary deposits can produce anisotropic properties for the rock mass as a whole. Typically, in the direction parallel to bedding, shear strength is lower and the modulus of elasticity is higher.

In the vicinity of fault zones, horizontal stresses can be significantly altered from the values initially generated during rock formation. In regions of normal faulting, horizontal stresses may be reduced to an active condition yielding a horizontal to vertical stress ratio (K_a) as low as 0.2. In regions of reverse faulting, horizontal stresses may be increased to a passive condition yielding a stress ratio (K_p) as high as 4.0. Ground that has undergone significant folding due to tectonic compressive forces can also develop substantial variation in horizontal stresses. Although it is less severe than in the active and passive limits which are the most extreme conditions.

TABLE 9. - Compressive strength and other selected properties of sedimentary rocks generally associated with bituminous coal producing regions

Type of rock	Location	Specific gravity average	Porosity (%) average	Compressive strength (psi) average	Impact toughness (psi)	Sclero-scope hardness	Abrasive hardness
Conglomerate	Ontario	2.67	-	24,000	-	-	-
Dolomite	Tennessee	2.84	0.70	46,700	5.9	74	14.0
Dolomite	Burnet Co., Texas	-	-	27,500	-	-	-
Dolomite, cambro-ordovician	Texas	-	-	21,600	-	-	-
Dolomite, pre-cambrian	Texas	-	-	19,900	-	-	-
Limestone, stylolitic	Ohio	2.69	0.70	28,500	8.6	58	10.0
Limestone, stylolitic	Utah	2.78	0.26	28,000	2.5	52	9.3
Limestone, stylolitic	West Virginia	2.68	6.00	23,000	2.5	61	9.6
Limestone, stylolitic	West Virginia	-	-	29,500	2.0	58	8.5
Limestone	Utah	-	-	23,600	3.1	52	10.0
Limestone, coarse	Alabama	2.83	0.90	24,000	6.6	66	7.0
Limestone, fossiliferous	Indiana	2.31	11.00	10,900	1.9	27	3.0
Limestone, fossiliferous and parallel to bedding	Indiana	-	-	9,700	2.1	-	-
Limestone, fossiliferous and parallel to bedding	Indiana	-	-	10,200	2.1	-	-
Limestone	Tennessee	-	-	37,600	3.2	63	11.0
Limestone (Cedar Park)	Texas	-	-	2,000	-	-	-
Limestone (Austin Chalk)	Texas	-	-	3,000	-	-	-
Limestone (Glen Rose)	Texas	-	-	3,500	-	-	-
Limestone (Edwards)	Texas	-	-	6,500	-	-	-
Limestone, kerogenaceous, magnesian (marlstone)	Colorado	2.25	-	16,600	3.7	56	10.0
Limestone, limonitic	Alabama	2.92	0.60	24,900	3.3	61	8.0
Limestone, mineralized with shale	Utah	2.93	0.62	34,800	7.4	64	15.0
Marlstone, shale, calcareous	Colorado	-	-	22,700	5.4	65	5.0
Marlstone, calcareous, dolomitic	Colorado	-	-	21,900	4.3	56	6.7
Marlstone, kerogenavroud	Colorado	2.24	0.51	13,000	6.9	47	8.7
Marlstone, calcareous and dolomite	Colorado	2.31	1.50	21,600	5.8	62	10.0
Marlstone, kerogenaceous	Colorado	2.02	2.20	12,500	6.2	47	9.5
Marlstone, calcareous and dolomite	Colorado	2.45	5.20	28,200	2.8	59	12.0
Marlstone, calcareous and dolomite	Colorado	2.26	12.00	23,200	3.2	57	6.9
Marlstone, kerogenaceous	Colorado	2.19	1.70	9,600	2.2	46	12.0
Marlstone, kerogenaceous	Colorado	2.25	2.10	13,400	1.3	44	12.0
Marlstone, kerogenaceous	Colorado	2.08	0.24	10,400	4.6	47	13.0
Marlstone	Colorado	2.29	-	18,900	-	-	-

TABLE 9. - Compressive strength and other selected properties of sedimentary rocks generally associated with bituminous coal producing regions (continued)

Type of rock	Location	Specific gravity average	Porosity (%) average	Compressive strength (psi) average	Impact toughness (psi)	Sclero-scope hardness	Abrasive hardness
Quartzite and slate	Michigan	-	-	30,600	19.0	81	29.0
Quartzite, pink	Texas	-	-	68,000	-	-	-
Salt (rock, halite)	Louisiana	2.50	-	5,000	-	-	-
Salt (rock, halite)	New York	-	-	1,080	-	-	-
Salt (potash, halite, sylvite mixture)	New Mexico	-	-	4,180	-	-	-
Sandstone (low strength)	Wyoming	2.28	16.43	8,810	-	-	-
Sandstone (high strength)	Wyoming	2.37	11.21	12,200	-	-	-
Sandstone	Ohio	2.06	16.00	10,400	1.8	31	2.0
Sandstone, parallel to bedding	Ohio	-	-	8,000	1.1	-	-
Sandstone, parallel to bedding	Ohio	-	-	7,700	1.1	-	-
Sandstone, coarse grained	Ohio	2.17	16.00	6,100	1.5	20	1.0
Sandstone, coarse grained and parallel to bedding	Ohio	-	-	5,200	1.4	-	-
Sandstone, coarse grained and parallel to bedding	Ohio	-	-	5,100	1.3	-	-
Sandstone	West Virginia	2.60	4.30	16,200	1.4	53	5.5
Sandstone	West Virginia	2.50	3.10	19,400	2.6	63	8.3
Sandstone	West Virginia	2.50	4.80	21,900	5.5	-	7.3
Sandstone	Utah	2.20	10.00	15,500	-	-	-
Sandstone	Utah	2.14	13.00	14,200	-	-	-
Sandstone	Utah	2.35	5.00	32,400	-	-	-
Sandstone	Utah	2.33	7.00	27,700	-	-	-
Sandstone, ferruginous	Alabama	3.14	3.10	24,200	4.2	58	5.0
Sandstone, fossiliferous, red	Alabama	3.26	2.90	22,400	3.4	50	7.0
Sandstone, ferruginous	Alabama	2.93	1.40	34,100	6.6	65	9.0
Sandstone, saltstone and shale	Alabama	2.76	1.70	26,800	5.6	63	13.0
Sandstone, ferruginous (weathered)	Illinois	-	-	2,270	-	-	-
Sandstone, (subgraywacke coarse grained)	California	2.46	10.30	7,900	-	-	-
Sandstone, (subgraywacke coarse grained)	California	2.49	9.70	4,400	-	-	-
Sandstone, (subgraywacke fine grained)	California	2.41	12.00	7,010	-	-	-
Sandstone, (subgraywacke medium grained)	California	2.44	11.50	7,080	-	-	-

TABLE 9. - Compressive strength and other selected properties of sedimentary rocks generally associated with bituminous coal producing regions (continued)

Type of Rock	Location	Specific gravity average	Porosity (%) average	Compressive strength (psi) average	Impact toughness (psi)	Sclero-scope hardness	Abrasive hardness
Sandstone, (Subgraywacke Medium grained)	California	2.49	9.70	7,350	-	-	-
Shale	Murdock, Illinois	-	-	4,970	-	-	-
Shale	Utah	2.81	0.90	31,300	6.0	58	7.0
Shale, silicified	Utah	2.80	0.57	33,500	7.4	71	14.0
Shale	West Virginia	-	-	15,000	2.9	34	-
Shale	West Virginia	2.6	6.10	11,600	0.9	-	4.3
Shale	West Virginia	2.4	-	18,500	3.2	-	2.5
Shale, calcareous marlstone	Colorado	-	-	22,700	5.4	65	5.0
Shale, mineralized and limestone	Utah	2.92	0.62	34,800	7.4	64	15.0
Siltstone and shale	Alabama	2.76	0.80	37,200	8.7	71	11.0
Siltstone and shale	Alabama	2.77	1.00	45,800	8.5	73	18.0
Siltstone, sandstone and shale	Alabama	2.76	1.70	26,800	5.6	63	13.0
Siltstone	Monticello Dam, California	2.50	10.30	3,500	-	-	-
Slate	Pennsylvania	2.74	1.00	30,400	3.7	57	3.0
Slate	Michigan	2.93	0.60	26,200	10.0	46	7.0

1. Impact toughness - Arrived at by Wuerker using the impact toughness test which is a modification of ASTM standard D3-18. It gives the height (inches) a weight has dropped to fracture a unit volume of rock.

2. Scleroscope hardness - The height of rebound is read in terms of arbitrary units on a scale of 140 divisions the value of 100 representing the rebound from hardened, pure high carbon steel.

3. Abrasive hardness - Cores are abraded against a rotating steel disk. The specimen loaded to 1,250 grams in ground for 1,000 revolutions using silicon carbide, 40 mesh, as an abrasive. The values shown in this table represent the so-called hardness coefficient, H_L, whose value is determined from the formula:

$$H_d = \frac{10^{-3}}{M_d}$$

where M_d is the weight of the material abraded in pounds per revolution per square inch.

Source: Wuerker and Texas Bureau of Economic Geology.

