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16. Abstract

Precast reinforced concrete tunnel support lining has been used in Europe for some time as a viable method in tunnel construction. In late 1975 UMTA sponsored a study on segmented concrete tunnel liner and sealant systems. A five-phase study plan was developed and work began in 1976. This report presents the five phases. Phase 1 consists of information gathering and review; Phase 2 consists of the development of segment liner design parameters and trade-off study; Phase 3 consists of the sealant materials and test program; Phase 4 consists of a program to test joint and sealant systems; and Phase 5 addresses the design and manufacture of liner systems.

The purpose of this study is to identify the design criteria for a bolted circular segmented concrete tunnel liner system; devise, fabricate and test all the components of that system; and develop specifications applicable to the tunneling industry. These specifications are to provide tunnel authorities, designers, contractors, owners, and the general public with proven data for the safe and economical implementation of segmented concrete liners for rapid transit tunnels. Reinforced concrete, a well-established structural material that can be easily designed to withstand the handling, erection, and in situ forces as a tunnel liner, presents the problem of potential leakage at segment junctures. Thus, the main objective of this effort is to identify sealant materials/systems that can demonstrate satisfactory watertightness characteristics at segmented concrete liner joints under simulated soft-ground tunnel environmental conditions.

17. Key Words

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SEGMENTED CONCRETE TUNNEL LINER
AND
SEALANT SYSTEMS

C. E. Selander
C. A. Nelson
B. V. Jones, et al.

U.S. DEPARTMENT OF THE INTERIOR
Water and Power Resources Service
Engineering and Research Center
Denver CO 80225

JULY 1980
FINAL REPORT

Prepared for

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URBAN MASS TRANSPORTATION ADMINISTRATION
Office of Technology Development and Deployment
Office of Rail and Construction Technology
Washington DC 20590

NOTICE

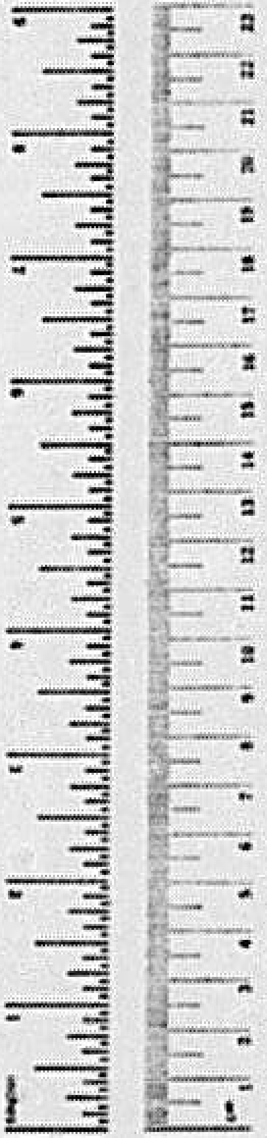
NOTICE

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

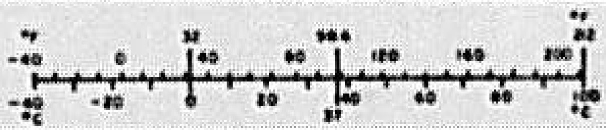
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

There is great national and worldwide interest in the development and use of rapid underground excavation and tunneling methods. Precast reinforced concrete tunnel support/lining has been used in Europe for over 30 years, but has not been employed to any significant extent in the United States until recently. The industry's reluctance to use precast concrete tunnel liners in rail transit tunnel construction was due to the general belief that the joints and sealants could not meet waterproofing specifications. The U.S. Department of Transportations' Urban Mass Transportation Administration, recognizing the potential cost savings of precast concrete segmented liners requested DOT's Transportation Systems Center (TSC) to initiate an investigation into precast concrete tunnel liner joint configuration and sealants.

In response to that request, TSC, under the leadership of Mr. Santo Gozzo, reached agreement with the Bureau of Reclamation, now called the Water and Power Resources Service (Service), to sponsor a study on segmented concrete tunnel liner and sealant systems. A study plan incorporating five phases was developed and work began early in 1976. Mr. Robert W. Spencer was Principal Investigator; however, he retired from the Service in 1979 before the study was completed. Mr. Chester C. Gore, Civil Engineering Technician, was the principal assistant in the study and provided significant technical input throughout the entire program. Many other persons, but mainly those listed as authors of this report, conducted major portions of the study or made significant contributions to it. TSC Technical Monitors were Messrs. Bruce Bosserman and James Lamond.

During the time this study was being conducted, the Service had two water conveyance tunnels under construction utilizing unbolted segmented reinforced concrete liner and sealant systems. One was Buckskin Mountains Tunnel, Central Arizona Project, near Parker, Arizona, which is approximately 22 feet in diameter; the other was

Stillwater Tunnel, Central Utah Project, near Duchesne, Utah, which is 8 feet 3 inches in diameter. Test data, design experiences, and particularly precasting techniques and construction experiences from these two tunnels were of benefit to this study.

In addition, two experimental reaches of segmented concrete lined transportation system tunnels were constructed in the eastern United States during the time of this study. Several Service personnel traveled to these sites to gain first-hand experience and knowledge to apply to this study.

Initially, progress in this study was reported monthly, February 1976 through December 1976. From December 1976 through the end of the study, comprehensive quarterly progress reports were submitted to TSC. In addition, semiannual oral reports were made, alternating between the Service, Engineering and Research Center, in Denver, Colorado, and TSC in Cambridge, Massachusetts. This report summarizes the data previously submitted to TSC in the progress reports and presents the final results of the study.

SUMMARY

1. BACKGROUND

Precast reinforced concrete tunnel support lining has been used in Europe for sometime as a viable method in tunnel construction. The liners are segments of precast reinforced concrete that comprise the support walls of the tunnel. This construction method has not been employed to any significant extent in the United States. Late in 1975, the Transportation Systems Center (TSC) in conjunction with the Urban Mass Transportation Administration (UMTA) reached agreement with the Bureau of Reclamation, now called the Water and Power Resources Service, to sponsor a study on segmented concrete tunnel liner and sealant systems. A study plan incorporating five phases was developed and work began early in 1976.

2. OBJECTIVE

The purpose of this study was to identify the design criteria for a bolted circular segmented concrete tunnel liner system; devise, fabricate and test all the components of that system; and develop specifications applicable to the tunneling industry. These specifications were to provide tunnel authorities, designers, contractors, owners and the public in general with proven data for the safe and economical implementation of segmented concrete liners for rapid transit tunnels.

Reinforced concrete is a well-established structural material whose behavior has been extensively studied and has seen significant applications to date in tunnel liners. Moreover, reinforced concrete can be designed to withstand the handling, erection, and in situ forces as a tunnel liner.

The weak link in a segmented concrete tunnel liner is the potential leakage that may arise at segment junctures. Thus, a primary objective of this effort has been to identify sealant materials and/or sealant systems that demonstrate satisfactory watertightness characteristics for segmented liner joints under simulated soft ground tunnel environmental conditions.

3. PROJECT APPROACH

The overall project structure is outlined in Figure S-1. The project was divided into five phases consisting of:

1) Information Gathering and Review
2) Development of Segmented Liner Design Parameters and Trade-off Study
3) Sealant Materials Test Program
4) Sealant Systems Test Program
5) Development of Design and Construction Specifications.

Phase 1 collected the historical data, such as what design factors were used and why, pertaining to the use of segmented concrete liners. Phase 2 examined that information encompassing all the aspects of tunnel construction. This led to the development of design criteria relating to the optimum size and number of segments. Phase 3 identified important sealant properties that affect performance, examined commercially available sealants, developed a screening testing program to identify candidate sealants and determine their physical properties. In Phase 4, watertightness tests were conducted on sealants and joint systems in a variety of joint configurations. Segment and joint repairability techniques were also developed. Sealants resistance to fire and corrosion potential of exposed metalwork in a bolted system were evaluated. The most promising materials and designs were incorporated in scale model tunnel tests in which the selected systems could be evaluated under combined hydrostatic and soil loads.

Phase 5 used the information obtained in the first four phases to develop guidelines and design specifications.

4. RESULTS

4.1. Segment Configuration and Size

The review of the literature on precast concrete segment lined tunnels did not indicate an optimum size and number of precast concrete segments per

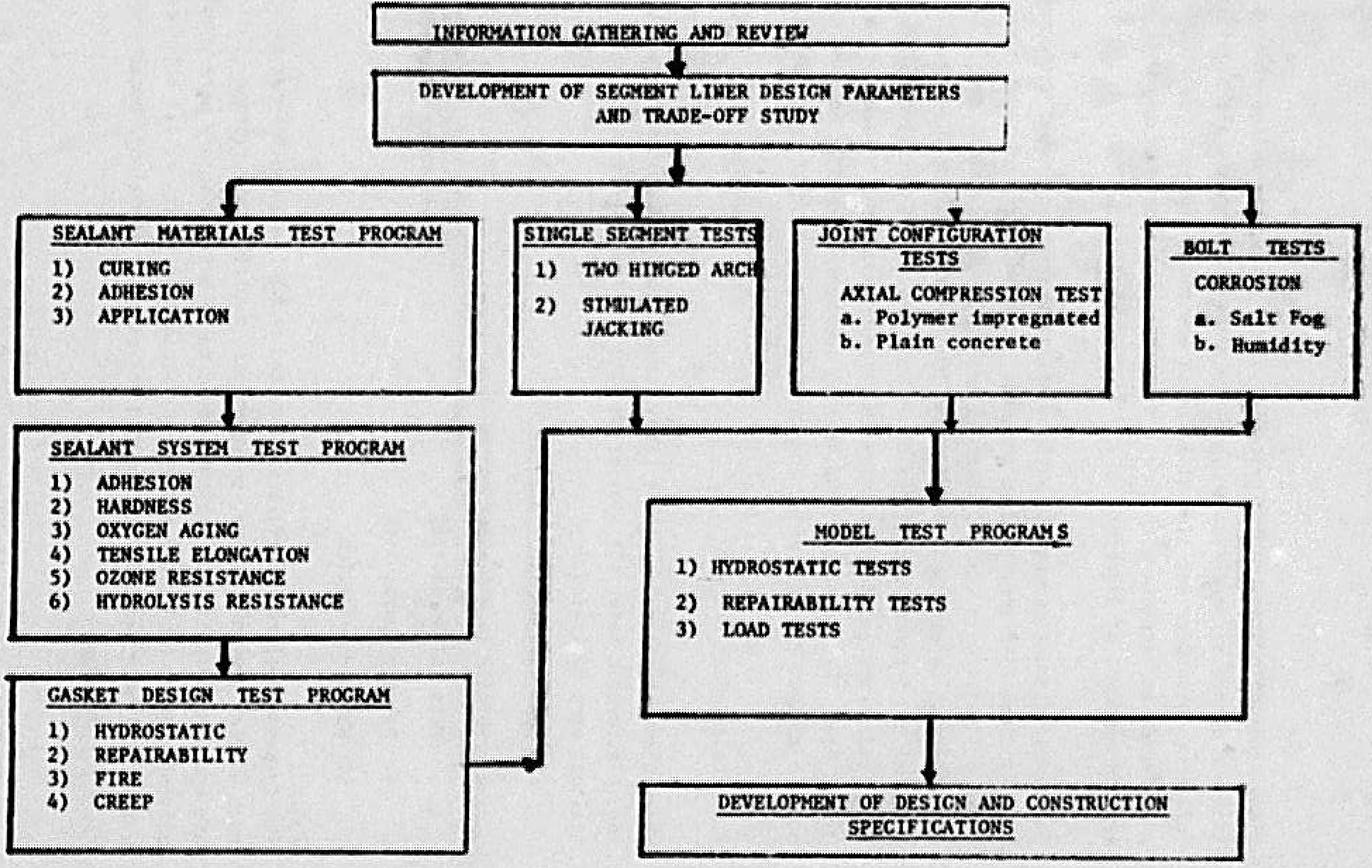


FIGURE S-1. PROGRAM DEVELOPMENT PLAN

ring. The geology and design criteria, labor costs, the method of excavation and degree of mechanization used to place the segments all significantly influence the number and size of segments per ring. Segment longitudinal width tends to increase with tunnel diameter. The number of segments per ring were independent of diameter.

The widest segment compatible with tunnel excavation equipment and construction handling clearances should be used. However, width of segment may be a serious liability in tunnels where squeezing ground is encountered. The segments must be designed to withstand longitudinal thrust loads required to overcome the friction resistance on the outside of the shield from ground loads and thrust required to drive the leading edge of a shield into a soft ground face. Proving good, true bearing surfaces and proper bearing material between segment rings, shield, and leading ring is also of critical importance.

4.2. Sealant Test Program

The sealants considered in this study were fluid-applied, temperature vulcanizing, elastomeric materials similar to high quality rubbery compounds. These sealants were evaluated for:

1. Application characteristics
2. Ability to withstand movement
3. Material durability
4. Adhesion durability
5. Water degradation

Thirty-seven sealant materials were tested emphasizing the polymer groups such as modified polysulfide, polyurethane, modified polyurethane, silicone, and epoxy modifications. Sealants found to be unsatisfactory were unvulcanized polychloroprene (neoprene) and epoxies because of their initial stiffness; acrylic polymers and chlorosulfonated polyethylene (hypalong) because of the poor water immersion characteristics; and butyl, ethylene, vinyl acetate, and related polymers because of their poor creep characteristics.

4.3. Sealant System Tests

Eleven of the sealants were selected as candidate sealant materials for further study. These materials were subject to a variety of tests, including adhesion, tensile elongation, hydrolysis resistance, hardness, flammability, heat stability, ozone resistance and oxygen aging. The results indicated that many polymers are seriously degraded by water especially when water is under pressure. In some cases, the time to failure of the sealant was reduced from several months to a few days when water pressure was increased.

4.4. Gasket System

The four gasket systems evaluated were:

1. Full surface crushable compression seal with calking groove - comprised of a high density 1/4 inch thick fiberboard.

2. Full surface sprayed elastomer - comprised of two part sprayed urethane.

3. Full surface preformed elastomeric gasket with calking groove - comprised of epoxy-modified urethane.

4. Local compression seal with calking groove - comprised of a fiberboard gasket.

Results showed that a fluid sealant must be part of any sealant system. Also, if loads near the ultimate joint strength are anticipated, only the fiberboard or equivalent should be used. A calking groove on the inner surface is necessary for maintaining the sealing capability of all systems.

Four methods of repairing leaking joints were examined: 1) calking grooves, 2) polymer gel injection, 3) polymer gel bentonite grout, and 4) polyurethane foam. Results indicate that satisfactory sealant system repairs can be made with the first three materials, especially the polymer gel-bentonite grout. This material completely sealed an extensive water leak, remained flexible, flowed to fill all cavities and is more durable in sealing canals and reservoir than plain bentonite grout. The polyurethane foam proved unsatisfactory because of its slow expansion and curing properties.

Fire tests were conducted on specimens especially fabricated to fit the test tunnel. In one test, neoprene gaskets were bonded by opposing faces of the individual blocks. In a second test, calking grooves were cast in the lower surface and longitudinal grooves were calked with a sealant material. The fire tests showed that expansion of the sealant from the sealant groove as the material became heated caused more sealant to soften and burn, destroying the effectiveness of the sealant.

4.5. Joint Design

Throughout the course of study, a large variety of joint configurations were tested. Six-inch samples of longitudinal and transverse joints were fabricated and evaluated for load-carrying capacity. In addition, the strength characteristics of polymer-impregnated concrete were also compared to plain concrete in joint configuration tests. The results show that changes in the joint configuration by addition of a gasket or sealant causes a reduction in joint strength. To achieve a watertight joint, it is necessary to sacrifice some compressive strength. A plywood cushion maintains or increases the joint strength by providing a more uniform bearing area and reduced lateral flow compared to other sealants and fillers.

Arch load tests and simulated jacking tests were performed on single liner segments. The initial failure mode in the arch tests was a tension crack on the inner surface of the arch at the point of the applied load. The arch continued to support increasing load until it completely failed. For the simulated jacking tests, loads were applied to the transverse joints in a large testing machine. The test results show that the segments can withstand jacking loads near the ultimate strength of the concrete. However, the total force that can be applied is dependent on the bearing area.

Common threaded fasteners were tested to determine their relative corrosion resistance in two laboratory exposures. The two exposures were salt spray fog and 100 percent RH (relative humidity), 73.4°F fog. The exposed materials were:

1) Mild steel
2) Mild steel with 2-mil-thick hot dip galvanized coating
3) Mild steel with 1-mil-thick electrodeposited zinc coating
4) Mild steel with 1/2-mil electrodeposited cadmium coating, and
5) 304 stainless steel.

The stainless steel bolts were unaffected throughout the exposure period in both exposures. Of the coated, mild steel bolts, the hot dip galvanized bolts suffered the least corrosion after a 17-week exposure period in both environments. No corrosion of the steel bolts with the hot dip zinc coating was experienced when exposed to the fog environment. The hot dip zinc galvanized bolts appear to be adequate for use in vehicular tunnels where corrosion-accelerating contaminants are not anticipated.

4.6. Model Tests

To establish the effectiveness of the hydrostatic pressure resistance tests in predicting the performance of candidate sealant systems, a one-eight scale model of the actual tunnel was developed, incorporating multiple-segment bolted rings, provision for widening and narrowing seams between segments, and a system for applying an external hydrostatic pressure. Tests on a half-round rubber gasket produced small leaks at low (2 lb/in^2)

pressure in two intersections but were readily sealed using a chemically set gel-bentonite mixture injected behind the liner. After these leaks were sealed, pressure was raised in increments to 26 lb/in^2 without adverse effects.

The one half scale model was designed and built with six segments rings (in order to increase the number of joints and gasket designs that could be tested) as well as discontinuous longitudinal joints to eliminate four-corner intersections and to minimize bending moments under load.

The principal purpose of the one half scale model was to demonstrate the performance of the candidate joint sealant systems under simulated underground conditions. The ground loading and ground/linear reaction was approximately in the model by loads applied through jacks. The model also included a system to apply hydrostatic head to simulate ground-water pressure. The results of the hydrostatic tests indicated that the three sealant systems performed satisfactorily. The analysis of the load tests could not be completed because controlled pressure regulation was not achieved due to nonuniform pressures resulting from swelling of the wooden filler used in the model. The model actually simulated variable, nonuniform ground loads with ground-water pressure rather than just hydrostatic loads from the water. The principal damage to the model was shear failure between adjacent rings. The failure mechanism appears to be wedging or punching shear stress at the bolted connections. The failure was brittle and sudden in nature. The fact that little warning was given prior to failure should be considered when designing the connections for segmented liner systems.

5. CONCLUSIONS

It can be concluded from this study that a liner system comprised of precast concrete segments with bolted connections between segments and rings is a viable alternative in soft ground transportation tunnels. A crushable compression seal and a fluid-applied sealant will provide watertight joints and minimum loss of joint strength between segments and rings in the assembled structure. Maintenance of tolerances in the segments can be achieved with reusable forms. It appears that four segments per ring is the best number to use, in order to decrease the number of joints and still permit acceptable handling ease. The length of the ring should be the longest that can be handled by the installation equipment within the tail shield. The segments can be designed to withstand jacking loads near the ultimate strength of the concrete. Backpacking and grouting behind the liner should be accomplished before jacking loads are applied to the segment.

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1. INTRODUCTION

Although some experimental reaches have been constructed in recent years, a sole liner composed of precast concrete segments for soft ground rapid transit tunnel systems has yet to become a reality in the United States. In general, cast iron, steel, or cast-in-place concrete are used for tunnel liners. The increasing cost of metal liner makes the development and use of precast concrete liner quite attractive. The new liners must not sacrifice safety, structural performance, speed of construction, or durability. The confidence to incorporate precast concrete for segmented tunnel liner use has been established although additional development programs for improvement are in order, especially in the systems approach to the sealant design. Admittedly, tunnel contractors are confident and secure in utilizing steel ribs and wood lagging or iron segmented primary liners since they have obtained considerable experience in their erection. This program was designed to provide tunnel authorities, designers, contractors, owners, and the general public with data for the safe and economical implementation of segmented concrete liners for rapid transit tunnel systems.

The general purpose of this research was to devise, fabricate, and test circular segmented liner systems displaying candidate joint configurations and sealants for possible future use in soft ground rapid transit tunnels. By direction, this study concentrated only on bolted segments; however, much useful data were obtained from other concurrent studies and work with unbolted segments.

Reinforced concrete is a well-established structural material whose behavior has been extensively studied and has seen significant application to date in tunnel liners. Moreover, reinforced concrete can be designed to withstand the handling, erection, and in situ forces as a tunnel liner. The weak link in a segmented concrete tunnel liner is the potential leakage that may arise at segment junctures. Thus, a primary objective of this effort has been to identify sealant materials and/or sealant systems that demonstrate satisfactory watertightness characteristics for segmented liner joints under simulated soft ground tunnel environmental conditions.

The study plan was divided into five phases. Phase 1 was an information gathering review of past research and construction techniques coupled with current research, state-of-the-art technology, and available experience from which a study plan incorporating the remaining four phases could be developed. Phase 2 was the development of design parameters for segmented liners with particular emphasis on radial and circumferential joint interfaces and their attachment and sealant systems, identification of ground and water conditions that will affect the segment design and performance, and identification of environmental conditions and limits that could degrade the system. Phase 3 involved the identification of important sealant properties, the screening and selection of candidate sealant materials, and a materials test program. Two segment materials were also tested: reinforced concrete and PIC (polymer-impregnated concrete). Phase 4 was the test program for selective sealant system joint configurations and included testing of movable joints as well as establishing methods of corrective maintenance (resealing) at leaking joints. Phase 5 evaluated prototype designs, manufacturing techniques, quality control, quality assurance, dimensional control, etc., to ensure manufacturing that provided good liner interface for watertightness.

2. PHASE 1 - INFORMATION GATHERING AND REVIEW

2.1. Literature Searches

The SDC (Systems Development Corporation) ORBIT III retrieval system was used effectively to search the NTIS (National Technical Information Service) and the SSIE (Smithsonian Science

Information Exchange) data bases. The NTIS of the Department of Commerce is a broad and cross-disciplinary file containing citations and abstracts of Goverment-sponsored research reports and other Government analyses prepared by Federal agencies or their contractors and grantees. The SSIE data base covers ongoing and recently completed research in the life, physical sciences, and social sciences, including both basic and applied research projects. Research identified is from Federal, State, and local organizations, nonprofit associations, colleges and universities, nonaffiliated investigators, private industry, and some foreign organizations.

To augment the NTIS and SSIE data bases, Lockheed Missiles and Space Company's Dialog Information Retrieval Service was used to access COMPENDEX (Computerized Engineering Index) data base supplied by Engineering Index, Inc. COMPENDEX provides information through citations and abstracts of the world's significant literature in engineering and technological applications.

Appendix A is a listing of bibliographic citations or citations and abstracts including research summaries and patent applications, both domestic and foreign, that were considered pertinent to this research program. These outputs were drawn, in part, from the NTIS, SSIE, and COMPENDEX data bases.

Most of the documents listed were obtained and reviewed early in this study. It was quite apparent that little research had been accomplished in the past related to this study and that little information on the state-of-the-art technology or construction techniques was available.

Other references cited in this report are listed in section 9 of this report.

2.2. Systems Study Plan

A systems study plan incorporating all areas of interest was developed and approved by TSC. The plan detailed specific study elements to be addressed in phases 2 through 5. These elements included the development of segmented liner design parameters, and a trade off study to determine the best size and number of segments. Also included was a study to identify important sealant properties that affect performance, the identification of commercially available sealants, a screening test program to identify candidate sealants or systems for further study, and a continuing study to establish the physical properties of the candidate materials. Long-term studies included evaluations of the creep characteristics of the candidate sealants and watertightness tests.

A series of single segment tests to compare precast concrete with PIC was also conducted.

From these tests, a study of sealant systems and liner joints evolved. Included were hydrostatic tests to evaluate the watertightness capability of the selected systems in a variety of joint configurations and the development of segment and joint repairability after loss of watertightness under water pressures comparable to subground tunnel pressures. All of these studies led to a one-half scale model tunnel wherein the selected systems could be evaluated under simulated conditions and loads.

The corrosion potential of exposed metalwork in a bolted system was evaluated in a series of corrosion tests. The effects on liner watertightness after simulated tunnel fires were also evaluated.

Initially, a cast iron interface study wherein the compatibility of cast iron liners and precast concrete segmented liners would be evaluated was included. However, because of the scarcity of cast iron liners in transportation tunnels and the very remote chance that the two systems would interface, this part of the study plan was eliminated by mutual consent. Because of the versatility of forming precast concrete segments, other interface studies were not included.

Finally, all of this work was to lead to a set of specifications for the construction of a segmented concrete-lined and -sealed transportation tunnel.

The study plan is included as Appendix B to this report.

3. PHASE 2 - DEVELOPMENT OF SEGMENTED LINER DESIGN PARAMETERS AND TRADE-OFF STUDY

3.1. Design Parameters

3.1.1. Introduction

It has been estimated that in 1985, tunnel construction in the United States will average 60,000 feet per year [1]*. This reference also predicts that precast concrete segment tunnel lining, designed to provide initial support and serve as the final lining, should reduce soft ground tunnel construction cost. While offering potential cost savings by eliminating the traditional construction sequence of placing initial support and, at a later date, final lining, precast concrete segment tunnel liners do not avoid traditional problems associated with

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* Number in brackets refer to references listed in Section 9.

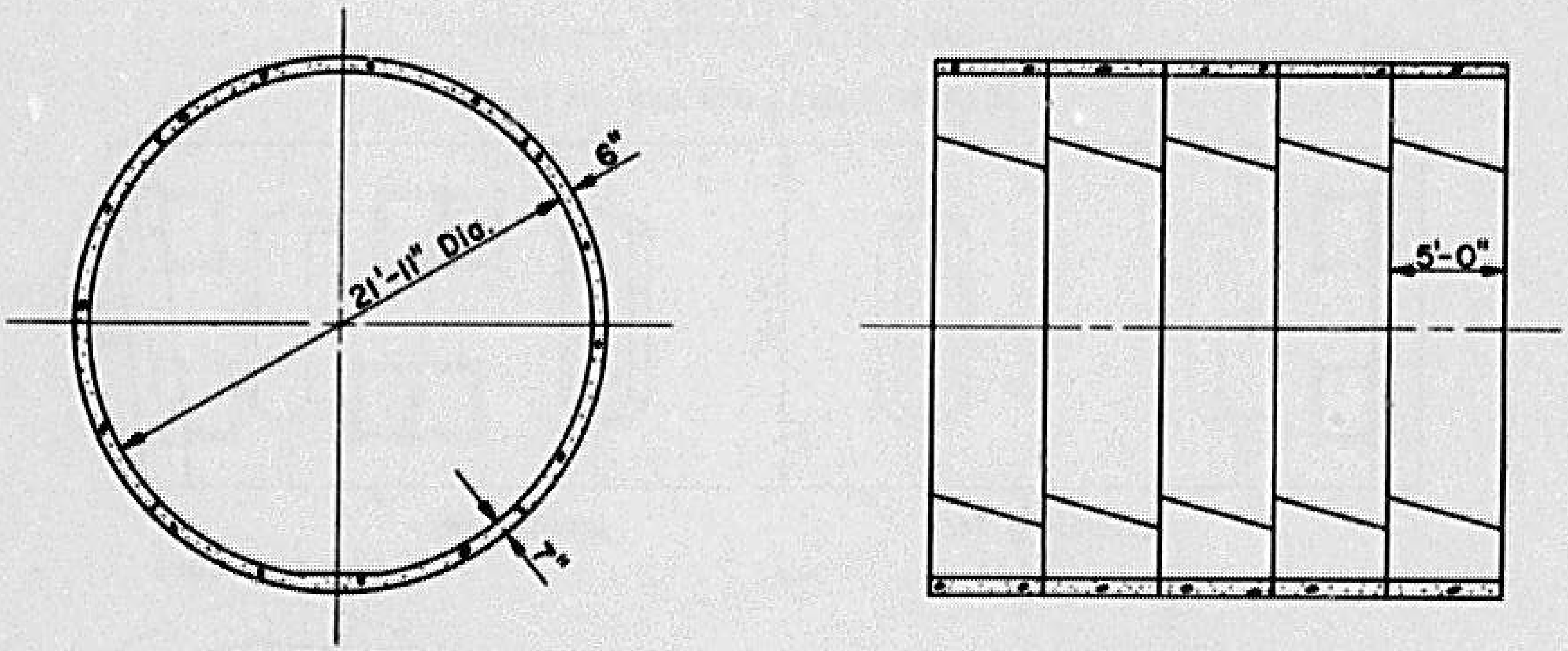
tunnel design in general and lining design in particular. The simplifying assumptions made in the design of tunnel support systems are still necessary. This reduction of a complex problem leads to the often-encountered observation that tunnel design is more art than science. Nothing in this report is intended to suggest otherwise. Design parameters for precast concrete segment lining in light of general tunnel design considerations are discussed.

3.1.2. Design Variables

a. Function. - Tunnels may be driven for a variety of final uses. Szechy [2] describes in some detail a number of these uses. He first distinguishes mining cavities whose purpose is the economic exploitation of excavated material from the underground structures of interest. He further defines tunnels as underground structures, constructed by special underground tunneling methods generally without disturbing the surface, whose purpose is to ensure the direct transportation of passengers or goods through certain obstacles.

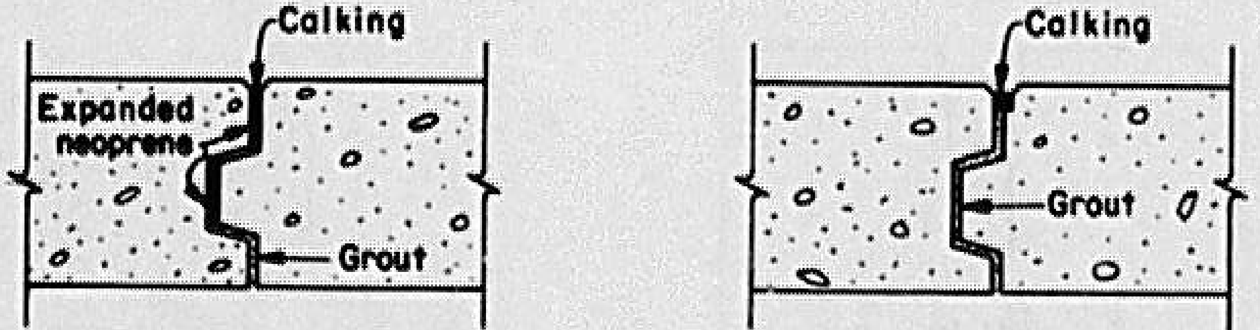
Two broad classifications, transportation and conveyance, are suggested. Transportation tunnels include highway, railway, pedestrian, navigation, and subway tunnels. Conveyance tunnels include power, water supply, sewage, and industrial products transport tunnels. Tunnels for storage might be added as a third classification.

Precast concrete segment linings have been used in North America for subway, water supply, and sewage tunnels; however, this experience is limited. Figures 3-1, 3-2, and 3-3 show three tunnels in the United States which have used precast concrete segments for initial support and



CROSS SECTION

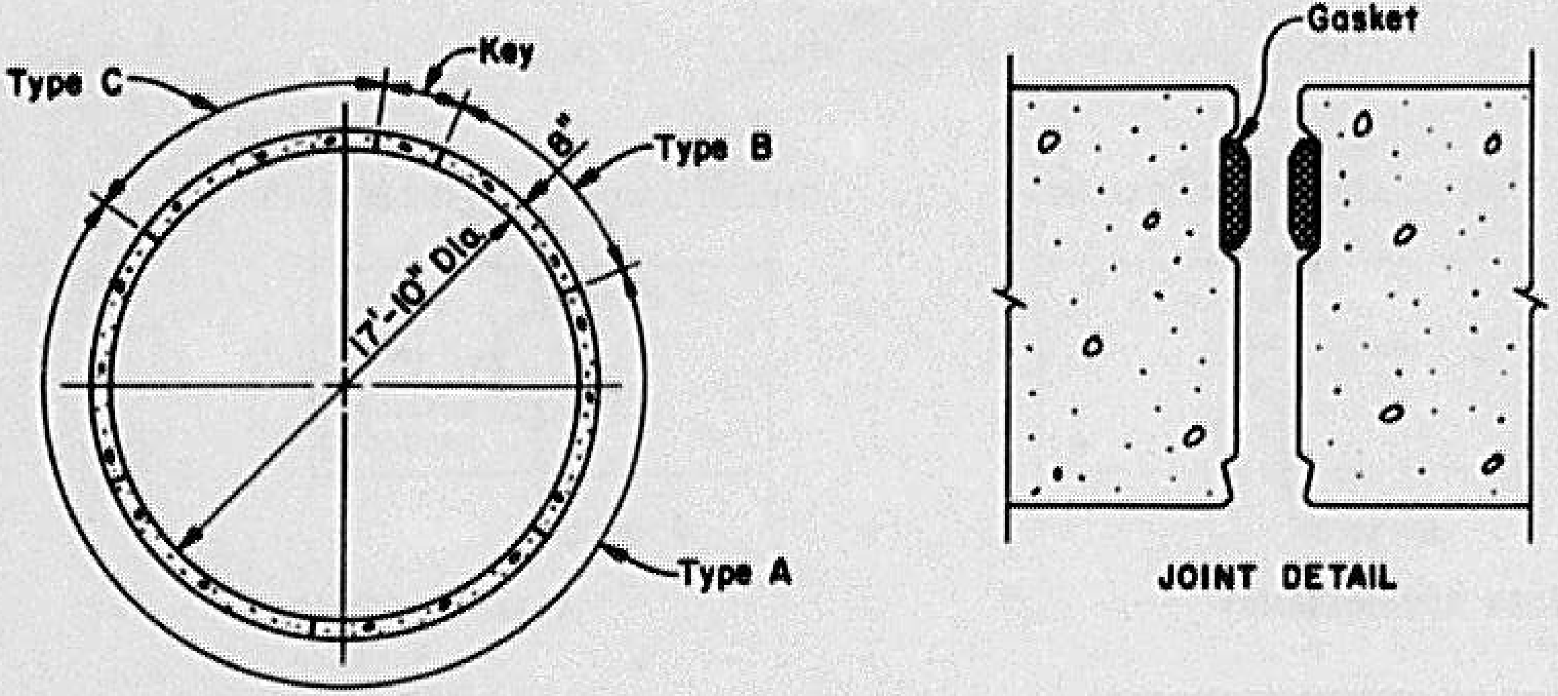
LONGITUDINAL SECTION



CIRCUMFERENTIAL JOINT DETAIL

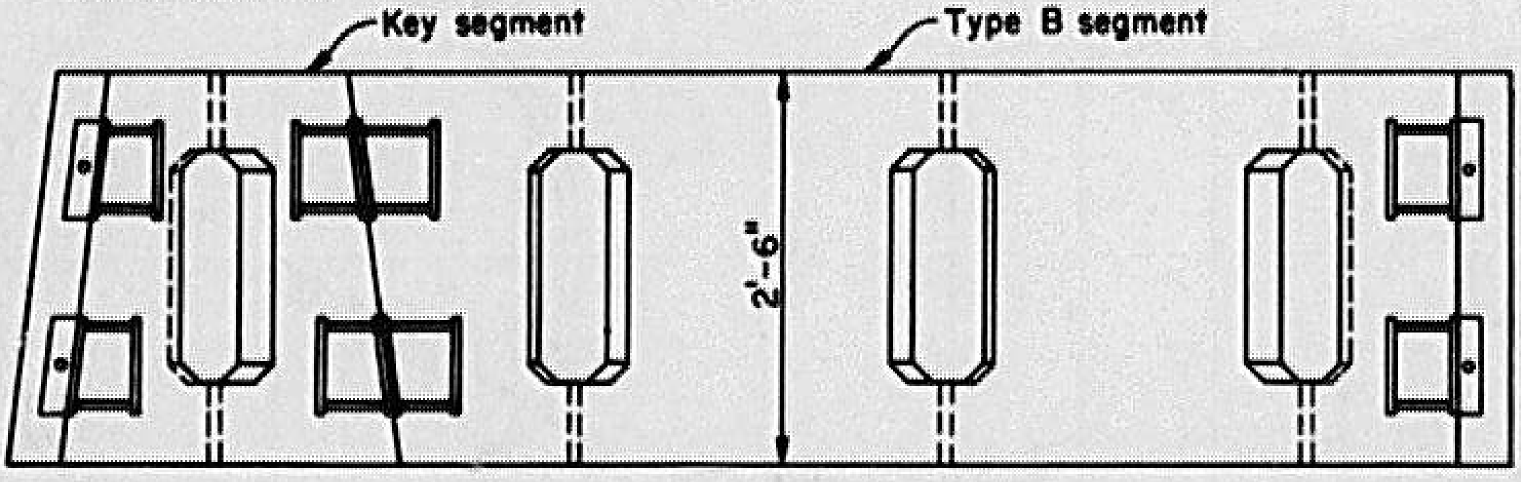
LONGITUDINAL JOINT DETAIL

FIGURE 3-1. BUCKSKIN MOUNTAINS TUNNEL JOINT DETAIL
WATER AND POWER RESOURCES SERVICE



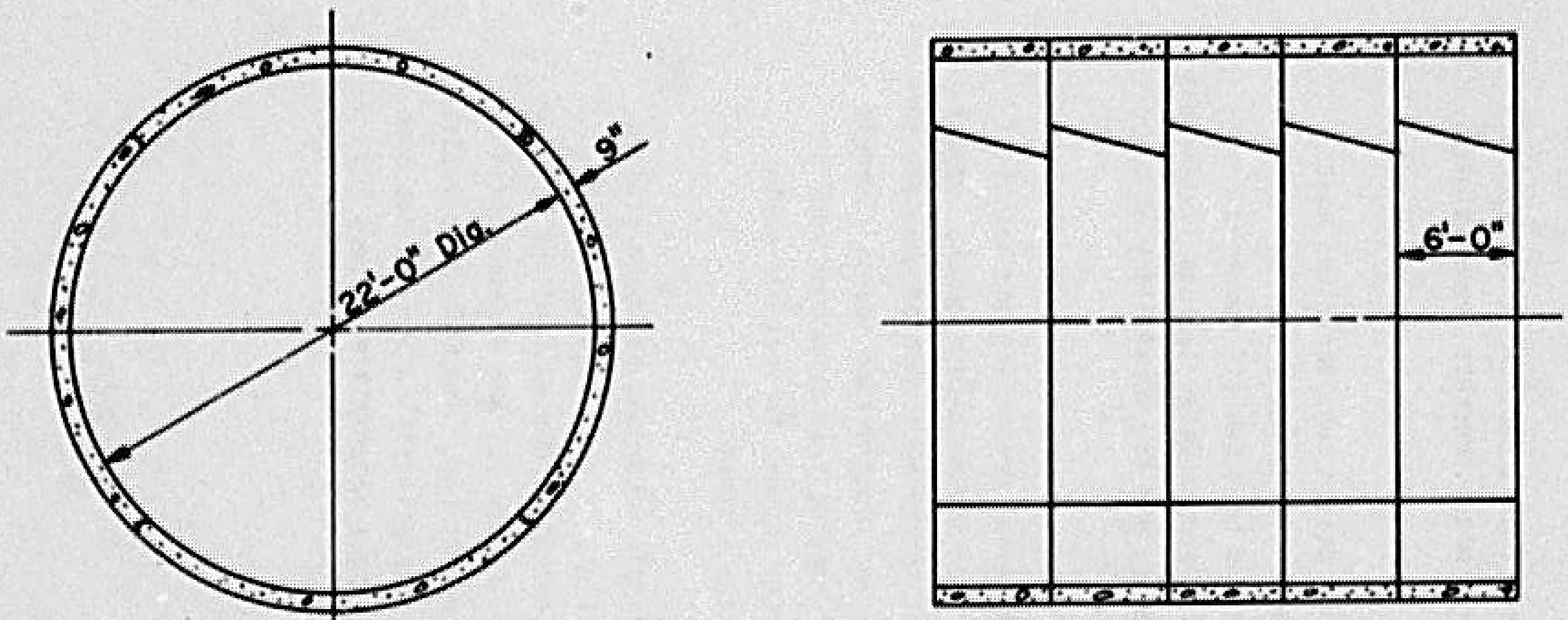
CROSS SECTION

JOINT DETAIL



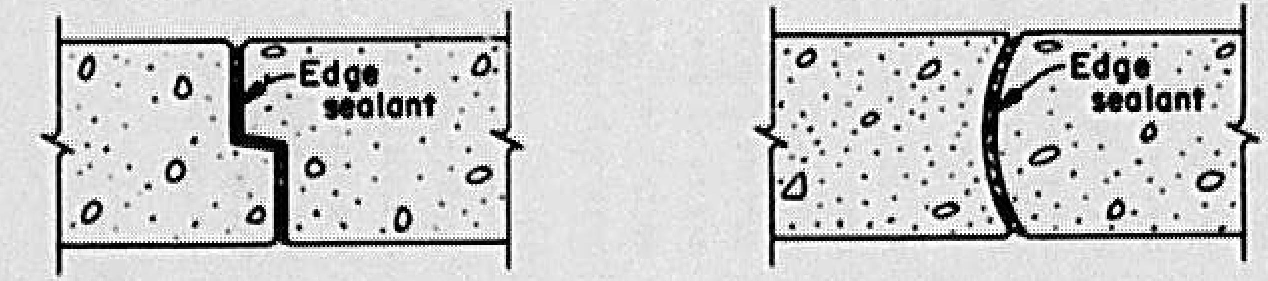
PLAN-KEY AND TYPE B SEGMENT

FIGURE 3-2. LEXINGTON MARKET TUNNEL SEGMENT
MARYLAND TRANSIT ADMINISTRATION



CROSS SECTION

LONGITUDINAL SECTION



CIRCUMFERENTIAL JOINT DETAIL

LONGITUDINAL JOINT DETAIL

FIGURE 3-3. PARK RIVER LOCAL PROTECTION TUNNEL
U.S. ARMY CORPS OF ENGINEERS

final lining. The purpose of this section is to describe the design parameters for precast concrete segments used in subway tunnels.