The removal of overburden due to weathering erosion or glaciation can result in horizontal stresses in excess of those expected from the sedimentary processes of deposition. Based on uniform deposition, the horizontal to vertical stress ratio, K, is a function of poisson ratio, ν, $K = \nu / (1 - \nu)$. A typical value of ν is 0.2 yielding K = 0.25 which is close to the active limit.

A continuous placed lining will experience the same long term ground induced loading as conventional step-formed lining. Distributed ground induced loads will generally not exceed 500 psi in a 20 foot diameter shaft. This corresponds to a compressive stress, in a 12 inch thick lining, of approximately 40 psi. Point source loads imposed by a block of ground having the worst possible joint orientation will generally not exceed 100 tons/ foot of depth. Concrete linings have substantial load redistribution capabilities, particularly thinner linings constructed of high strength concrete. The deformation and load redistribution capabilities of concrete linings mitigate the danger of cracking due to such loads.

The short term strength requirements of a slipformed lining will depend on the ground relaxation characteristics and on the timing of concrete placement. Typically, the ground relaxes (moving radially inward) following excavation. Excluding squeezing or swelling ground conditions, most of this relaxation occurs within 2 diameters above the sinking operation. The load required to support the ground, if it is not allowed to relax, can be extremely high. No relaxation would require a radial stress equal to the original horizontal ground stress prior to excavation. The magnitude of this stress is discussed in detail in this section. If the ground is allowed to relax, the support required diminishes to a minimum requirement which is dependent on rock strength, jointing, and in situ stresses. If the ground is allowed to relax unsupported beyond this point it can become unstable, and the support required to inhibit further movement increases. The slipforming operation should be located at an optimum distance above the sinking operation to take advantage of this relaxation behavior. The lining should be placed just prior to the ground relaxing to the point requiring minimum support. As the ground then relaxes further, the lining will begin to take load, thus inhibiting further movement. If the lining is placed 2 diameters (40 ft.) above the sinking face of a machine excavated shaft, the ground will have relaxed for at least 8 hours. The lining will then have to deform with the relaxing ground for an additional 3 hours until it has attained sufficient strength to inhibit further movement. The rate of radial deformation with time is geometrically decreasing. Thus, the total radial deformation over the 3 hour period is a small portion of the total deformation. The concrete lining must be capable of matching this deformation without cracking or strength degradation.

The concrete lining is expected to deform as much as a ½ inch radially inward while behind the slipform which is evident from the ½ inch radial taper designed into the form. Additional deformation required in zone 3 is minimal. The concrete is already capable of taking load, having a uniaxial compressive strength greater than 25 psi upon exiting the slipform. The additional time required for the concrete strength to then increase to 40 psi to take the entire ground induced loads is less than 1 hour. It should be noted that squeezing and swelling ground conditions can exert loads an order of magnitude greater than 500 lb/ft.^{2}, but these higher loads develop slowly with time. As with conventionally placed concrete, the ultimate strength of the CSL concrete, which will well exceed 3000 psi, will be capable of handling these longer term ground loads. Squeezing ground conditions are the result of high in situ stresses which increase with depth. Coal bearing strata are generally less than 2000 feet deep. Squeezing ground conditions generally do not occur above a depth of 4000 feet in all but the weakest rock formations or when severe lateral ground compression has developed due to folding or faulting. Swelling ground conditions are occasionally encountered in shales and claystones which are common to coal bearing strata.

5.2.1.3 Lining Geometry

Any opening in the ground is subjected to stress concentrations based on the opening geometry. In rectangular openings, these concentrations can reach an order of magnitude greater than the in situ stress present prior to excavating the opening. In a given direction, a circular opening generates a parallel tangential stress concentration of 3 times the previous in situ stress, and reduces the perpendicular tangential stress by the previous in situ stress. In a uniform horizontal stress field containing a circular shaft opening, a tangential stress of 2 times the in situ stress will be generated. In the most extreme case, a shaft intersecting a reverse fault could experience relatively high horizontal stress due to the nonuniformity as well as the high stress ratio, K. For a passive horizontal stress ratio of $K_p = 4.0$ in the direction of faulting combined with a relatively low stress ratio $K = 0.5$ in the direction perpendicular to faulting, concentration of tangential stress could attain a magnitude of 11.5 times the vertical stress. At depth of 2000 feet below rock of an average unit weight of 160 lb, the vertical stress would be 2200 psi. In the extreme reverse fault condition described above, a tangential stress of

24,000 psi would exist in the shaft wall. Under nonfaulting conditions, the stress would have been comparable to the vertical stress.

Severe stress concentrations are often encountered at the intersection of the shaft with the access tunnel at a given mine level. The wedge of rock common to the shaft and tunnel often requires additional reinforcing or bolting. Alternately this corner can be rounded off to reduce the concentration.

5.2.1.4 Hydrology

Ground water inflow is a major concern in many shaft sinking projects. Regardless of the sinking method used, ground water inflows must be controlled. In blind bored shafts and raised shafts, pregrouting is the primary control mechanism.

Ground water inflows affect the CSL both during and after construction. During construction after initial excavation, the ground water pressure drops to zero at the exposed shaft wall and is drawn down to a steady state flow in time. When the CSL seals off the inflow, the zero pressure surface begins to rise as the ground water backs up. Depending on the rate of strength gain of the concrete, the rate of advance of the slipform and the rate of hydrological pressure gain, the water may exert excessive pressures on the still green concrete lining. If the ground water pressure increases at a fast rate, the water may force its way through the unset concrete and percolate up along the inside of the slipform. This piping effect may be tolerable if flows are sufficiently small. Once the concrete clears the form tail, drains can be installed through the lining to relieve ground water pressure build-up. If the ultimate water head exceeds the permissible pressure on the lining when drains are closed, then the drains must be permanently installed.

Large inflows require water panning, water rings and drains to be placed prior to lining. In this event, the drawdown is continuously maintained and little pressure is exerted on the lining either during or after construction. A 12 inch thick unreinforced concrete lining cast in a 22 foot diam shaft and composed of 3000 psi concrete can withstand approximately a 250 foot head of water. Such a lining should be able to withstand the unrelieved ground water pressure of most aquifers down to 2000 feet. The occasional aquifer with static pressure substantially exceeding this value should be grouted off to reduce the inflow and the inflow that persists should be permanently drained.

The ability of unreinforced circular concrete linings to withstand uniform outside pressure has been calculated both using thin wall ring theory, Table 10, and empirically, Figure 62.

5.2.1.5 Adjacent Mining Activity

Where a shaft passes through a level of an ore body which is being mined, additional loads may be placed on the lining. If mining is conducted within a few diameters of the shaft, stress concentration will develop in the pillar between the shaft and mine cavern. Such concentrations can exceed an order of magnitude of the original vertical stress, and thus, could damage the lining. Under most circumstances, economics dictates that sufficient pillar be left to protect the existing lining rather than to increase the strength of the lining itself.

5.2.1.6 Construction Technique

Shaft sinking techniques can directly and indirectly influence the loading on the shaft lining. Various aspects of the construction practice contribute to loads including:

a. Preliminary stabilization used

b. Water control techniques used

c. Rate of shaft sinking

d. Distance behind shaft bottom that lining is placed

e. Excavation technique

f. Grouting behind lining.

Preliminary stabilization and water control effects on lining loads have been discussed under hydrology.

The rate of shaft sinking and the distance above shaft bottom that the lining is placed determine how much time and distance is allowed for the rock to relax or creep into the opening. An optimum amount of both elastic and creep movement will minimize the rock loads on the lining. However, too much movement must be avoided or the rock structure begins losing its integrity and strength as a unit. Placing lining in the vicinity of 1-½ to 2 diam above the shaft bottom will generally allow sufficient movement. In poor ground conditions this distance may have to be reduced. In extremely squeezing ground, a greater relaxation distance and time may be necessary.

TABLE 10. - Required thickness of unreinforced concrete shaft liners under hydrostatic pressure

Outside Pressure PSI		100	200	300	400	500	600
Ft	Concrete PSI	Thickness of the lining in inches: safety factor: 3 $\sigma cr. - 1.35\ f_c$					
14	3000	7.1	15.5	25.7	38.0	53.7	73.9
	4000	6.0	11.1	17.9	25.6	34.7	45.4
	5000	6.0	8.7	13.7	19.3	25.7	32.8
	6000	6.0	7.1	11.1	15.5	20.3	25.6
	7000	6.0	7.0	9.4	13.0	16.9	21.1
16	3000	8.1	17.7	29.3	43.5	61.4	-
	4000	6.5	12.7	20.4	29.3	39.7	51.9
	5000	6.5	9.9	15.7	22.1	29.3	37.5
	6000	6.5	8.1	12.7	17.7	23.2	29.3
	7000	6.5	8.1	10.7	14.8	19.3	24.0
18	3000	9.1	20.0	33.0	49.0	69.0	-
	4000	7.2	14.3	23.0	33.0	44.6	58.4
	5000	7.2	11.2	17.6	24.9	33.0	42.2
	6000	7.2	9.1	14.3	20.0	26.1	33.0
	7000	7.2	9.1	12.0	16.7	21.7	27.1
20	3000	10.2	22.2	36.7	54.4	76.7	-
	4000	8.2	15.9	25.5	36.6	49.6	64.9
	5000	8.2	12.4	19.6	27.6	36.7	46.8
	6000	8.2	10.2	15.9	22.2	29.1	36.6
	7000	8.2	10.2	13.4	18.5	24.0	30.1
22	3000	11.2	24.4	40.3	59.9	-	-
	4000	9.2	17.5	28.1	40.3	54.5	71.4
	5000	9.2	13.6	21.6	30.4	40.3	51.5
	6000	9.2	11.3	17.5	24.4	32.0	40.3
	7000	9.2	11.3	14.7	20.4	26.5	33.1

Triaxial Stress Condition.

TABLE 10. - Required thickness of unreinforced concrete shaft liners under hydrostatic pressure (Continued)

Outside Pressure PSI		100	200	300	400	500	600
Ft	Concrete PSI	Thickness of the lining in inches: safety factor: 3					
	3000	9.9	22.4	38.8	61.1	-	-
	4000	7.5	16.4	27.2	40.7	57.9	80.5
14	5000	6.0	12.1	19.6	28.4	38.8	51.3
	6000	6.0	9.9	15.8	22.4	30.0	38.8
	7000	6.0	8.3	13.2	18.5	24.5	31.2
	3000	11.3	25.6	44.3	69.8	-	-
	4000	8.5	18.7	31.1	46.5	66.1	-
16	5000	6.5	13.9	22.4	32.5	44.3	58.6
	6000	6.5	11.3	18.0	25.6	34.3	44.3
	7000	6.5	9.5	15.0	21.0	28.0	35.6
	3000	12.7	28.8	49.8	78.5	-	-
	4000	9.6	21.1	35.0	52.3	74.4	-
18	5000	7.3	15.6	25.3	36.5	49.9	65.9
	6000	7.2	12.7	20.3	28.8	38.6	49.8
	7000	7.2	10.7	16.9	23.8	31.5	40.1
	3000	14.1	32.0	55.4	-	-	-
	4000	10.7	23.4	38.9	58.1	-	-
20	5000	8.2	17.4	28.1	40.6	55.4	-
	6000	8.2	14.1	22.5	32.0	42.9	-
	7000	8.2	11.9	18.8	26.4	35.0	-
	3000	15.5	35.2	60.9	-	-	-
	4000	11.7	25.7	42.8	63.9	-	-
22	5000	9.2	19.1	30.9	44.6	60.9	-
	6000	9.2	15.5	24.8	35.2	47.1	-
	7000	9.2	13.1	20.7	29.1	38.5	-

Uniaxial Stress Condition

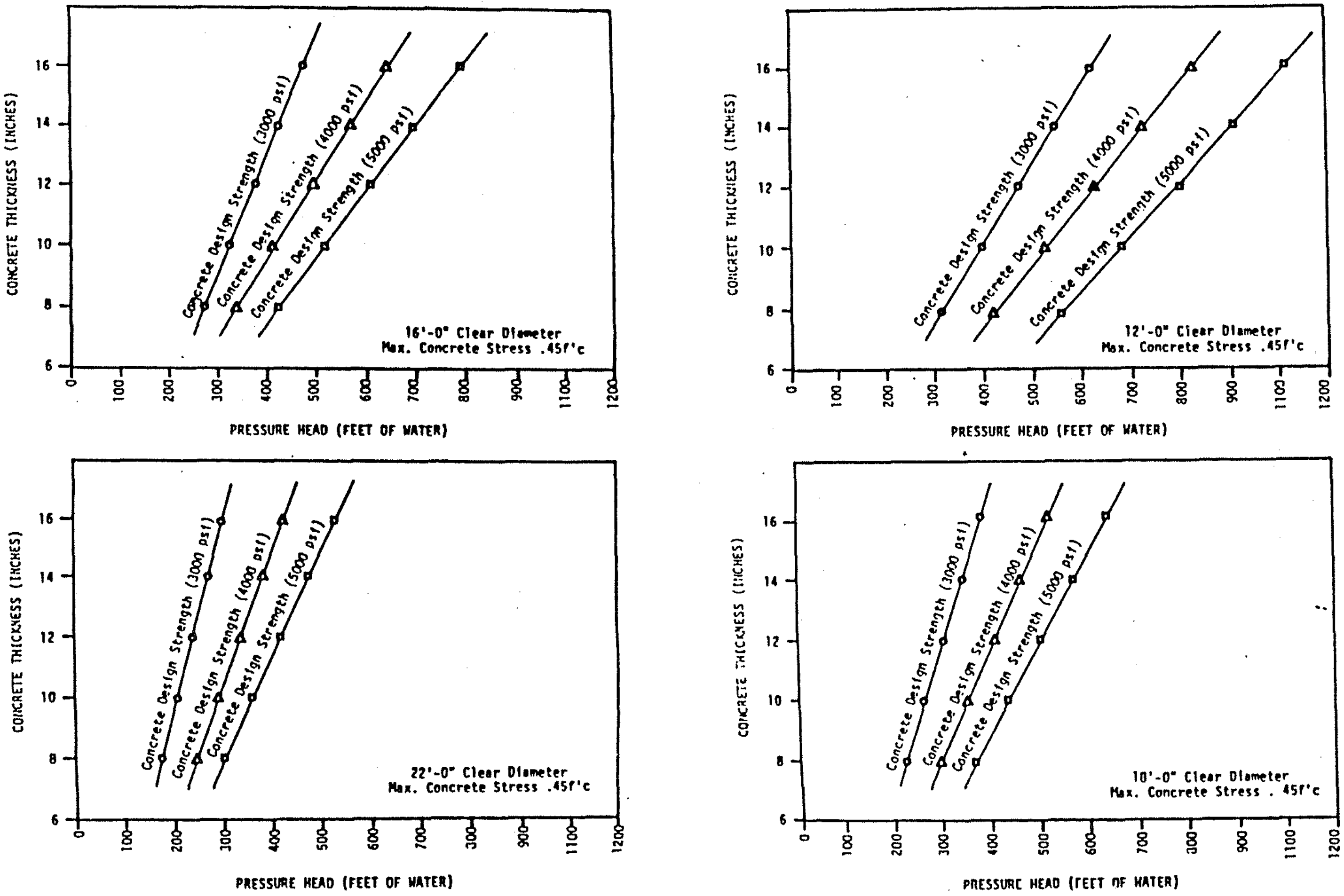


FIGURE 62. - Suggested water head to lining thickness relationship.

Mechanical excavation techniques in general cause substantially less damage to immediate wall rock thus reducing the likelihood of concentrated loads due to a loosened rock block impinging on the lining. The combination of pregrouting and mechanical excavation should virtually eliminate this type of loading.

Grouting following lining, however, places an additional, but temporary load on the lining due to the high pressures (typically 200 psi) used for pressure grouting. High pressure grouting to seal off aquifers after the lining has been placed should therefore proceed with caution.

5.2.2 Patching Techniques

5.2.2.1 Introduction

It is not reasonable to assume that even in machine bored shafts the shaft wall will be smooth and unbroken. The outer curb ring seal has been designed to accommodate overbreakage and small slough zones up to 3-½ inch deep and essentially continuous around the full circumference. There will be instances where shaft wall imperfections will exceed the capabilities of the outer curb ring seal. In these instances, an attempt will be made to "patch" this zone and bring it into compliance with the outer seal specifications.

5.2.2.2 Adverse Conditions and Corrective Methods

Slipforming in a downward mode is a new concept thus, there is no past experience to rely upon. The successful implementation of the CSL system will, in part, depend on the ability of the form to maintain the internal concrete pressures. Therefore, an effective curb ring seal will be a major factor. The texture of the shaft wall will be a function of ground conditions and the type of gauge cutter used on the boring head. Cutter costs are a major item with any drilling system and must be chosen for performance and durability. It is not reasonable at this time to assume that wall texturing requirements will affect cutter selection. Therefore, it is assumed that the rock conditions will determine the wall texture.

Grouting is probably the only method by which the in situ rock condition can be altered. However, the pre-construction geological study will not yield much information on the nature and severity of fractured zones. Therefore, any altering of the rock formation by grouting will be incidential to pre-construction water control. In essence, the CSL system will have to deal with varying rib conditions as they are encountered.

Listed below are some of the ground conditions that are likely to cause problems. Some possible solutions to these problems will be offered for consideration:

Vertical Fractures < 12 inches C-C

If the vertical fractures are closely spaced, the action of the cutters should ravel the ribs and leave a very irregular surface. If the spalls are numerous and the failure zone is large, very little can be done to repair the area; and the jump form mode will be required. However, if there is sufficient time, a small area might be healed by using sprayed foam to smooth the surface.

Vertical Fractures > 12 inches C-C

As the spacing of the vertical fractures becomes greater, there should be fewer but deeper spalls. Jump forming might be required, but it should be possible to repair an area with the scheme shown in Figure 63.

Air or Water Slaking

Certain types of ground deteriorate rapidly when exposed to air or water. It is possible to seal the ground to prevent failures. A foam type product referred to above can be used for this purpose.