For transportation tunnels, design considerations must include ventilation, vehicle clearance, grade restrictions or requirements, stations and branches (if required), architectural requirements, ground-water leakage limitations and control, fire resistance, and the possibility of toxic products of combustion.

b. Geology. - Geologic material properties and height of cover over a tunnel determine the long-term ground support requirements. The support system must also be adequate for surface pressure loadings and construction loads. Tunnels may be driven in material ranging from competent rock or earth requiring little or no support to unstable earth material requiring extensive support.

The classification of geologic materials has been studied extensively. Ground loads are related to a particular classification system. Terzaghi proposed loadings based on a qualitative description of rock [3] and a description of the behavior of earth materials [4]. The RQD (Rock Quality Designation) is a quantitative classification and has been related to the more qualitative descriptive systems [5].

This study is concerned with a transportation tunnel driven in soft ground. A design example is provided in appendix C to illustrate some details of support design theory.

c. Special geologic conditions. - Beyond the ground strength and cover and resulting implications for the lining strength and excavation method, special geologic conditions may influence the tunnel design. Some of these conditions are listed below.

(1) A high ground-water table may require extensive dewatering or construction of the tunnel under compressed air. High temperature of the ground water can further complicate the situation.

(2) The presence of explosive and/or toxic gas may require special safety provisions.

(3) Seismic considerations may influence the alinement. Design provisions to accommodate seismic events have been discussed by Kuessel [6]. In this paper, the BART (Bay Area Rapid Transit System) earthquake design criteria are presented. One tunnel which employed reinforced precast concrete segments for initial support was subjected to earthquake forces before the final lining was placed with only minor damage reported [7].

(4) Subsidence is a major problem in urban areas. Tunnel construction may cause intolerable deflections in surface structures and/or adjacent utilities. One study used a number of finite element analyses to predict subsidence on the Washington Metropolitan Area Transit Authority System [8]. With the proper assumptions, the finite element method offered a plausible explanation of the

observed settlements. In any case, provision for subsidence must be made in the tunnel construction program. Grouting and/or underpinning adjacent structures may be required.

(5) Corrosion problems may arise from the geologic formation outside the tunnel or from the atmosphere within the tunnel.

d. Method of excavation. - Tunnels may be excavated by three general methods: (1) drill and blast, (2) TBM (tunnel boring machine), (3) hand excavation. Geologic conditions determine the possible methods of excavation, and economic considerations influence the final choice of excavation method. The support strength requirements, in turn, are influenced by the method of excavation. The use of a shield in which the precast segments can be erected is required in all ground conditions where the opening is not self-supporting to provide time enough to install the initial support system. The construction loads on the support system are influenced by the method of excavation.

e. Environmental conditions. - A completed tunnel has little effect on the environment. However, during construction, extensive remedial measures may be necessary to protect utilities and surface structures from damage. Where drainage water into a tunnel is encountered during construction, preventing pollution of ground and surface waters is necessary. Disposal of excavated material (tunnel muck) requires careful consideration even in remote locations. The problem is compounded in urban centers. In a few instances, however, this excavated material may be salable.

The use of waterproofing or sealing compounds may require special handling outside the tunnel and special construction procedures inside the tunnel.

f. Cost. - Cost considerations are of paramount importance in the decision to undertake a tunnel construction project. During the design stages, the selection of allowable construction alternatives may be influenced by anticipated cost although more often technical aspects and tradition are considered more important factors [6]. One of the obstacles to the use of precast concrete segment tunnel lining in the United States is the lack of experience with this system despite an apparent cost advantage.

g. Contract requirements. - Contractual requirements influence the tunnel design to the extent that the excavation method or support system must be technically feasible. Precast concrete segment lining should be designed to be compatible with alternative support systems. The design of precast concrete segments requires that the segments should be designed for the worst anticipated loading condition or that the segments be compatible with an alternative support and lining system.

h. Design procedures. - The designer must estimate the loading condition to which the initial support and final lining will be subjected. Haggman [9] presents a comprehensive list of loadings for liner plate supports and includes for external loads:

Earth load
Live load
Superimposed loads
Hydrostatic

Hydrodynamic
Lining weight
Loads due to lost ground and unfilled voids
Time dependent effects
Fatigue
Effect of advancing adjacent tunnels
Effect of blasting on static and dynamic loads
Seismic loads

and for internal loads:

Hydrostatic
Hydrodynamic

For subway design, hydrostatic loads may be deleted from the internal loads and live loads due to rail traffic added.

Design criteria for underground structures must be developed for each project and may vary considerably from one subway to another. Four general approaches to tunnel design are of interest.

Service Design Methods

The Service primarily is engaged in the design of water conveyance tunnels. Aside from the use of the tunnel, some differences exist between a typical Service tunnel and a typical subway tunnel in: (1) height of cover, (2) material investigations, and (3) the need for a smooth interior surface.

Cover depths exceeding 1,500 feet are not uncommon in Service tunnels. Because of this depth of cover, material investigations are generally limited, for economic reasons, to locations along the alinement where the tunnel is near the ground surface. In contrast with shallow cover, material investigations may be undertaken at almost any desired location along the alinement. Another implication of tunnel construction at great depth is that excavation normally proceeds through rock material. On long tunnels, zones of extremely difficult excavation are encountered on a more or less random basis and generally give way to areas of more stable ground conditions. The uncertainties associated with minimum ground property investigation and the discontinuous nature of geologic formations lead to the design procedures described below based on a general rock classification system. Some refinement in subway design procedures may be possible.

The Service designed two precast concrete segment lined tunnels: (1) Buckskin Mountain Tunnel and (2) Stillwater Tunnel, with mixed success. Buckskin Mountains Tunnel was holed through May 24, 1979. The contract on Stillwater Tunnel was terminated in September 1979 due to unanticipated ground conditions (squeezing shales). A second contract for completion of Stillwater Tunnel will be awarded in 1980. Continued use of a precast concrete segment lining for this contract is under study. In both tunnels, the precast concrete segments were designed without bolts for interior smoothness and employed sealant systems consisting of a gasket-type material and calking.

Design procedures for these two tunnels are summarized as follows:

(1) Design the entire support system for a rock load described by Terzaghi in "Rock Tunneling with Steel

Supports" by Proctor and White [10], or by the U.S. Army Corps of Engineers' "TUNNELS" computer program [11]. This computer program uses a linear elastic resistance to deflection at specified points around the support structure in conjunction with specified boundary conditions and static loads to describe the equilibrium condition and accompanying stresses and deflections. The stiffness method of analysis is used in the computer program to solve for the equilibrium condition. The elastic spring constant is a function of the surrounding rock (or soil) material. In addition to rock load, a number of other external and internal loads must be considered [9]. In most circumstances, the design for rock load with an appropriate safety factor is the controlling loading condition.

(2) Provide flexibility in the design to accommodate a range of tunneling conditions. This becomes more difficult to do as the technology of the construction method and support system becomes more sophisticated. For example, in drill and blast excavation with steel ribs and timber lagging for initial support, the length of tunnel advance per shot and the spacing of steel supports may easily be adjusted to ground conditions. For a machine-excavated tunnel with steel supports, the excavation is essentially a go or no go proposition and the machine must be adequate for the worst anticipated conditions. Excavation in which a machine cannot advance usually requires extensive hand spading and becomes an expensive, time consuming, and sometimes uneconomical construction process. Provided the machine can progress, the steel rib support spacing can easily be varied to suit ground conditions. With machine excavation and precast concrete segments for initial support and final

lining, the capacity of the support system may be varied only within narrow limits by varying the thickness of the precast concrete segments. Flexibility must be accomplished through contract provisions which require capability to shift to an alternate support system.

AASHTO Design of Liner Plate

The AASHTO (American Association of State Highway and Transportation Officials) has published criteria for the design of liner plate [12]. The liner plate must have adequate joint strength, handling and installation strength, strength to prevent buckling of the liner plate wall, and strength to prevent excessive deflection. Where soils properties are adequately known, the AASHTO criteria suggest the ground load on the liner plate can be determined from the Marston formula used for the design of concrete pipe [13]. If the soils properties are not adequately known, AASHTO recommends the full overburden pressure be used as the ground load on the liner plate.

The distribution of earth loading and foundation reaction is not specified.

Soviet Design Criteria

The Soviet standard specifications described in "The Art of Tunneling" [2] require that loadings on tunnel structures be assumed functions of cover-depth, the geologic conditions, ground-water occurrence, seismic activity, the dimensions of the excavated cavity, the construction methods, and the sequence of the tunneling and lining processes. They also require that tunnel structures be sized on the most unfavorable combination of loads and effects on the structure, either during construction or operation.

The rock load on the tunnel structure may be evaluated according to Protodyakonov's theory. This theory is similar to Terzaghi's in that it depends on a strength factor determined from a general rock classification system. The Soviet theory has been criticized because a wide range of strength factors are given for one rock classification. The relationship between the Protodyakonov and Rankine ground arches has been described by Haggman [14].

Other Theories

Deere, et al., suggest the following design procedure [5]:

(1) Provide adequately for the ring thrust to be expected. The authors observe that in clay soils, the average ring thrust may be less than the full overburden pressure (in unusual soils where the overload factor is unity or less), or greater than the full overburden pressure (where highly plastic clays exert an average pressure on the lining greater than overburden pressure). Their conclusion for clay soils is that the full overburden pressure is a reasonable value for the expected ring thrust. For coherent frictional ground and cohesionless ground, the authors recognize the fact that under ideal conditions, the average ring pressure on the lining might be much less than the full overburden pressure. They suggest, however, that loads due to lost ground or unfilled voids may increase the pressure on the lining significantly. Further, they observe that the need to control ground loss requires the installation of a lining

before appreciable stress relief has occurred in the ground and results in higher pressures on the lining. The effect of advancing tunnels was also mentioned as a source of load increase on a tunnel lining. The recommended design procedure is to carry the full overburden pressure in ring thrust.

(2) Provide for the anticipated distortions due to bending. The authors present a table showing measured distortions for a number of tunnels. They suggest that a relative deflection for design may be chosen based on measured relative distortions for similar tunnels in similar ground. A lining is designed to accommodate the bending moment resulting from the design deflection.

(3) Give adequate consideration to the possibility of buckling. The study suggests a lining should have certain minimum resistance to local buckling, torsional failure, and other modes of failure that may develop as a result of construction procedures and irregularities. Buckling due to forces in planes normal to the axis of the tunnel was not considered critical in the report.

(4) Make allowance for external condition not included in (1) to (3) above. Adjacent tunnel excavation and legal liability were mentioned as external influencing factors.

This method is considered appropriate for subway design and is used as the design criteria in the design example. Similar criteria were used for the design of the Mexico City subway. Details of that design are described by Chase [15].

3.2. Trade-Off Study

Table 3-1 is a summary of information accumulated from a review of the literature on precast concrete segment lined tunnels. It is difficult to determine an optimum size and number of precast concrete segments used per ring from a review of the tabulated data, but a trend is evident. The geology and design criteria, labor costs, and the method of excavation and degree of mechanization used to place the segments all significantly influence the number and size of segments per ring.

Figure 3-4 shows the variation of segment thickness with tunnel diameter for the 50 tunnels described in Table 3-1. Variations in segment thickness can be attributed to differences in design procedure, geologic conditions, and excavation and erection methods. The expected general increase in segment thickness with increasing tunnel diameter is evident. For an increase in tunnel diameter, an increase in the total weight of lining per longitudinal foot of tunnel is inescapable. As a result, the capacity of segment handling equipment must increase with increasing tunnel diameter or the weight can be reduced by providing more segments per ring or by reducing the width of each segment.

TABLE 3-1. SUMMARY OF TUNNELS WITH PRECAST CONCRETE SEGMENTED LINING

Tunnel	Location	Use completion date (expected date)	Length ft (m)	Internal dia. 1/ ft (m)	No. and size of segments					
					No.	Minimum thickness in (mm)	Width in (mm)	Connection	Remarks	Reference
Buckskin Mountains	Arizona, U.S.A.	Water supply (1979)		22	4	7	60		Tapered segments tongue and groove joints	B51 (Groseclose, 1976)
Stillwater	Utah, U.S.A.	Water supply		8.25	4	5	36		Flat face longitudinal Shiplap circumferential	
Park River	Connecticut, U.S.A.	Drainage siphon		22	4	9	72		Knuckle longitudinal Shiplap circumferential	B54 (U.S. Corps of Engineers, 1976) B67 Wilford, T. (1979)
Saugus	North of L.A., California	Water supply Began 1967	25,900 (4 tunnels)	23.5 o.d.	3	12	44	Weld or bolt steel	Embedded shape composite section crown joint; expanded; 8-ton segment	B44, B43 (Mix, 1968) (Construction Method, 1968)
Newhall	California, U.S.A.			26	3	12	48		Beam stubs, modified Saugus design	B43 (Mix, 1970)
San Fernando	California, U.S.A.	Water supply Began Oct. 1969	29,000	22	3 + key or 4	8	48	Bolted	Steel butt plates Wire mesh reinforcement Wedge segments	B43 (Mix, 1970)
	Portland, Oregon U.S.A.	Sewer	6,300	8.0	4	6	60		Expanded (usual 1 in) flat face	
Lexington Market Line	Baltimore, Maryland U.S.A.	Subway	1,600	17.8	6 + key	8	30	Bolted	Flat face all sides with gasket except tapered key	B65 Baltimore Region Rapid Transit System, 1976
Bart (design only)	San Francisco, California	Subway design		16.3	6 + key	7	30	Bolted		B26 (Bartlett, 1971) B34 (Birkmyer, 1975)
	Thunder Bay, Ontario, Canada	Sewer	11,000	7.08 (2.16)	4	(110)	(1000)		Unreinforced trapezoidal	B63, B66 (Water & Wastes Engineering, Oct. 1976), (Morton, 1977)

TABLE 3-1. SUMMARY OF TUNNELS WITH PRECAST CONCRETE SEGMENTED LINING (CONTINUED)

Tunnel	Location	Use completion date (expected date)	Length ft (m)	Internal dia. 1/ ft (m)	No. and size of segments				Remarks	Reference
					No.	Minimum thickness in (mm)	Width in (mm)	Connection		
West Middlesex	England	Drainage 1937		4-10.5					Reinforced concrete steel hoops between rings	045 (Concrete and Constructional Engineer, 1966)
Ilford	England	Railway 1939		to 17.3				Bolted	Transverse ribs	045 (Concrete and Constructional Engineer, 1966)
	London	Water supply (pressure) 1951		8.3	10	6			Don Seg lining	045 (Concrete and Constructional Engineer, 1966)
Potters Bar	North from London	Railway 1959		22.5	19 + 2 key + invert	27				045 (Concrete and Constructional Engineer, 1966)
Finsbury Park				12.5	14 + wedge	9			Measurements showed 6-in thickness, OK, longitudinal joint	045 (Concrete and Constructional Engineer, 1966)
Fawley Power Station	England	Utility		14				Bolted		045 (Concrete and Constructional Engineer, 1966)
	Under Mersey River	Highway		34	10 + key	12	36	Welded	Steel frame filled with concrete	043 (Ito, 1970)
Hamburg		Rail (4 track)	(713)		1				10 m wide, 7 m high, 5.7 m long, 400 (tons)	013 (South African Tunnelling, 1975)
	Munich, Germany	Subway		19.5 19.3	6	14	15	unbolted	Spiral ring final lining	026 (Bartlett, 1971) (Birkmyer, 1975)
Isar Tunnel	Munich, Germany	Subway 1975	(2310)	(6.9 o.d.)	8 + key	(350)	(1000)	Bolted	Double lining 502 m	042 (Braun, 1975)

TABLE 3-1. SUMMARY OF TUNNELS WITH PRECAST CONCRETE SEGMENTED LINING (CONTINUED)

Tunnel	Location	Use completion date (expected date)	Length ft (m)	Internal dia. 1/ ft (m)	No. and size of segments				Remarks	Reference
					No.	Minimum thickness in (mm)	Width in (mm)	Connection		
	Hamburg, Germany	Railway underpass		17.2	4 + key	13-3/4	36	Unbolted		B34 (Birkmyer, 1975)
Rhein Tunnel	Dusseldorf, Germany			10.7	4	10			Curved bolts	B34 (Birkmyer, 1975)
Tee Rib Design	Germany			18.2	5		36	Bolted	Longitudinal curved bolts	B34 (Birkmyer, 1975)
Madrid	Madrid, Spain								Trapezoidal with key, no bolts	B15 (Robbins, 1975)
Metro De Caracas		Subway		15.3	6 + key	8-1/2	33	Bolted		B34 (Birkmyer, 1975)
Castiglione	Castiglione, Italy	Rail high speed 155 mi/h		Horseshoe (11.1 o.d.)	6 + key	(275)		Bolted	Moment connection	B15 (Robbins, 1975)
Metro Di Roma	Italy	Subway		18.1	4 + key	10-5/8	2.63 ft		Curved Dywidag rods across longitudinal joint; longitudinal rods	B34 (Birkmyer, 1975)
	Prague			(1.6)	3	(140)	(320)		205 kg	B21 (Benda, 1972)
	Austria			(2.3) (2.7) (2.8)	5 5-1/2 4	(160) (100) (140)	(320) (600) (320)		153 kg 254 kg 267 kg	B21 (Benda, 1972) B21 (Benda, 1972) B21 (Benda, 1972)
	Poland			(3.5) (3.7)	4 4	(160) (140)-(180)	(240) (320)		239 kg 350-438 kg	B21 (Benda, 1972) B21 (Benda, 1972)
	Czechoslovakia			(3.9)	9	(160)	(490)		277 kg	B21 (Benda, 1972)

TABLE 3-1. SUMMARY OF TUNNELS WITH PRECAST CONCRETE SEGMENTED LINING (CONTINUED)

Tunnel	Location	Use completion date (expected date)	Length ft (m)	Internal dia. 1/ ft (m)	No. and size of segments					Reference
					No.	Minimum thickness in (mm)	Width in (mm)	Connection	Remarks	
	Yugoslavia			(4.0) (4.0)	3 4	(160) (140)- (160)	(320) (320)		415 kg 380-420 kg	B21 (Benda, 1972) B21 (Benda, 1972)
	Belgium			(4.2)	4-1/2	(200)	(320)		491 kg	B21 (Benda, 1972)
	Hungary			(5.5)	5	(200)	(600)		1180 kg	B21 (Benda, 1972)
Paris Subway	France	1970	2,600	33	13 + key	26	40			B43 (Hix, 1970)
Sesuragich Subway	Yokohama, Japan	Subway		18.2	5-1/2	14	2.8 scaled		Bolted steel face (3/16 in)	B34 (Birkmyer, 1975)
	Tokyo, Japan	Subway		20.2	5-54° 2-37° 1-16°	14	2.63 ft		Bolted	B34 (Birkmyer, 1975)
Talow Tunnel	Teheran		32,150	8.9						B45 (Concrete and Constructional Engineer, 1966)
Yonge Subway Extension	Toronto, Canada	Subway		16	8 + key	6	24	Bolted		B26, B29 (Bartlett, 1971) (Bickley, 1979)
	Edmonton, Canada	Sewer	3,278 (1000)	7.7 (2.286)	4	4.3 (110)	(1000)	Unbolted	Weakened planes to give eight segments; expanded	B41 (Construction West, 1978)
Tacubaya	Mexico City, Mexico	Subway (Aug. 1970)	3700 (1140)	30 o.d. (8.5)	3	10 (250)	30		Expanded at 120° joint; 5000 lb/in²; crown joint	B5 (Engineering News Record, April 16, 1970) B7 (Chase)
Stoke on Trent Sewer	Stoke on Trent, England	Sewer	Trial length		20	(114)	(610)	Steel dogs	Two sizes of blocks; lead bars fit in dogs	B12 (Collins, 1976)

TABLE 3-1. SUMMARY OF TUNNELS WITH PRECAST CONCRETE SEGMENTED LINING (CONTINUED)

Tunnel	Location	Use completion date (expected date)	Length ft (m)	Internal dia. 1/ ft (m)	No. and size of segments					Reference
					No.	Minimum thickness in (mm)	Width in (mm)	Connection	Remarks	
Heathrow Extension	Picadilly Line (Fleet Line Stage)	Subway		13.9	20 + 2 wedge	7				834 (Birkmyer, 1975)
New Victoria Line	London, England	Subway		12.5	10	6	1.96		Expanded	834 (Birkmyer, 1975)
Victoria Line Extension	London, England	Subway	73,000	12.5		14		Unbolted	Expanded	824 (Bartlett, 1971)
Fleet Line Stage 2	London, England	Subway		12.5	11	6	1.96		Two configurations; bolted and expanded	834 (Birkmyer, 1975)

1/ Finished diameter unless otherwise noted.

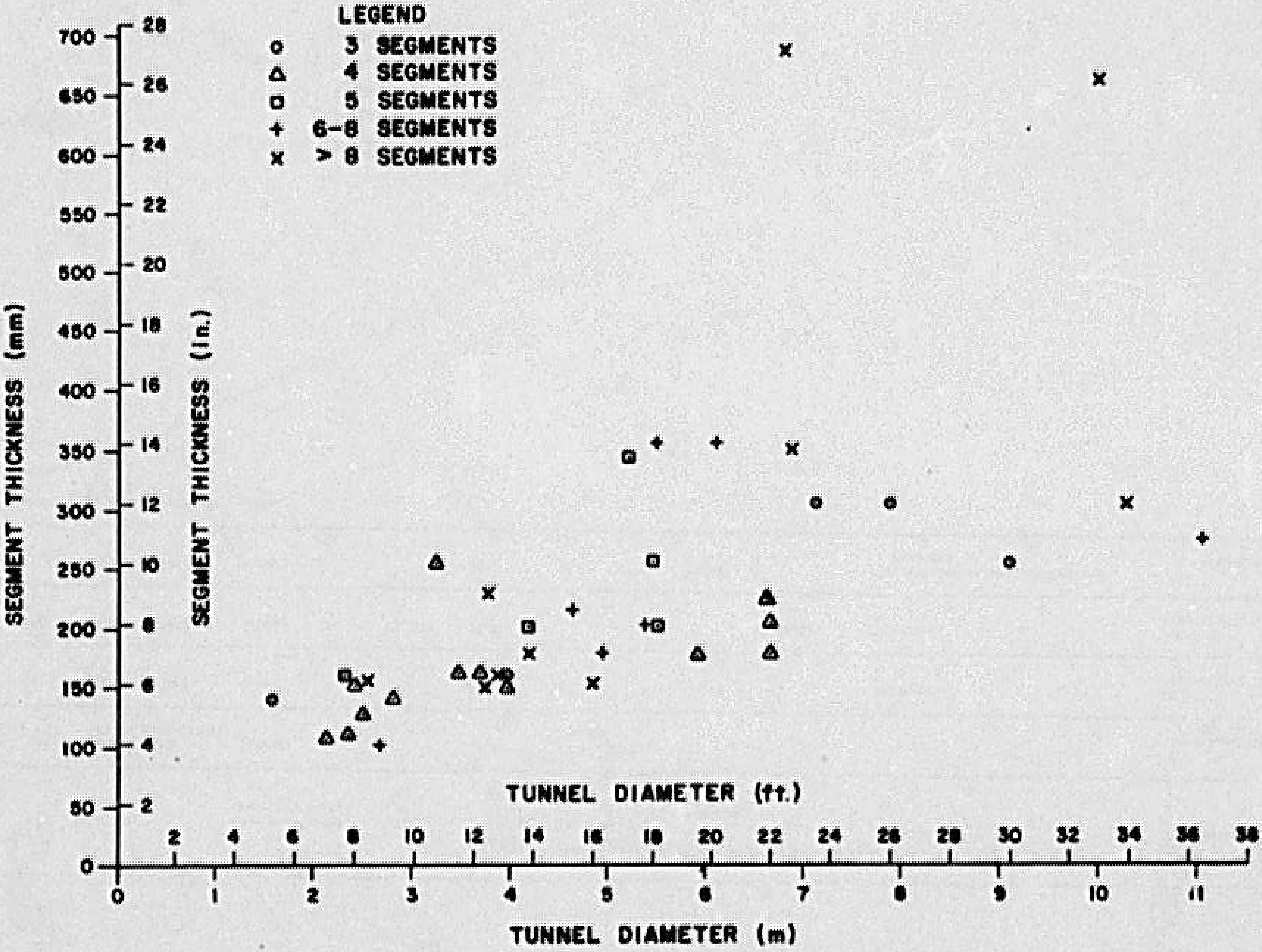


FIGURE 3-4. SEGMENT THICKNESS VERSUS TUNNEL DIAMETER

Figure 3-5 shows width of segment (i.e., ring length) as a function of tunnel diameter, and Figure 3-6 shows the number of segments as a function of tunnel diameter. Both figures are based on the tunnels listed in Table 3-1. Neither figure indicates that a hypothesis of constant segment handling capability is valid. Segment width shown in Figure 3-5 tends to increase with tunnel diameter indicating an increased need for segment handling capability. Also, as shown in Figure 3-6, the number of segments per ring appears to be independent of diameter, indicating the handling capacity does not control the number of segments used per ring.

Figure 3-7 shows the frequency distribution of the number of segments per ring for the 50 tunnels used in this sample. Key segments and smaller segments were counted as full segments for this figure. Three segments per ring is the fewest number used. Nearly one-half of the sample had three, four, or five segments per ring. Four segments were used most frequently.

A comparison of the tunnel designs for Park River and Buckskin Mountains Tunnels with the alternate designs submitted by the contractors and approved for construction is of interest. Both the Park River Auxiliary Conduit Tunnel and the Buckskin Mountains Tunnel are water conveyance tunnels where eight segments per ring were specified in the contract documents. In both instances, the tunnel construction contractor proposed and installed a four-segment ring. The segments actually used were wider than the original designs. A three-segment design is feasible; the Tacubaya Subway in Mexico City used such a design.

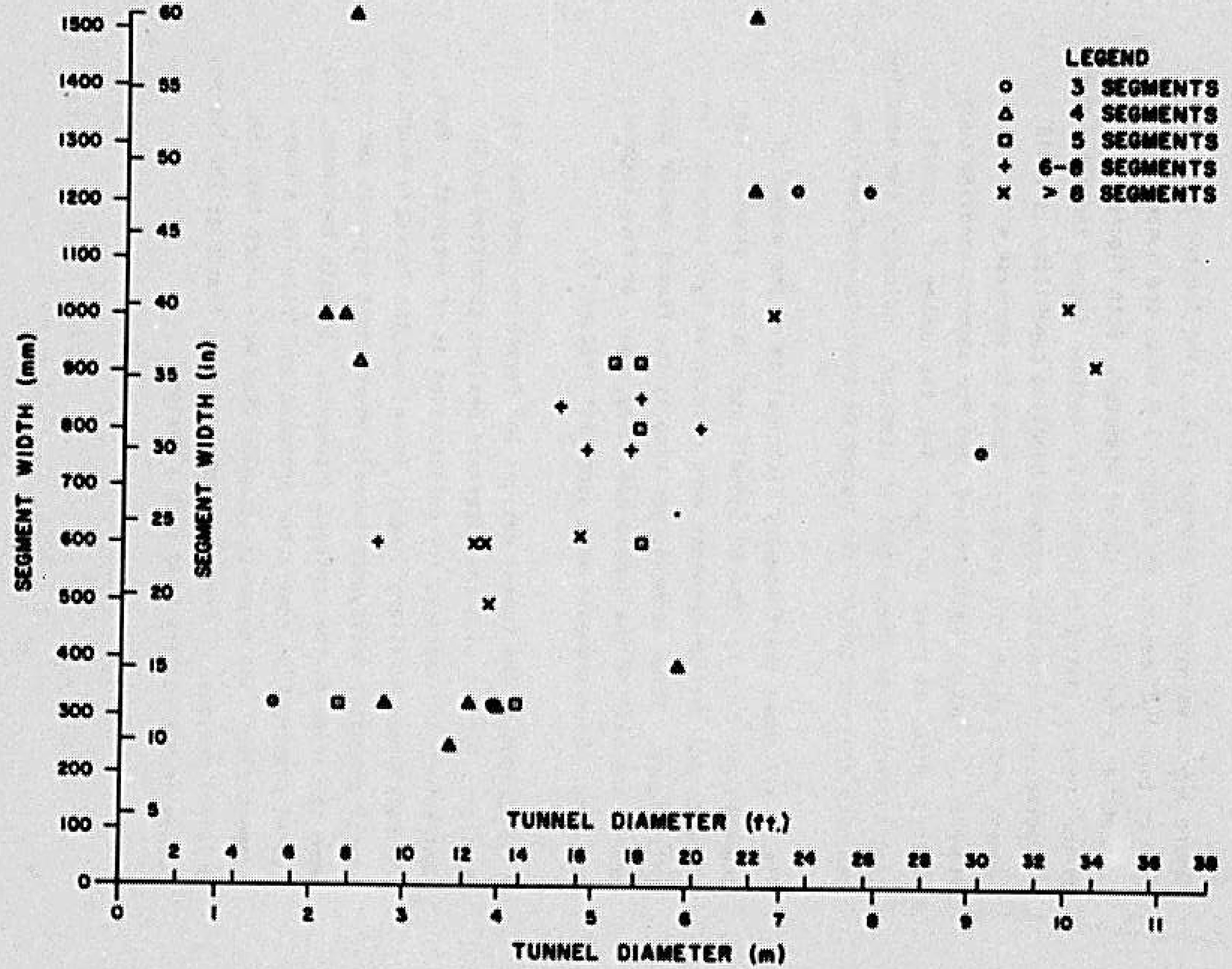


FIGURE 3-5. SEGMENT WIDTH VERSUS TUNNEL DIAMETER

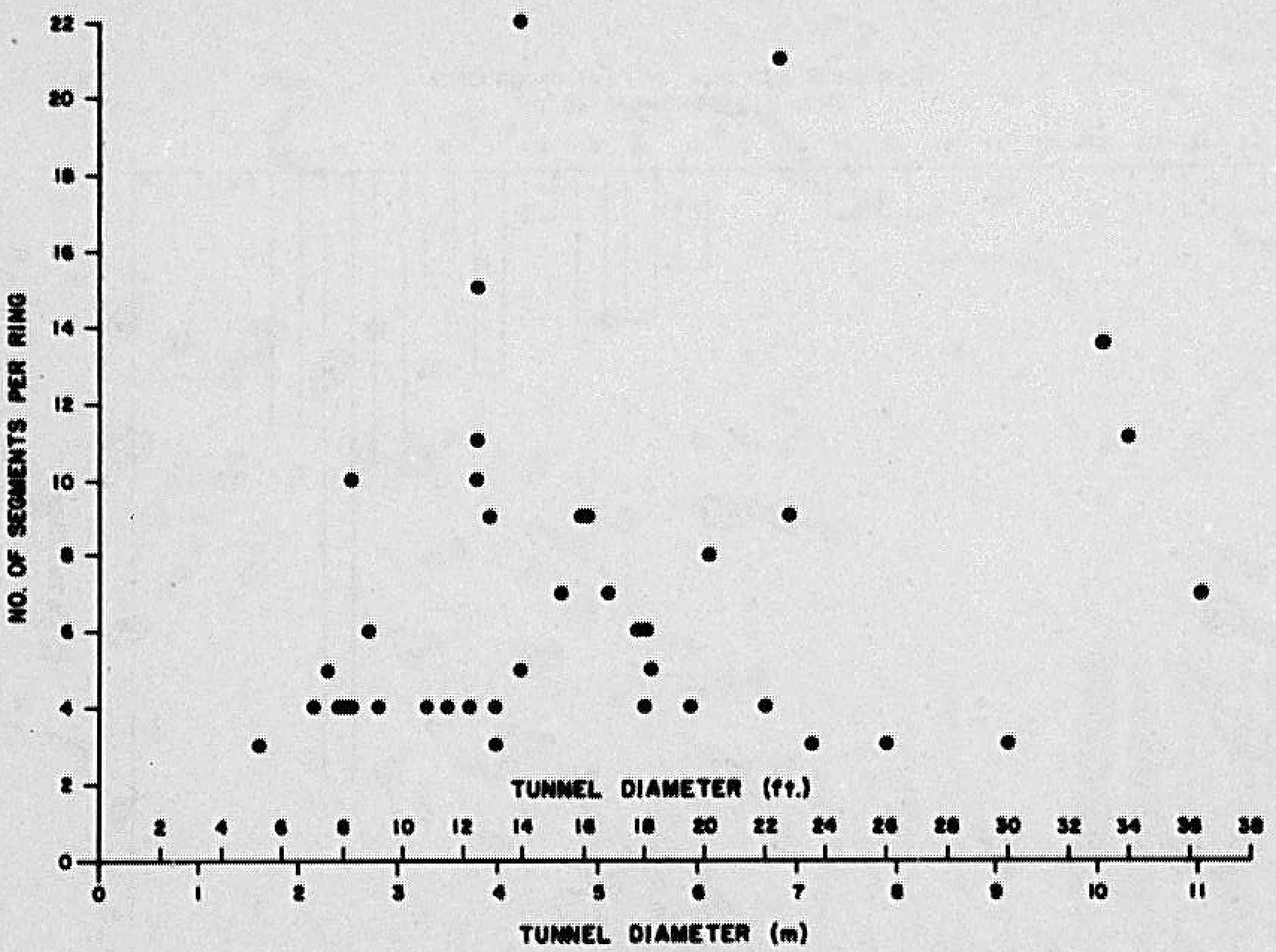


FIGURE 3-6. NUMBER OF SEGMENTS PER RING VERSUS TUNNEL DIAMETER

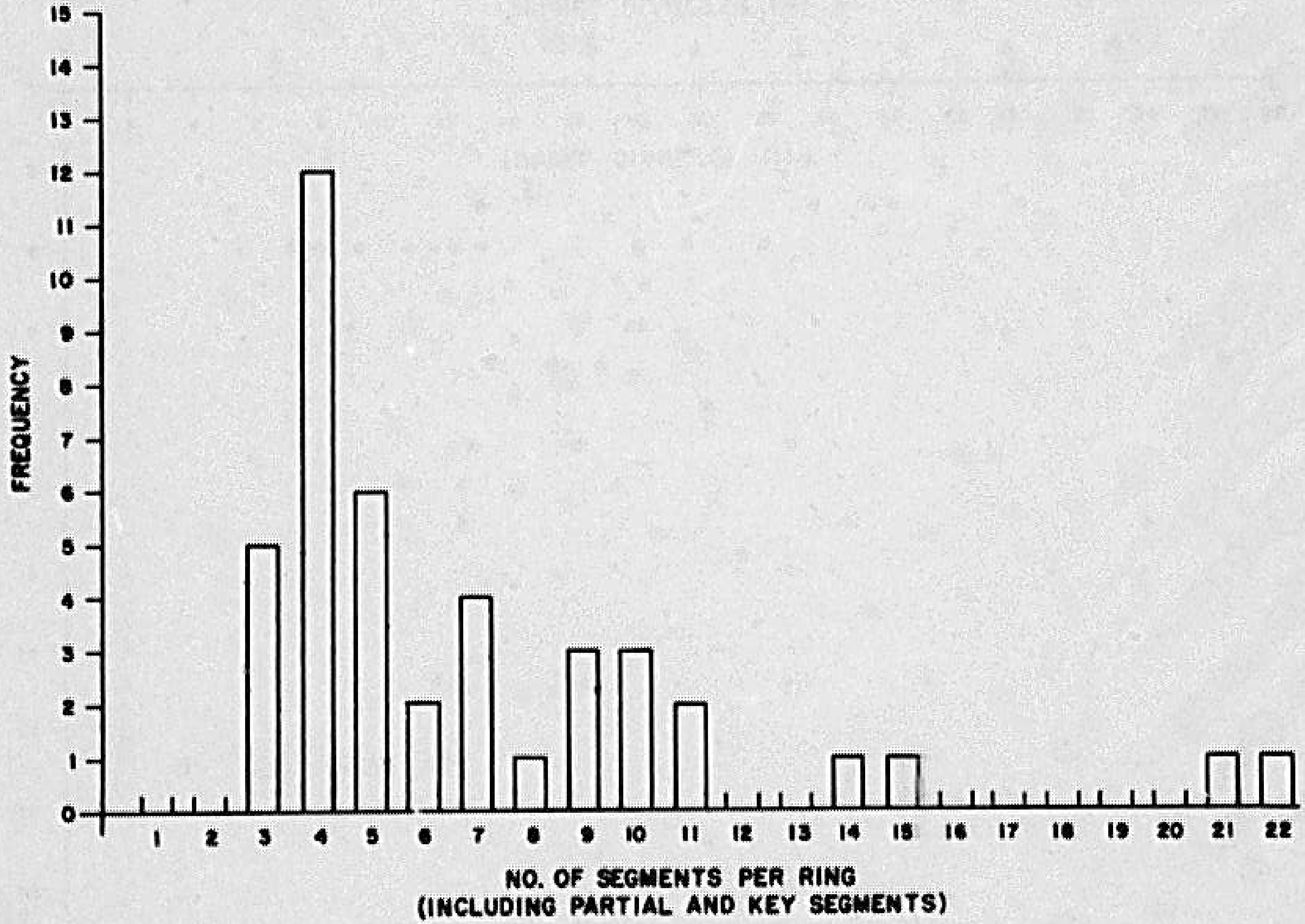


FIGURE 3-7. FREQUENCY OF THE NUMBER OF SEGMENTS USED PER RING

Based on data collected for this study, it appears that the optimum number of segments per ring for a 16.4-foot-diameter finished subway tunnel is four.