Weak Bonding Between Horizontal Laminations

If there are natural partings between the sedimentary layers, the rock should break at 45 deg to the free face. Failures of this type will be very common and will provide a generally ragged surface over a large area. The irregularities are within 5/8 of an inch from a true surface. Little can be done about this type of failure. It will be necessary to design a curb ring seal to handle these relatively small irregularities.

Low Strength Zones

There will be zones of coal or other soft material that will fail after the shaft is excavated. The grippers on the boring machine will disturb this type of ground and contribute to the failure. Failures of this type will have to be handled individually by any of the methods previously discussed.

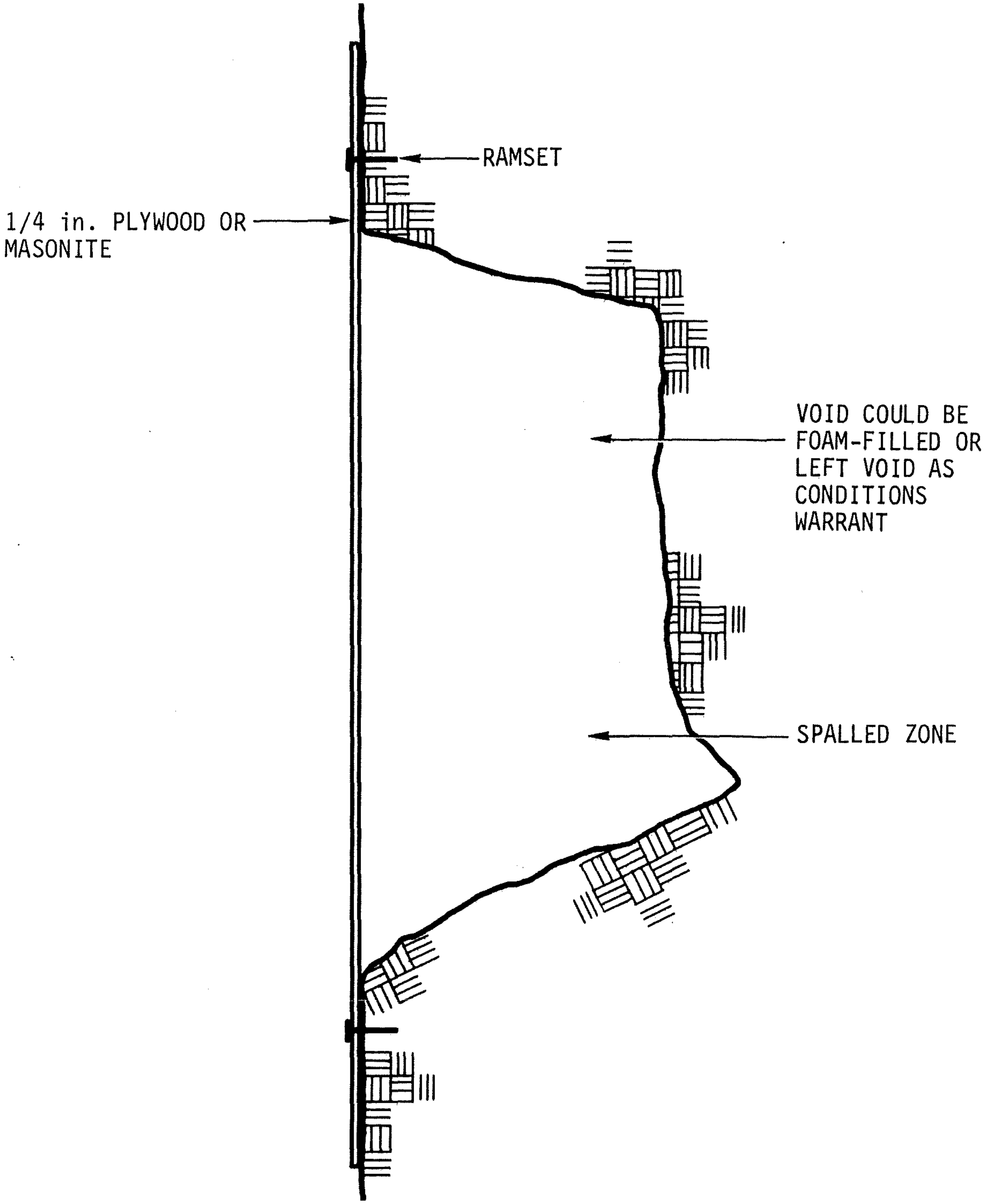


FIGURE 63. - Repair of slough zone.

Jump Form Mode

Except in special cases, large rib failures will be overcome by jumping the form and overriding the bad zone with the curb ring seal. The jump mode is described in Volume 1, subsection 2.3. The jump form mode will be a reliable method to use, even in the extremely bad zones. Unfortunately, it will be disruptive to cost and schedule. When the curb ring approaches a bad zone, the slipforming process will halt and the system will go on hold until the concrete within the form has set up enough to support its own weight and resist damage from the action of lowering the curb ring and slipform. This process might take 4 or 5 hours. It might be possible to accelerate the mix to minimize this delay. The need to jump the form will normally be known several hours in advance. Occasionally it will not be possible to jump the curb ring into a sound area beyond the slough zone. Therefore, it may be necessary to have a means to expand the curb ring radially as in conventional forming. Two commonly used schemes to accomplish this are shown in Figures 64 and 65.

5.2.2.3 Patching Materials

Foams

Foams are used in existing mines to prevent air slaking and to seal air stoppings. The use of materials that react chemically underground is, of course, a concern of MSHA. Many foams are combustible and yield toxic gases. Also skin contact to the chemical components and the inhalation of airborne particles can cause problems. MSHA approves sealants for underground use. An up-to-date listing of the acceptable sealants is included in the Appendix N. Apparently there is no "ideal" sealant from the viewpoint of Industrial Safety Division of MSHA. They recognize there is a need for mine sealants and are approving materials using an "acceptable risk" criteria.

Plastering

Extensive areas of surface voids could be filled with manually applied plaster. This method would require two or three workmen hand troweling a cement-based mortar. This activity would not necessarily add workmen to the CSL crew. The CSL crew will be sized to meet the worst condition and during many activities there might be manpower available.

There are a great variety of patching materials offered for commercial sale, but not all of these materials have been used underground. The patch materials are usually a Portland cement base or epoxy resin, although other bases are available. A list is included in Appendix N.

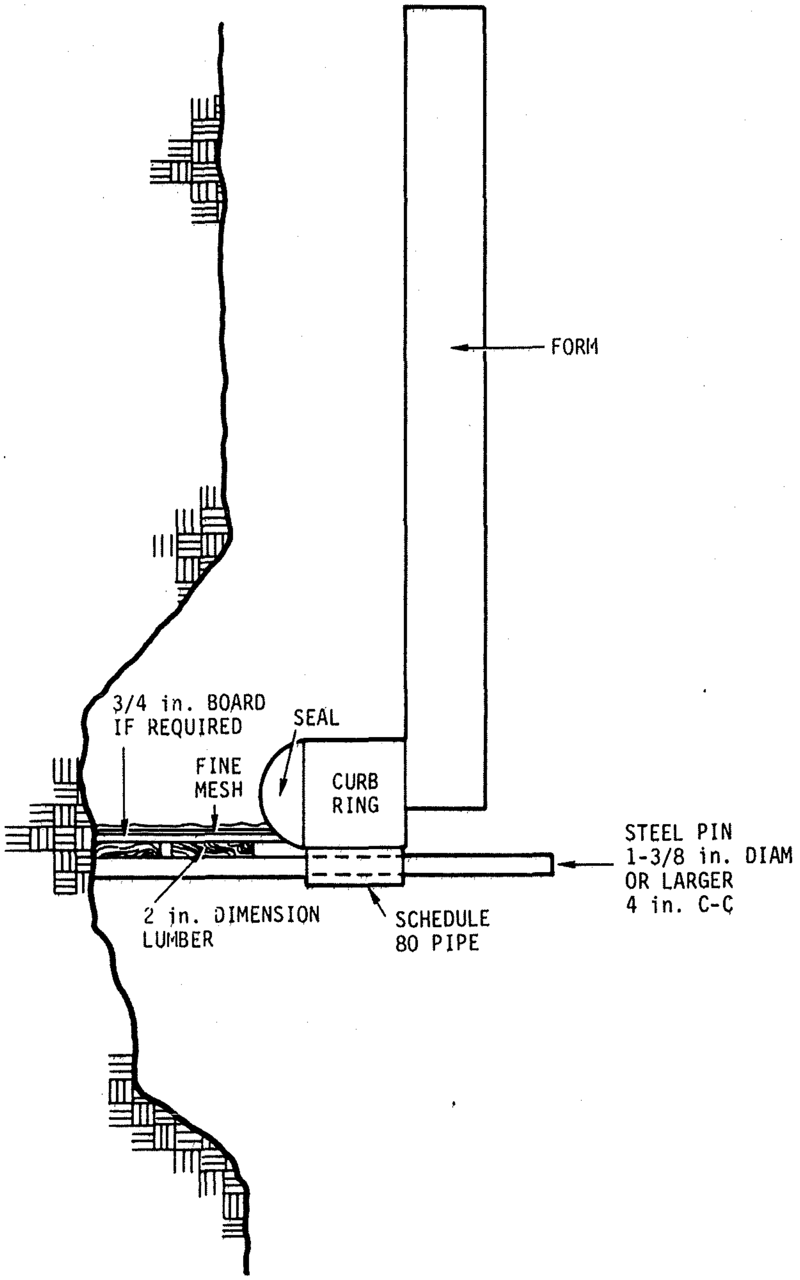


FIGURE 64. - Curb ring modification for deep slough zone.

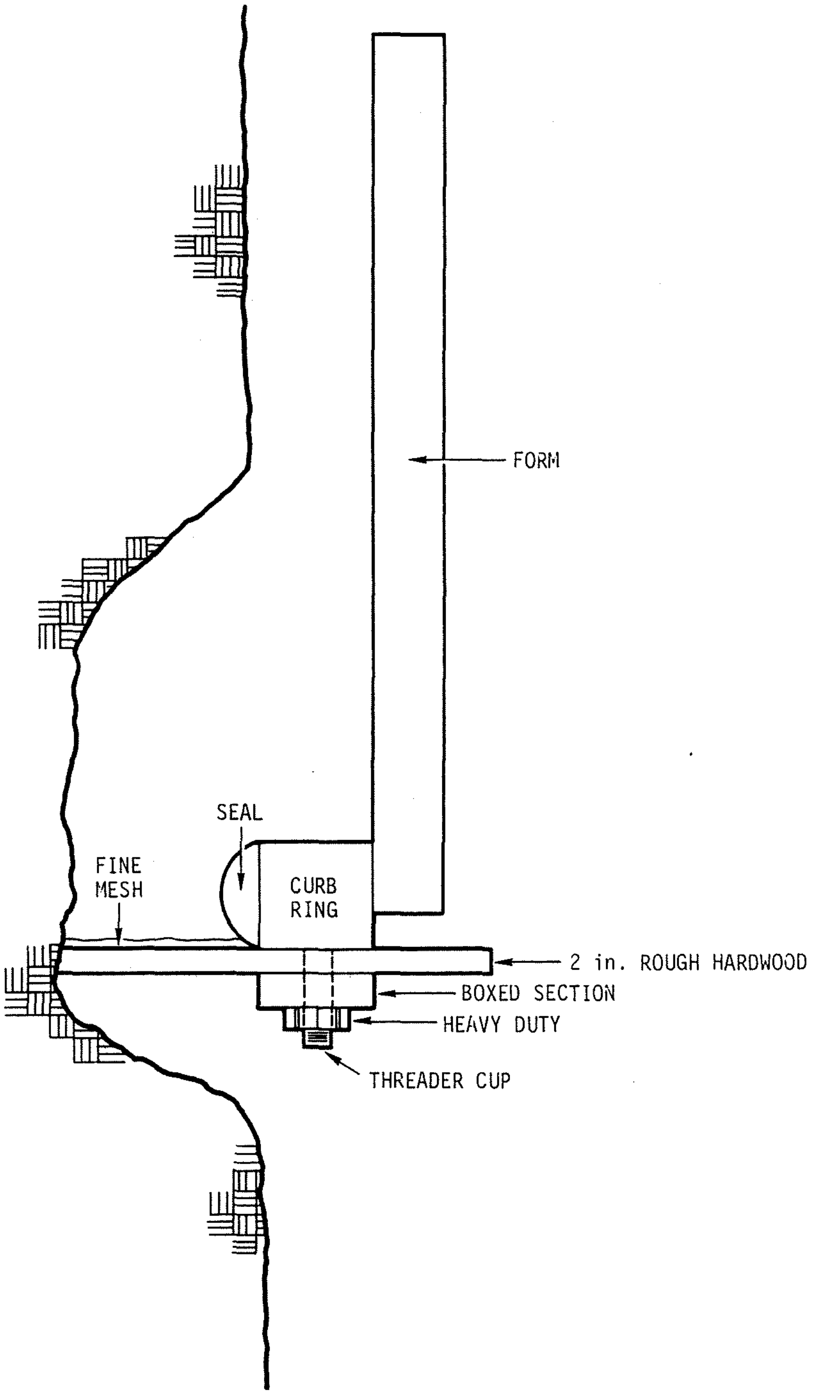


FIGURE 65. - Curb ring modification for deep slough zones.

5.2.3 Water Control Techniques

5.2.3.1 Introduction

The control of ground water is the essence of shaft sinking. Effective underground production consists mainly of solving the material handling problems. As water inflow increases, it must be removed often at the expense of other more productive activities. Water control under high head and high flow conditions can be very time-consuming and expensive. There are many case histories of shafts that yielded high pressure water at hundreds of gallons per minute. Here in the United States these shafts are normally found in the western mineral zones such as the uranium mines near Grants, NM. However, water inflows normally found in the coal fields are of moderate flow rates and pressures.

Unfortunately, bad ground conditions often accompany water problems. Water zones are often located in fractured rock, and in many instances, a slow advance rate due to aquifers leads to time related ground problems such as saturation and sloughing. This is a normal occurrence in the coal fields because of the shales and mudstones.

In most cases there is an inadequate amount of groundwater information available to the shaft contractor. Many site investigations deal primarily with depth, thickness and quality of the coal. The geology just above the coal seam and its probable effects on mine roof control is also a topic of the investigation. Core holes are normally logged indicating the type of rock, however, information about the location and particularly the quantity of inflows is often very sketchy.

A complete subsurface investigation should yield the following information:

a. Drillability of the rock

b. Type of rock and its reaction to water

c. Location of water zones

d. Initial inflow and the recharge characteristics of each water zone

e. Quality of water to ascertain surface handling problems

f. Location of fractured zones.

This type of subsurface investigation is often considered expensive and unnecessary, but if this type of information is provided to the contractor, it can yield the following benefits:

a. Pregrouting techniques might be indicated. This work can be done at the beginning of the project with a reduction in overall costs. A successful pregrouting program will lead to increased production rates.

b. Water conditions affect equipment selection and plant setup. If conditions are generally unknown, the prudent contractor must have a full array of equipment and supplies on site to handle almost any conceivable condition.

c. Water conditions will affect the overall project schedule and should also affect management investment decisions concerning the timing of other construction activities.

5.2.3.2 Preventative Measures

There are certain techniques that can be employed prior to any excavation that will potentially reduce future inflows. It is obvious that a good subsurface investigation is a prerequisite to this activity. Some of the possible programs are as follows.

Pregrouting

The principle of this technique is to inject grout into the fractures or unconsolidated zones and make the shaft area impervious to the flow of water. The techniques and materials used are naturally a function of the conditions encountered. Grouting is more an art than a science. A typical operation would be to drill a series of holes around the perimeter of the shaft. When water is encountered, the rate of inflow is recorded and grout is injected. After the grout has hardened, the holes are redrilled and the inflow is measured. This process continues to increasing depths until satisfactory results are obtained. The law of diminishing returns usually applies in all types of grouting, that is, 90 percent of the effort is usually required to cut off the last 10 percent of the inflow.

Grout can consist of cement or specialized chemicals or a combination of both. The pumping pressures, the rate of injection and the time allowed for set varies with conditions. The whole operation consists of an educated search for something that will work.

Freezing

Water with soft ground conditions can be cut off by drilling perimeter holes and inserting coolant pipes. The soil mass around the shaft perimeter will be frozen and excavation can proceed through the area cautiously. This technique is often used in collaring a shaft where the overburden is thick and contains aquifers.

The drill holes must be accurately placed to insure complete coverage just outside the shaft perimeter. The coolant plant must be adequately sized to meet the conditions. Many times the excavation through these areas is done manually. Ground support is provided by steel liner plate. The outside voids are then grouted.

Well Points

If the water-bearing zones are very permeable, it is possible to drill holes and insert well points to establish a draw down surface outside the shaft perimeter. This system would stay in operation until the shaft lining is sealed into an impervious zone under the aquifer. The permeability and recharge characteristics of the wet zone are the key elements to the success of this system.

The easiest and least costly application of all the preventive measures occurs when the work is done from the surface. However, each technique can be done from a shaft bottom if necessary. All drill holes are fanned out or the shaft diameter is increased to facilitate vertical drilling. Work of this nature is always disruptive to cost and schedule. In most cases the shaft excavation crew will have to be replaced or retrained to perform the work. Also, the drilling equipment suitable for this long-hole drilling would not normally be on hand.

5.2.3.3 In-Shaft Pumping Systems

Once excavation is under way and water enters and accumulates in the shaft, it must be controlled if reasonable productivity is to be maintained. Usually, all water that reaches the shaft must be removed. With most excavation operations, inflows up to 5 gpm would be considered more or less routine. Production problems increase dramatically above 5 gpm with considerable problems occurring after 20 gpm are obtained. The following list outlines the various pumping systems commonly used to remove water from a shaft.