The widest segment compatible with tunnel excavation equipment and construction handling clearances should be used. However, width of segment may be a serious liability in tunnels under high covers excavated by a TBM where squeezing ground is encountered. It is most important in such circumstances to limit the time the tunnel boring machine remains stationary and to limit the shield surface area subject to squeezing ground pressures. The wider segment may require a longer shield and probably slightly longer erection time. Therefore, in bad ground conditions, the most desirable width of segment would be less than that for excavation in better ground. In connection with ground loads on a shield, the segments must be designed to withstand horizontal thrust loads required to overcome the frictional resistance on the outside of the shield from ground loads and the thrust required to drive the leading edge of a shield into a soft ground face. Providing good, true bearing surfaces and proper bearing material between segment rings and between the shield and the leading ring also is of critical importance.

3.3. Specifications Considerations

For a tunnel construction project, specifications paragraphs should address the major topics listed in the general outline contained in the following paragraphs. The outline does not include many critical topics such as safety and environmental quality protection, nor does the outline address general provisions. This outline lists items which are most directly related to construction of a tunnel with precast concrete segment lining. (It is assumed that the concrete segment lining would provide initial ground support and act as the final lining.)

Geologic and hydrologic conditions, method of excavation, and even details of the tunnel boring machine and shield affect the segment design, and such requirements should be specified. General Tunnel Construction paragraphs and Excavation paragraphs must be tailored to fit the given conditions and design.

3.3.1. Tunnel Construction

General. - Describes the work to be accomplished, methods of construction, and cites specific limitations and considerations such as monitoring of surface settlement, survey requirements, and auxiliary tunnel and shaft work.

Reference. - Lists paragraphs pertinent to tunnel construction; for example, excavation, ventilation, tunnel support, grouting, dewatering, and lining.

Measurement and payment. - Standard paragraph describing pay items and methods for measuring and payment.

3.3.2. Tunnel Excavation for Precast Concrete Segment Lining

General. - Describes the work covered under this section, required submittals by the contractor, special requirements and restrictions such as blasting restrictions, and the required use of a tunnel boring machine or shield.

Tunnel machine or shield. - Describes equipment required for this excavation.

Excavation. - Describes details of the excavation including acceptable and required methods for controlling the face, launching the tunneling machine, the sequence of excavation, advancing the machine, handling unstable material or water inflows, muck disposal, and disposal of the machine or shield.

3.3.3. Installation of Precast Concrete Segment Lining

General. - Describes the erection sequence, bolting requirements, method of handling curves in alinement, the temporary bracing of segments, the placement of backpacking and grout around the outside of the segment, sealing or calking the segments, and repair or replacement of damaged segments.

Quality control. - Describes measurements and tests the contractor will be required to make on the in-place segments, limits the number of required measurements and tests, describes tests to be performed by others and the contractor's responsibility for cooperation, and describes leakage test requirements and sets minimum acceptable limits for leakage.

Measurement and payment. - Standard paragraph describing pay items and methods for measuring and payment.

3.3.4. Precast Concrete Segment Liners

General. - Describes the materials for and fabrication of precast segments, including concrete and reinforcing, finishes, dimensional tolerances, drawing or material submittals, formwork, curing, coating, marking, demonstrational assemblies, quality control, delivery, storage, and handling.

Special conditions. - Describes environmental restrictions regarding coatings or other hazardous chemicals.

Sealant system. - These paragraphs describe the material to be used to seal joints between precast concrete segments. The description covers acceptable types of sealant material properties, test specification required submittals, and certifications or tests.

Measurement and payment. - Standard paragraph describing pay items and methods for measuring and payment.

4. PHASE 3 - SEALANT MATERIALS TEST PROGRAM

4.1. Introduction

The sealant materials test program of this study included identifying important sealant properties, a screening test program from which candidate materials were selected for further testing, and a program determining critical physical properties of the candidate materials, including resistance to creep and watertightness.

In this study, sealants are considered to be fluid-applied, room temperature vulcanizing, elastomeric materials. Such materials are sometimes thought of as high quality rubbery calking compounds. Proper performance of the sealant materials depends primarily on adhesion to the joint surfaces of the structure.

4.2. Sealant Critical Properties

The properties that are usually of interest for any sealant application are: application characteristics, ability to withstand movement, and material and adhesion durability. Considering the construction and operating environments expected for rail mass transportation tunnels, several special areas of emphasis must be considered for each of these properties.

4.2.1. Application Characteristics

Vertical and overhead application requires an acceptable nonsag grade. Toxicity and flammability need to be at suitably low levels because of the relatively close conditions, air ventilation, and traffic patterns. It is highly desirable to have materials that can be properly installed quickly and easily because of the difficult working conditions and the high ratio of joint length to tunnel length.

4.2.2. Ability to Withstand Movement

Movement between segments is expected to be severely restricted because of the temperature-stabilizing effect of the underground location and the probability that bolted segments will be used. However, ground loads may cause deflection of the tunnel shape from circular toward oval. Therefore, provisions must be made for some shear movement. Although as much as 0.02 inch of movement can be expected in a large-diameter tunnel as a result of rotation at the longitudinal joint, reasonable movement in shear will likely place greater strain on the sealant. Movement in shear equal to the sealant width will result in 41 percent sealant strain, although one-half that movement would produce only 12 percent strain.

The high ratio of joint length to tunnel length makes it economically undesirable to increase the joint width to accommodate the expected movement using materials having low elongation. Further, in order to accommodate shear in the joint without unacceptable shear stress at the bond interface, a sealant depth to width ratio very close to one should be used. Observations made during the testing program indicate that a 1/2-inch depth of sealant may be required to withstand hydrostatic pressure. Therefore, it appears that 1/2-inch minimum sealant width should be established.

With a 1/2-inch joint width, movement of 0.02-inch from joint rotation would result in 4 percent strain. Since at least twice that strain from shear could be reasonably expected, shear movement will establish the required elongation the sealant must withstand unless the joint can be designed to minimize shear.

Considering the above as one of the performance criteria, any candidate sealant should be able to withstand at least 10 percent initial strain over a substantial period of time under the design water head. This standard was established as a goal in the sealant hydrostatic pressure tests.

4.2.3. Material and Adhesion Durability

The durability of sealants is mainly a question of polymer degradation in a specific environment. The basic processes of polymer degradation pertinent here are oxidation (including ozone attack), biological attack, water attack (material and adhesion), thermal degradation (from fire), and physical damage such as resistance to flow under pressure. Acidic or alkaline exposure is not pertinent since in normal operation there are not expected to be concentrations strong enough to attack the polymers making up the sealants. However, the highly alkaline environment at the concrete/sealant interface is a critical factor in performance. The polymers are resistant to mild concentrations of acids and alkalies, probably at least as resistant as the concrete from which segments are fabricated. Similarly, conditions associated with outdoor weathering such as photodegradation or salt spray attack were not considered because of the absence of these conditions in service. Biological attack is generally controlled by addition of fungicides during manufacture.

Water degradation of the material and its adhesion to concrete, especially when continually immersed, is the most severe environment to which these materials are most likely to be exposed. The test program was therefore weighted heavily in that direction.

4.3. Sealant Screening Test Program

A review of sealant literature and extensive Service experience [16, 17, 18, 19, 20, 21, 22, 23] with both canal and building sealants indicated that polymer groups most likely to be satisfactory for the expected service were modified polysulfide, polyurethane, modified polyurethane, silicone, and epoxy modifications of any of the above groups. Sealants made from polymers thought to be unsatisfactory were unvulcanized polychloroprene (neoprene) and epoxies because of their initial stiffness; acrylic polymers and chlorosulfonated polyethylene (Hypalon) because of the poor water immersion characteristics of known products; butyl, ethylene, vinyl acetate, and related polymers because of their poor (for this use) creep characteristics; and newer rubberized acrylics because of lack of field data and industry standards for existing products and the fact that some promising products are in the developmental stage. Further, nearly all of the rejected polymer families except the epoxies are only available in solvent or water evaporation curing systems. This results in slow curing, fume problems, and shrinkage, none of which are tolerable in tunnel sealing.

Selection of specific products was done on the basis of previous experience and the recommendation of the manufacturer. An effort was also made to provide a wide range of hardnesses. In some instances, undesirable application characteristics discovered after receipt of the sample, or results of preliminary tests precluded further testing of the material. All of the materials included in the screening test program and the results of the tests conducted on them are shown in Table 4-1. The first 11 sealants are those selected as candidate sealant materials for further study.

4.4. Physical Properties Testing

The 11 candidate sealant materials were subjected to a variety of tests, including adhesion, tensile elongation, hydrolysis resistance, hardness, flammability, heat stability, ozone resistance, and oxygen aging. The tests and test results are discussed in the following paragraphs; the data are tabulated and presented in Table 4-2.

Application characteristics were judged either satisfactory or unsatisfactory during screening tests (Table 4-1) and only sealants rated as satisfactory were retained as final candidates. Ability to withstand movement is discussed along with the discussion of effects of water on durability since this property is so closely related to the effect of water on the material itself and its adhesion to concrete.

4.4.1. Adhesion to Concrete

Test specimens of elastomeric sealant applied to cement mortar blocks were prepared in accordance with ASTM: C 719 except that the blocks were 1/2-inch deep instead of 1 inch (Figures 4-1 and 4-2). Specimens were tested after 14 days'

TABLE 4-1. SEALANT SYSTEM SCREENING TESTS

Sealant no.	Generic type	Curing characteristics	Application characteristics	Adhesion properties 1/	Effect on joint performance 2/	Candidate material	Reason for eliminating material as candidate	Trade name	Manufacturer
1	2-part urethane	Set in 24 hours	Easily worked	Excellent	No adverse effect	Yes		U-Seal	Edoco Technical Products, Inc.
2	2-part coal tar polysulfide	Set in 24 hours	Easily worked	Excellent	No adverse effect	Yes		E-4	American Poly-Therm Co.
3	2-part urethane	Set in 1 hour	Easily worked, but short pot life	Good	Reduced ultimate strength of joint 3/	Yes		Concoat 145	Commercial Shearing, Inc
4	1-part PVC-bitumen blend	Cures on cooling	Suitable for horizontal surfaces only. Hot pour	Good	No adverse effect	Yes		Superseal 444	Superior Products Inc.
5	1-part silicone	Set in 48 hours	Easily worked	Good	No adverse effect	Yes		No. 790	Dow Corning Co.
5A	1-part silicone	Set in 48 hours	Easily worked	Good	No adverse effect	No	Received too late It could be con-considered as a candidate.	No. 795	Dow Corning Co.
6	2-part polysulfide building sealant	Set in 48 hours	Easily worked	Good	No adverse effect	Yes		Chem-Calk 200	Woodmont Products Co.
7	2-part epoxy modified urethane	Set in 24 hours	Easily worked	Excellant	No adverse effect	Yes		Dymeric	Tremco Corp
8	1-part urethane	Set in 72 hours	Fairly difficult to apply	Excellent	No adverse effect	Yes		Monocaulk 100	Grove Specialties Co.
8A	1-part urethane	Set in 72 hours	Fairly easy to apply	Excellent	No adverse effect	No	Partial tests show early bond failure in water exposure	Monocaulk 100R	Grove Specialties Co.
9	1-part coal-tar modified urethane	Set in 96 hours	Fairly easy to apply	Excellent	No adverse effect	Yes		Vulchem 203	Mameco International
10	1-part urethane	Set in 72 hours	Fairly easy to apply	Excellent	No adverse effect	Yes		Sikaflex 1A(FC)	Sika Chemical Corp.
11	2-part urethane	Set in 4 hours	Easily worked but difficult to blend two components	Excellent	Reduced ultimate strength of joint 3/	Yes		Tremproof 50	Tremco Corp.
12	2-part urethane	Set in 1 hour	Easily worked but short pot life	Excellent	Reduced ultimate strength of joint 3/	Yes		FP 1209	Fluid Polymer, Inc.
13	1-part urethane	Set in 72 hours	Fairly difficult to apply	Excellent	No adverse effect	No	Cohesive failure during cure	S-201	J. F. Shea Co.
14	1-part urethane foam	Set in 24 hours	Very difficult to apply	Fair to poor	No adverse effect	No	Poor bond to concrete	Fomofill	Justa-foam Products, Inc.

TABLE 4-1. SEALANT SYSTEM SCREENING TESTS (CONTINUED)

Sealant no.	Generic type	Curing characteristics	Application characteristics	Adhesion properties 1/	Effect on joint performance 2/	Candidate material	Reason for eliminating material as candidate	Trade name	Manufacturer
15	Preformed urethane tape	Precured tape	Adhesive required	Variable - fair to poor	Reduced strength of joint	No	Poor performance in initial watertightness test	Flat Comcoat Tape	Commercial Shearing, Inc.
16	Impregnated wool felt conforming to MIL-G-20241B	Precured tape	Adhesive required	Fair to good	Reduced strength of joint	Yes		Spring Felt 73170	Rhopac, Inc.
16A	Preformed fiberboard	Precured board	Adhesive required	Good	Improved joint strength	Yes		Nomex 300 Board	Dayton Sure-Grip and Shore Co.
17	Neoprene rubber gasket	Precured gasket	Adhesive required	Good	Reduced strength of joint	Yes		Neoprene gasket	Construction Gaskets, Inc.
17A	Extruded Buna-N rubber gasket	Precured gasket	Adhesive required	Fair to good	Minimal adverse effect	Yes		Half-round rubber extrusion	Midwest Rubber Co.
18	Rubberized asphalt mastic	Precured	Difficult to work	Good	Reduced strength of joint	No	Poor performance in initial watertightness test	Ram-Nek Rope	K. T. Snyder Co., Inc.
19	Rubberized asphalt mastic	Precured	Very difficult to work	Fair	Reduced strength of joint	No	Poor performance in initial water watertightness test	Sikaflex 40B Igas Rope	Sika Chemical Corp.
20	Expanded cellular neoprene rubber	Precured tape	Fairly east to apply	Good	Reduced strength of joint	No	Poor compression set characteristics	Neoprene sponge	Kirkhill Rubber Co.
21	2-component, low density urethane foam	Set in 30 minutes	Easily worked, but short pot life	Fair	Slight reduction in strength of joint	No	Unsatisfactory performance in watertightness test	HT123	Furane Plastics, Inc.
22	1-part urethane	Set in 72 hours	Easily worked	Good	Reduced ultimate joint strength	No	Early bond failure in water submergence	GS400	Grove Specialties, Inc.
23	Preformed urethane	Precured	Adhesive required	Not tested	Not tested	No	Received too late; could be considered as a candidate	Shaped Comcoat tape	Commercial Shearing, Inc.
24	2-component, low density urethane foam	Set in 15 minutes	Special mixer-applicator equipment required	Fair to good	Not tested	No	Unsatisfactory compression set and water retention	Uralane XB7675 A/B	Furane Plastics, Inc.

TABLE 4-1. SEALANT SYSTEM SCREENING TESTS (CONTINUED)

Sealant no.	Generic type	Curing characteristics	Application characteristics	Adhesion properties 1/	Effect on joint performance 2/	Candidate material	Reason for eliminating material as candidate	Trade name	Manufacturer
25	Rubberized asphalt mastic	Precured	Must be heated to 300 °F before application	Good	Not tested	No	Unsatisfactory performance in water tightness test	Sikaflex 405, Igas pressure grade	Sika Chemical Corp.
26	Rubberized asphalt mastic	Precured	Must be heated to 300 °F before application	Good	Not tested	No	Unsatisfactory performance in water tightness test	Sikaflex 406, Igas, knife grade	Sika Chemical Corp.
27	Filled synthetic rubber	Precured	Easily worked	.Fair	Reduced ultimate joint strength	No	Poor cohesion strength	Forma-seal	Metalcrete Manufacturing Co.
28	2-part urethane	Set in 30 minutes	Special mixer-applicator equipment required	Excellent	No adverse effect	No	Similar in properties to sealant No. 2 Could be a candidate material	U-Seal 3201	Edoco Technical Products Co.
29	1-part coal-tar polysulfide	Set in 14 days	Easily worked	Excellent	No adverse effect	No	Curing rate too slow for tunnel use	OPM-200	American-Polytherm Co.
30	2-part coal tar polysulfide	Set in 30 minutes	Special mixer-applicator equipment required	Excellent	No adverse effect	No	Similar in properties to sealant No. 2 Could be a candidate material	Machine Grade Canal Sealant	American-Polytherm Co.
31	1-part PVC-bitumen blend	Cures on cooling	Must be heated to 250 °F before application	Poor	No adverse effect	No	Unsatisfactory bond to concrete	Superseal 444C	Superior Products Co.
32	1-part urethane	Cures in 96 hours	Cured in container on receipt	Not tested	Not tested	No	Very short shelf life	S-202	J. F. Shea Co.
33	Glass cloth reinforced rubberized asphalt mastic	Precured tape	Surface and tape must be preheated	Excellent	Reduced ultimate joint strength	No	Extruded from joint under pressure	Ram-Nek Tape	K. T. Snyder, Inc.
34	1-part moisture activated polymer	Set in 24 hours	Easily worked; expands on contact with moisture	Poor	Not tested	No	Highly flammable	Water-Stop	Effective Building Products, Inc.
35	Glass cloth reinforced rubberized coal tar	Precured	Primer required Easily worked	Good	Reduced ultimate joint strength	No	Extruded from joint at low pressure	Jiffy Seal	Protecto Wrap, Inc.
36	1-part polymercaptan	Set in 96 hours	Easily worked	Excellent	Not tested	No	Received late; insufficient service history	PM Polymer	Phillips Petroleum Co.
37	Rubberized asphalt sheet	Precured	Easily worked	Excellent	Reduced ultimate joint strength	No	Insufficient material available; could be a candidate material	W. F. Cushion	Weyts and Freytag

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1/ Initial adhesion properties prior to exposure to test environments.
2/ Effect on reducing ultimate compressive strength of joint caused by plastic flow of sealant.
3/ Joint strength affected when used as full face gasket, but not when applied in calking groove only.

TABLE 4-2. PHYSICAL PROPERTIES OF FINAL CANDIDATE SEALANTS

		Property							
Sealant no.	Generic type	Tensile strength at 150% elongation or ultimate (lb/in^2)	Elongation (percent)	Hydrolysis resistance change in tensile strength (percent)	Hardness durameter A initial	Flammability (limited oxygen index test)	Heat stability (°F)	Ozone resistance	Oxygen aging change in stiffness (percent) 1/
1	2-part urethane	9.5	150	-23	2	20	>240	Pass	210
2	2-part coal-tar polysulfide	24.4	150	-67	5	21	>175	Pass	20
3	2-part urethane	69.5	100	-22	50	23	>240	Pass	43
4	1-part PVC-bitumen blend	9.5	150	+12	25	25	>175	Pass	10
5	1-part silicone	25.5	150	-48	15	34	>240	Pass	39
6	2-part polysulfide building sealant	26.4	150	-100	20	23	>240	Pass	86
7	2-part epoxy modified urethane	31.7	150	-54	30	20	>240	Pass	111
8	1-part urethane	121.0	38	-96	50	19	>240	Pass	-17
9	1-part coal-tar modified urethane	34.7	150	+661	40	22	>240	Pass	514
10	1-part urethane	82.3	150	+134	38	21	>240	Pass	100
11	2-part urethane	50.1	150	-41	33	20	>240	Pass	50

1/ After 18 months at 73 °F.

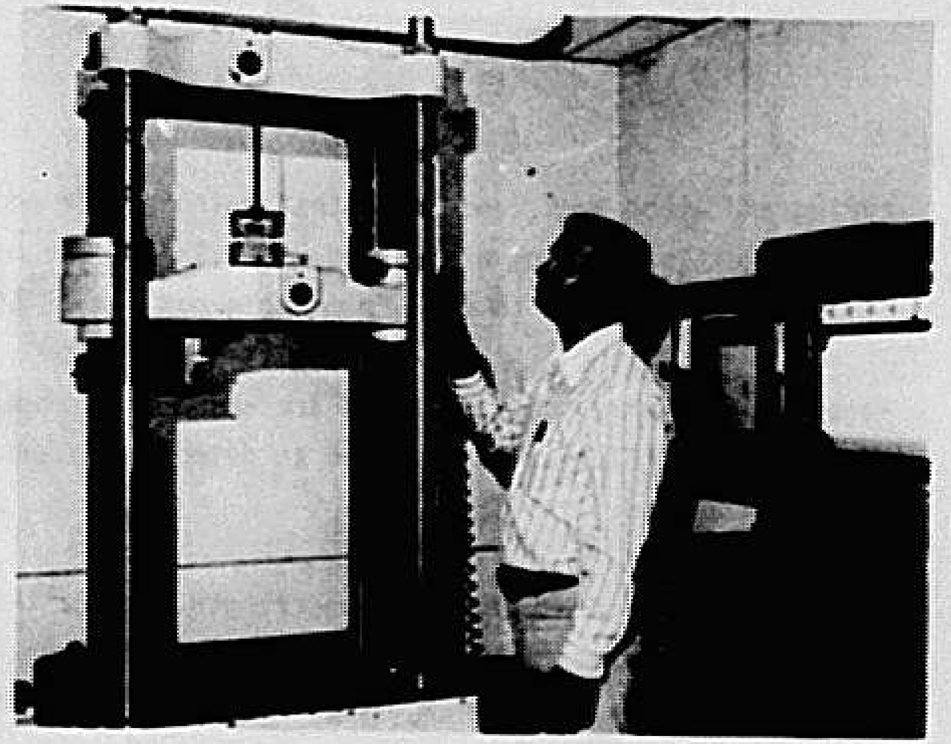


FIGURE 4-1. VIEW OF A TENSILE ADHESION SPECIMEN IN THE TENSILE TESTING MACHINE. THE PURPOSE IS TO TEST THE EXTENSIBILITY OF THE SEALANT AND TO DETERMINE THE BOND TO CONCRETE UNDER HIGH STRESS CONDITIONS

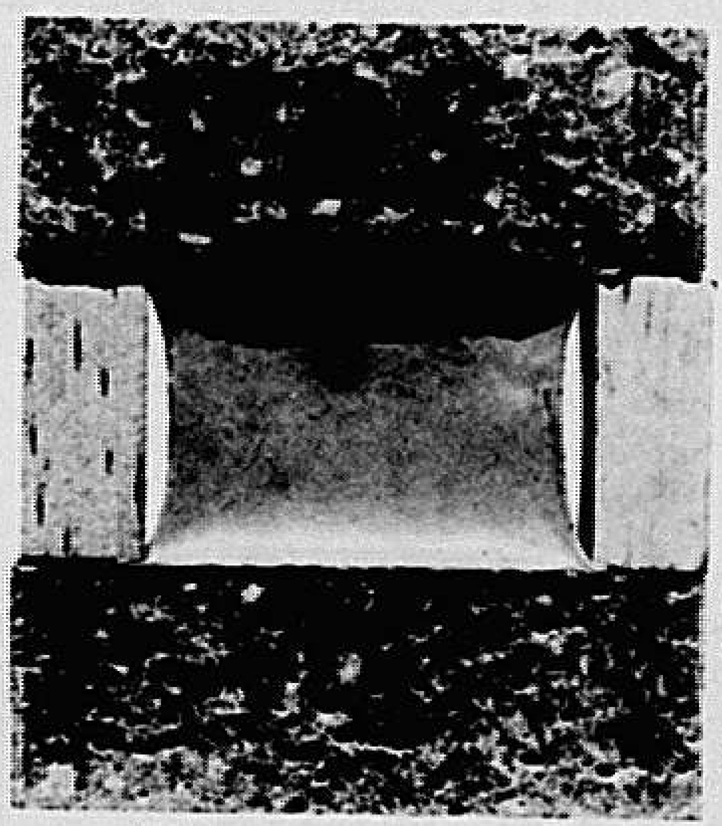


FIGURE 4-2. CLOSEUP VIEW OF A TEST SPECIMEN AFTER EXTENDING TO 150 PERCENT OF ITS ORIGINAL LENGTH

curing and after 3, 9, and 18 months' aging in air and water. Tensile testing machine head speed was 0.2 inch per minute. Samples were extended to failure or to a maximum of 150 percent.

Results of tensile adhesion tests are shown in Tables 4-3 through 4-13. Elongation was used to determine change in sealant adhesion.

Elongation is more pertinent than strength because the joint movement of massive concrete segments is not influenced by sealant strength. Seal integrity is dependent upon the ability of the sealant to follow joint movement.

To facilitate evaluation of elongation changes with time, an elongation factor was developed. This was necessary because tensile tests were terminated at 150 percent elongation rather than failure. The factor consists of crediting each tensile specimen with points as follows:

Ultimate elongation	Points
150+	5
100 to 149	4
50 to 99	3
25 to 49	2
15 to 24	1
0 to 14	0

Since three specimens were used for each test, a maximum of 15 points was possible for each test. Figure 4-3 illustrates the change in elongation factor with time for each of the 11 final candidates.

TABLE 4-3. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 1

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens)								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	12 mo	3 mo	9 mo	12 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	1.3	1.6	2.4	4.1	1.1	1.4	1.2	1.0	0.7
50	A	4.5	4.2	8.2	13.5	4.2	4.6	3.4	2.7	2.2
	B	4.5	6.0	8.8	12.2	3.7	3.6	3.9	3.6	2.3
	C	3.7	*	6.1	11.0	3.3	3.5	3.3	<0.5	1.3
100	A	6.8	6.5	12.3	19.9	6.7	6.5	5.1	3.6	2.9
	B	7.3	8.8	13.2	18.4	5.7	5.3	5.9	5.0	2.9
	C	5.6	*	9.4	16.5	5.1	5.2	5.0	<0.5	1.6
150	A	9.1	8.1	15.5	25.7	8.4	8.1	6.9	4.5	3.7
	B	9.5	11.8	16.2	24.2	7.0	5.3	7.3	5.3	3.7
	C	7.2	*	11.8	21.2	6.5	5.2	6.2	<0.5	1.4
		No. of specimens passing out of three possible								
150 for 24 hours	A	3	3	3	3	3	3	3	3	3
	B	3	3	2	2	1	3	3	3	1
	C	3	3	0	3	2	3	3	0	1

* No test.

1/ Surface A = ground and primed; B = ground; C = formed.

TABLE 4-4. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 2

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	12 mo	3 mo	9 mo	12 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	5.8	4.6	5.2	6.8	4.8	5.7	6.6	1.9	*3/
50	A	14.0	14.1	13.1	15.3	13.1	9.0 (40)	11.1 (50)	3.8	
	B	13.7	12.5	13.1	16.2	11.3	14.1	15.6	*	
	C	14.3	11.0	13.8	16.2	11.3	9.7 (37)	9.9 (33)	5.1	
100	A	19.7	20.5	19.3	22.4	17.5 (100)	0	0	5.7	
	B	19.4	18.6	19.5	23.0	16.8 (100)	15.6 (79)	18.2 (51)	*	
	C	20.2	17.1	20.4	23.2	15.7	0	0	6.3(99)	
150	A	24.0	25.6	24.6	27.3	0	0	0	7.6	
	B	23.5	23.6	23.6	28.7	0	0	0	*	
	C	24.4	21.9	25.6	28.8	19.3	0	0	0	
		No. of specimens passing out of three possible								
150 for 24 hours	A	3	3	3	3	*	*	*		
	B	3	3	3	3	*	*	*		
	C	3	3	3	3	0	*	*		

* No test.
1/ Surface A = ground and primed; B = ground; C = formed.
2/ Elongation shown in parenthesis if less than that shown in column 1.
3/ 240 °F too high for this material.

TABLE 4-5. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 3

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	12.4	14.0	14.1	16.1	12.3	13.7	15.1	9.6	13.2
	A	28.8	22.0	28.0 (45)	29.2	31.9	29.9 (44)	31.6	27.8	42.4
50	B	44.2	40.0	53.0	47.4 (39)	43.7	39.0	42.2 (46)	31.1	34.0
	C	55.8	72.8	66.0	67.4	40.4	53.5	47.8	37.0	49.7
	A	31.3 (59)	24.0 (56)	0	30.0 (54)	35.0 (61)	0	32.0 (53)	33.5 (77)	43.0 (52)
100	B	69.5 (100)	41.9 (56)	55.0 (53)	0	54.8 (84)	43.5 (62)	0	43.2 (90)	37.6 (74)
	C	63.7 (68)	96.5 (80)	76.5 (64)	72.4 (67)	55.3 (86)(	67.0 (71)	53.0 (58)	55.4 (100)	68.5 (89)
	A	0	0	0	0	0	0	0	0	0
150	B	0	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0
		No. of specimens passing out of three possible								
150	A	*	*	*	*	*	*	*	*	*
for	B	*	*	*	*	*	*	*	*	*
24 hours	C	*	*	*	*	*	*	*	*	*

* No test.

1/ Surface A = ground and primed; B = ground; C = formed.

2/ Elongation shown in parenthesis if less than that shown in column 1.

TABLE 4-6. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 4

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens)								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	0.8	1.2	1.2	1.1	1.1	1.1	2.3	0.9	* 2/
50	B	3.1	5.4	6.4	6.6	4.5	5.5	6.9	2.4	
	C	2.9	5.5	6.4	6.8	4.8	6.2	7.0	2.7	
100	B	6.8	10.5	13.1	13.9	8.5	10.9	13.5	4.8	
	C	6.7	11.2	13.9	14.4	9.0	12.0	14.2	5.6	
150	B	9.5	15.5	17.3	18.5	12.9	14.7	17.1	7.3	
	C	9.5	15.3	19.2	19.6	13.5	16.0	19.0	8.9	
		No. of specimens passing out of three possible								
150 for 24 hours	B	3	3	3	1 of 1	1 of 2	3	1	3	
	C	3	3	3	2 of 2	3	3	3	2 of 2	

* No test.
1/ Surface B = ground; C = formed.
2/ 240 °F temperature too high for this material.

TABLE 4-7. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 5

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	7.5	8.6	10.4	10.9	6.6	6.8	4.7	3.9	5.0
50	B	13.2	18.0	19.0	23.1	10.0	12.6	5.1 (20)	6.3	8.1
	C	17.4	16.7	25.2	24.5	16.9	18.9	16.1	10.2	13.5
100	B	16.3	22.6	23.9	29.3	13.8	14.2	0	7.3	10.0
	C	22.0	20.7	31.7	31.7	19.8	22.0	19.1 (100)	12.0	17.3
150	B	19.0	25.8	28.5	34.6	14.7	16.2	0	8.0 (135)	11.9
	C	25.5	25.7	37.0	37.6	21.5	23.2	0	12.6 (110)	20.8
		No. of specimens passing out of three possible								
150 for 24 hours	B	3	3	3	3	0	2	*	*	3
	C	3	3	2 of 2	3	0	3	*	*	2 of 2

* No test.
1/ Surface B = ground; C = formed.
2/ Elongation shown in parenthesis if less than that shown in column 1.

TABLE 4-8. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 6

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	6.5	9.5	12.7	12.6	7.8	10.5	9.8	0	0
50	B	16.1	19.9	21.4	25.1	10.2 (34)	13.0 (27)	17.3 (41)	0	0
	C	15.0	18.1	26.7	26.3	16.0	14.2 (42)	15.9 (33)	0	0
100	B	22.4	24.8	22.0 (62)	33.8 (100)	0	0	0	0	0
	C	20.4	23.9	35.1	29.9	20.1 (100)	0	0	0	0
150	B	27.8	24.2	0	0	0	0	0	0	0
	C	25.2	27.0	41.3	40.0 (128)	0	0	0	0	0
		No. of specimens passing out of three possible								
150 for 24 hours	B	0	0	*	*	*	*	*	*	*
	C	1	0	0	*	*	*	*	*	*

* No test.

1/ Surface B = ground; C = formed.

2/ Elongation shown in parenthesis if less than that shown in column 1.

TABLE 4-9. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 7

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	9.3	15.1	21.0	19.1	7.5	6.1	5.1	4.3	*
50	A	20.1	35.0	47.2	41.4	18.0	15.6	13.8	8.3	*
	B	21.6	36.7	43.2	45.5	17.9	15.6	14.6	9.6	
	C	20.6	35.6	46.6	42.5	18.3	14.8	13.0	9.9	
100	A	25.4	46.3	59.6	56.7	22.5	20.3	18.0	9.6	*
	B	27.6	48.6	55.3	62.3	23.0	20.2	19.1	10.6	
	C	25.9	47.9	59.6	58.7	20.0 (75)	19.2	16.5 (95)	11.2	
150	A	30.3	57.1	68.8	70.8	25.0	23.0	20.1 (140)	10.7	*
	B	32.8	61.3	67.0	77.0	25.9	23.6	22.4	12.3	
	C	30.8	58.7	68.4	72.8	0	20.2 (119)	0	12.2	
		No. of specimens passing out of three possible								*
150 for 24 hours	A	3	3/ 0	3/ 0	3/ 0	1	1	*	1	*
	B	3	0	0	0	2	3	3	3	*
	C	3	0	0	0	*	*	*	3	*

* No test.

1/ Surface A = ground and primed; B = ground; C = formed.

2/ Elongation shown in parenthesis if less than 150 percent.

3/ Cohesion failures.

TABLE 4-10. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 8

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	53.2	44.7	47.9	45.2	33.3	32.7	31.6	2.0	1.0
50	B	121.0 (38)	97.0 (32)	136.0 (42)	115.0 (40)	56.3 (31)	78.9 (46)	49.6 (30)	0.8 (9)	2.7
	C	109.0 (27)	103.0 (29)	124.0 (34)	120.0 (39)	30.6 (16)	33.4 (17)	41.2 (19)	2.8 (11)	<0.5
100	B	0	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0
150	B	0	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0
		No. of specimens passing out of three possible								
150 for 24 hours	B	*	*	*	*	*	*	*	*	*
	C	*	*	*	*	*	*	*	*	*

* No test.

1/ Surface B = ground; C = formed.

2/ Elongation shown in parenthesis if less than 150 percent.

TABLE 4-11. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 9

Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	18 mo	3 mo	9 mo	18 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	7.0	15.1	34.4	43.1	9.6	23.2	26.6	53.3	10.8
50	B	19.6	23.8	67.5	71.1	33.3	46.7	51.4	87.3 (49)	25.7
	C	21.4	36.2	66.2	84.8	23.8	38.5 (41)	45.2 (46)	80.4	23.2
100	B	28.5	33.3	75.8 (85)	74.8 (88)	43.5	58.1	58.0 (78)	0	28.6 (69)
	C	30.2	47.9	80.6	98.3 (100)	29.9 (95)	0	0	82.4 (65)	28.6 (83)
150	B	33.6	36.5 (140)	0	0	46.2 (136)	59.7 (111)	0	0	0
	C	36.3	53.4 (140)	83.8 (126)	0	0	0	0	0	0
		No. of specimens passing out of three possible								
150 for 24 hours	B	0	*	*	*	*	*	*	*	*
	C	1	*	*	*	*	*	*	*	*

* No test.
1/ Surface B = ground; C = formed.
2/ Elongation shown in parenthesis if less than 150 percent.