Bailing

Bailing is the removal of water with the use of a muck bucket and a hoist. If the water is deep, a flat valve can be installed on the bucket bottom and the removal process can take place without men in the hole. When the water is less than the height of the bucket, the water is pumped into the bucket with high volume low head electric or air pumps. A 600 gal bucket with a 10 min hoist cycle can remove 60 gpm. This is a reasonable rate, but no other production activity can normally take place while bailing is in progress. The technique should be avoided for this reason (see Figure 66).

Submersible Pumps with Downhole Sumps

This method requires the drilling of an 8 to 12 inch diam hole, cased with a lightweight pipe, just outside the shaft perimeter. A multistage deep-well, high-head electric pump is then hung in the hole. Normal pump diameters are 6 inches. The water is directed into the downhole via a 1-½ to 2 inch diam drilled hole from the shaft. Often several attempts are

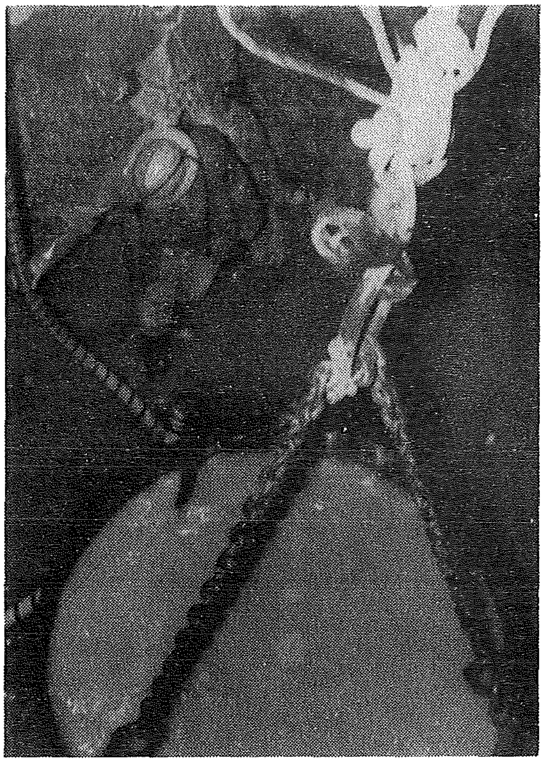


FIGURE 66. - Bailing of water with bucket.

necessary to make a connection. The multistage impellers of these pumps are sensitive to abrasive materials. Therefore, this method has its drawbacks for removal of water at the shaft bottom. It does have an application for use with a water ring. Permissible motors are normally not required for submerged pumps used in an external hole. Figure 67 shows a typical deep-well pump.

High-Head Placement Pump

There are multistage piston type pumps available that can discharge over 50 gpm at greater than 500 psi discharge head. These pumps are compact and can be powered by air or electricity. The pumps require routine lubrication and inspection, therefore they must remain accessible. A sound discharge line is required due to the pulsating action of the pistons. These pumps work best with clear water but certain pumps have an option that provides ball valves which will handle an increased amount of sediments.

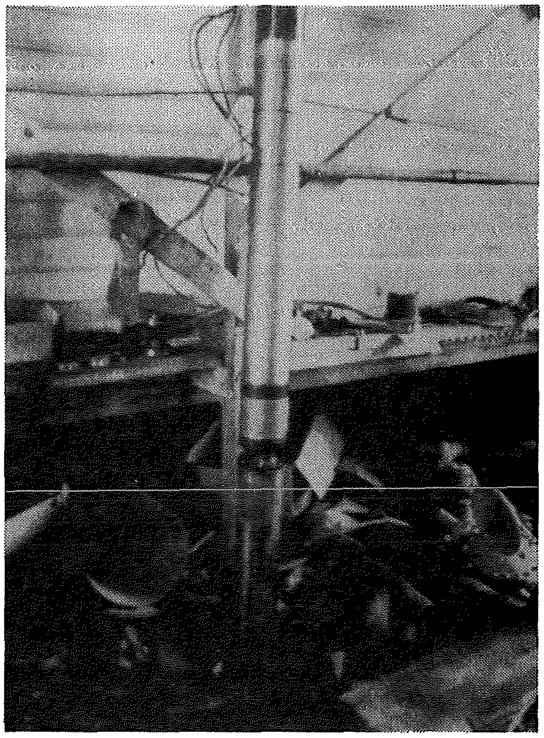


FIGURE 67. - Typical deep well pump.

Moyno Pumps

The Moyno pump is manufactured by Hewitt Robbins. It consists of a multilobed rotating rod inside a rubber sheath surrounded by a pipe. The geometry of the system provides multistages with high head and volume. The larger sized pumps are long and can be mounted vertically in a shaft. These pumps will handle fine-particle slurries; therefore, they are applicable to use on the shaft bottom. Naturally, frequency of component replacement is a function of the solids pumped.

Diaphragm Pumps with an Airlift Assist

A typical shaft bottom low head high volume utility pump is the M-8 or M-16 Wilden Double-Acting Diaphragm Pump. The discharge head is a function of the service air pressure. One hundred psi of air pressure will yield a discharge head of approximately 200 feet. Compressed air can be injected into the discharge side of this pump, decreasing the unit weight of the water and increasing the discharge head proportionately. This system is simple and compact. Ten gpm at 1000 feet has been removed by this method (see Figure 68).

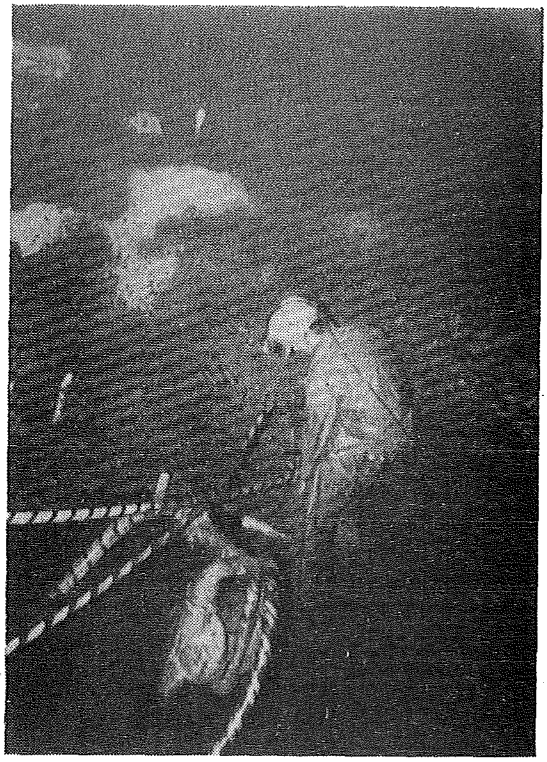


FIGURE 68. - Wilden sump pump.

5.2.3.4 In-Shaft Techniques to Control or Reduce Inflows

As stated earlier, when water reaches the shaft bottom, it begins to inhibit production and must be controlled immediately. This water enters the shaft in two modes, through the concrete lining or through the ground under the lining. In the latter case, the water must be controlled so that good quality concrete can be placed. After the lining is placed, water will percolate through it or enter through discontinuities such as construction joints. The discussions below will outline the techniques used to control water that enters through these two modes.

Contact Grouting of the Lining

The goal of contact grouting is the stopping of the water coming through the lining. No attempt is made to prevent water from percolating through the ground outside the lining. Drill holes typically do not go beyond the concrete-rock interface.

Sound concrete does not always stop the flow of water. Small weeps may develop on what seems to be a solid surface. The frequency and quantity of this inflow is directly related to the water pressure outside the lining. The only way to stop this type of inflow is to inject a sealing grout into the weeps. Typically the grout pump is hand or air operated. Relatively small quantities of grout are used. Patience and time is required to do the program successfully. After sealing an area, it is not unusual to have some leaks redevelop.

In a conventional shaft lining operation, the concrete is placed from the curb ring up, in segments of 10 to 24 feet (a function of ground conditions). Each pour closure will leave a major discontinuity in the lining and provide a prime location for water leaks. It is very important that these closures are poured as full as possible. In actual practice, less than ideal results are usually achieved. Voids may have to be grouted closed. The typical sequence is to make one pass with low pressure cement and return with successive passes of chemical grout until the seepage stops. Water stops would be useful in wet joints. However, they are difficult to install with most curb ring designs. Seasonal temperature variations will expand or contract the shaft lining closures and affect the total inflow.

There are basically three types of grout used in shaft work which are described as follows.

Cement Grout

This is a mixture of cement and water with an occasional addition of an expanding medium such as oats, cottonseed hulls, or sawdust. The batches are usually mixed underground with an air power mixer. A positive displacement grout pump is used to place the material. Pressure varies with conditions but normally does not exceed 200 psi.

Time Reactive Chemical Grouts

This grout consists of a two component chemical mix that sets up into a gel as a function of time and temperature. Normally each component is added in equal volume. The set-up time is adjusted by varying the concentration of one of the components. It is usually applied with a two-sided piston pump with a common drive linkage. These pumps are low volume and powered by hand or air. These grouts are fairly expensive and not applied in high volumes. Common trade names are Geoseal, Terraseal, AM-9, and Halliburton PWG.