TABLE 4-12. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 10

Elongation percent	Surface condition 1/	Tensile strength - lb/in² (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	17 mo	3 mo	9 mo	17 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
10	All	14.7	25.5	27.4	30.1	22.0	23.5	25.3	34.4	*
50	A	48.8	72.1	74.6	81.8	60.6	67.3	76.8	90.1	*
	B	48.0	74.4	74.5	84.2	60.3	66.2	73.9	81.4	
	C	47.7	77.2	77.1	78.5	46.7 (38)	60.5 (46)	51.3 (38)	90.3	
	D	46.7	77.1	82.2	92.5	67.4	74.6	77.0	57.5 (28)	
100	A	70.4	95.1	107.0	120.0	83.7	97.7	111.0	106.0 (75)	*
	B	71.0	101.0	110.0	126.0	80.8 (97)	86.2 (81)	81.4 (60)	88.0 (62)	
	C	71.2	102.0	114.0	119.0	0	0	0	99.8 (62)	
	D	68.8	99.2	117.0	134.0	87.4 (89)	96.0 (83)	110.0	0	
150	A	80.5	105.0	122.0	140.0	97.0	110.0	127.0	0	*
	B	80.6	112.0	125.0	148.0	0	0	0	0	
	C	91.3	110.0	129.0	139.0	0	0	0	0	
	D	78.5	109.0	133.0	150.0	0	0	117.0	0	
		No. of specimens passing out of three possible								
150 for 24 hours	A	3	3	3	3	3	3	0	*	*
	B	3	2	2	0	*	*	*		
	C	3	3	0	0	*	*	*		
	D	3	3	0	2	*	*	0		

* No test.

1/ Surface A = ground and primed; B = ground; C = formed; D = formed and primed.

2/ Elongation shown in parenthesis if less than 150 percent.

TABLE 4-13. SEALANT TENSILE - ADHESION PROPERTIES

Sample No. 11

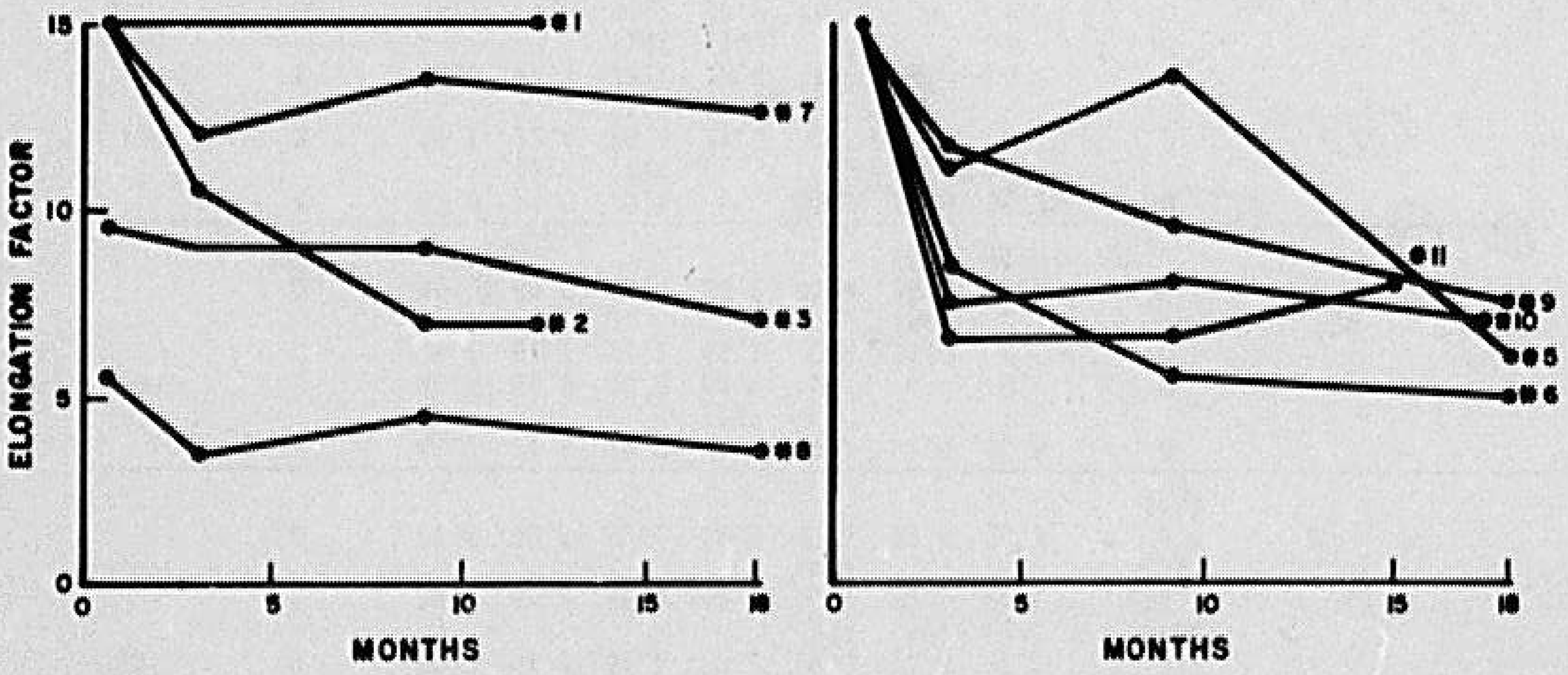
Elongation percent	Surface condition 1/	Tensile strength - lb/in^2 (average of three specimens) 2/								
		Air aging				Water aging			Accelerated aging	
		14 day	3 mo	9 mo	15 mo	3 mo	9 mo	15 mo	14 day 95 percent RH 176 °F	4 hr 100 percent RH 240 °F
50	A	34.9	53.6	59.2	60.2	37.0	40.3	41.5	10.6 (24)	*
	B	46.9	54.7	61.1	52.2	25.0 (35)	27.8 (32)	27.2 (42)	10.8 (23)	
	C	29.5	44.2	52.3	48.9	30.2 (48)	30.5	24.1 (50)	13.1 (35)	
	D	29.6	49.6	52.5	46.9	31.8	33.8	34.2	6.4 (16)	
100	A	48.2	71.9	78.2	77.7 (98)	49.7	52.0	55.5	0	*
	B	48.4	69.5	78.2	68.9	0	0	0	0	
	C	39.4	61.7	72.2	68.1	0	31.9 (56)	0	0	
	D	45.0	69.0	73.4	64.8	41.4	36.3 (64)	40.4 (100)	0	
150	A	52.8	74.0 (124)	79.6 (118)	0	53.1	54.6 (117)	58.2	0	*
	B	50.1	72.4	79.4 (115)	72.9 (113)	0	0	0	0	
	C	46.0	67.2	78.1 (142)	72.4 (143)	0	0	0	0	
	D	49.7	74.2	81.2 (144)	70.2	44.9 (104)	0	0	0	
		No. of specimens passing out of three possible								
150 for 24 hours	A	0 3/	* 3/	*	* 3/	0 3/	*	*	*	*
	B	0	0	*	*	*				
	C	0	0	*	*	*				
	D	0	0	*	0	*				

* No test.

1/ Surface A = ground and primed; B = ground; C = formed; D = formed and primed.

2/ Elongation shown in parenthesis if less than 150 percent.

3/ Cohesion failure.



Average of ground and formed surfaces (No Primer)

FIGURE 4-3. CHANGE IN ELONGATION FACTOR DURING CONTINUOUS WATER IMMERSION

In evaluating the performance, the elongation at the end of the rating period is of primary importance. It has been speculated that of two materials having a certain value at the end of 18 months, the one that had changed the least was the better. This would be true only if the trend continued, but the tendency in this study was for some materials to deteriorate less with time while others had a sudden increase in deterioration rate. The argument is thus academic, and the sealants were rated according to their elongation factor at test end, except that any previous lower value was used to reflect variability in the sealant adhesion characteristics. These ratings are shown in the top chart in Figure 4-4.

Of the five top-rated sealants, four were tested with and without primer on a ground surface. Figure 4-5 illustrates the beneficial effect of the primer and the importance of its use.

The effect of surface condition on initial adhesion is shown in Figure 4-6. This was typical of many sealants, although there were exceptions as the data in Tables 4-3 through 4-13 indicate. The significant information here is that a clean formed surface, not contaminated with release agent (such as form release oil or a type of curing compound which is unsatisfactory as a primer), is nearly as good as a ground surface. It also shows that grinding with a carborundum wheel is superior to sandblasting for removing some types of surface contamination. Sandblasting leaves a surface that is harder for these viscous materials to "wet." However it remains the main choice of cleaning for volume work. It also has the benefit of cleanly removing some types of contamination that may be redeposited by grinding.

It has been Service experience that high-pressure water blasting is sometimes a satisfactory alternative to sandblasting or even better in some cases. Its disadvantage is that drying is

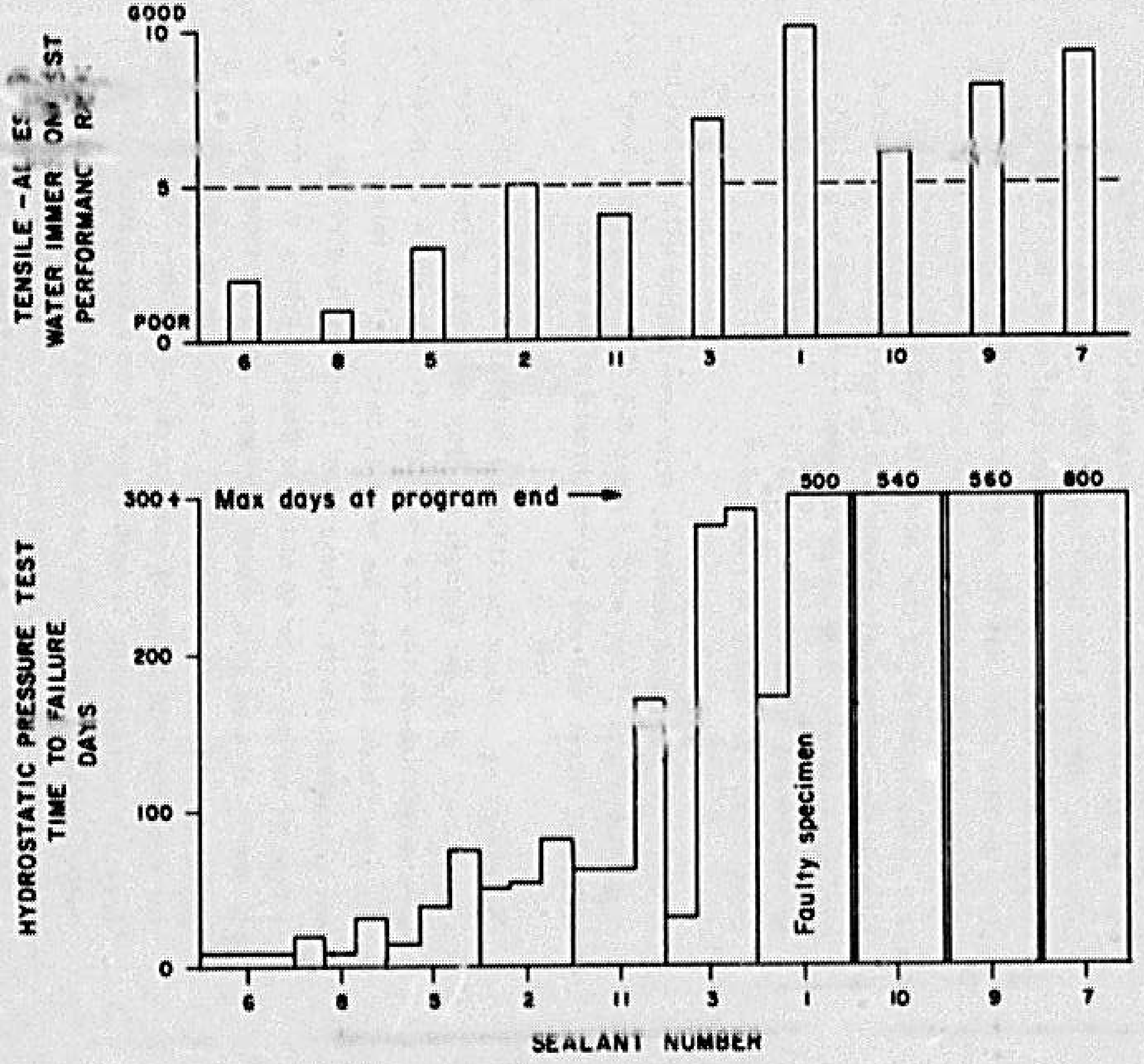


FIGURE 4-4. COMPARISON OF DURABILITY TEST

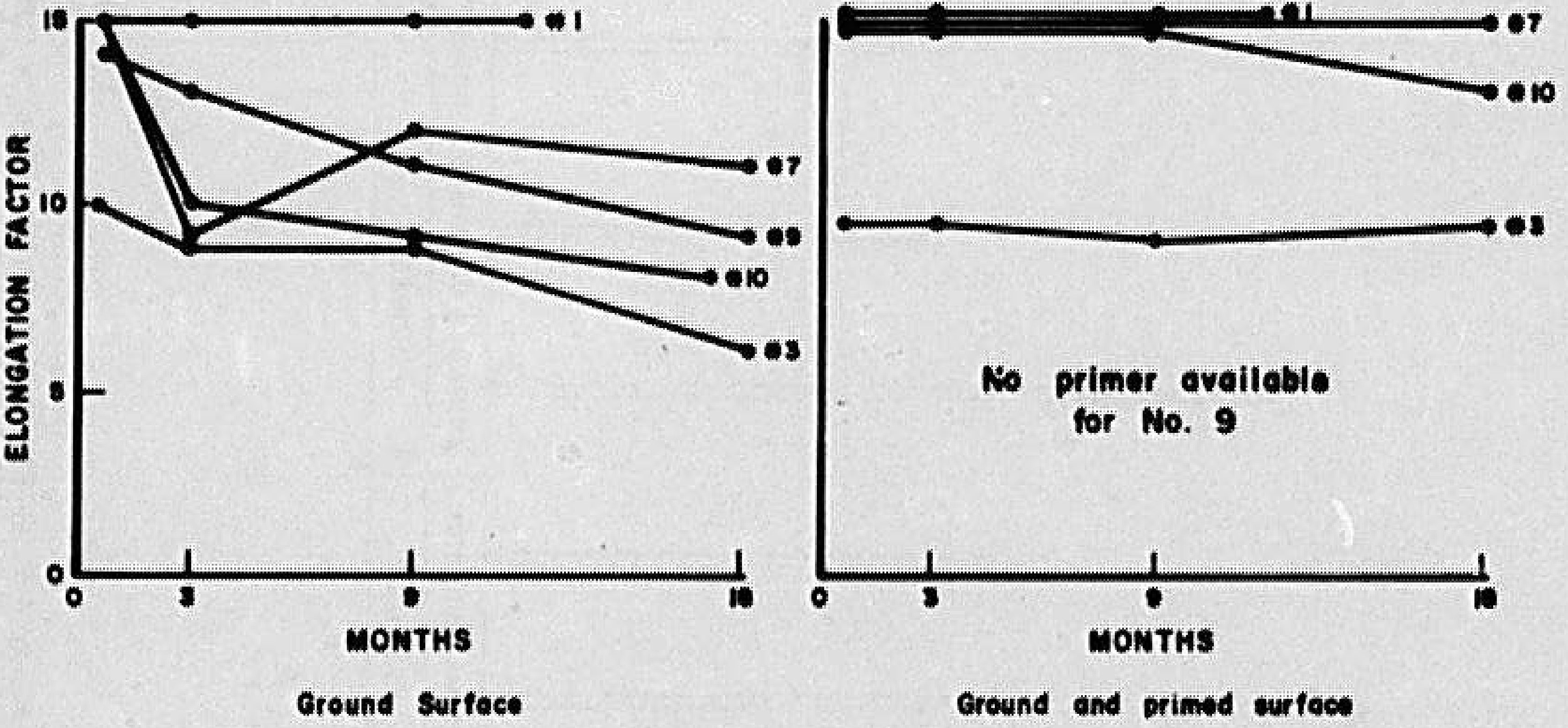


FIGURE 4-5. EFFECT OF WATER AGING ON SEALANT ADHESION OF 5 BEST SEALANTS WITH AND WITHOUT PRIMER

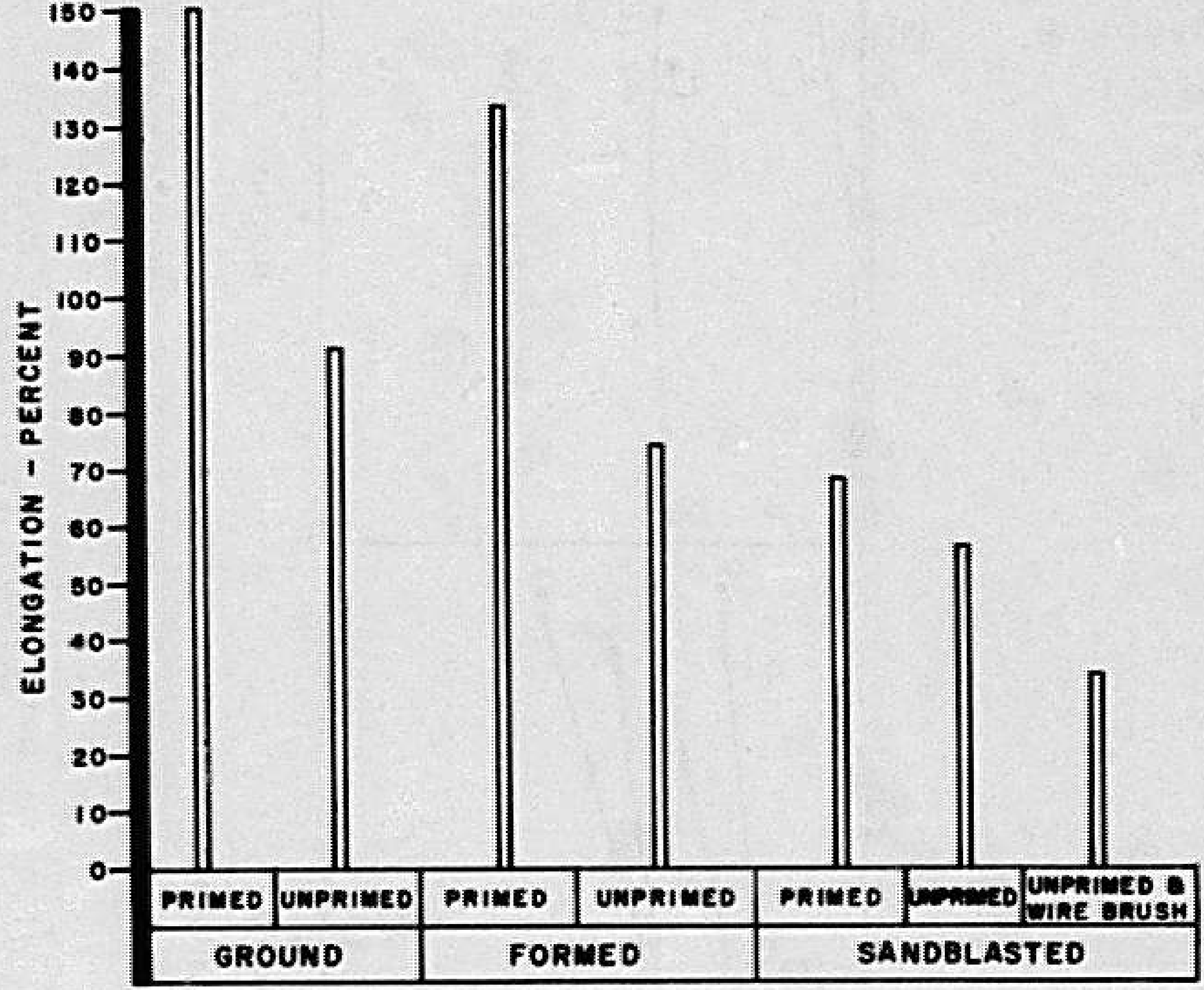


FIGURE 4-6. EFFECT OF SURFACE CONDITION ON ELONGATION FOR SEALANT NO. 5a

required, but high-pressure air-drying immediately prior to sealant application will provide a dry enough surface for some materials.

The effect of water on the sealant material properties is illustrated in Figure 4-7. Of the five top-rated materials, nos. 1 and 3 showed the least hardening in air or water. No. 7 shows some softening in water which is of moderate concern since this material was somewhat adversely affected in the high humidity test.

The two single-component materials (nos. 9 and 10) hardened substantially during the 18-month aging and in much the same proportion as in the high humidity test. Where joint movement is expected to diminish with time, either of these materials may be satisfactory since their hardening rate seems to be diminishing. However, where continued joint opening is expected, a limit to age hardening should be imposed.

A very short-term, high-humidity test was evaluated during the program; 4 hours exposure at 240 °F and 95 percent relative humidity. The reduction in time would be very desirable for acceptance testing purposes. Unfortunately, it is too high a temperature for some materials. This test should only be used when both consumer and supplier agree that it will correlate with the 14-day test. In this context, it would appear to be useful for quality control.

Special mention should be made of Sealant no. 11. Particular care must be taken with this material to assure proper mixing and application; this can best be done with a mixer-applicator apparatus. Hand-mixing methods tend to incorporate very small air bubbles which reduce the tensile strength of cured sealant.

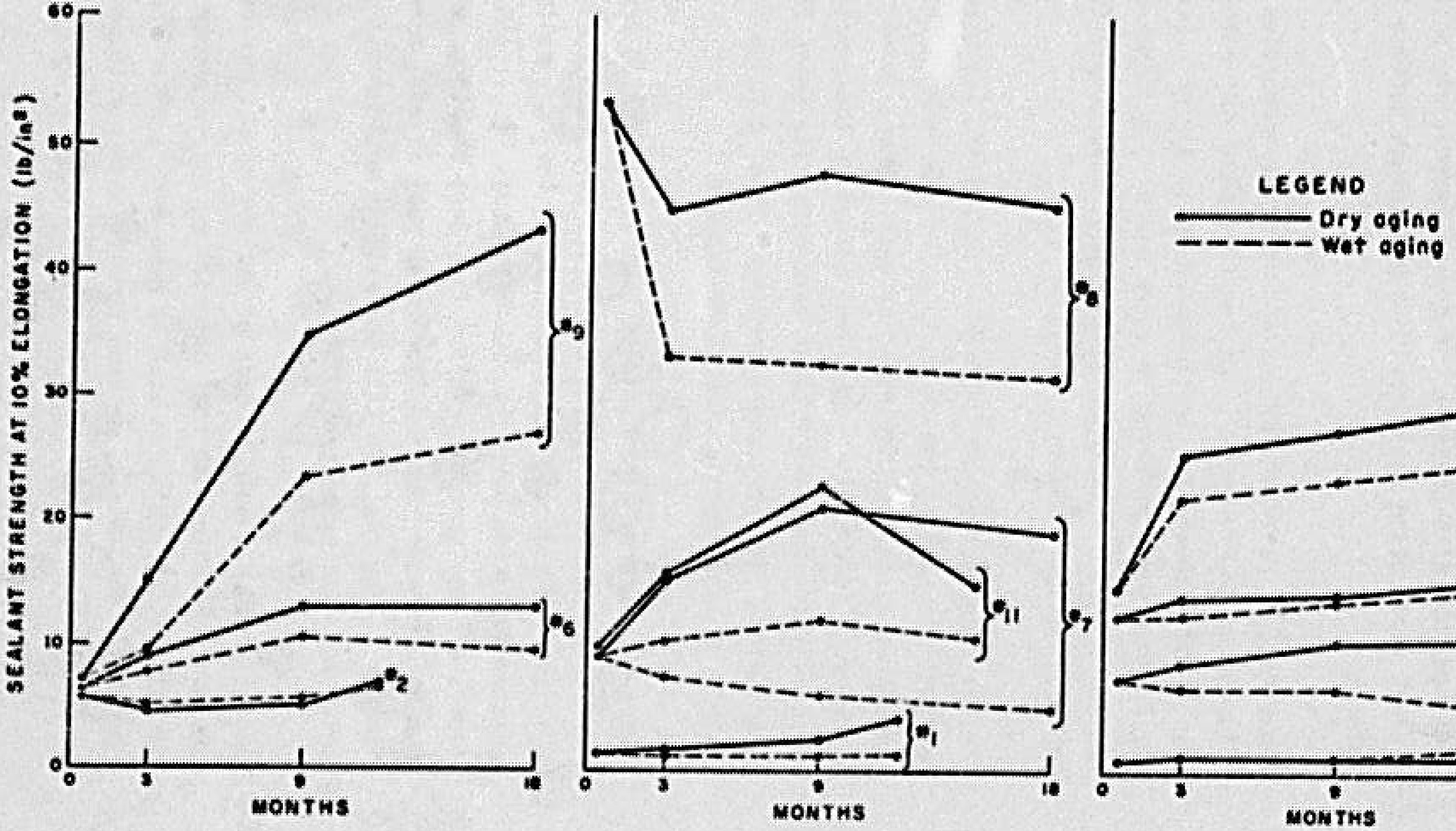


FIGURE 4-7. EFFECT OF WET AND DRY AGING ON SEALANT STIFFNESS

4.4.2. Effect of Water

Many polymers are seriously attacked by water. The more resistant the material is to water penetration, the less chance that attack will occur. Water vapor permeates a mass of material more easily and rapidly than water in a liquid state. Because of the potential for deterioration by water, tests having high humidity or high humidity plus high water pressure often will quickly expose a weakness to water attack. Such tests, however, may require elevated temperatures.

Some materials will be adversely affected by high temperatures, thus invalidating the results. Other materials, particularly where adhesion is concerned, for some reason, exhibit adverse reactions only at relatively low temperatures. Consequently, long-term water immersion is essential to the study of water reactions. However, the short-term, high-humidity tests were also run with the hope that they would be useful for specifications tests where brevity is essential.

The addition of pressure to the water exposure environment which was done in the hydrostatic tests proved to be a rather dramatic accelerating factor in examining adhesion durability. In some cases, failure was observed within a few days (Figure 4-8) where months of nonpressure water immersion was required to expose such weakness. One material (Sealant no. 8), which could withstand 30 percent elongation after several months water immersion, could withstand less than 10 percent after a few days at 26-lb/in^2 water pressure.

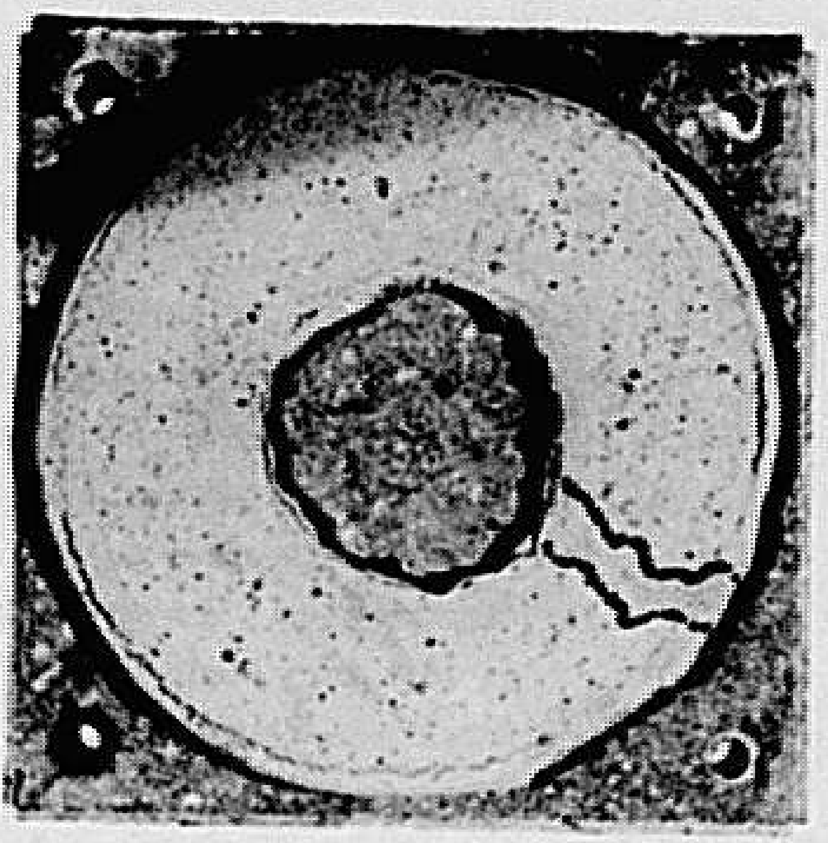


FIGURE 4-8. FAILURE AFTER WATER AND PRESSURE TEST

4.4.3. Ozone Resistance

Ozone resistance of sealant materials was determined in accordance with ASTM: D 1149, "Accelerated Ozone Cracking of Vulcanized Rubber." The test was conducted for 28 days at 0.50 p/m ozone concentration, 100 °F, and 20 percent elongation. Test data are shown in Table 4-2.

Only one of the final candidate sealants suffered visible attack during ozone exposure. This generally good resistance was not entirely unexpected because of the resistant nature of the molecular structure of these materials. Attack in service would be even less likely since only insignificant surface attack occurs in polymers not under continuous strain in excess of approximately 5 percent or more. Such a situation is unlikely to occur in tunnel joints because of the slow and limited movements expected and the strain relaxation characteristics of the sealants.

The one sealant which did show some cracking (Sealant no. 1) was attacked only after very high strain (100 percent) was induced in the material. The material was selected for high strain because of its low tensile modulus. Even at high strain, the cracking rate was reduced with time and appeared to have stopped after 3 days as relaxation characteristics of the material began to reduce the stress.

The results of these tests, therefore, indicate that ozone attack, although a possibility, is not likely to occur with any candidate sealants, except in very unusual circumstances.

4.4.4. Limited Oxygen Index Classification Test

This test operates on the premise that some of the burning characteristics of materials can be established by varying oxygen/nitrogen ratio in the combustion chamber, i.e., more flammable materials will burn in atmospheres of lower oxygen content. Fifteen materials were evaluated in this test. The test apparatus is shown in Figure 4-9.

Results of sealant material fire testing are shown in Table 4-2. None of the sealants appear to have any significant fire resistance except possibly Sample no. 3 which has an oxygen index just slightly higher than most other urethanes. Samples no. 4 and 5 are more resistant to burning because of their molecular structure.

Sample no. 10, the sealant material used in the ASTM: E 84 test (Section 5.5.), has a very low oxygen index, yet did not burn rapidly or contribute significant smoke in the test. This indicates that the tunnel is a relatively mild environment as far as sealant burning hazards are concerned. Although the burning characteristics of the sealant can be improved, the tests indicate this is likely a lower priority than restricting fuel potential contribution of anything entering the tunnel, either during construction or service.

4.5. Creep Resistance

Resistance to creep and the ability to resist extrusion from the joint was determined by placing 5- by 6-inch material samples between two concrete blocks (Figure 4-10). Compressive force was applied to the concrete blocks starting with 15 lb/in^2 (Figure 4-11). This was maintained until creep deformation was approximately linear. The same procedure was repeated with the same specimen at

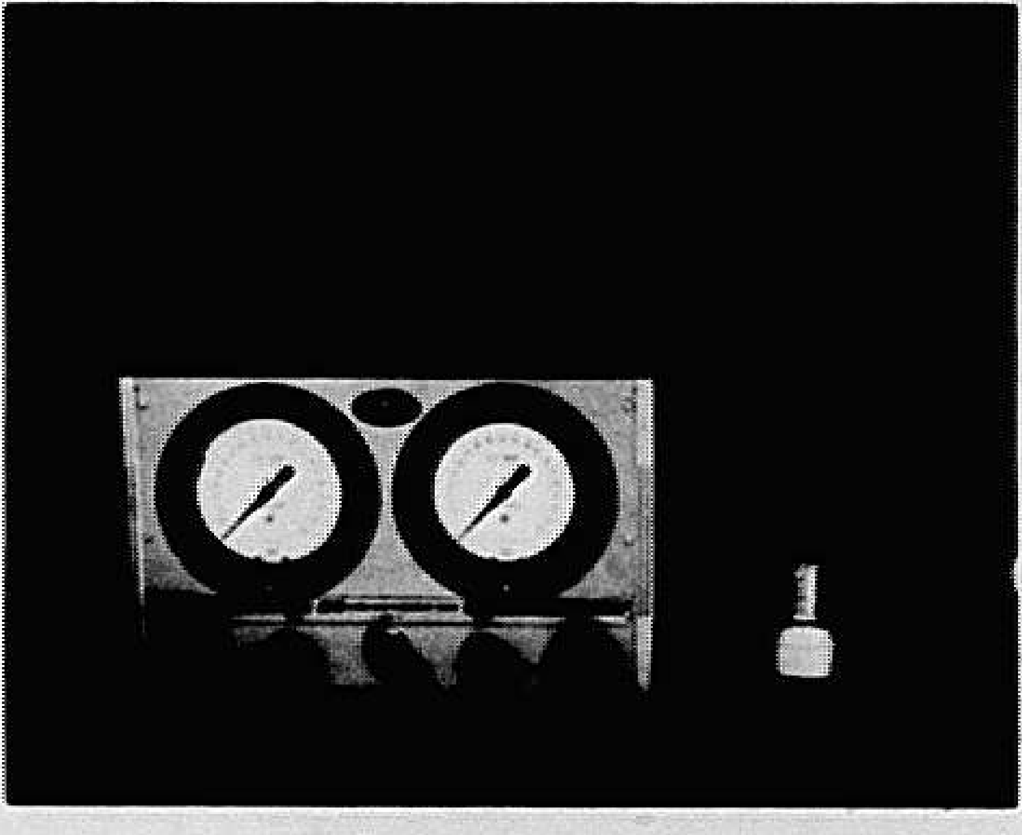


FIGURE 4-9. LIMITED OXYGEN INDEX CLASSIFICATION APPARATUS

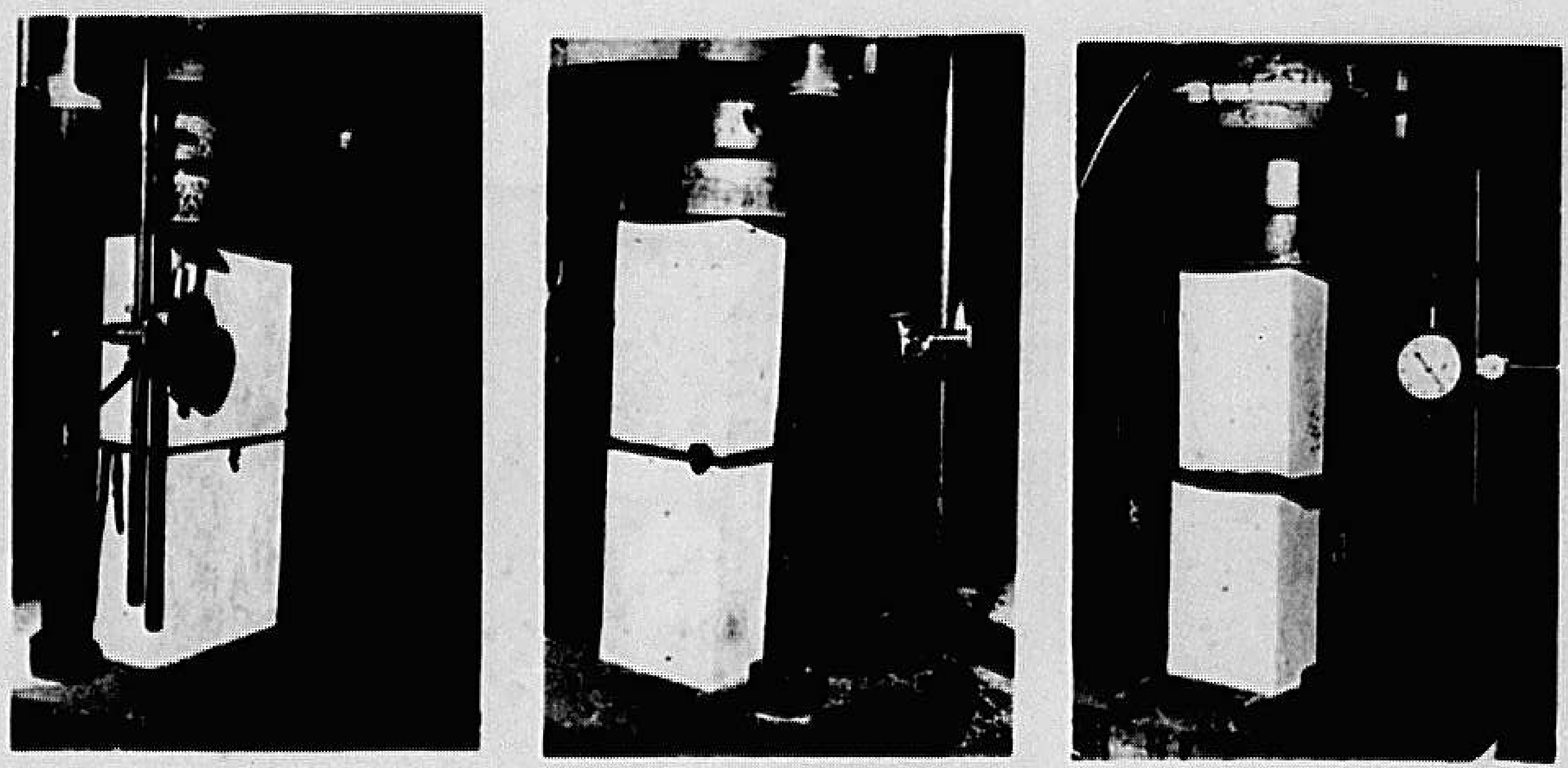


FIGURE 4-10. SUSTAINED LOAD TEST OF WOOL FELT, NEOPRENE EXTRUDED RUBBER GASKET AND WFT-1 CUSHION TAPE AT 150 LB/IN^2 LOAD