Water Reactive Chemical Grout

The Japanese have developed a grout called TACCS that will not react until the mixture comes in contact with water. It has two components. The main substance is a polyurethane base that is sensitized with an accelerator. When exposed to water, the grout foams and expands to fill the void with a sticky, foamy substance. It does an excellent job if properly applied. It is imported directly from Japan at a cost of approximately $20/gal depending upon the exchange rate.

Water Rings

A water ring is imbedded in the lining to intercept the water and transfer it to a pump for removal. A discharge pipe can be imbedded in the lining or bolted on the lining. Also the water can be diverted downhole, outside the lining, for discharge to the surface. Some shaft designs call for the long-term use of water rings with no contact grouting required. Sometimes temporary rings are set up for construction use only (see Figure 69). For the water ring to be effective, it is necessary to divert all inflows down the lining. Burlap curtains are often hung to collect the water and prevent misting. Figure 70 shows two permanent water ring designs.

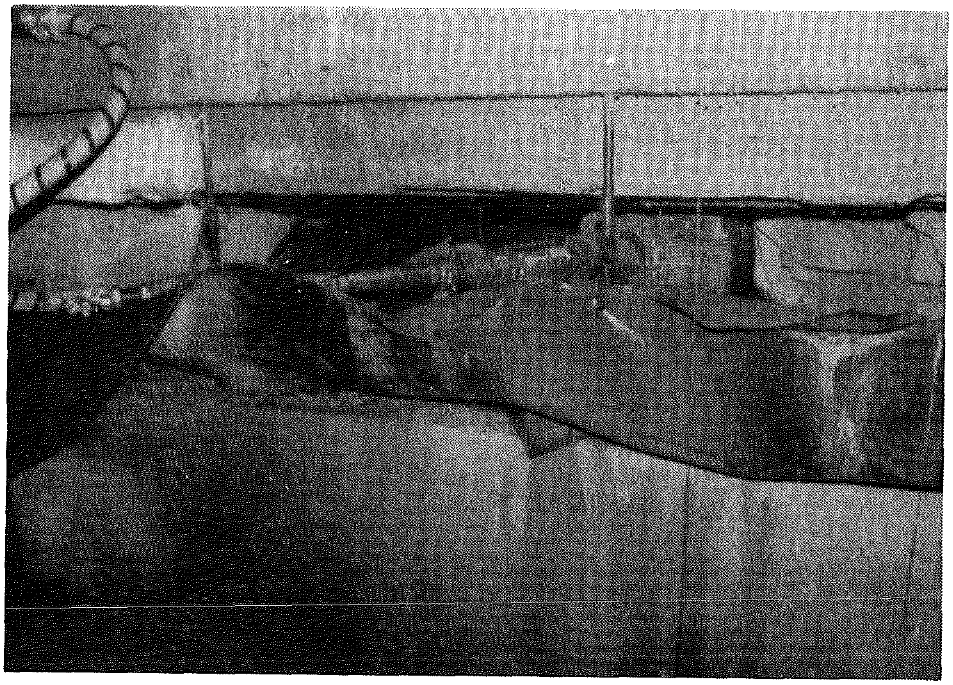
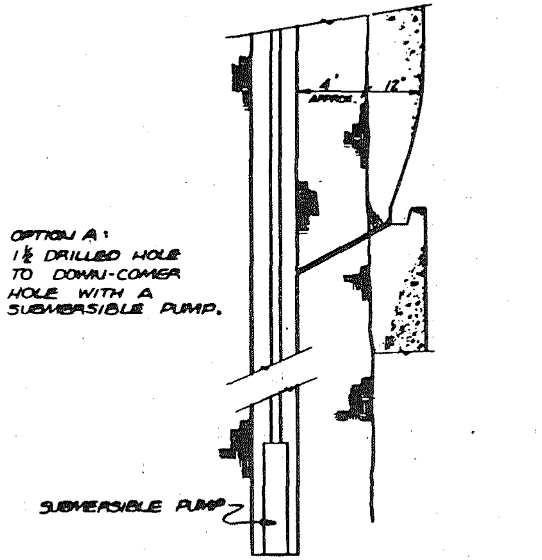


FIGURE 69. - Temporary water ring with a Moyno pump.

5.2.3.5 Control of Generalized Weeps under the Lining

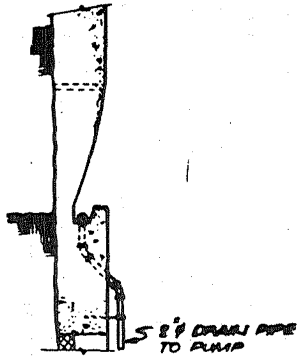
Generalized weeps often occur in permeable sandstones. The goal to accomplish under these conditions is to pump away the accumulated water and set up a system whereby quality concrete can be placed to cut off the inflow. The washng of cement paste from the concrete is the most common problem. If the inflows are moderate, sometimes it is possible to pour concrete on the high side in the form and chase the water to a low point in the form so that it can be removed. There will always be some "washing" of the top of each lift, therefore, it is advisable to batch a rich high slump mix. Seven to eight sacks of cement per CY with 6 to 7 in. slump would be recommended. Vibrations should be held to a minimum. If the proper attention is given to the placing methods, a good quality lining can be placed under moderately wet conditions. If too much washing occurs then it is necessary to prevent the water from reaching the concrete.

Washing is prevented by placing a barrier between the concrete and the rib and forcing the water down the interface. Various materials are used to accomplish this: corrugated metal, polyurethane sheeting, or butyl rubber sheeting are common. All these materials are referred to as panning. Each material works satisfactorily under the right conditions. If full perimeter panning is required in blasted shafts, then rubber sheeting is



TYPICAL WATER RING

OPTION A



TYPICAL WATER RING

Dravo Engineers and Constructors

Civil Mining & Marine Division
Pittsburgh Pennsylvania

Dravo

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SCALE NO SCALE						

FOSTER MILLER ASSOCIATES INC.
CONTINUOUS SHAFT MINING SYSTEMS

WATER RING

CONTRACT EP-8562
DWG NO WD-6
REV

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FIGURE 70. - Water ring design alternatives.

preferred, rock bolted to the rib or hung off the previous pour. It is sometimes necessary to install vertical weep pipes behind the panning to insure that the concrete pressure will not seal the interface and cause the water to accumulate and balloon the panning.

The use of panning yields two undesirable effects. First, the adhesion between the concrete and the rib is lost, and second, an empty space is provided for the water to accumulate and build a vertical head. The first effect may or may not cause a problem depending upon conditions; however, the increased head often comes back to haunt you. It is possible to carry the water down the shaft via the weep pipes until a water ring can be established. Carrying water can be self-defeating if the volume increases with time and/or depth. As an alternative, the outside of the panning can be grouted after each pour and cut off the water before advancing. This task is troublesome because it is difficult to establish a seal at the curb ring so the grout pump can build pressure. Also, anytime grouting behind a lining is used, there is a risk of exerting too much pressure over too large an area and jacking a section of concrete off the wall. During cyclical grouting after each pour, there is the advantage of the support provided by the form.

It is possible to apply shotcrete to a weeping area and chase the water to one location. At that location a void can be established with a pie tin that has a drain hose attached. The drain hose can be directed outside the form during pouring. This technique requires ideal conditions, a good shotcrete man, and fine control of the accelerator volume. If the shotcrete absorbs too much water from the rib, it will slough off before it can set up. Shotcreting in a shaft bottom with normal ventilation is a dirty job. Also, many of the accelerators can cause chemical burns.

5.2.3.6 Control of Localized Flows

Water percolating through fractured zones will naturally follow the path of least resistance and enter the shaft in a localized area. If you plug off this spot, the water will find another path of less resistance and show up somewhere else. A common technique employed is to drill into the flowing zone until the water flows out a hole. Then a pipe is packed into the hole and the water is diverted outside the form. After the concrete pour the pipe can be plugged. If the water reappears, then consideration can be given to some long-hole grouting to close the fractures. Grouting fracture zones in the shaft to cut off water is very difficult. The water will build up head and the contractor will find himself just chasing it around.

5.2.4 Cold Joint Techniques

In conventional shaft lining operations, a cold joint is formed after every concrete pour. A cold joint is defined as an interface between two distinctly separate concrete slabs where no physical or chemical bond is present between the concrete slabs. It is, in other words, an ideal weak point in the lining for ground water to inflow. In CSL operations, cold joints still may exist, but occur in significantly fewer numbers. In conventional lining there will be a cold joint at least every 20 ft in the lining. In a continuously slipformed lining, cold joints may occcur once in a day (100 ft), or, in theory, there could be no joints at all. Regardless of which shaft lining technique is used, if cold joints are expected, then procedures for sealing the joints should be used.