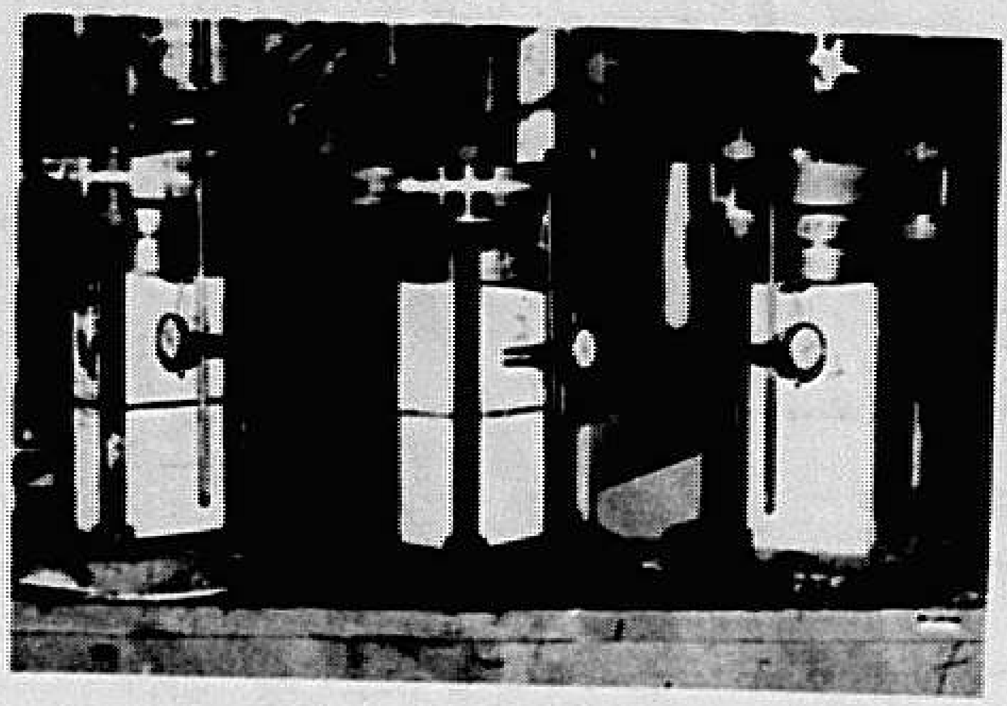


FIGURE 4-11. VIEW OF LONG TERM PRESSURE TEST (CREEP)

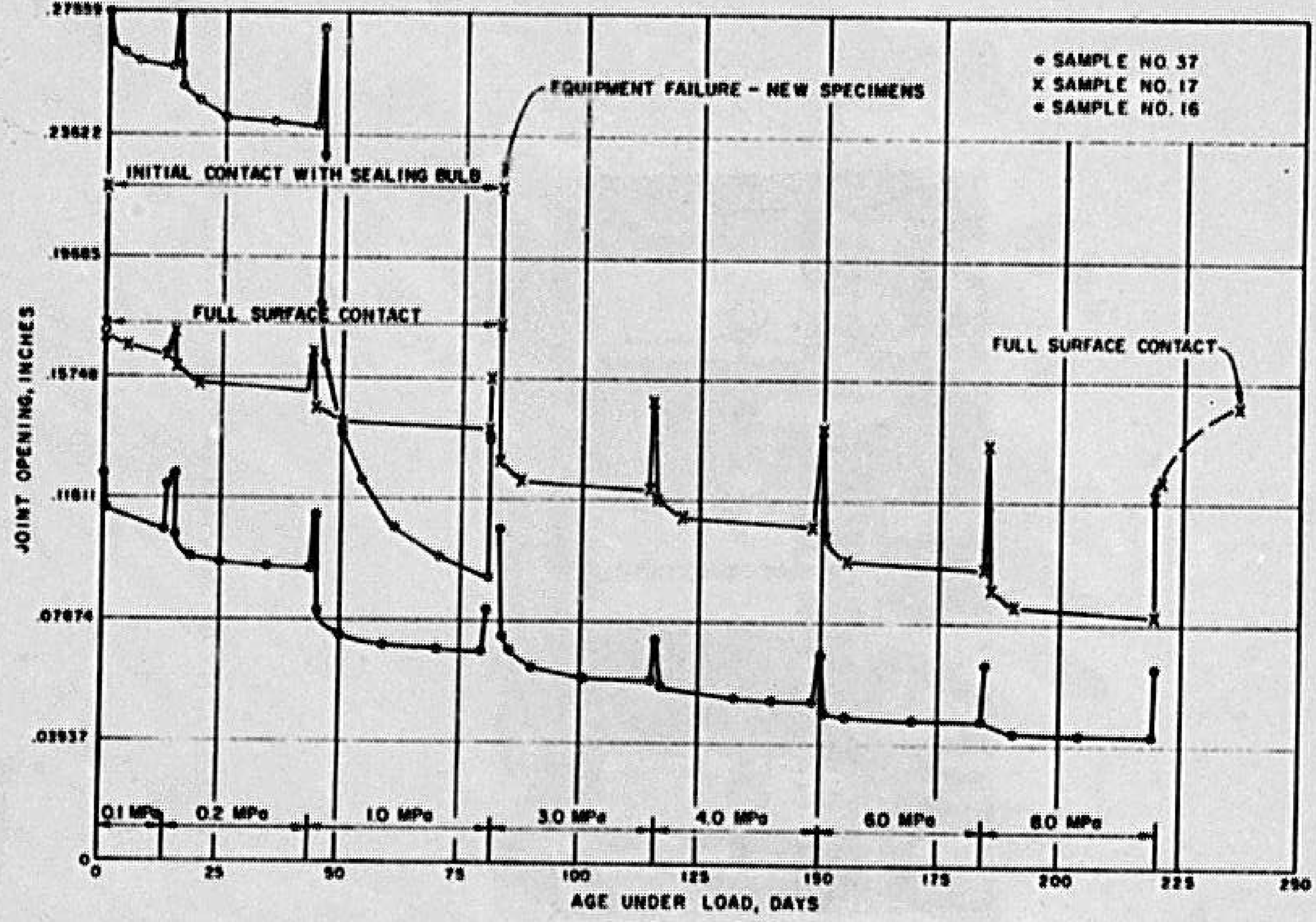


FIGURE 4-12. CONSTANT LOAD TESTS OF MATERIALS INTENDED TO SERVE BOTH AS JOINT CUSHIONING AND WATER SEAL

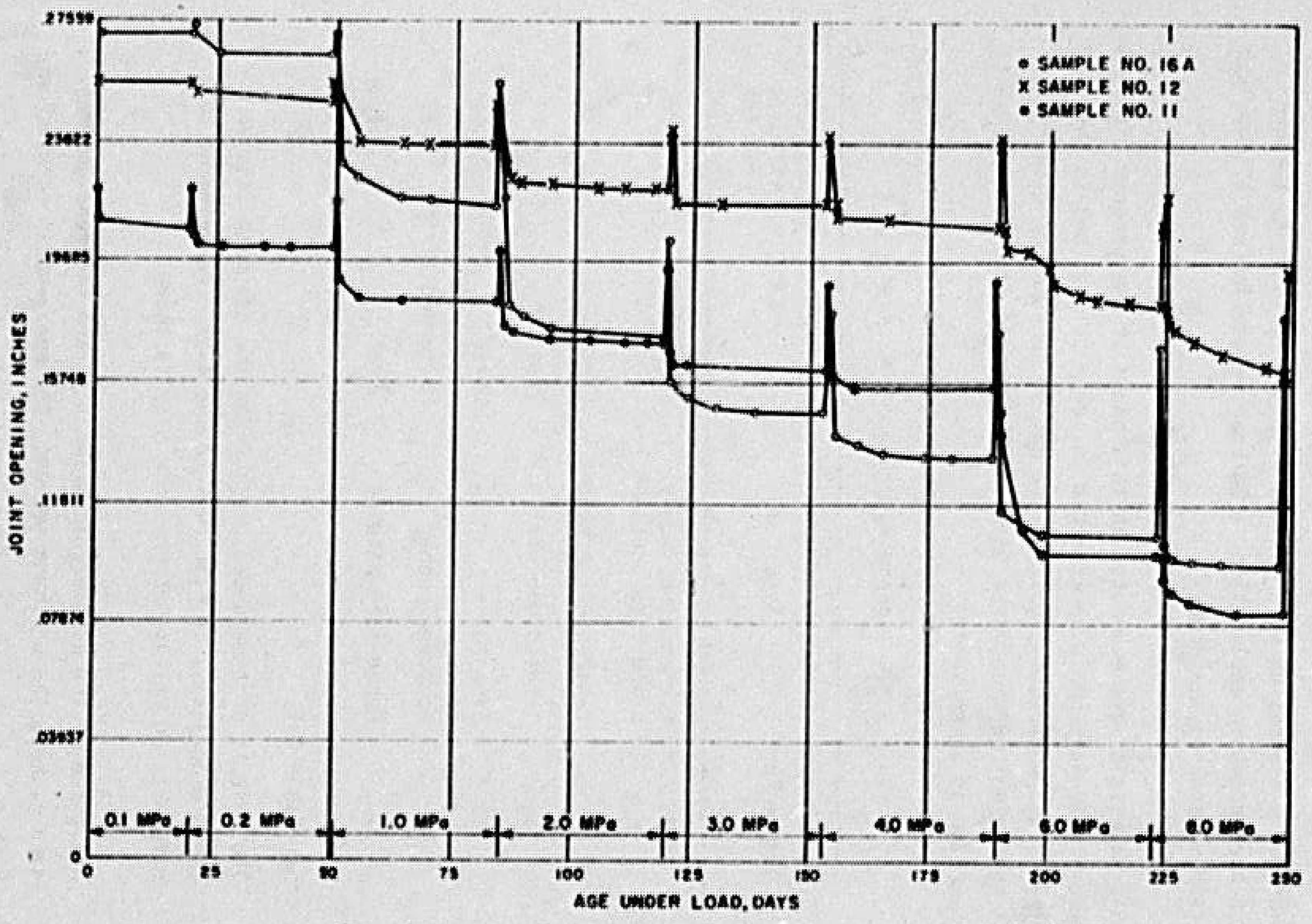


FIGURE 4-13. CONSTANT LOAD TESTS OF MATERIALS INTENDED TO SERVE BOTH AS JOINT CUSHIONING AND WATER SEAL

various pressures up to a maximum of 1,200 lb/in^2. At the end of each pressure application, a 24-hour relaxation was allowed and sample recovery measured.

Six materials were evaluated in this phase of the program (Table 4-14). These materials would be expected to serve as cushions in the joints and would cover most of the mating surfaces of either longitudinal or transverse joints. They would also be expected to function as water seals.

TABLE 4-14. CREEP RESISTANCE TEST SAMPLES

Sample No.*	Type	Form	Original thickness (inches)
11	2-component, epoxy modified urethane	Liquid	0.22
12	2-component urethane	Liquid	0.26
16	Treated wool felt	Tape	0.13
16A	Fiberboard	Sheet	0.28
17	Neoprene rubber	Preformed strip	0.18
37	Rubberized bitumen	Sheet	0.28

*See Table 4-1.

The effects of time under pressure on the six materials are shown graphically in Figures 4-12 and 4-13. Behavior of the materials on release of pressure also is shown.

All three of the elastomeric materials, the neoprene compression gasket, the urethane sealant, the epoxy-modified urethane sealant, and the fiberboard gasket have satisfactory properties in this environment. All are sufficiently resilient to maintain a water seal under pressure.

The rubberized bitumen material, however, lacks the needed coherence to remain in place under even a small constant pressure. Similarly, the treated wool felt material loses its saturant continuously under pressure.

4.6. Watertightness

From the tests conducted on sample materials in water, Section 4.4.2., and reported in Table 4-2, a test was developed using water and pressure. The 11 candidate materials were subjected to this test, as were several combination sealant systems. These tests and the results are discussed in Section 5.2, Hydrostatic Pressure Resistance.

5. PHASE 4 - SEALANT SYSTEMS TEST PROGRAM

5.1. Introduction

A sealant system shall be defined as any combination of materials required to obtain a satisfactory seal including the manner in which they must be used. A system could, therefore, consist of one or more compression seals, one or more fluid-applied materials, or a combination of both. As directed, the study is primarily concerned with bolted segments although many of these remarks will apply to sealant systems for unbolted segments. However, much of the work and findings are applicable for unbolted segments. With a tunnel lining consisting of unbolted segments, the requirements for sealants for the longitudinal joints are different than for transverse joints.

5.1.1. Sealant System Approaches

To examine the proper functioning of sealant systems studied in this program, it is first necessary to define what is expected. In addition to having components with desirable properties as discussed in Section 4, Service experience indicates that a sealant system should provide an immediate and at least temporary water seal as soon as newly placed segments are bolted in place. This serves several purposes: it will allow construction to proceed in areas of high ground water; it will allow immediate, effective grouting whether there is ground water or not; and it will allow fluid-applied sealants to be placed later under more desirable conditions. The sealing system should be flexible enough to allow some movement between segments and should allow repairs to be made at the interior surface. Finally, it must be able to accommodate poor fit between segments and should help minimize sealant system damage either during handling or subsequent stressing.

It is evident from observations of tunnel construction that the need for significant improvement of in-place fit as well as need for repairability demand that a fluid-applied sealant be part of the system, or, at the very least, that a calking groove or equivalent be provided for subsequent use. Even if a temporary seal is obtained using a high profile gasket, the compression set characteristics of the gasket combined with uneven fit, thus uneven compression, make subsequent seepage a good possibility unless a fluid-applied sealant can be utilized with the system.

Considering the above, four systems were considered. They are presented in order of their general desirability. All systems except b. were used in the tunnel model. Sample numbers of the systems correspond to those in Table 4-1.

a. Full surface crushable compression seal with calking groove. - A material such as high-density 1/4-inch-thick fiberboard, Sample no. 16A, is adhered to all mating surfaces. If ground water is not present, sealant material is not required. If only small seeps are occasionally encountered, recesses cast in the face of the concrete mating surfaces can be arranged to carry water to sumps. Where considerable water is present, a calking groove can be formed for sealant application by cutting the width of the fiberboard 1/2-inch shorter than the segment thickness.

This system will allow considerable shear since it does not rely on adhesion for sealing. It will allow joint rotation in bolted segments since rotation will increase the compression at some location in the fiberboard. Where fit is particularly poor, increased thickness may be used and grooves or some effective pattern may be molded into the surface of the material to facilitate collapse where the load is lightest. This system will also accommodate grout intrusion. Since it is full face, any grout intruding in local areas will be cushioned to keep subsequent movement from causing undesirable high loads. The material also swells slightly when in contact with water to facilitate sealing. Because of its nonflow characteristics, it is the most desirable in terms of transmitting high loads at the joint. In all of the joint strength tests conducted (see Section 5.6.), only this material, plywood, and high-density polyurethane foam transmitted loads without diminishing the joint strength. The fiberboard is likely to have the best combination of low cost and high uniformity. It, as well as plywood, can be treated for rot resistance. The polyurethane foam, of course, has the advantage of being inherently rot resistant. The principal deficiency of this system is that it is most suitable for bolted segments, where compression can be somewhat controlled. Also, since the fiberboard does not flow laterally, some joint intersections may require sealant injection to assure watertightness.

This system was one of the three used in the tunnel model (see Figure 5-1). However, because of material delivery problems, Sample no. 16 was used instead of Sample no. 16A. The material used (no. 16) was saturated with a sticky resin which helped establish and maintain a very watertight seal, but the saturant tended to reduce the joint strength. Although it was less than one-half as thick as suggested, it proved to be as watertight in the model as it was in the hydrostatic test. One small seep at a joint intersection was noted when the water head was raised from 40 to 60 feet, but this sealed itself in 3 days.

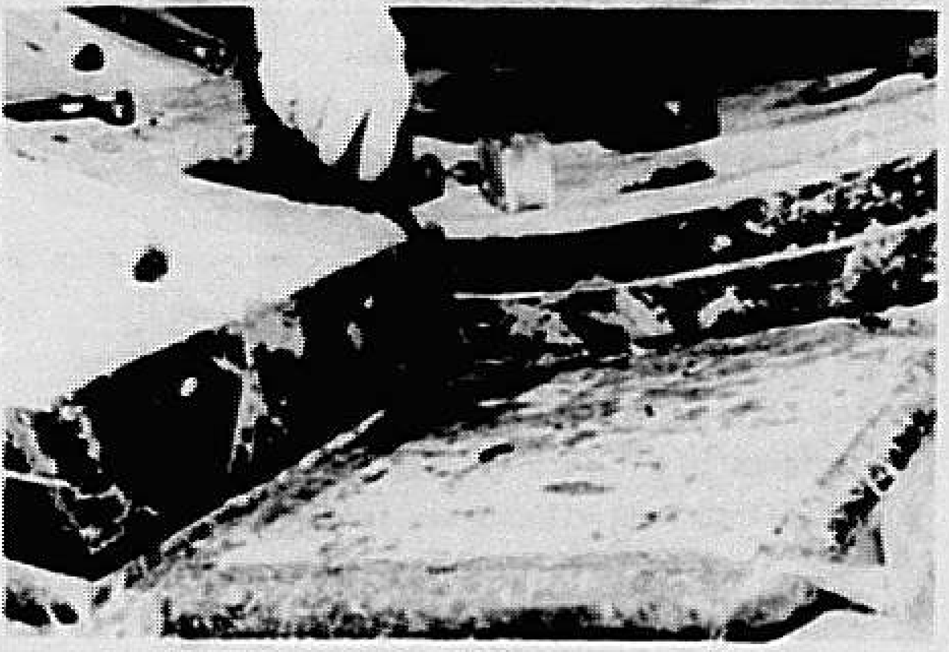


FIGURE 5-1. FULL SURFACE CRUSHABLE COMPRESSION SEAL WITH CALKING GROOVE

The final attractiveness of this system is that it is undoubtedly the lowest in cost, especially if ground-water problems are moderate.

b. <u>Full surface sprayed elastomer</u>. - This system would consist of an elastomeric material such as Samples no. 3, 11, or 12. One of these materials was used in at least one Canadian tunnel. Prior to this use, the Service had worked with the manufacturer for a number of years trying to obtain greater product performance consistency. More than one manufacturer can now produce such a product.

The sealant consists of two liquid components which are mixed together at the nozzle of a paint spray gun. The mixed materials are then sprayed on the surface of the mating faces of the concrete segments. The material should be designed to set very rapidly so that it can be sprayed on a vertical surface without sag (Figures 5-2 and 5-3).

When the segments are put into place and pressed together, a compression seal results. In time, because of specially chosen material properties, the elastomer surfaces fuse together somewhat to allow some working of the joint while maintaining watertightness without relying on compression.

This system has certain advantages in common with system a., i.e.,

(1) It can be applied to the segments in the casting yard under far better conditions than in the wet, dirty tunnel.

(2) The uniformity of application can be easily inspected.

FIGURE 5-2. VIEW OF SEGMENTS HAVING GENERALLY SATISFACTORY SEALANT APPLICATION (SEGMENTS WERE UNACCEPTABLE BECAUSE OF PHYSICAL DAMAGE)

FIGURE 5-3. UNACCEPTABLE SEGMENT (ROUGH SEALANT APPLICATION; BOND OF SEALANT TO CONCRETE WAS GOOD; THICKNESS AT CUT WAS ABOUT 0.15-IN.)

(3) It cushions the concrete segment edges, hopefully reducing the chipping and breakage during handling.

(4) It is difficult to dislodge the sealant.

Since the material is rapid setting, it can be applied as a calking material to any openings caused by poor fit with good bond assured because it adheres well to itself, which is a further advantage. Thus, each joint, regardless of segment fit, could be fitted and completely sealed.

The main disadvantage with the system is that elastomers reduce the ultimate crushing strength of the joint by translating some of the compressive force to a tensile force in the concrete as a result of lateral flow.

Other disadvantages are that it may be more expensive than system a., and it requires somewhat more exotic materials and handling equipment than other systems. It is generally an unfamiliar product to tunnel builders, which along with the somewhat sophisticated application techniques required for spray application, may be a major factor in the slow acceptance of the system.

An alternative to spray application which is less complicated is the notched trowel approach. This would likely result in a more uniform application but might be slower. The trowel would have to be deeply notched to apply enough material. A pressure-fed shoe designed to leave a similar pattern would speed the operation.

c. Full surface preformed elastomeric gasket with calking groove. - This system consists of an extruded gasket consisting of a half-round solid rubber compression bulb, having a flange 1/16-inch on one side of the half-round base and 2-1/2 inches on the other side (Figure 5-4). This system attempts to combine the best parts of systems b. and d. while eliminating some of their problems, although not that of joint strength reduction.

While it did eliminate the roll-out problem experienced with system d. and the thickness variation of system b., it has some application difficulties on the curved segment sides. This could be solved by obtaining curved pieces or by cutting gussets in the flange. Either method could increase the cost considerably. The system also requires some skill in handling the rubber and the required contact adhesives during application to the concrete. In the model, sealant was used at joint intersections (Figure 5-5).

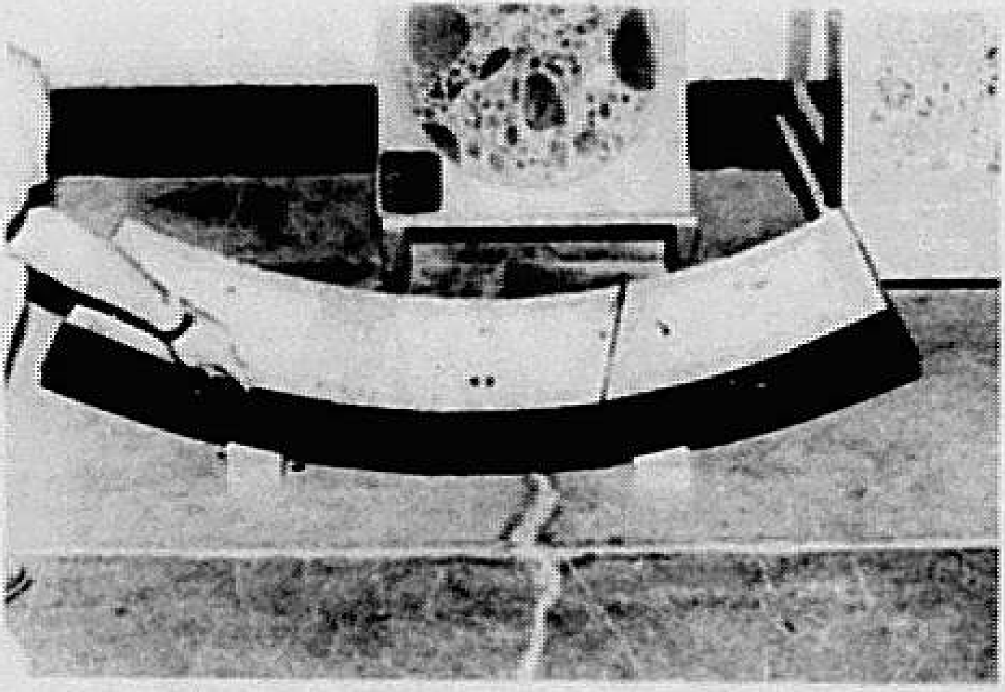


FIGURE 5-4. FULL SURFACE PREFORMED ELASTOMERIC GASKET WITH CALKING GROOVE

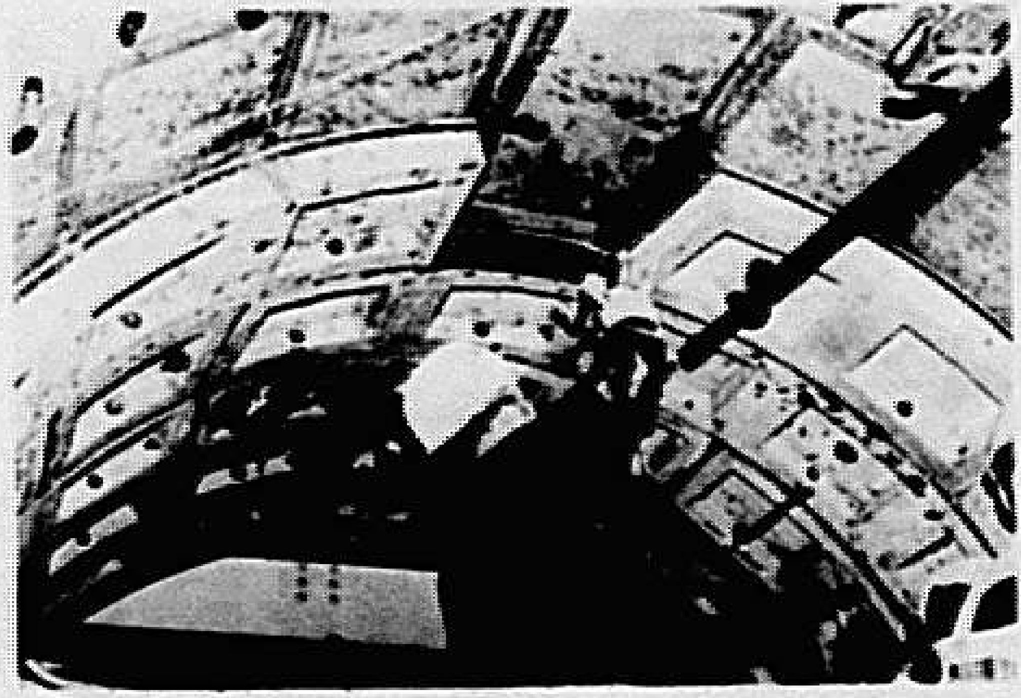


FIGURE 5-5. SEALANT USED WITH FULL SURFACE PREFORMED GASKET IN MODEL

In this study, to minimize concrete segment form changes, the compression bulb was placed in the same location as system d. Observations made during handling indicate that in actual use, the bulb should be moved closer to the center to minimize edge spalling.

d. Local compression seal with calking groove. - This system (Figure 5-6) is similar in its simplicity to system a. It is feasible only if very good field fit and close segment dimensional tolerances, such as obtained in the Service laboratory, are obtained in the field. Such fit eliminates the need for a cushioning material (no stress concentration) and allows use of a low profile compression gasket similar to pipe gasket design. Although it is unlikely that the required precision in casting and placing can be widely obtained, it may be worthwhile to put the cost saved by the system simplicity into obtaining such precision.

Using this joint in the model and the minitunnel (Section 5.2.1.), it was found that in addition to the requirement for precision the system has two unique disadvantages. These are: (a) a tendency for the gasket to become disbonded during installation ("roll-out," see Figure 5-7), and (b) spalling of the segment edge near the gasket. The gasket is placed near the outside edge of the segment to minimize grout intrusion into the joint which, if uneven (as it usually is), will cause serious spalling problems. In the model, grout intrusion was minimized by placing a sealant bead on the outside edge, a process that might be difficult in construction. Both of these problems could be minimized somewhat by adding a small flange (approximately one-half inch) to both sides of the bulb, similar to system c., and a recess in the concrete so that the flange would

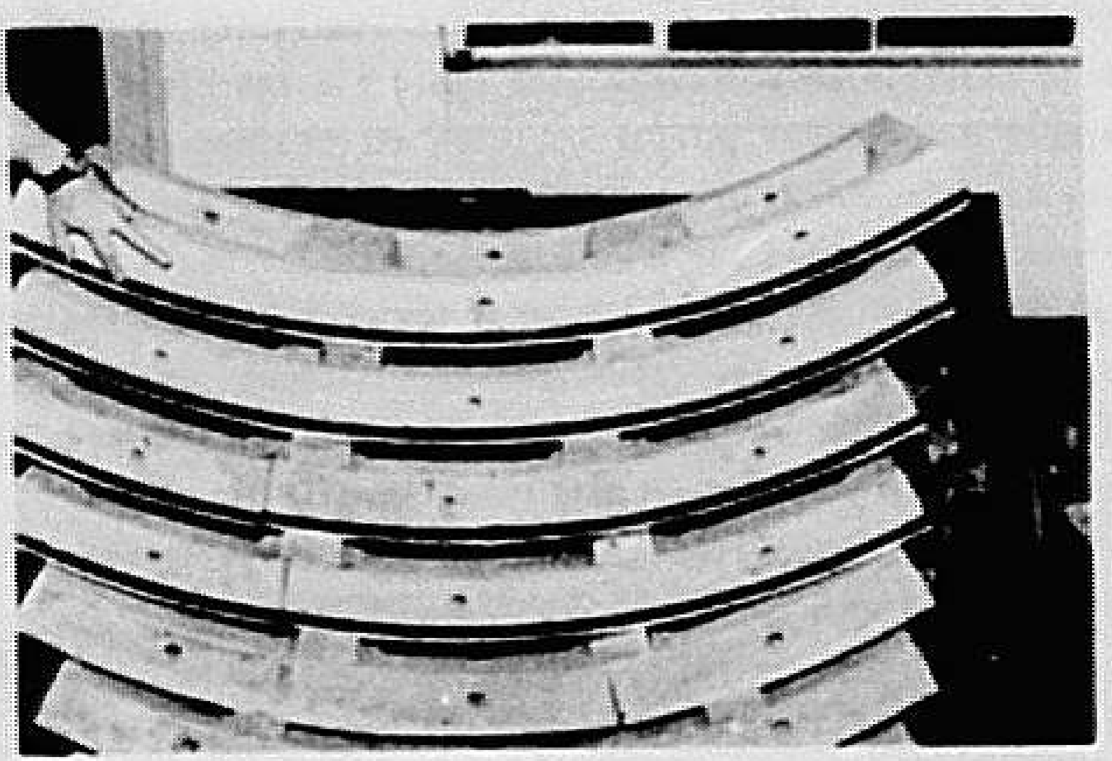


FIGURE 5-6. LOCAL COMPRESSION SEAL WITH CALKING GROOVE

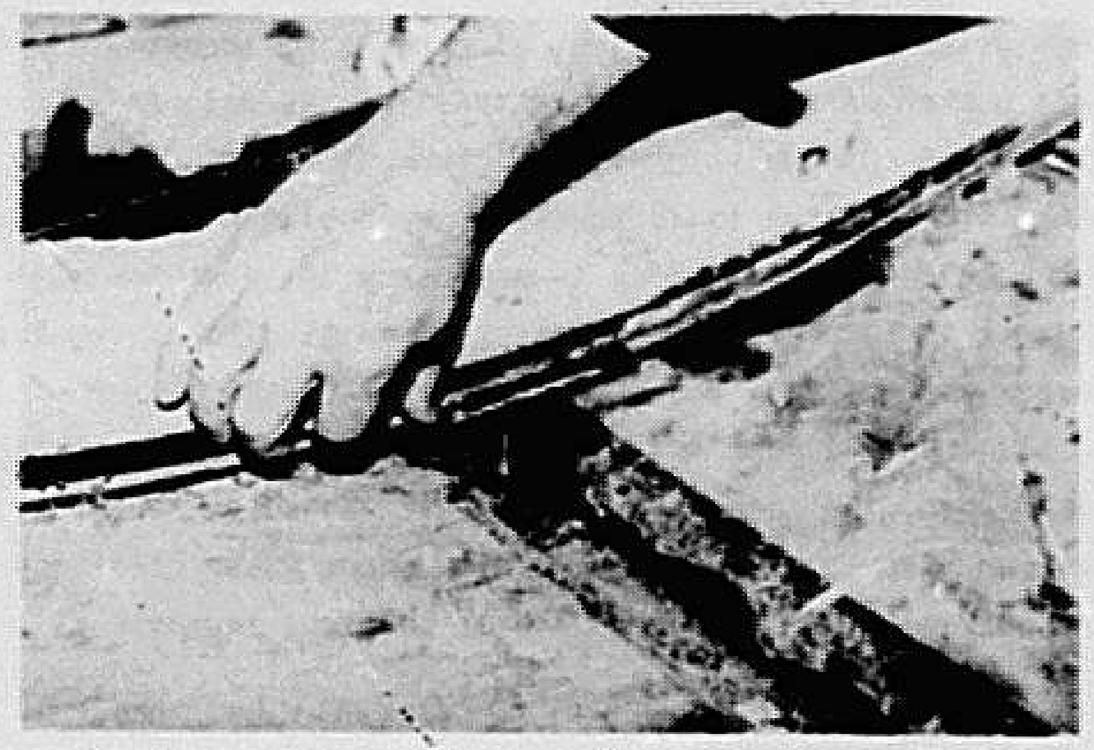


FIGURE 5-7. ROLL-OUT OF LOCAL COMPRESSION SEAL

not be under high compression. With rotation, however, edge damage similar to that experienced in the minitunnel would likely result unless the bulb was moved closer to the center and the width of the outside flange was increased (Section 5.2.1.). This would begin to introduce the installation difficulties experienced with c. and require a higher profile gasket.

The system could be modified, of course, to accept a limitless number of different gasket designs, as well as a variety of cushioning pads, to accommodate some degree of poor fit. None of this, however, would eliminate the need for a calking groove which is necessary at least for maintenance if not for initial watertightness. The system then loses it simplicity and becomes similar to the rather complicated and costly system used in the Baltimore Lexington Market Line Tunnel*. Such a belt-and-suspenders approach, however, has some merit, especially where water conditions are difficult and while the use of concrete segments is still new in this country.

5.1.2. Effect of Dirty Conditions on System Performance

An effort was made to simulate the wet, dirty conditions usually encountered in actual tunnel conditions. This was done with systems using compression seals and a fluid applied sealant in one system. Water and mud were applied when assembling a small scale hydrostatic test specimen (Figure 5-8) and the tunnel model (Figures 5-9 and 5-10). The liberal amounts of dirt and water applied did not interfere with any of the three systems tested in the model or with the small scale test.

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* Baltimore Region Rapid Transit System, Mass Transit Administration, Department of Transportation, Maryland.

FIGURE 5-8. MUD MIXTURE BEING APPLIED TO FACE OF RUBBER GASKET PRIOR TO BOLTING BLOCKS TOGETHER FOR HYDROSTATIC TESTING

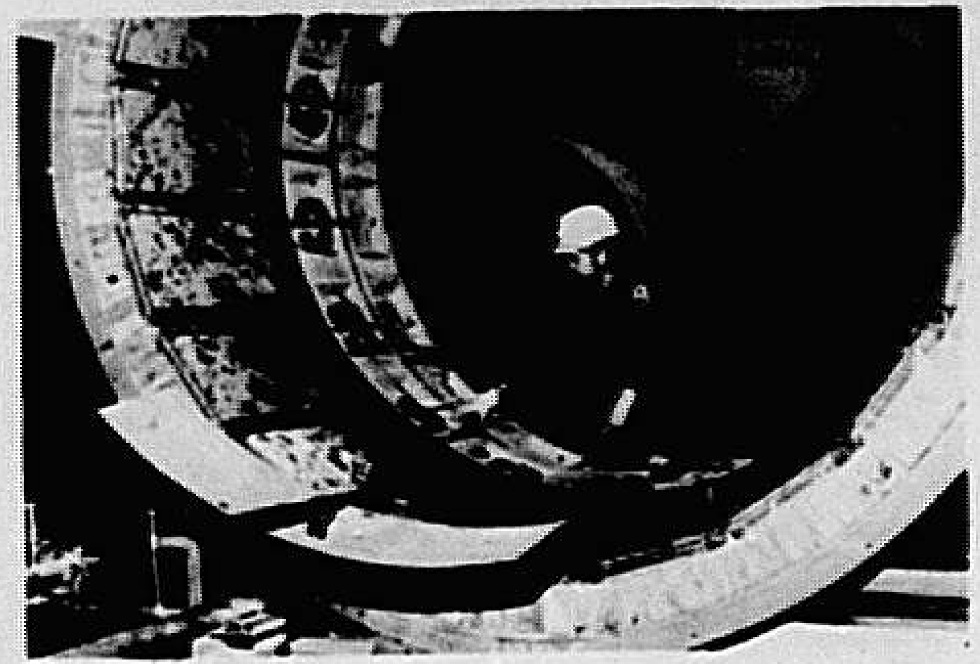


FIGURE 5-9. "DIRTY" JOINTS IN MODEL

FIGURE 5-10. SPRAYING WATER TO SIMULATE WET TUNNEL CONDITIONS

There is obviously some level of contamination that would be unacceptable. However, both laboratory and field experience indicate that initial waterproofing can be obtained under very dirty conditions if large particles are removed. Greatest durability for fluid-applied materials can be obtained by calking after the compression seal and grouting have established clean and dry conditions.

5.1.3. Compression Seal Considerations

In its simplest form, compression seal design is mainly a matter of deforming a rubber gasket shape to nearly fill, but not overfill, a cavity of a different shape. The force required to maintain the deformed shape opposes the force of the water to be retained. The resisting force obtained will initially be a function of the hardness of the rubber, the degree of difference between the cavity volume and the gasket volume, and the shape of the gasket and the cavity. Overfilling the cavity will generally result in unacceptably high tensile stresses in the concrete since the rubber system is designed to be deformed, not compressed.