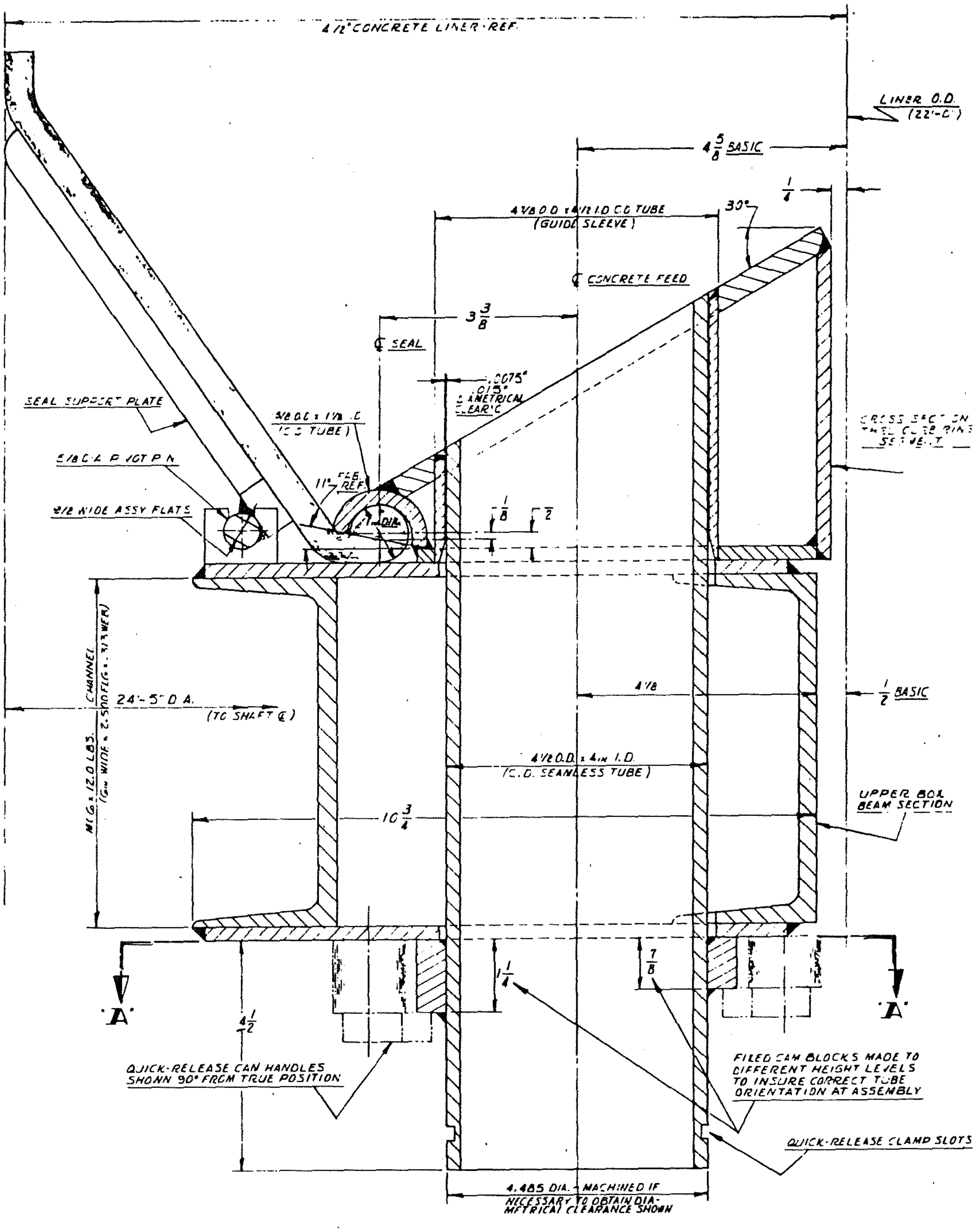
The use of traditional water stops used in conventional construction is difficult to apply to CSL operations. This is due to the inaccessibility of the curb ring where the water stop must be installed. A seal/water stop system was conceptualized by Rapidex in their final report (6). Figure 71 details the arrangement of the seal/water stop and its mounting atop the curb ring. Figure 72 depicts the operational procedure for deploying the combination seal/water stop. The seal is an extruded polyurethane shape manufactured for use as a water stop. When the lining operation is halted, the seal is to remain behind as an embedded water stop. This would seal the cold joint upon resumption of the lining operations. This system has never been demonstrated and appears to be an expensive operation with regard to the cost of replacement seals and the labor cost to reinstall new seals at each joint.

The present CSL design does not incorporate a direct method for embedding water stops into the lining at each cold joint. The approach taken was to use an appropriate gasket material which could seal the cold joint. The procedure used can be described as follows:

a. Standard operating procedure for CSL operations requires the curb ring to be pulled free from the lining once the concrete has cured following a routine termination in operations.

b. The underside of the lining will be exposed at this time, allowing access.

c. A gasket is manually attached to the lining and the slipform reinserted into the previously cast lining in preparation for starting slipforming operations.



SECTION VIEW THROUGH CONCRETE INLET PIPE

FIGURE 71. - Detail of Rapidex curb ring assembly.

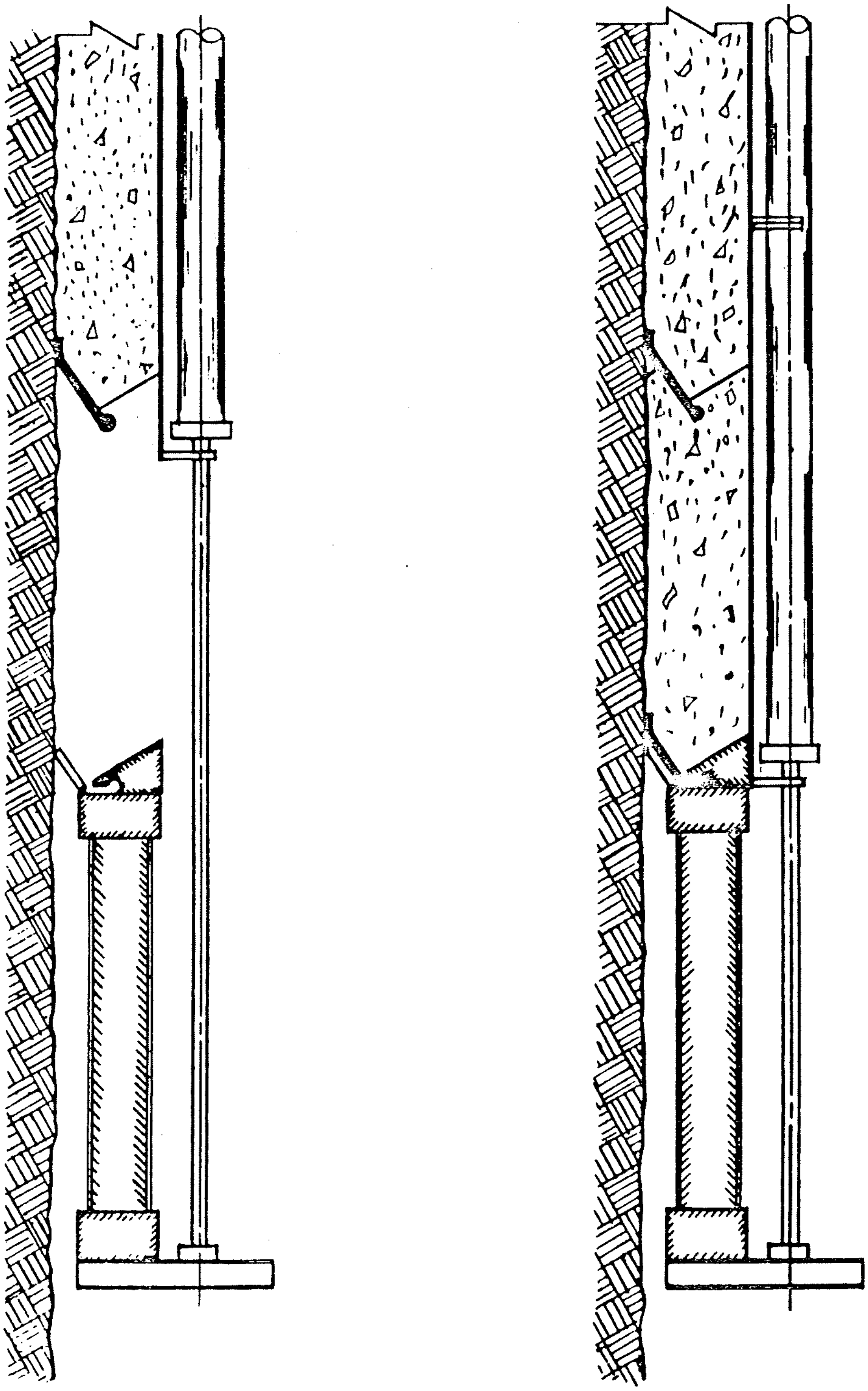


FIGURE 72. - Illustration of the Rapidex curb ring seal, functioning as a waterstop.

d. Once the void is filled with concrete, a competent, water-tight cold joint will be formed.

Various gasket materials are commercially available, however, one material produced by Dow Chemical Company was selected. Dowell Chemical Seal Ring Gaskets are manufactured from a unique polymer which swells in water. When the gasket is confined in a lining joint, the rubber like nature of the material makes it possible to create a water-tight structure. The Chemical Ring Gasket is pliable enough to accommodate expansion and contraction of the lining while providing a positive seal. Any water flowing through the joint will be imbibed by the gasket causing it to swell and seal even tighter. There is no evidence of seal degradation with time nor is there a limit on the number of wet/dry cycles it can withstand.

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