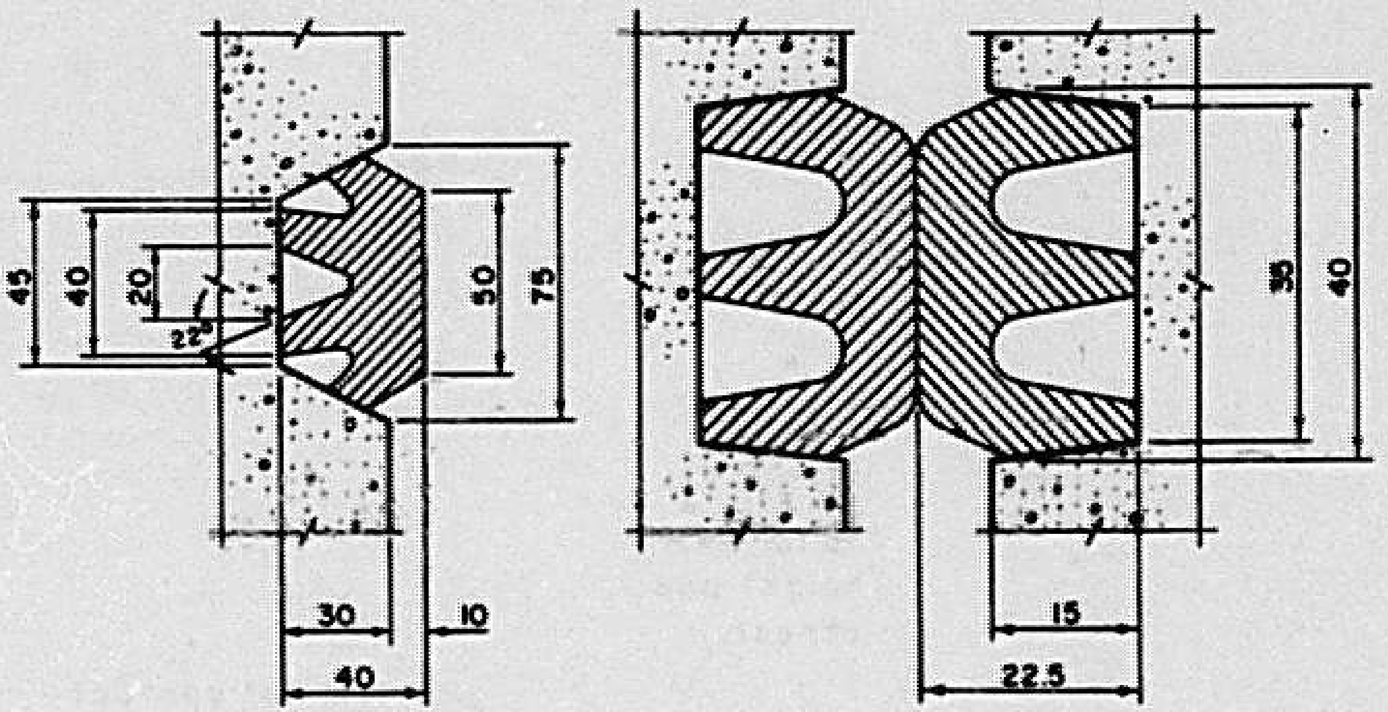
a. Selecting the compound. - No elastomer (rubber) is truly elastic. Consequently, the degree of compression force resistance achieved with time will be the original diminished by the compression set (stress relaxation) of the rubber. Compression set characteristics vary with each polymer type; that is, some polymers are naturally more resistant to set while it is difficult to compound for resistance with others.

A review of technical literature indicated that numerous studies have been conducted concerning these compression set characteristics [24, 25, 26, 27, and 28]. Many studies have dealt with environmental extremes of heat, cold, or corrosive moderate temperatures is fairly well established. Fortunately, the temperature and the environment to which tunnel gaskets will be exposed, being similar to that often encountered by concrete pipe, is relatively mild, and thus needs no special polymer requirement. Therefore, it would be appropriate to use gasket material conforming to the requirements of ASTM: C 361-78, Specifications for Reinforced Concrete Low-Head Pressure Pipe.

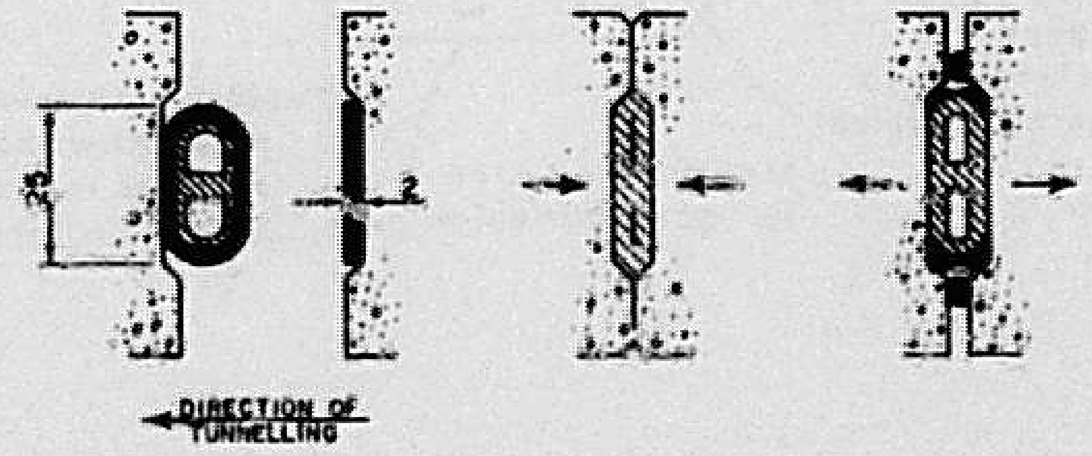
b. Gasket design. - The half-round gasket and V-shape groove used in the model were selected for maximum simplicity. Since the gasket worked well in the model, except for problems previously discussed, any change in width, height, or shape is only necessary to accommodate a poorer fit than obtained in this rather carefully constructed tunnel. Several different approaches to this situation have been recorded [29], some of which are shown in Figure 5-11.

The basic parameters influencing shape selection are illustrated in Figure 5-12.

Each of the above methods that departs from a solid rubber section relies on deformation of relatively thin rubber elements (cell walls). Taken to the extreme, this represents cellular or "sponge" rubber which does not perform as well in long-term compression set as the same rubber compound in solid form. This negative experience, together with lack of long-term service data for such designs under moderate water head, is the reason for recommending the additional use of a fluid-applied elastomeric sealant in a calking groove at the tunnel interior edge of the joint.



GERMANY **GREAT BRITAIN**



(a) Before installation (b) Compressed (c) Re-opened

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FIGURE 5-11. VARIOUS COMPRESSION SEAL DESIGNS AND THEIR COUNTRIES OF ORIGIN

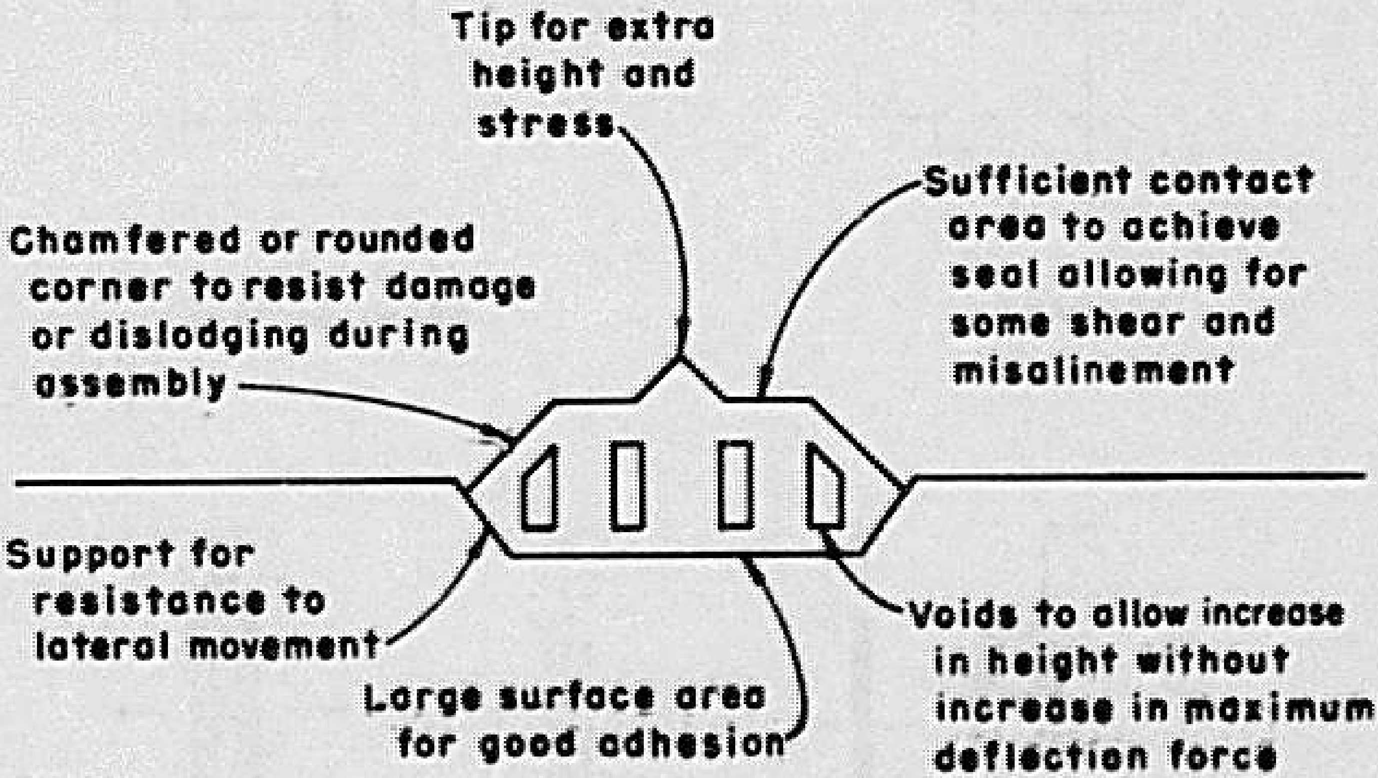


FIGURE 5-12. IMPORTANT PARAMETERS OF COMPRESSION GASKETS FOR CONCRETE TUNNEL SEGMENTS

5.2. Hydrostatic Pressure Resistance

Early in the program, hydrostatic tests were run with small, flat, three-piece bolted specimens as shown in Figure 5-8. A flanged tank containing water was clamped to the specimen and pressure applied with compressed air. A number of these tests were run on preformed sealant systems being considered for the tunnel model. This scheme was too cumbersome for extensive hydrostatic tests, so a system utilizing two concrete plates was devised. Sealant materials were tested by forming a ring (1-inch-wide, 1/4-inch-thick, 3-inch inside-diameter) between the two concrete plates (Figures 5-13 and 5-14). The distance between the plates was increased to simulate the effect of joint movement or articulation.

Results of hydrostatic tests are shown in Table 5-1. The results for 10 final candidates are graphically represented by the bottom chart in Figure 4-4. This figure illustrates generally good overall correlation between hydrostatic pressure resistance and tensile adhesion. However, it can be seen that much more rapid adhesion durability results can be obtained with this method than with the tensile-adhesion test.

This test is also more predictive if separate specimens are tested at different stress levels and different joint openings. In this study, the same specimens were used for different joint openings and pressures. For this, higher pressure was applied only at the end of a long period of moderate pressure. This, coupled with several defects in the test apparatus, limited the evaluation potential of the test to one of simple relative ranking of sealant performance.

Sealant nos. 7, 8, 9, 10, 13, and 15 could not be extended easily to provide a 10 percent opening, either because of unusual stiffness that overtaxed the extending mechanism or because of

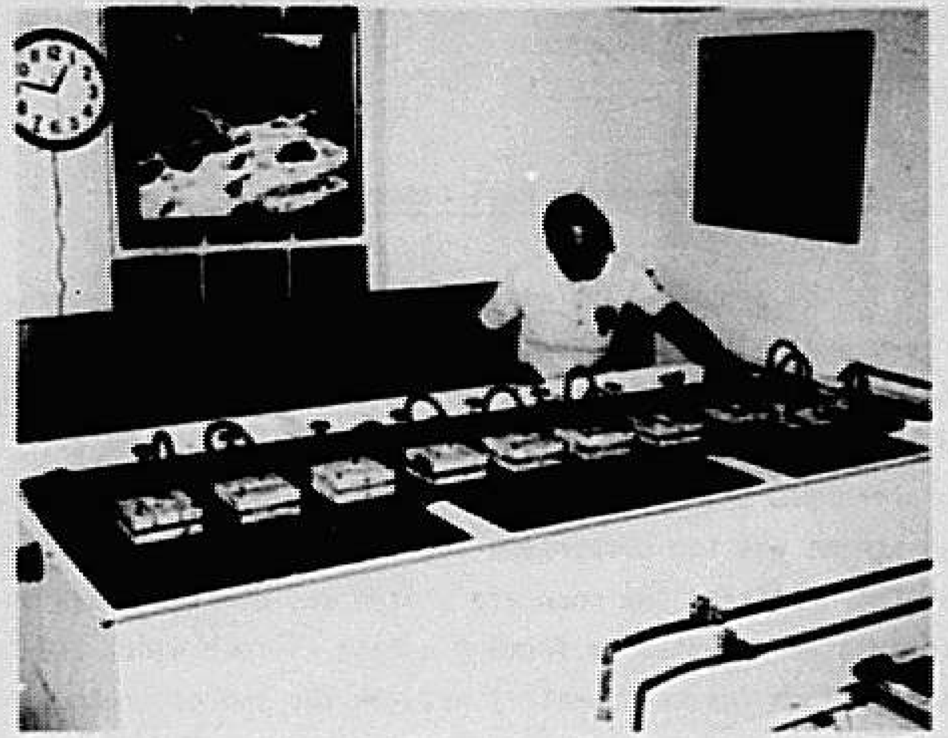


FIGURE 5-13. HYDROSTATIC TEST APPARATUS

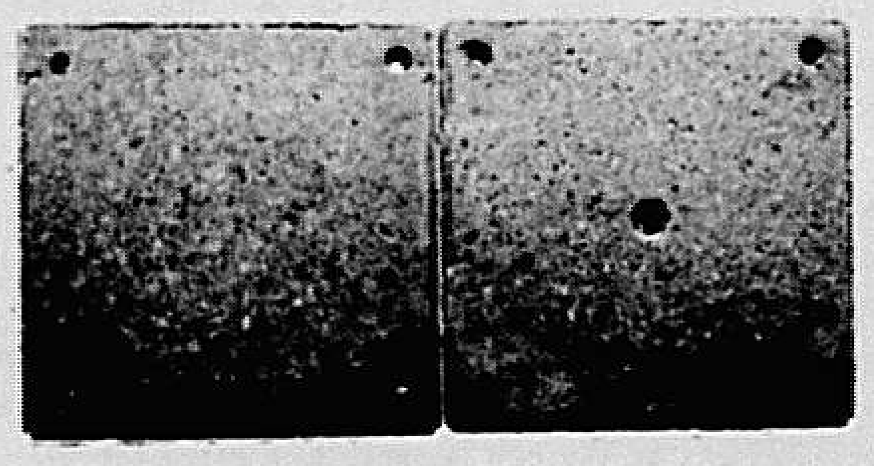


FIGURE 5-14. CONCRETE TEST PIECES USED TO FABRICATE SPECIMENS FOR THE HYDROSTATIC PRESSURE RESISTANCE TESTS (SURFACES ARE GROUND SMOOTH FOR OPTIMUM BONDING CONDITIONS AND TO ASSURE PARALLEL FACES)

TABLE 5-1. SEALANT HYDROSTATIC TESTS

Test No.	Sealant No.	Sealant type	Specimen No.	Orig. gap (inch)	Max joint opening (percent)	Test duration at 26-30 lb/in² (days)		Remarks
						Total	After max. gap	
1	1	2 parts urethane medium fast set fluid applied	1	0.25	30	500	336	No failure; completed additional 2 weeks at 52 lb/in²
2	1	2 parts urethane medium fast set fluid applied	2	0.25	85	170	5	Failure at sealant to sealant bond line Fabrication flaw reduced sealant width to 1/4 normal
3	1	2 parts urethane medium fast set fluid applied	3	0.25	30	500	336	Same as test 2 but held 52 lb/in² for 9 days at 50 percent maximum joint opening
4	2	2 parts polysulfide coal tar modified fluid applied	1	0.25	0	52		Failure at sealant to sealant bond line. Fabrication flaw (air pocket) reduced sealant width. Would have performed substantially better with proper application
5	2	2 parts polysulfide coal tar modified fluid applied	2	0.25	0	80	-	Same as test 4
6	2	2 parts polysulfide coal tar modified fluid applied	3	0.25	0	51	-	Same as test 4
7	3	2 parts urethane	1	0.25	20	289	7	Assembled after curing; used surface activator for improved adhesion; leaked in plane of small air bubbles near concrete surface; would have performed better with proper application
8	3	2 parts urethane	2	0.25	10	33	25	Same as test 7
9	3	2 parts urethane	3	0.25	5	278	150	Leaked after increasing gap 25 percent at end of 278 days; small leak developed to large leak in 6 days; otherwise same as test 7
	4	Not tested when nonsag grade failed in screening tests						

TABLE 5-1. SEALANT HYDROSTATIC TESTS (CONTINUED)

Test No.	Sealant No.	Sealant type	Specimen No.	Orig. gap (inch)	Max joint opening (percent)	Test duration at 26-30 lb/in^2 (days)		Remarks
						Total	After max. gap	
10	5	1 part silicone	1	0.25	5	37	33	70 percent area failure of bond to concrete
11	5	1 part silicone	2	0.25	5	71	0	60 percent area failure of bond to concrete
12	5	1 part silicone	3	0.25	0	67	-	50 percent area failure of bond to concrete
13	5	1 part silicone	4	0.25	0	0	-	Failure of bond to concrete
14	5	1 part silicone	5	0.25	5	15	0	Failure of bond to concrete
15	6	Polysulfide	1	0.20	0	1	-	20 percent area failure of bond to concrete
16	6	Polysulfide	2	0.20	0	2	-	Same as test 15
17	7	2 parts urethane	1	0.25	7	800	800	No failure; gap change was obtained by allowing water test pressure to separate the unrestrained plates; additional gap opening up to 30 percent was obtained after 800 hours by increasing pressure to 52 lb/in^2; no failure after 15 days
18	7	2 parts urethane	2	0.25	8	430	430	Leak at very small area of failure of bond to concrete; leakage occurred when gap opened to 30 percent at 26 lb/in^2 after 430 days at 8 percent gap increase
19	7	2 parts urethane	3	0.25	23	800	800	Leak similar to test No. 18; separation similar to test No. 17 except 40 percent opening at 52 lb/in^2 and failure in 5 days
20	8	1 part urethane	1	0.25	0	28	-	Failure of bond to concrete approximately 1/2 in wide

TABLE 5-1. SEALANT HYDROSTATIC TESTS (CONTINUED)

Test No.	Sealant No.	Sealant type	Specimen No.	Orig. gap (inch)	Max joint opening (percent)	Test duration at 26-30 lb/in^2 (days)		Remarks
						Total	After max. gap	
34	10	1 part urethane	3	0.25	<3	540	480	Same as test 30
35	11	2 parts urethane bitumen modified	1	0.25	10	61	57	20 percent area bond to concrete failure
36	11	2 parts urethane bitumen modified	2	0.20	37	172	see remarks	Cured before assembly; two halves of test specimen cured before test piece assembled; gap compressed 33 percent and held in dry condition for 7 days. Water pressure introduced for 4 days. At that time compressed gap opened 12 1/2 percent, opened to 25 percent at 60 days (seep), opened to 32 percent at 110 days (seep), opened to 37 percent at 172 days (leak). Leak at sealant to sealant interface.
37	12	2 parts urethane without surface activator	1	0.20	35	240	90	Sealant cured before joining halves of assembly; sealant compressed to achieve 2/3 initial gap to fuse cured sealant; after 14 days under water pressure, gap opened 10 percent; sealant to concrete bond failure
38	12	2 parts urethane with surface activator	2	0.20	400	2	<1	Fixture broke overnight allowing wide extension of gap; sealant to concrete bond failure
39	13	1 part urethane	1	0.25	0	<1	-	Assembled cured; leak between sealant and concrete at 5 lb/in^2
40	13	1 part urethane	2	0.25	8	42	7	Assembled cured; leak between sealant and concrete
41	13	1 part urethane	3	0.25	0	<1	-	Assembled cured; leak between sealant and concrete during initial pressurization at 10 lb/in^2

TABLE 5-1. SEALANT HYDROSTATIC TESTS (CONTINUED)

Test No.	Sealant No.	Sealant type	Specimen No.	Orig. gap (inch)	Max joint opening (percent)	Test duration at 26-30 lb/in^2 (days) Total	After max. gap	Remarks
42	13	1 part urethane	4	0.25	0	<1	-	Assembled uncured; pressurized after 24 hours cure; blow out after 2 minutes at 30 lb/in^2
43	13	1 part urethane	5	0.25	5	152	145	Assembled uncured; no failure
44	14	Urethane foam	1	0.25	0	1	-	Leak through foam
45	15	Precured urethane tape	1	0.25		37	-	Leak between tape and adhesive; stopped leak with 5 percent compression
46	15	Precured urethane tape	2	0.25	2	104	0	20 percent initial compression; leak between tape and adhesive when gap opened to - 15 percent original; minium gap extension before leak - 2 percent.
47	15	Precured urethane tape	3	0.25	1	240	0	Similar to test 47 except only 1 percent gap extension before leak
48	16	Impregnated wool felt adhesive tape 1/8-in thick. Specimen was 6-in. diameter with 3/8 in centerhole 2-ply	1	0.20	-	1/4	-	Established 10 lb/in^2; compressive load on tape and introduced water; leak at 15 lb/in^2 as hydrostatic pressure was being raised; maintained compressive load for 2 days without hydrostatic pressure; no leak at 26 lb/in^2 for 5 hr; felt to felt bond good; felt to concrete bond poor
49	16-8	Same as test 48 except 4-3/8 in square specimen formed from four tape strips 1 x 3-3/8 in. Corners sealed with sealant No. 8	2	0.20	-	5	-	10 lb/in^2 compressive load on tape (plus load to compensate for internal test assembly pressure); leakage caused by lateral displacement of 1-in-wide strip at center of strip length

TABLE 5-1. SEALANT HYDROSTATIC TESTS (CONTINUED)

Test No.	Sealant No.	Sealant type	Specimen No.	Orig. gap (inch)	Max joint opening (percent)	Test duration at 26-30 lb/in^2 (days)		Remarks
						Total	After max. gap	
50	16-8	Same as test 48	3	0.20	-	10	-	10 lb/in^2 compressive load maintained for 48 hrs without water; no leak in 10 days
51	16-8	Same as test 48 plus vegetable shortening as lube between felt layers	4	0.20	-	2	-	Leak caused by shortening dissolving felt saturant
52	16-8	Same as test 48 plus gasket lube (soap) between felt layers	5	0.20	-	28	-	No leak - most of soap squeezed out of joint - good adhesion of felt to felt. Fair adhesion of felt to concrete
53	16-8	Same as test 48 except 1/16 in felt	6	0.10	-	80	-	No leak
54	16-8	Same as test 48 but only one layer	7	0.10	-	2	-	No leak
54	17	Solid neoprene "D" shape compression seal with 1/16-in flange for full face protection (each face)	1	0.06	-	200		"D" shaped seal placed in "V" groove in segment element; three blocks fitted to form "T" shape intersection; sealed bell jar and ends of intersection with sealant No. 5
55	18	Rubberized asphalt mastic	1	0.25	-	1		Rope compressed to form 1-inch-wide seal; blow out at 10 lb/in^2
56	18	Rubberized asphalt mastic	2	0.25	-	<1		Same as test 55
57	18	Rubberized asphalt mastic	3	0.125	-	3		Same as test 55, but blow out at 20 lb/in^2
58	18	Rubberized asphalt mastic	4	0.125	-	3		Same as test 57
59	18	Rubberized asphalt mastic	5	0.25	-	5		Rope compressed to form 2-inch-wide seal; blow out at 5 lb/in^2

TABLE 5-1. SEALANT HYDROSTATIC TESTS (CONTINUED)

Test No.	Sealant No.	Sealant type	Specimen No.	Orig. gap (inch)	Max joint opening (percent)	Test duration at 26-30 lb/in^2 (days)		Remarks
						Total	After max. gap	
60	18	Rubberized asphalt mastic	6	0.25	-	2		Same as test 59
61	19	Rubberized asphalt Mastic (harder grade than sealant No. 18)	1	0.25	-	14	-	Maintained 10 lb/in^2 for 3 days; blow out at 20 lb/in^2 after additional 11 days
62	19	Rubberized asphalt Mastic (harder grade than sealant No. 18)	2	0.25	-	14	-	Same as test 61
63	20	Neoprene sponge rubber, 1/2 in thick		0.25	-	10	-	Compressed rubber until until leakage stopped at 26 lb/in^2 (approx. 50%); after disassembly found concrete wet on both sides of sponge rubber, but no water penetration of sponge over 1/8 in from cut edges

defective assemblies. Efforts were made to wedge the joint open with only limited success. Ultimately, the 10-percent opening was achieved by increasing the hydrostatic pressure to 52 lb/in^2.

Only hydrostatic tests were conducted on Sealant nos. 12 and 13; these sealants had marginal application characteristics and limited availability.

Material nos. 14 through 20 were included in the hydrostatic test even though they were not sealants. Sealant nos. 16 and 17 were to be used in the model and the others had possible usage with other materials or in special situations.

5.2.1. The Minitunnel Hydrostatic Test

To establish the effectiveness of the hydrostatic pressure resistance tests (6-inch-square flat plate hydrostatic tests) in predicting the performance of candidate sealant systems, this test setup was developed. In essence it is a one-eighth scale model of the actual tunnel incorporating in miniature all of the features of the actual tunnel; viz., multiple-segment rings in bolt-assembled construction, provision for widening and narrowing seams between segments, and a system for applying an external hydrostatic pressure. For this model, four seemed to be the ideal number of segments which would evaluate the effect of an articulated lining ring, being neither so few as to obfuscate the basic premise, nor so many as to make the size of individual components unduly small. Dimensional changes in transverse or ring joints, equal in effect and magnitude to those in the prototype, are developed through an external bolting arrangement. A scheme for causing dimensional changes in longitudinal joints was considered; however, it was decided that this could be more easily studied in the larger one-half scale model. External hydrostatic pressure is produced in a steel jacket which encloses the exterior surfaces of the model while providing access to interior surfaces. Three complete rings were decided on as the minimum number for a proper study of discrete barrels.

The minitunnel hydrostatic test apparatus is shown in Figures 5-15 and 5-16.

Only the half-round buna-N rubber gasket was evaluated in this test because of time limitations. Small leaks were found at low (2 lb/in^2) pressure, mainly at two intersections. These leaks were readily sealed using a chemically set gel-bentonite mixture (Section 5.3.3.) injected behind the liner. After these leaks were sealed, pressure was raised in increments to 26 lb/in^2; after 2 months, the test was discontinued since no leakage developed.

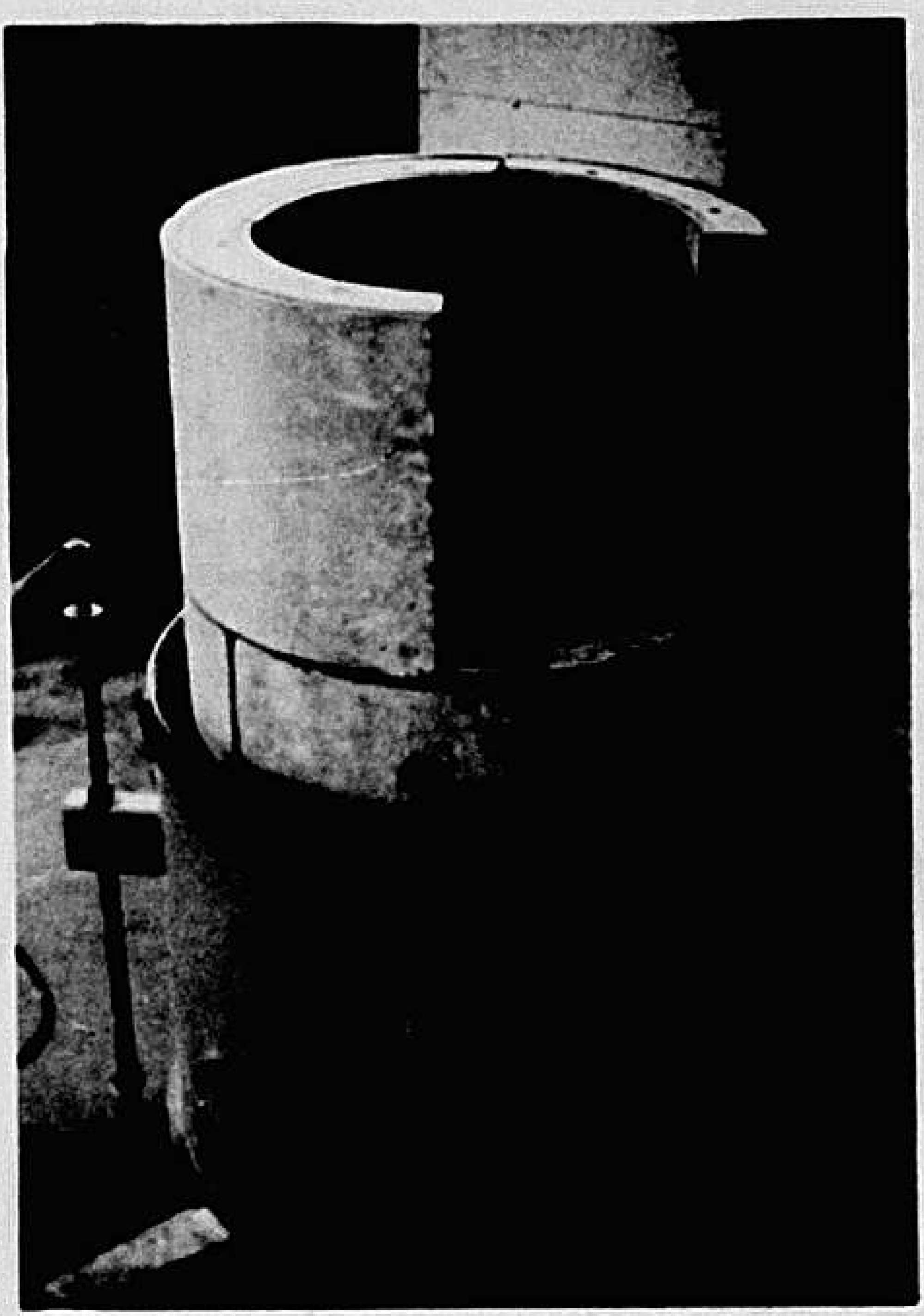


FIGURE 5-15. MINITUNNEL ASSEMBLED EXCEPT FOR LAST SEGMENT AND TOP HALF OF STEEL SHELL

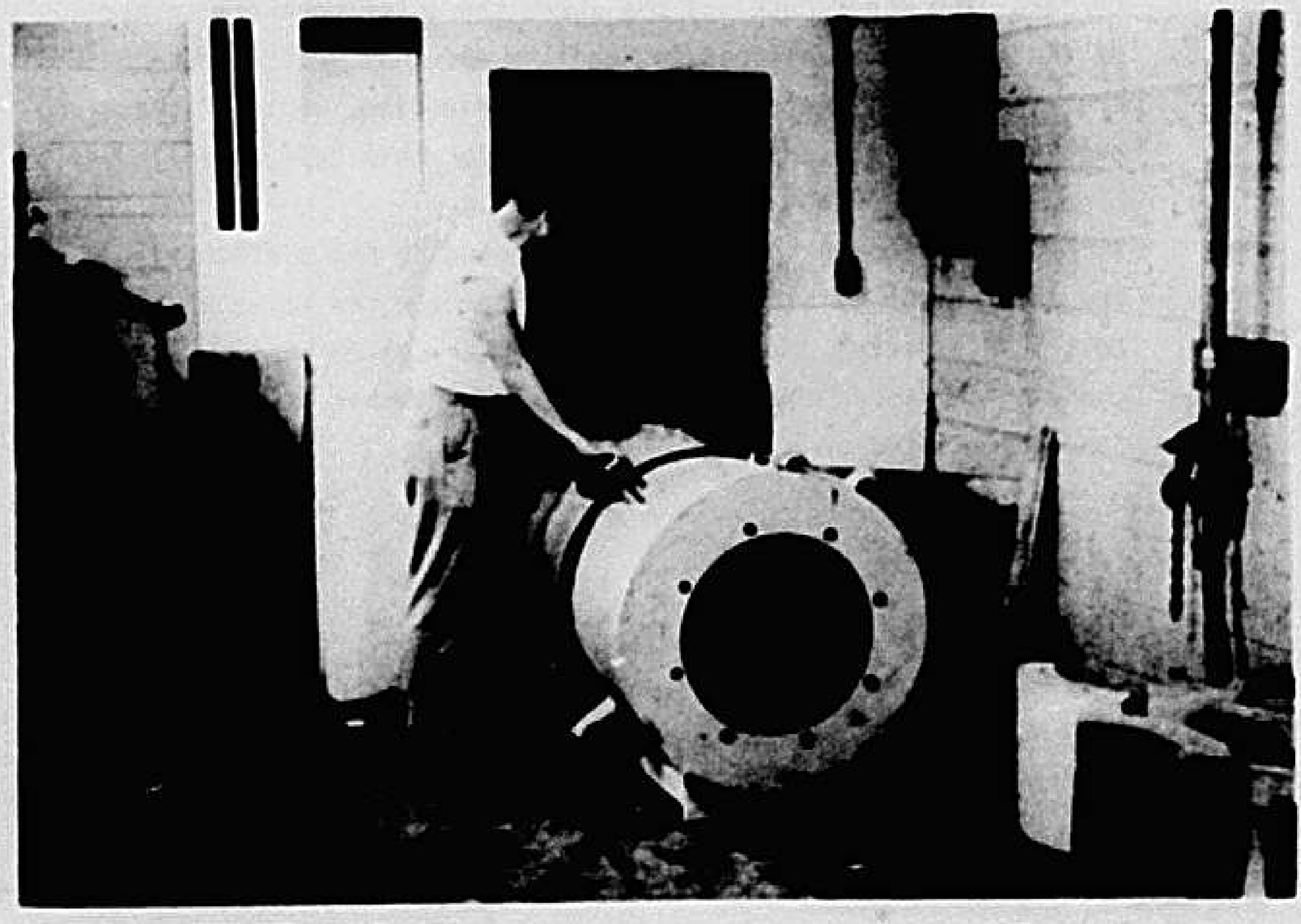


FIGURE 5-16. MINITUNNEL FULLY ASSEMBLED AND IN HORIZONTAL POSITION READY FOR TESTING

The two intersection leaks were not caused by normal failure of the gasket to fill the intersection. In one case, a segment form had warped and the segment, bulging at the center of a circumferential face, could not compress the gasket near the corner. The other case was one where the outer concrete corner of the segment was chipped in handling and thus left no concrete to support the gasket at the intersection. Both of these problems, however, are seen as typical for this type of seal.

Although only one gasket system was tested in the minitunnel the information gained was enough to indicate the value of the test. As expected, the assembly is rather convenient for changing test specimens once set up, and a number of systems can be evaluated over a relatively short time.

5.3. Sealant System Repairs

Four methods of repair were examined in this study. They are: (1) the calking groove, (2) polymer gel injection, (3) polymer gel-bentonite grout, and (4) polyurethane foam.

5.3.1. The Calking Groove

This is listed as a repair method because application of an elastomeric sealant at the surface is one of the simplest and surest ways of obtaining a seal where it has not been used. Where the seal has been used (Sealant nos. 1, 3, 7, 9, or 10) and failed, the failed material may be removed. After the problem has been analyzed, fresh material can be installed using either improved practice or material, depending on the problem. This method was to have been used to repair leaks in the tunnel model had the segments not failed before the seal.

5.3.2. Polymer Gel Injection

Dowell Polyacrylamide Gel Chemical Seal Ring was successfully injected into leaking hydrostatic test specimens and leaks at the bulkhead of the tunnel model, both while under 60 feet waterhead, using a 3-inch, 12-gage hypodermic needle and syringe. This gel cures and expands upon contact with water. Although it generally worked well in the tests, observations indicate that it requires good backup to avoid being gradually displaced. Its value, then, is mainly for temporary water shutoff to obtain a dry condition for sealant application or other repairs. Other similar commercial products are available.

5.3.3. Polymer Gel-Bentonite Grout

A polyacrylamide gel-bentonite grout (Dow Chemical Soil Sealant no. J-225) was used to seal the minitunnel. Leaks initially developed at two joint intersections and at several cracks in segments which inadvertently had been given no steel reinforcement. Leakage was quite bad at about 5 feet of waterhead and became a hard jet at 60-foot head. The grout completely sealed all leaks. The polymer-treated product was selected because it flows much better to fill all cavities than plain bentonite or portland cement grout; it has been more durable in sealing canals and reservoirs than plain bentonite; and unlike portland cement grout, it remains flexible and ready to seal any subsequent cracks [30].

5.3.4. Polyurethane Foam

This single-component polyurethane foam was packaged in a pressurized can for froth extrusion (similar to shaving cream). Unfortunately, even in dry trials, the product proved difficult to handle. Its consistency was somewhat rubbery, it had a rather greasy outer surface before cure so that it would not stay in place easily, and it was very slow in final expansion and cure. Undoubtedly, a suitable product can be made for rapid filling of voids. It would facilitate repair and in some cases could provide a permanent water plug; however, in these tests, it was not successful.

5.4. Corrosion Considerations

Metallic components with potential corrosion problems in tunnels constructed of precast concrete segments are the embedded steel reinforcement and the fasteners and appurtenant metalwork used to connect adjacent segments.

The usual grout fitting is a 2-inch-inside-diameter pipe coupling with standard interior pipe threads, centrally located, and penetrating the segment. It is used as a pickup point for handling and installing the segment and, after placement, for introducing cement grout behind the lining. Before placing the tunnel in service, these fittings are closed, often with a specially shaped concrete plug bonded in place with an epoxy adhesive. These fittings are not considered to be a significant corrosion problem, although some loss of threads may occur during segment storage prior to installation. To minimize this potential, a suitable rust-preventive compound should be applied to the thread surfaces.

Portland cement concrete embedment of steel derives its corrosion-inhibiting quality from formation of an insoluble, passivating oxide film on the steel surface due to the highly alkaline environment. In addition, when voltage is imposed on concrete-embedded steel, the passive film generates a countervoltage such that, within limits, no current will flow. The passivity and resistance to current flow developed by properly designed, dense, high-quality portland cement concrete are sufficient to overcome potential differences in virtually all naturally occurring buried and atmospheric conditions to which tunnel lining normally would be exposed. Environments high in concentration of the chloride ion and/or stray currents are the major exceptions. Therefore, the corrosion potential of the steel reinforcement is considered to be very low, particularly if minimum cover is maintained at 2 inches and exposure is not made in environments detrimental to the concrete itself. Therefore, emphasis was placed on the corrosion potential of fasteners and appurtenant metalwork in this investigation.

Appurtenant metalwork to fasteners would include the sleeves for forming the hole for the bolts and perhaps washers. Once the hole is formed by casting the concrete, the sleeve will have fulfilled its function and would then be expendable.

Fasteners, like any other form of metal, potentially will react with moisture and oxygen and corrode. The water or moisture, which is a necessary ingredient for corrosion, may occur in vehicular tunnels in the form of fog, dew, condensation, atmospheric humidity, etc. The rate of corrosion can be further accelerated by pollutants, such as vehicle exhaust gases, industrial contaminants, and airborne salts.

Because of this potential for corrosion, even in vehicular tunnels, a test of common threaded fasteners was made to determine their relative corrosion resistances in two laboratory exposures. The two exposures were salt fog in accordance with Federal Test Method Standard No. 141a, Method 6061, and 100 percent RH (relative humidity), 73.4 °F (fog). These exposures were selected because the fog environment simulates maximum atmospheric moisture content; the salt fog superimposes upon the moisture one of the more effective corrosion accelerators, the chloride ion. The salt fog is perhaps more severe than conditions anticipated in a vehicular tunnel; nevertheless, it serves the purpose of accelerating deterioration such that relative performance of various coatings and materials can be determined in relatively short periods. Maximum exposure period in this test was 17 weeks.

Common 1/2-inch-diameter bolts with and without coatings were exposed. The exposed materials and/or materials and coating combinations were:

a. Mild steel, ASTM: A 307 Grade A

b. Mild steel with 2-mil-thick hot dip galvanized coating, in accordance with ASTM: A 153

c. Mild steel with 1-mil-thick electrodeposited zinc coating, in accordance with ASTM: A 164

d. Mild steel with 1/2-mil electrodeposited cadmium coating, in accordance with ASTM: A 165

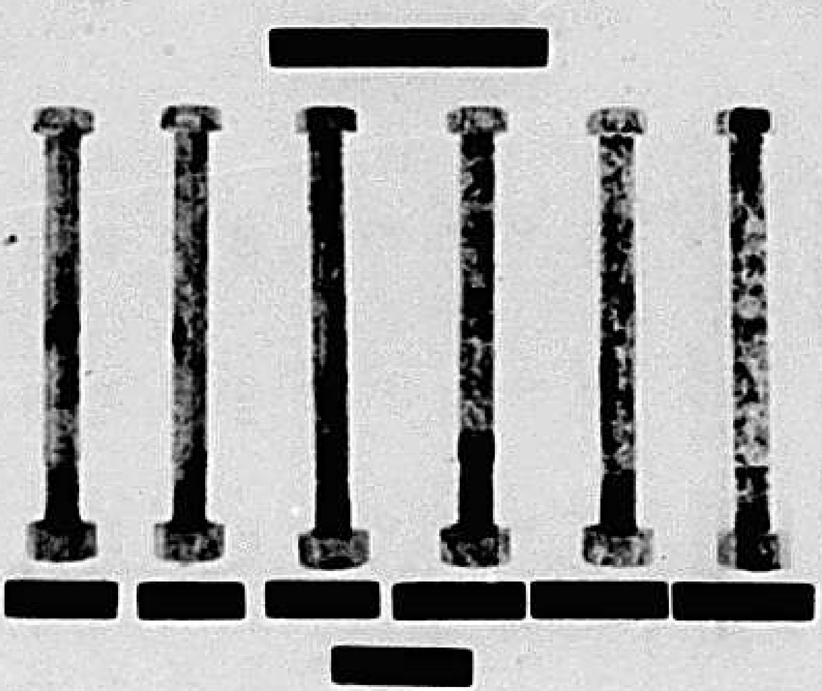
e. Stainless steel, Alloy 304, in accordance with ASTM: F 593.

Replicate specimens were exposed such that samples could be removed and evaluated after 1, 3, and 7 days, and 3-, 7-, and 17-week exposure periods. Table 5-2 and Figures 5-17 through 5-25 show the results of these tests.

As can be seen, and as was expected, the stainless steel (type 304) bolts were unaffected throughout the exposure period in both exposures. Of the coated, mild steel bolts, the hot dip galvanized bolts suffered the least attack after the 17-week exposure

TABLE 5-2. TEST RESULTS, CORROSION OF FASTENERS

Exposure	Bolt material	Bolt coating	Performance (% of steel surface corroded) after exposure period					
			1-day	3-day	7-day	3-week	7-week	17-week
100% R.H., 73 °F	Mild steel	--	10	20	30	50	75	100
	Mild steel	Hot dip zinc	0	0	0	0	0	0
	Mild steel	Zinc plate	0	0	0	1	5	5
	Mild steel	Cadmium plate	0	0	0	0	0	5
	Stainless steel	--	0	0	0	0	0	0
Salt fog	Mild steel	--	75	90	100	100	100	100
	Mild steel	Hot dip zinc	5	10	10	10	25	75
	Mild steel	Zinc plate	5	20	30	50	75	90
	Mild steel	Cadmium plate	1	5	10	25	90	100
	Stainless steel	--	0	0	0	0	0	0

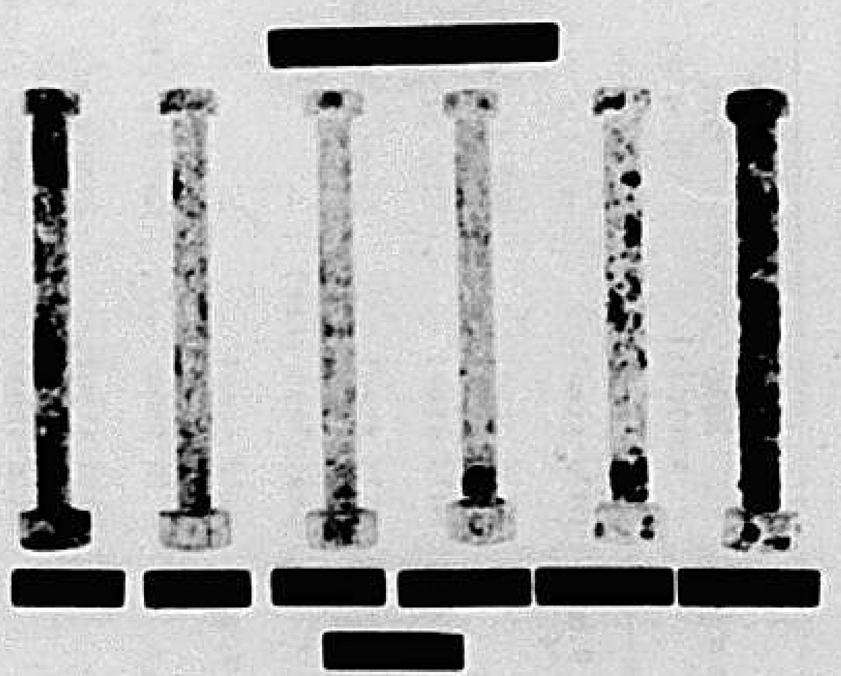


[redacted]

[redacted] [redacted] [redacted] [redacted] [redacted] [redacted]

[redacted]

FIGURE 5-17. GALVANIZED STEEL BOLTS AFTER FOG EXPOSURE



[redacted]

[redacted] [redacted] [redacted] [redacted] [redacted] [redacted]

[redacted]

FIGURE 5-18. GALVANIZED STEEL BOLTS AFTER SALT SPRAY FOG EXPOSURE

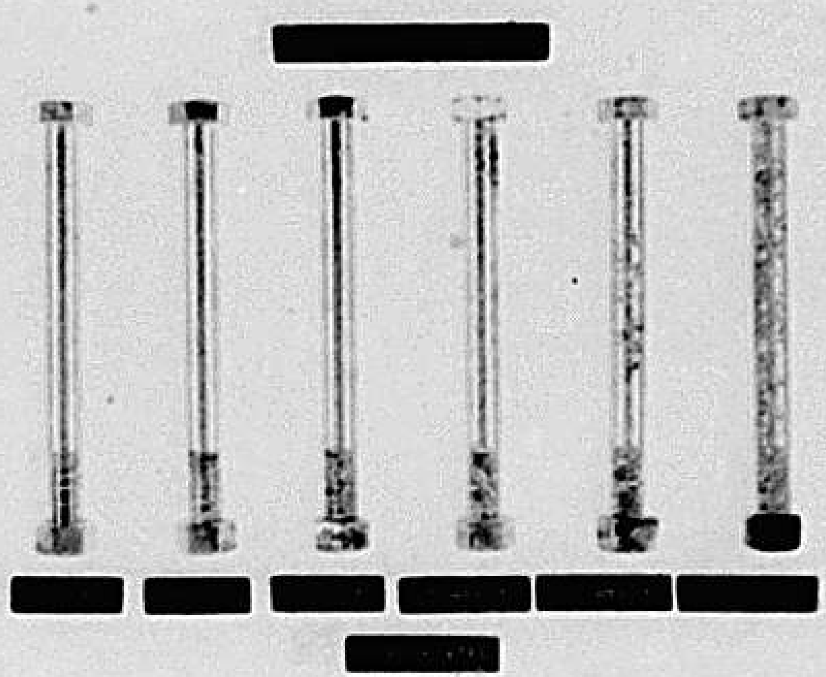


FIGURE 5-19. ZINC-PLATED BOLTS AFTER FOG EXPOSURE

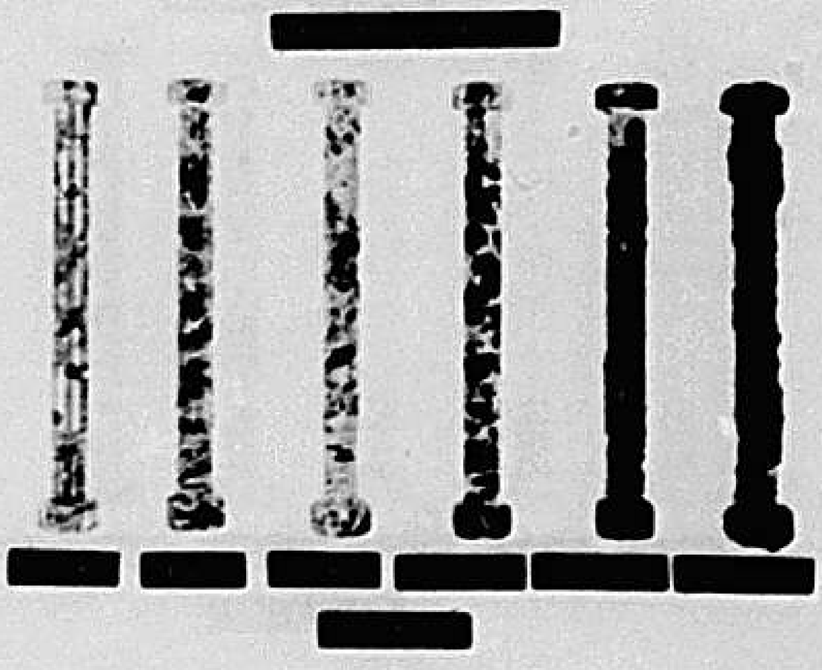


FIGURE 5-20. ZINC-PLATED BOLTS AFTER SALT SPRAY FOG EXPOSURE

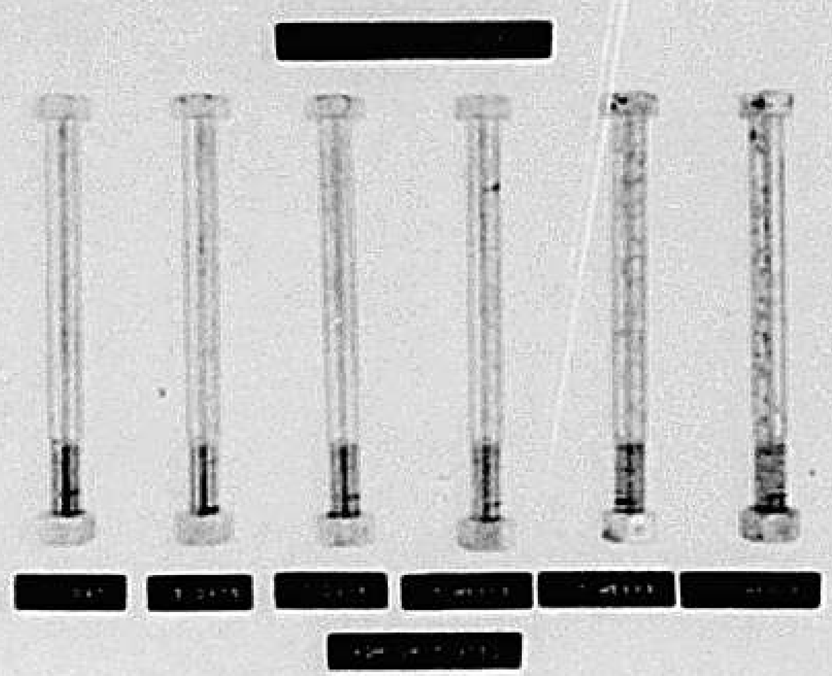


FIGURE 5-21. CADMIUM-PLATED BOLTS AFTER FOG EXPOSURE

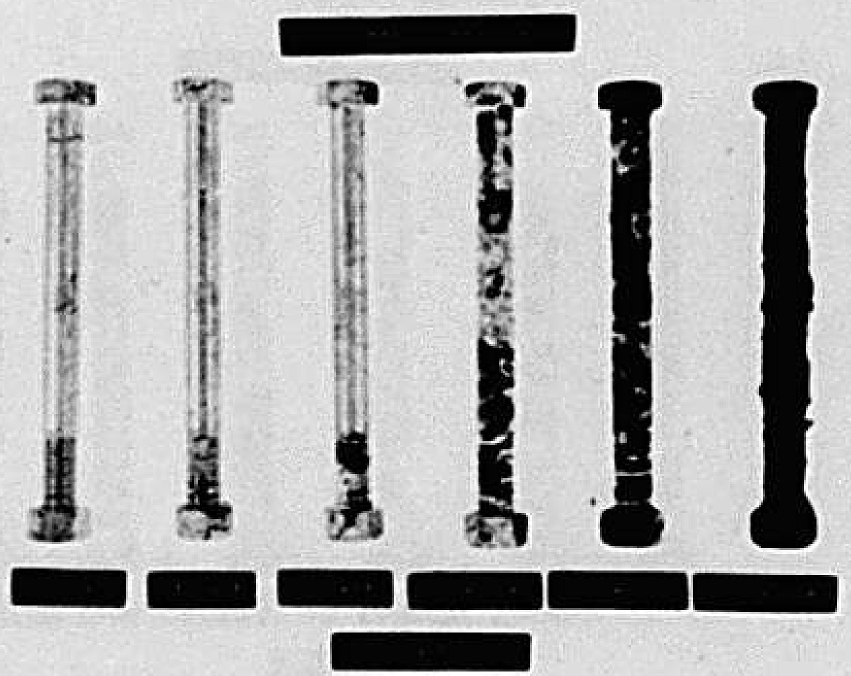


FIGURE 5-22. CADMIUM-PLATED BOLTS AFTER SALT SPRAY FOG EXPOSURE

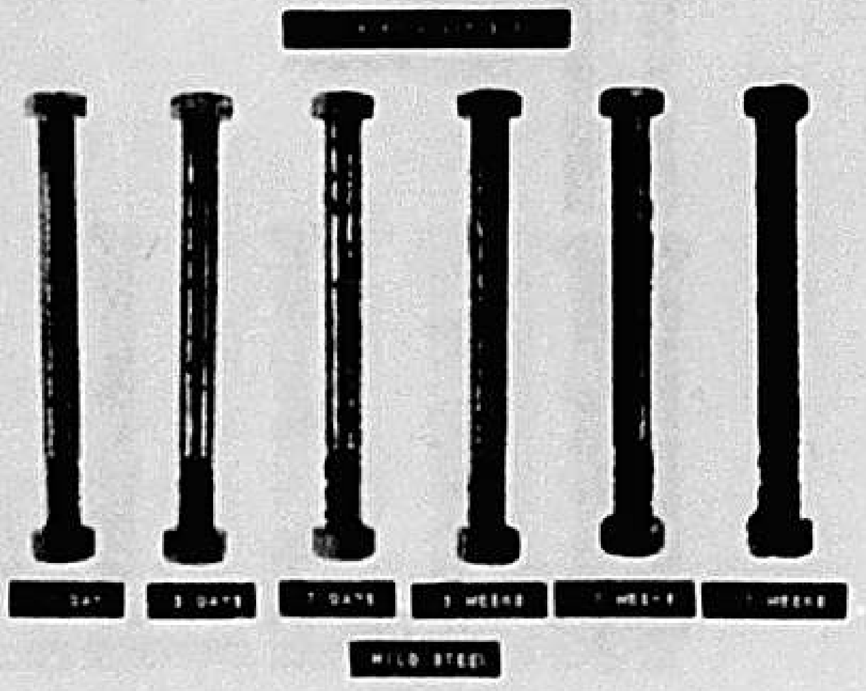


FIGURE 5-23. MILD STEEL BOLTS AFTER FOG EXPOSURE

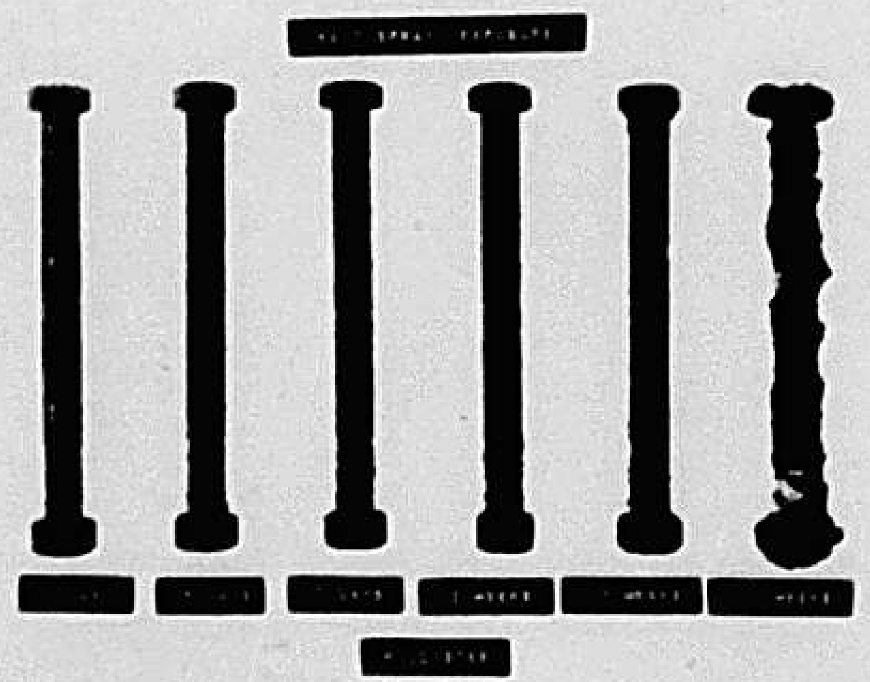


FIGURE 5-24. MILD STEEL BOLTS AFTER SALT SPRAY FOG EXPOSURE

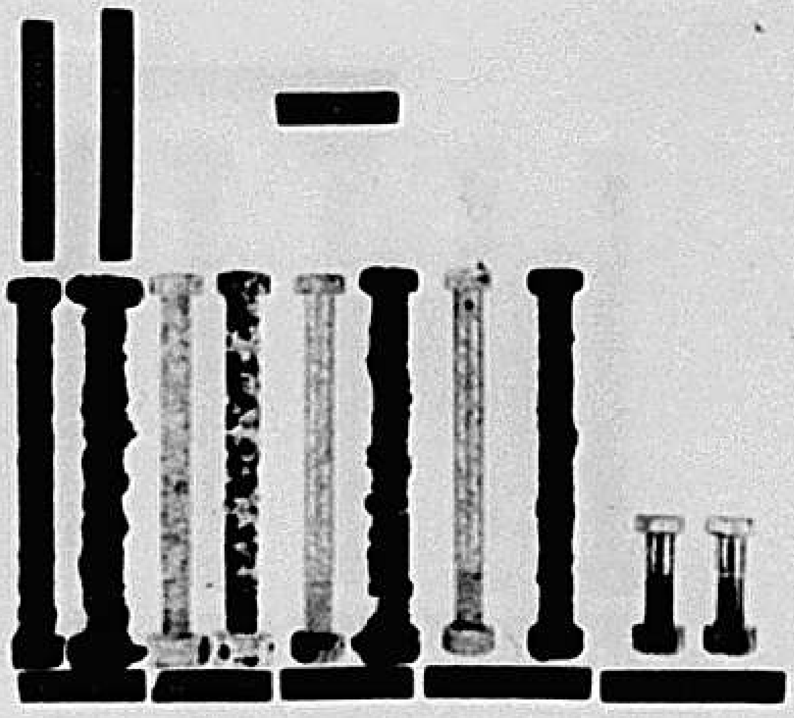


FIGURE 5-25. MILD STEEL, GALVANIZED, ZINC-PLATED, CADMIUM-PLATED, STAINLESS STEEL BOLTS AFTER 17 WEEKS' EXPOSURE

period in both environments and no corrosion of the steel coated with the hot dip zinc coating was experienced when exposed to 100 percent relative humidity, 73.4 °F environment.

Therefore, the hot dip zinc galvanized bolts would probably be adequate for joining segments for vehicular tunnels where corrosion-accelerating contaminants are not anticipated. In severe exposures such as in industrial areas or near coastal areas where airborne chlorides are likely, the use of stainless steel fasteners is indicated.

5.5 Fire Tests

Tests in accordance with ASTM: E 84, "Standard Test Method for Surface Burning Characteristics of Building Materials," were conducted at the Johns-Manville Research and Development Center, Denver, Colorado. Specimens used in the tests were fabricated to fit the J-M tunnel (Figures 5-26 and 5-27). Tests were conducted in accordance with ASTM E-84, except for specimen configuration; specimens were thicker (4 inches total thickness) than the test tunnel will accommodate and, therefore, extended 2 inches into the tunnel from the top. This had two effects. The cross-sectional area of the tunnel was decreased and the airflow pattern was changed. The airflow was probably more turbulent as a result of the irregular surface of the specimen.

FIGURE 5-26. VIEW OF ASTM E-84 FIRE TEST TUNNEL

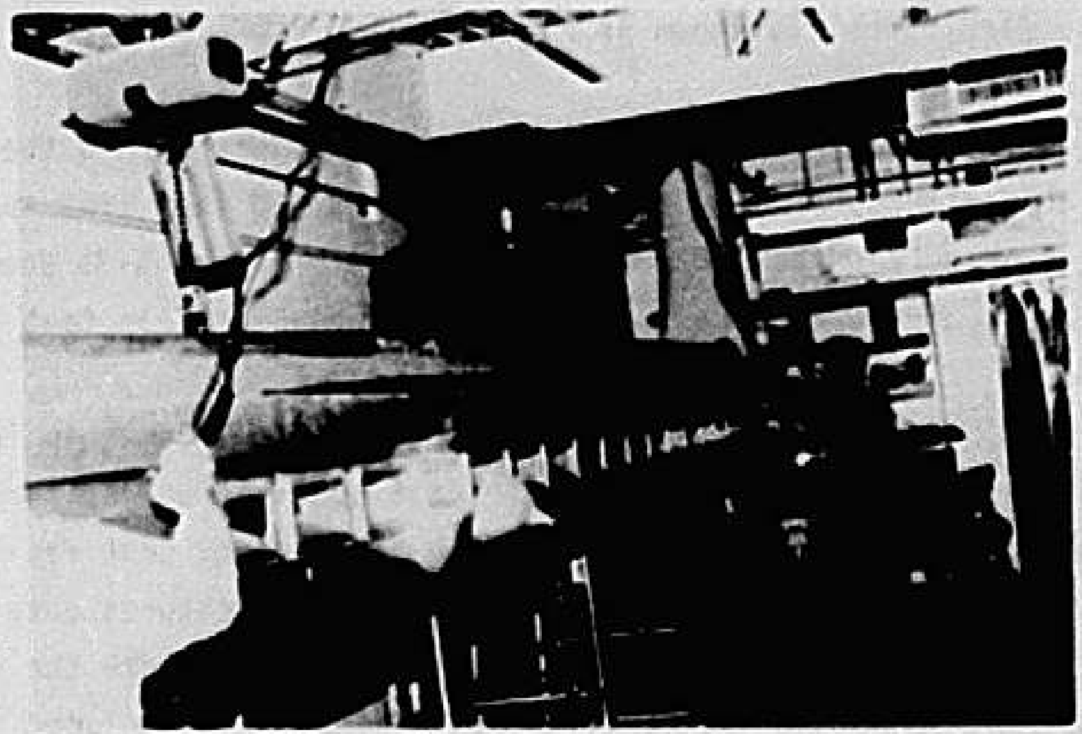


FIGURE 5-27. INSTALLATION OF VAPOR-TIGHT LID ON FIRE TEST TUNNEL

Test specimens were 21 inches wide by 21 feet long, comprised of 28 individually cast concrete blocks 10-1/4 inches wide by 18 inches long (Figure 5-28). In the first test, neoprene gaskets were bonded to opposing faces of the individual blocks (Figure 5-29). For the second test, calking grooves were cast in the lower surface and longitudinal grooves were calked with Sikaflex 1A 10 days before testing. Figure 5-30 shows longitudinal bolting of one pair to form the test specimen. A complete test specimen installed in the fire tunnel is shown in Figure 5-31.

Concrete temperatures were recorded at five points during the fire test at distances of 0.5, 2.0, 3.5, 5.0, and 7.0 feet from the flame source (Figures 5-32, 5-33, and 5-34). Figure 5-35 shows the effect of the fire test on calking material used in test 2.

Figure 5-36 is a graph of the time-temperature relationship found at various locations in the concrete test specimen during fire testing conducted in the Johns-Manville fire tunnel test facility. The graph also shows representative exhaust temperatures obtained from testing red oak and asbestos cement board which are the high and low standard materials for the test. These are included for comparison purposes. It can be seen from the graph that the large mass and good heat sink properties of the concrete and the lack of fuel contribution, especially in test 1, have reduced the exhaust temperature well below even the noncombustible asbestos cement board. Most actual tunnel conditions would provide an even better heat sink, thus making it even more difficult for fire to spread by tending to hold materials below their combustion temperature. This, of course, does not mean that selection of materials for use in a tunnel should be done without regard to burning characteristics. It simply indicates that properly selected material will be used in an environment that will tend to reinforce whatever resistance to burning the selected materials have.

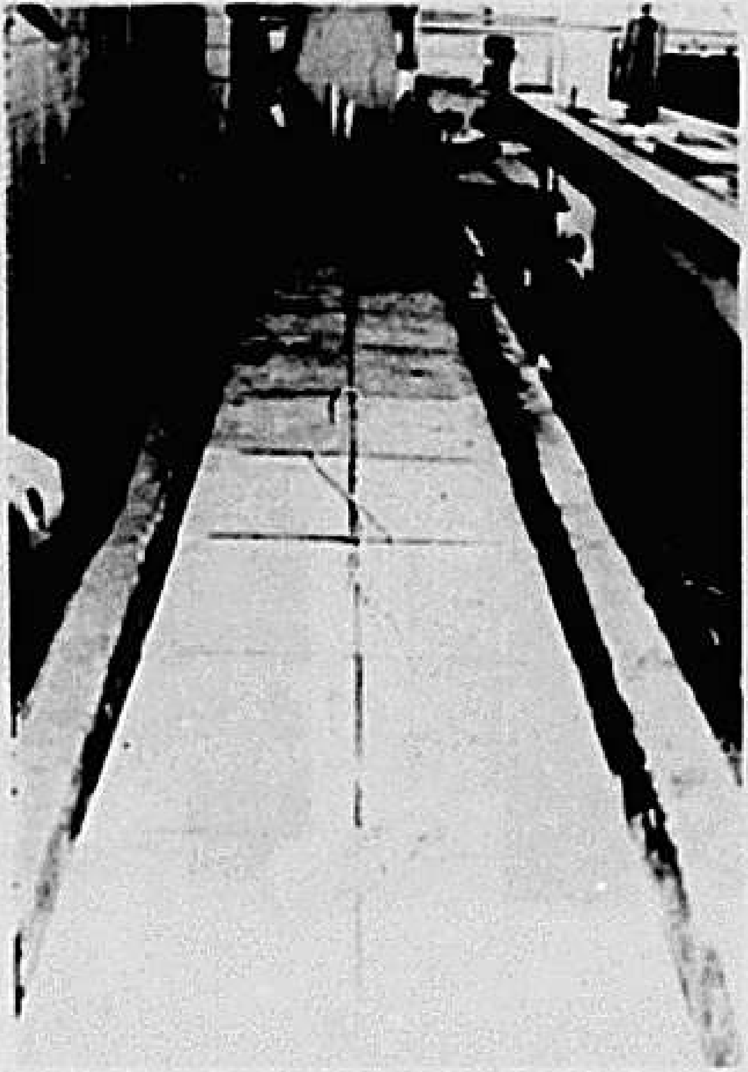


FIGURE 5-28. TEST SPECIMENS IN PLACE IN FIRE TEST TUNNEL

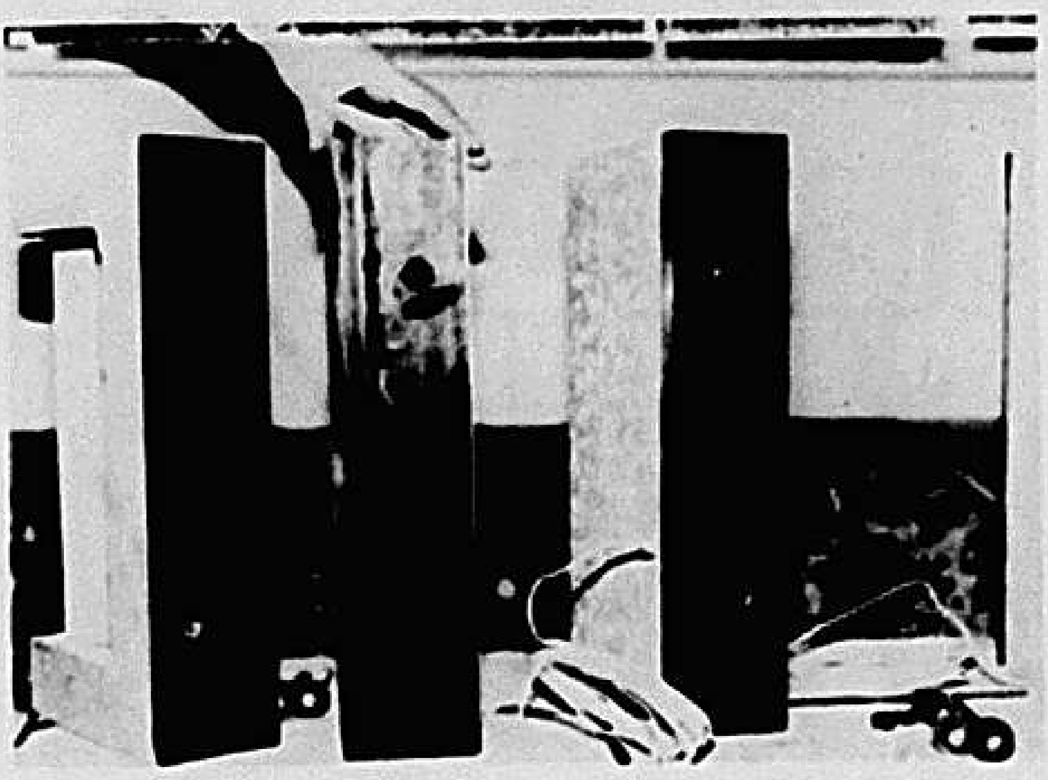


FIGURE 5-29. NEOPRENE GASKET IN POSITION ON FIRE TEST SPECIMEN

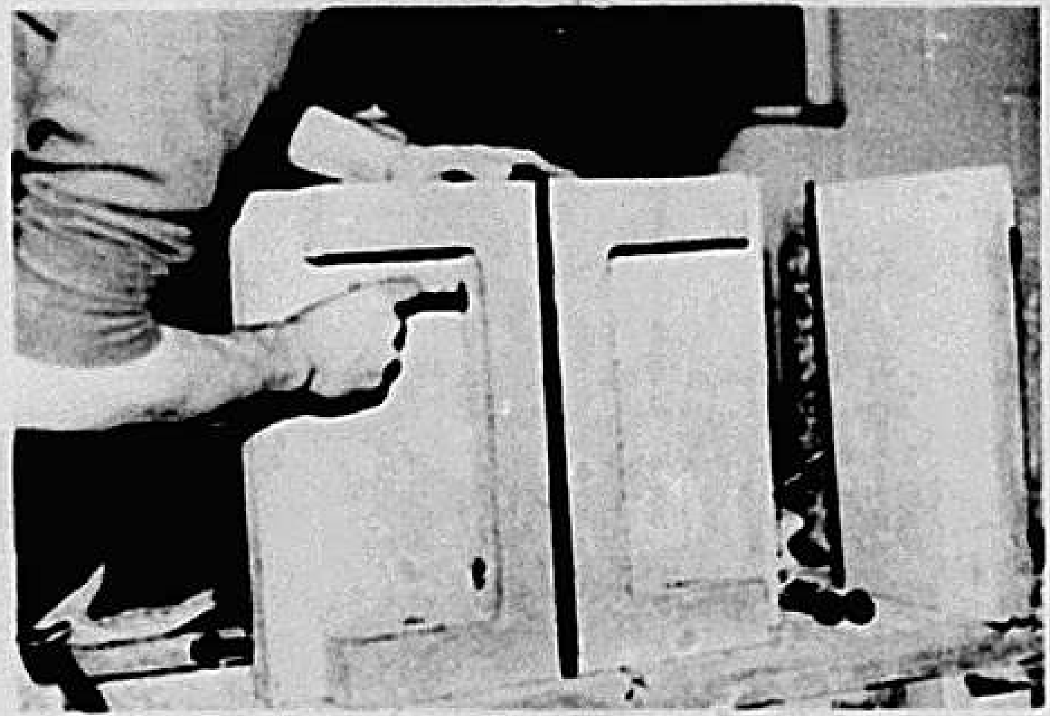


FIGURE 5-30. BOLTING THE TEST SPECIMENS TOGETHER TO FORM A LONGITUDINAL JOINT

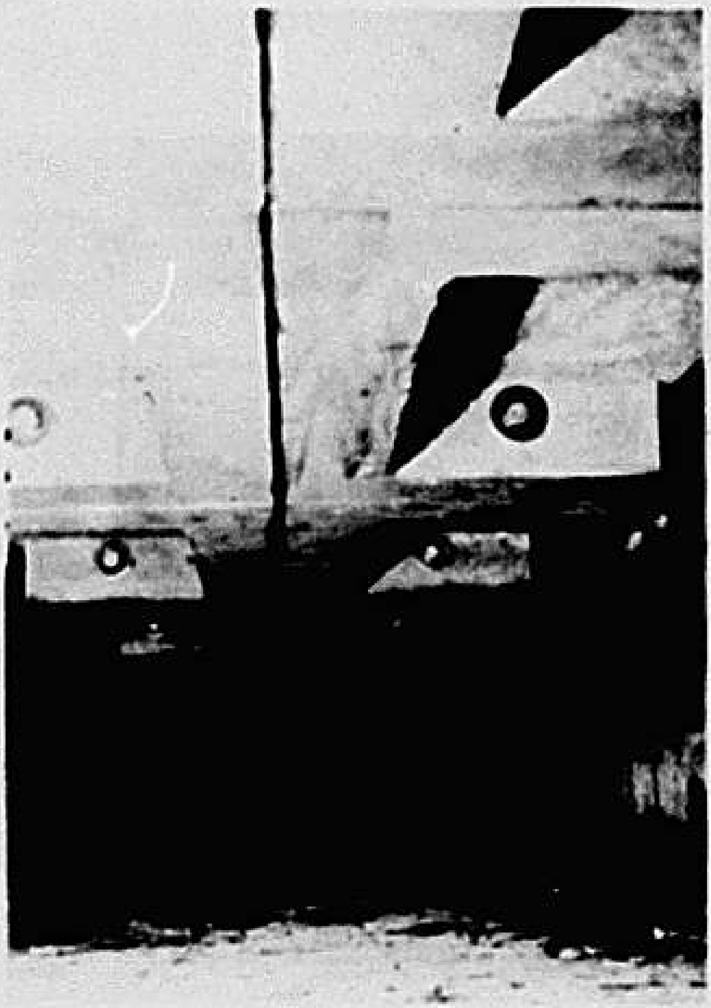


FIGURE 5-31. VIEW OF TEST SPECIMENS INSIDE THE FIRE CHAMBER BEFORE TEST

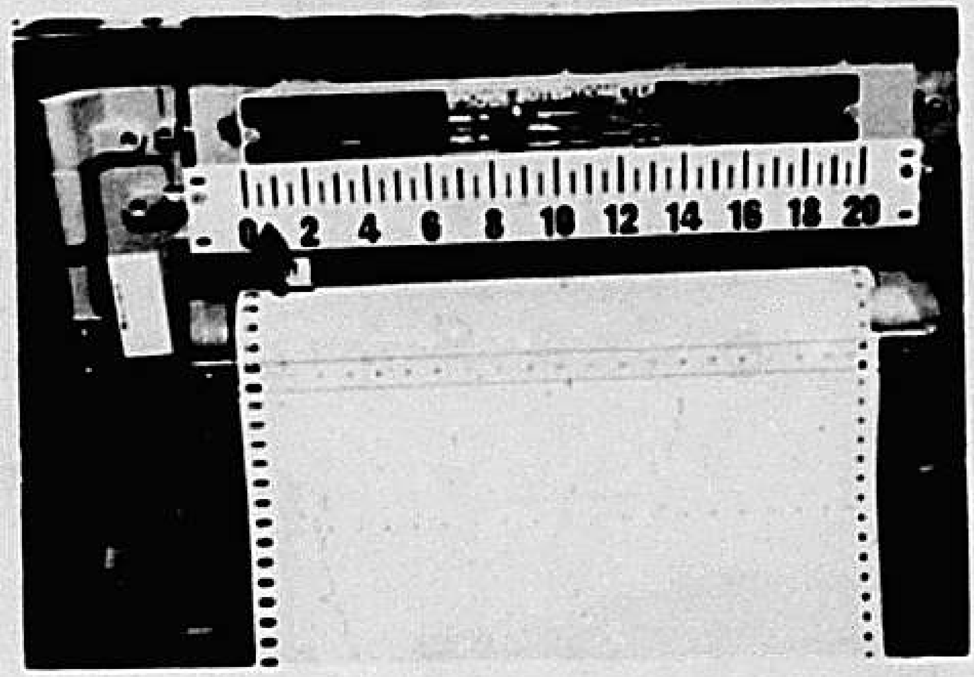


FIGURE 5-32. TEMPERATURES AT FIVE POINTS RECORDED ON A STRIP CHART

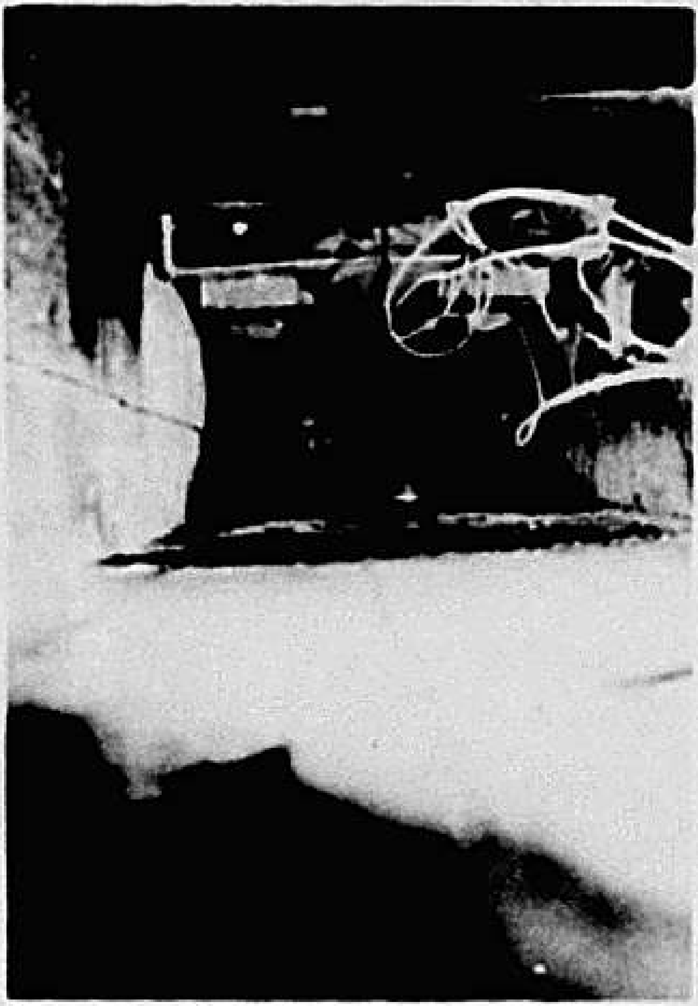


FIGURE 5-33. INTERIOR CHAMBER SHOWING GAS NOZZLES

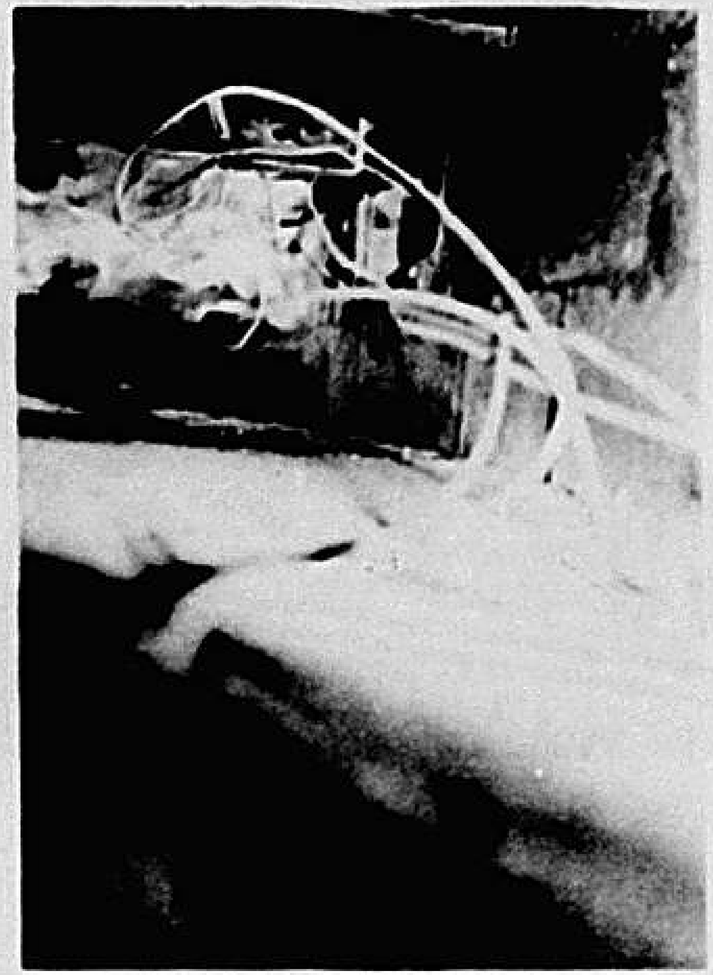


FIGURE 5-34. VIEW OF INTERIOR DURING TEST

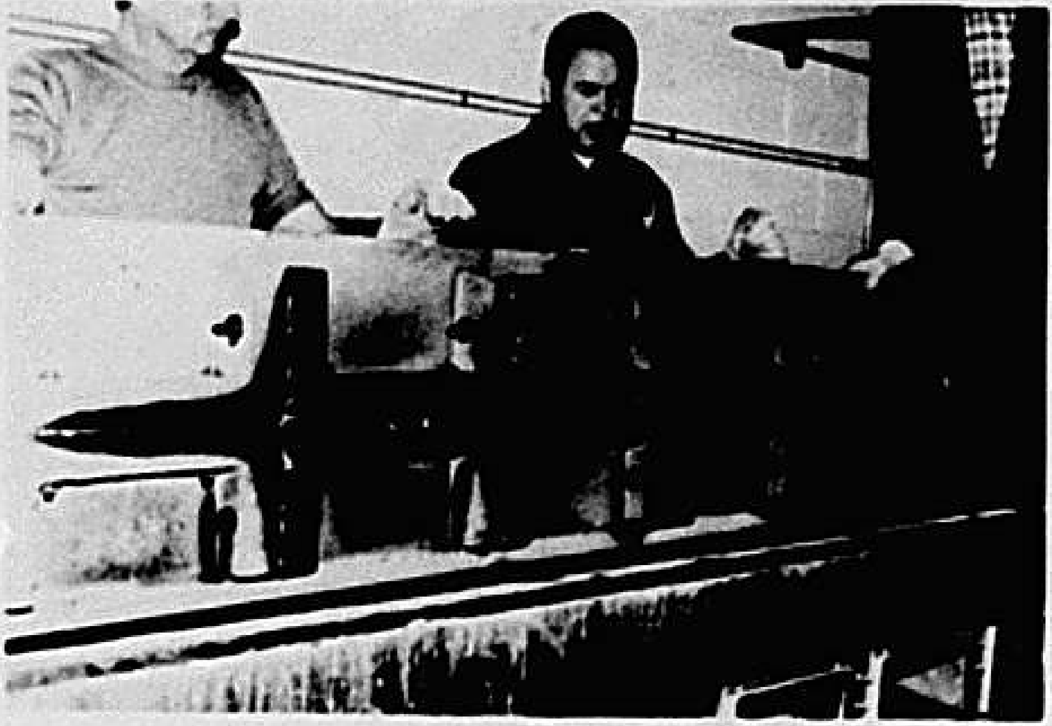


FIGURE 5-35. VIEW OF EFFECT OF FIRE ON CALKED SEGMENTS

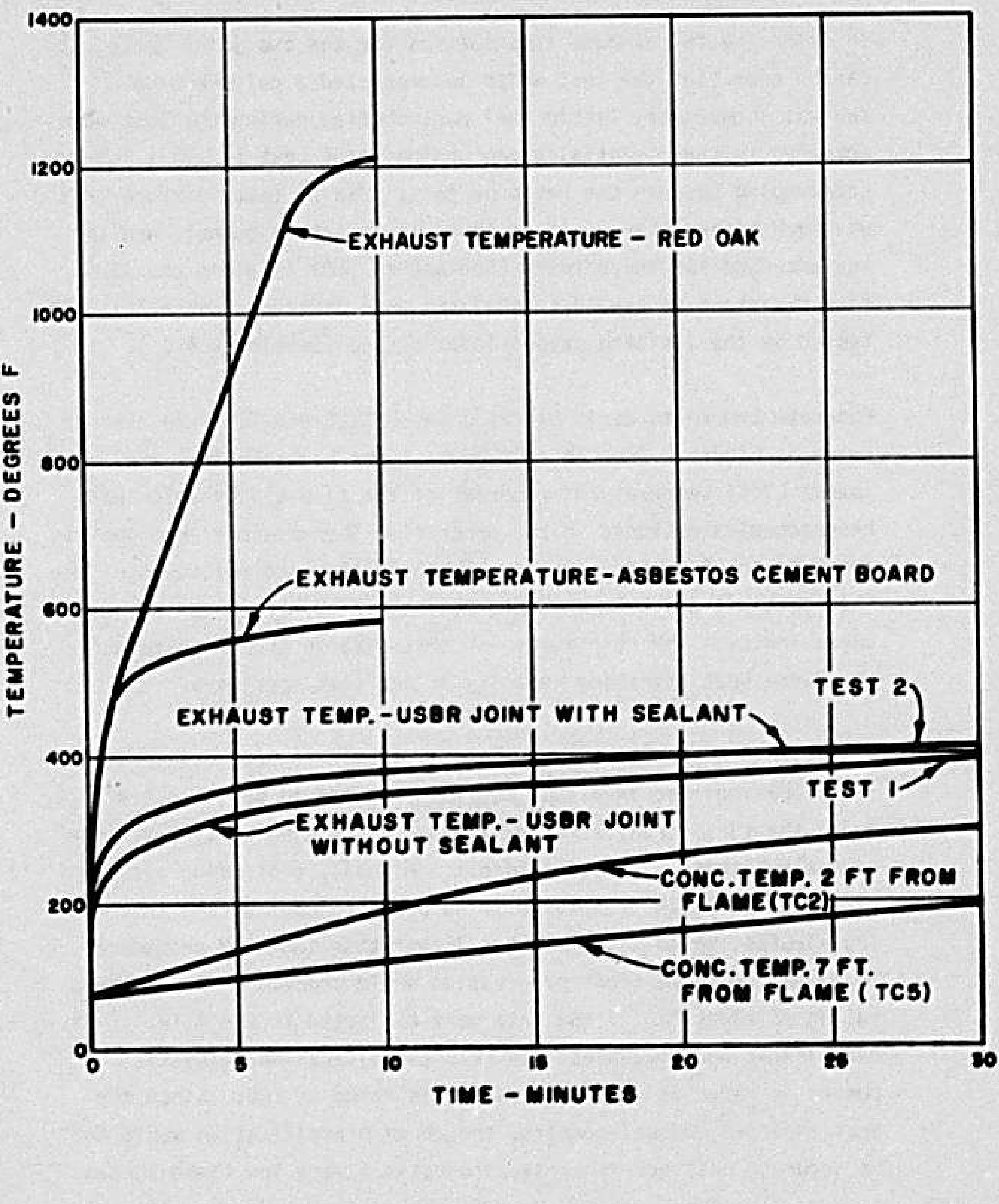


FIGURE 5-36. TIME/TEMPERATURE RELATIONSHIPS DURING FIRE TESTING

In observing the exhaust temperatures for the two joint tests, it can be seen that the test which incorporated a polyurethane sealant showed very little fuel contribution during the test when compared to the essentially nonburning joint test 1. This is encouraging because the ratio of joint area to total surface area was much higher than would be found in an actual tunnel, and the sealant used for these tests (Sealant no. 10) is among the least fire resistant of candidate sealants when individual materials are tested by the limiting oxygen index method (Section 4.4.4.).

Concrete temperatures in blocks 2 and 5 (TC2 and TC5) are also shown in Figure 5-36. These represent the highest (TC2) and lowest (TC5) temperatures recorded of the five blocks which had thermocouples embedded in the concrete. Thermocouple location was about 1 inch from the top surface of the specimen (midpoint of the thin section) and near the compression seal slot. These temperatures indicate the relatively low heat rise in the concrete and the large heat absorbing capacity of the test specimens.

Flame front advancement was rather difficult to see because of the small burning area involved, but was observed to be 4 minutes to reach the first transverse joint and 7 and 9 minutes to reach the second and third transverse joints. A small, protruding sealant tip near the fifth transverse joint began to char at the test end (30 minutes, which is 20 minutes longer than the ASTM procedure). This rate of flame front progression would produce a flame spread rating of about "1" if the data were subjected to the ASTM: E 84 classification procedures. In this classification, asbestos cement is rated as zero and red oak is rated as 100. Since the test employed unusual samples, the above classification would not be accurate but, nevertheless, indicates a very low flame spread.

Continuous recording of the photoelectric cell for measuring smoke density revealed no measurable smoke development.

The most significant event during the second joint test was expansion of the sealant from the sealant groove as the material became heated. This allowed for more sealant to burn than if the expansion had not taken place and burning had been consequently restricted to more nearly a surface condition. This also appeared to have destroyed the effectiveness of the sealant due to softening alone, if not to displacement.

The effect of fire on calking compound in test 2 may be seen in Figures 5-37 through 5-43.

5.6 Joint Configuration Study

Throughout the course of study, a large variety of joint configurations were tested. Joint shapes for longitudinal and transverse joints were evaluated. The test specimens were fabricated to represent 6-inch lengths of joint. All of the joints considered were tested for their load-carrying capacity. The longitudinal joints were also tested for their load-carrying capacity in shear. A constant axial load of 12.9 kips was applied during the shear tests. A schematic diagram of the shear test setup, along with shear and moment diagrams, is shown in Figure 5-44. Shear test data for two joint configurations and two types of seals are shown in Table 5-3. The test setup and appearance of Specimen no. 18C1 after failure are shown in Figure 5-45.

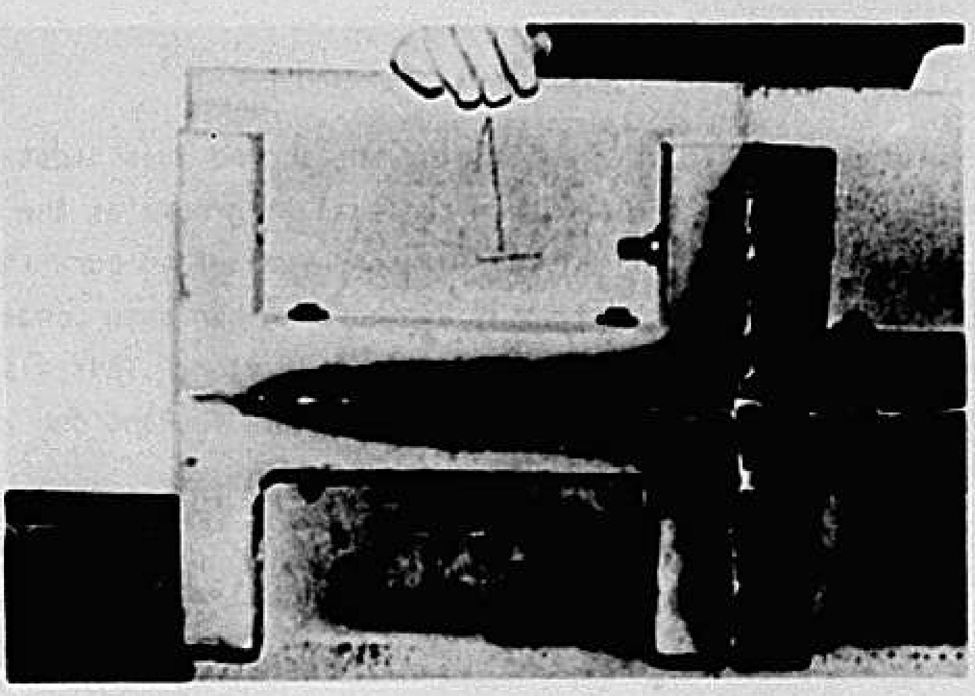


FIGURE 5-37. SEGMENT PAIR 1 AFTER FIRE TEST (THIS PAIR WAS CLOSEST TO FLAME SOURCE)

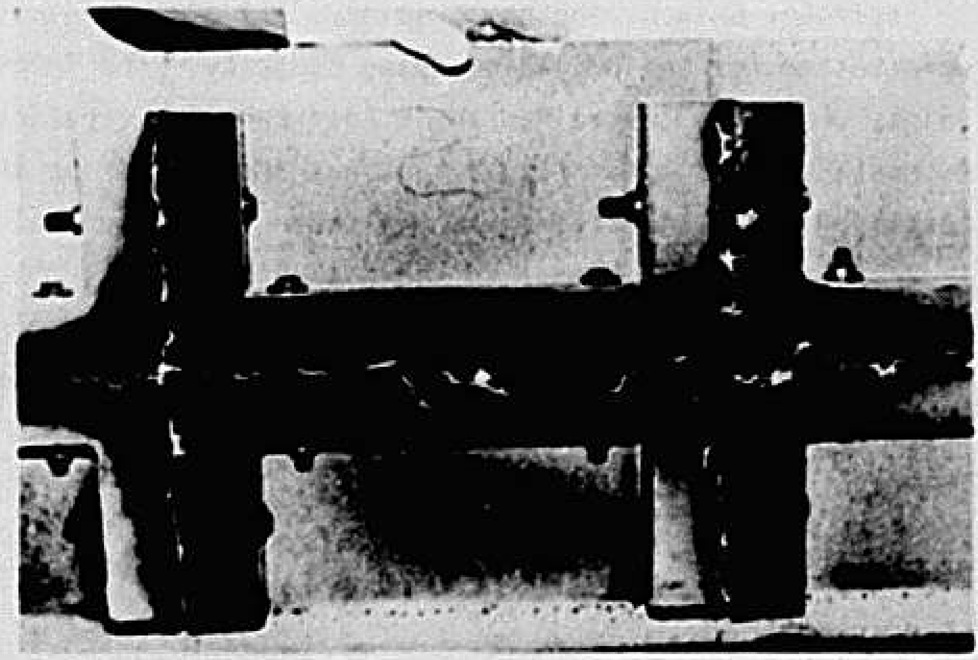


FIGURE 5-38. SEGMENT PAIR 2 AFTER FIRE TEST

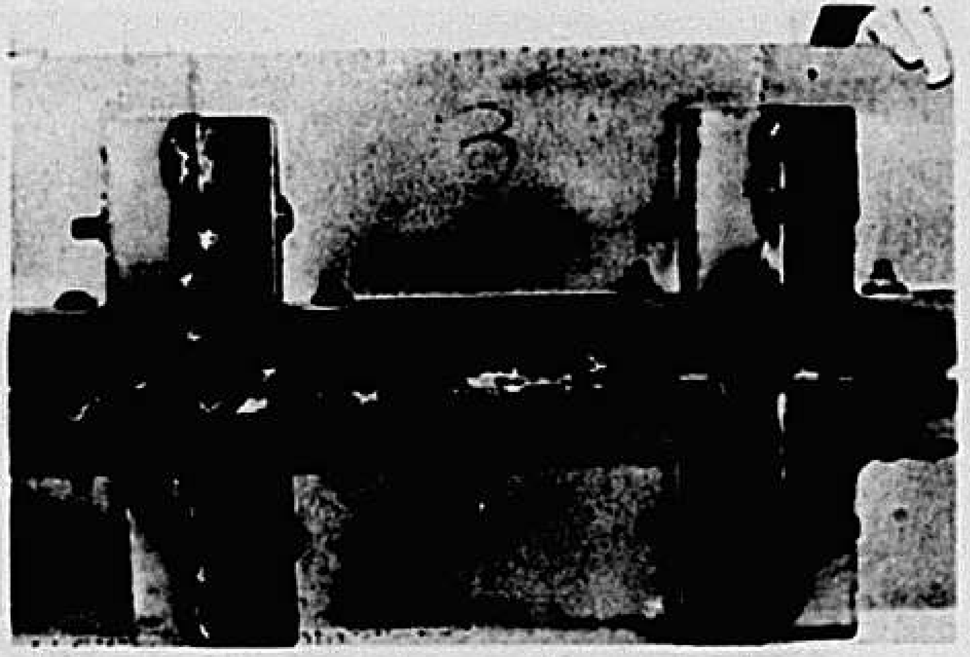


FIGURE 5-39. SEGMENT PAIR 3 AFTER FIRE TEST

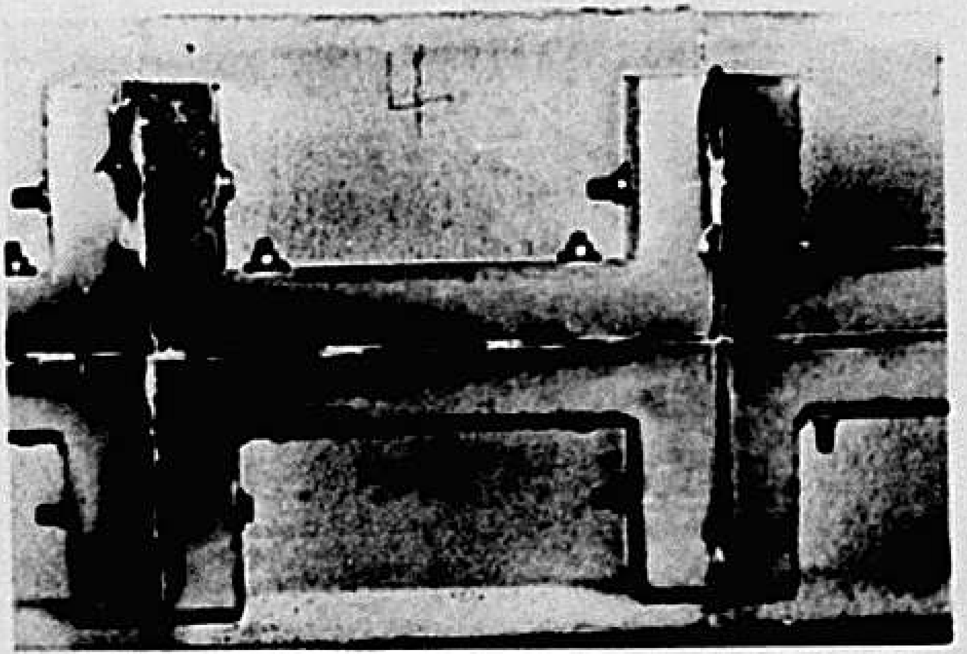


FIGURE 5-40. SEGMENT PAIR 4 AFTER FIRE TEST

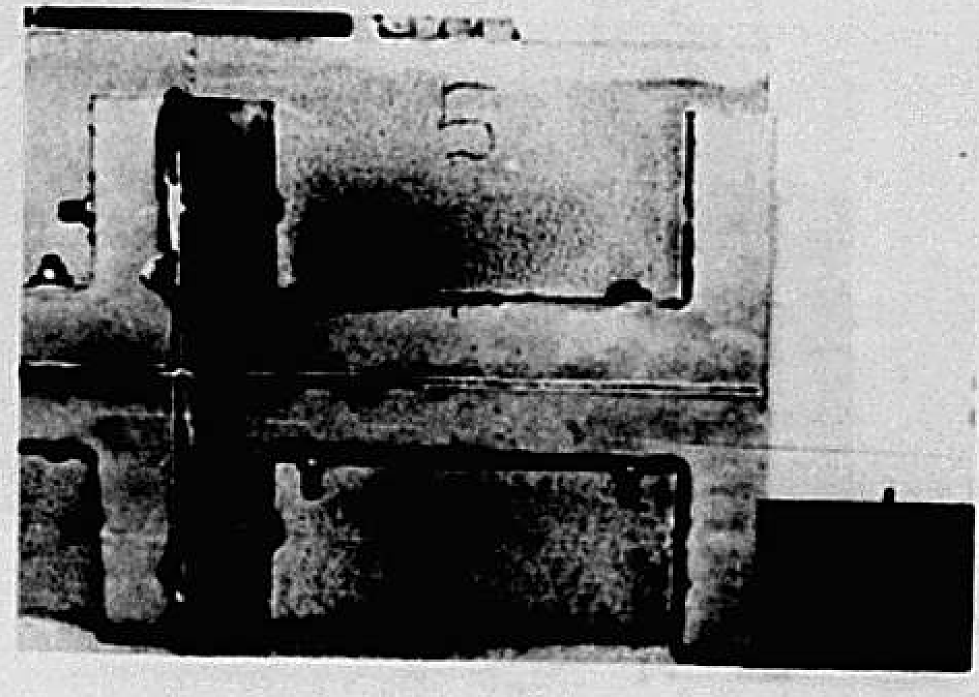


FIGURE 5-41. SEGMENT PAIR 5 AFTER FIRE TEST

FIGURE 5-42. SEGMENT PAIR 6 AFTER FIRE TEST

FIGURE 5-43. SEGMENT PAIR 7 AFTER FIRE TEST

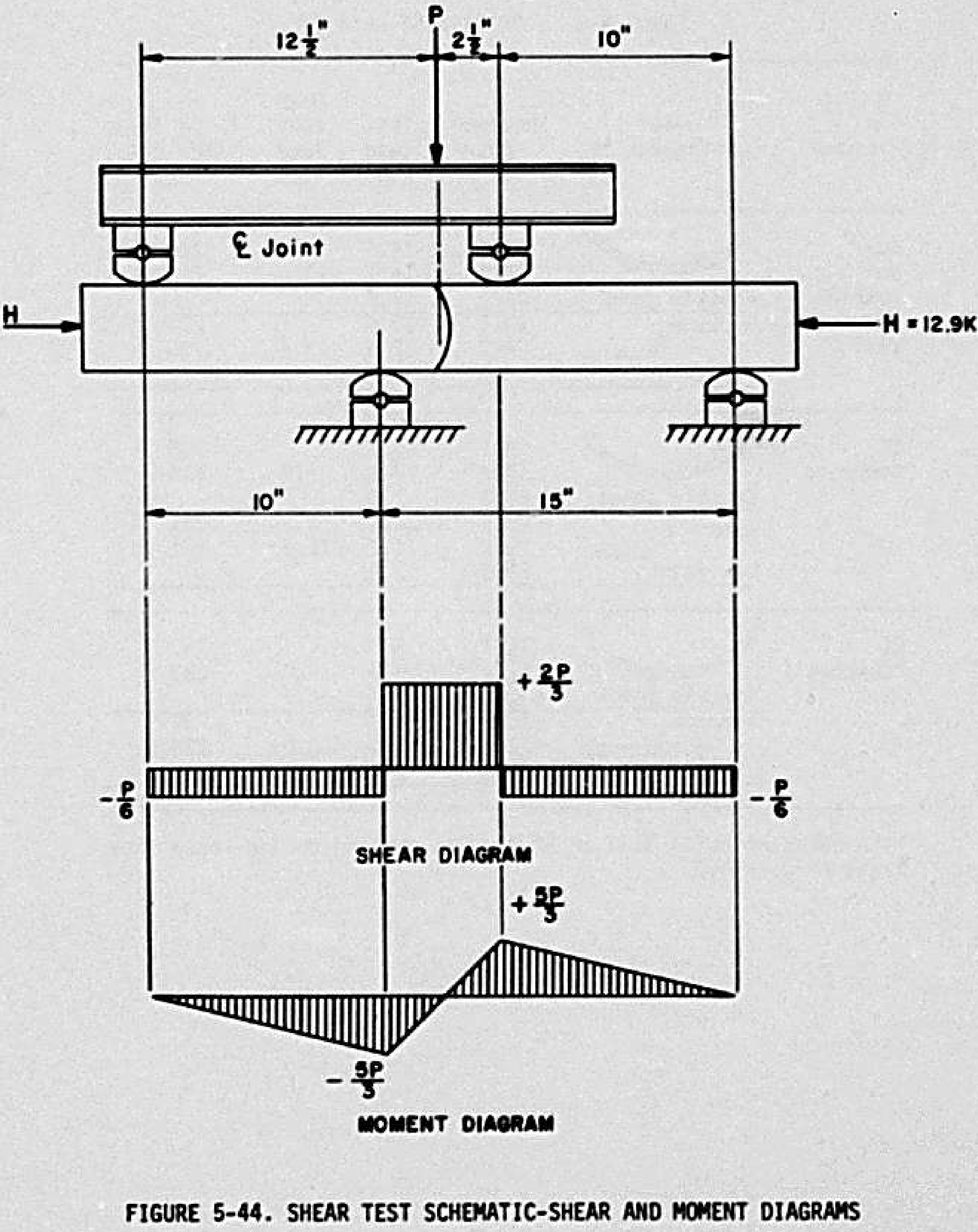
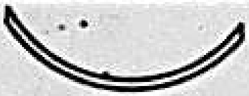


FIGURE 5-44. SHEAR TEST SCHEMATIC-SHEAR AND MOMENT DIAGRAMS

TABLE 5-3. SHEAR TEST DATA 1/

Group	Joint configuration	Specimen No.	Test load kips	Mean test load kips	6- by 12-in std. cyl. kips
AC No cushion or seal	 Knuckle joint	1AC1	16.6		216
		1AC2	16.7	17.0	223
		1AC3	17.8		
	 Lap joint	2AC1	13.6		224
		2AC2	12.9	13.8	220
		2AC3	14.9		
BC Neoprene	 Knuckle joint	1BC1	8.9		230
		1BC2	8.8	8.9	224
		1BC3	9.0		
	 Lap joint	2BC1	11.4		231
		2BC2	11.2	11.9	231
		2BC3	13.0		
CC "Comcoat"	 Knuckle joint	1CC1	8.7		230
		1CC2	8.9	9.0	233
		1CC3	9.4		
	 Lap joint	2CC1	10.8		235
		2CC2	9.4	10.0	228.5
		2CC3	9.9		

1/ A constant axial load of 12.9 k was applied during these shear tests (fig. 5-44).

FIGURE 5-45. SHEAR TEST OF SPECIMEN NO. 1BC1

Two joint configurations pertinent to this study were tested in axial compression tests to determine the relative strengths with and without sealants. The first set of joints, designated A, B, and C, is the joint configuration for the one-half scale model segments. The second set, designated D, E, and F, represents the joint configuration of the precast concrete segments used in the Baltimore Lexington Market Line tunnel. These, too, are one-half scale specimens and model a 6-inch length of joint. The relative data are shown in Table 5-4. Pictorial collages of these joint tests are shown in Figures 5-46 through 5-51.

In addition to the tests reported in paragraph 5.7, polymer-impregnated concrete was also compared to plain concrete in joint configuration tests. Both cushioned and uncushioned joints were tested. The results are tabulated in Table 5-5. The uncushioned joints are considered controls and did display the highest load-carrying capacities. In each case, the flat butt joints had higher strengths than the grooved joints. These test results show that changes in the joint configuration by addition of a gasket or sealant causes a reduction in joint strength. The reduction will vary from shape to shape and with sealant characteristics. The results also show that the partially impregnated joints are considerably stronger than plain concrete joints. These joints are called partially impregnated because only the joint surfaces were polymer impregnated by a soak process. There are numerous reports available on concrete polymer materials. The two referenced Summary Reports [31, 32] will provide the reader with introductory information on PIC. PIC results when conventional hardened concrete is impregnated with a liquid monomer which is then polymerized in place.

The results show that to achieve a watertight joint, it is necessary to sacrifice some compressive strength and factor of safety. It is also apparent that a plywood cushion maintains

TABLE 5-4. JOINT CONFIGURATION STUDIES

Compression tests

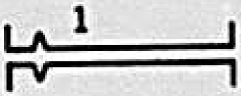
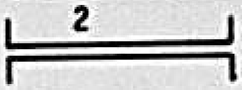
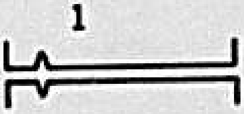
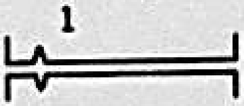
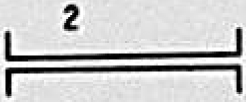
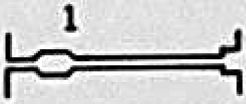
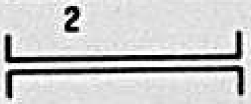
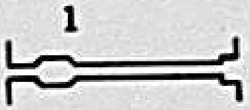
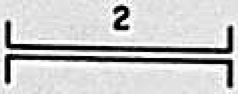
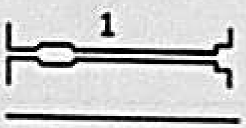
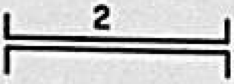
Group	Joint configuration	Specimen No.	Test load kips	Mean test load, kips	6x12 std. cyl. Loads 1/ kips	6x12 std. cyl. Mean kips
A No gasket or sealant		A1	107		147	
		A1	99	104		147
		A1	107		146	
		A2	117		145	
		A2	119	115		143
		A2	109		142	
B Rubber gasket in groove		B1	103		149	
		B1	111	105		144
		B1	101		138	
		B2				
		B2		115		143
		B2				
C Rubber gasket in groove and sheet rubber over entire joint		C1	80		144	
		C1	78	80		149
		C1	83		2/ 154	
		C2	103		148	
		C2	90	92		144
		C2	82		139	
D No gasket or sealant		D1	74		144	
		D1	71	72		150
		D1	70		2/ 155	
		D2				
		D2		115		144
		D2				
E Rubber gasket in groove		E1	67		148	
		E1	66	66		152
		E1	65		2/ 156	

TABLE 5-4. JOINT CONFIGURATION STUDIES (CONTINUED)

Compression tests

Group	Joint configuration	Specimen No.	Test load kips	Mean test load, kips	6x12 std. cyl. Loads 1/ kips	6x12 std. cyl. Mean kips
E Rubber gasket in groove (cont)		E2 E2 E2		115		143
F Rubber gasket in groove and 2-in wide strip of Bituthene on bearing surface		F1 F1 F1	74 66 66	69	150 2/ 158	154
		F2 F2 F2	100 80 90	90	152 2/ 152	152

1/ Concrete at 5 days' age.
2/ Concrete at 6 days' age.

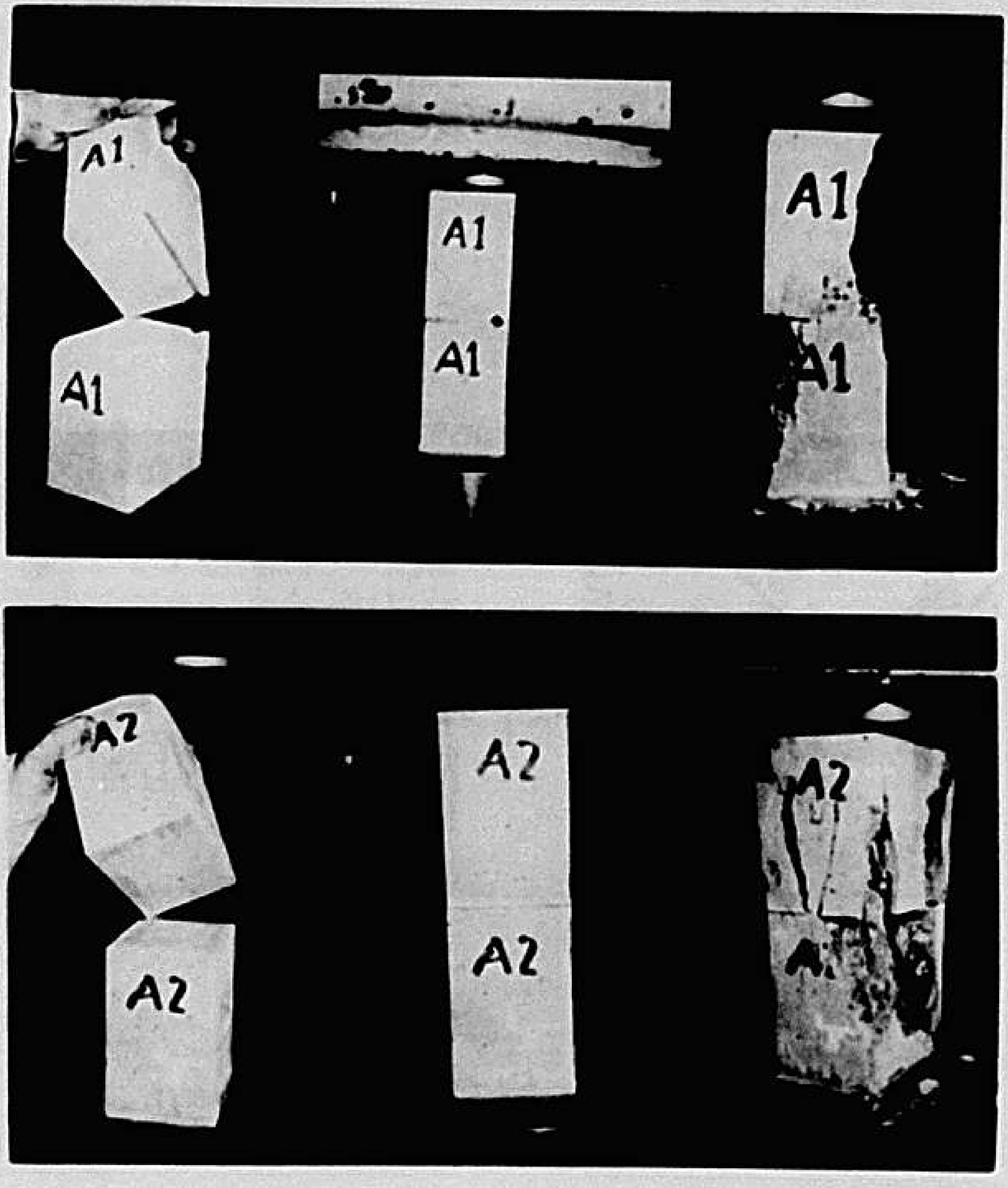


FIGURE 5-46. JOINT TEST ON "A" SPECIMENS HAVING NO JOINT GASKET OR SEALANT

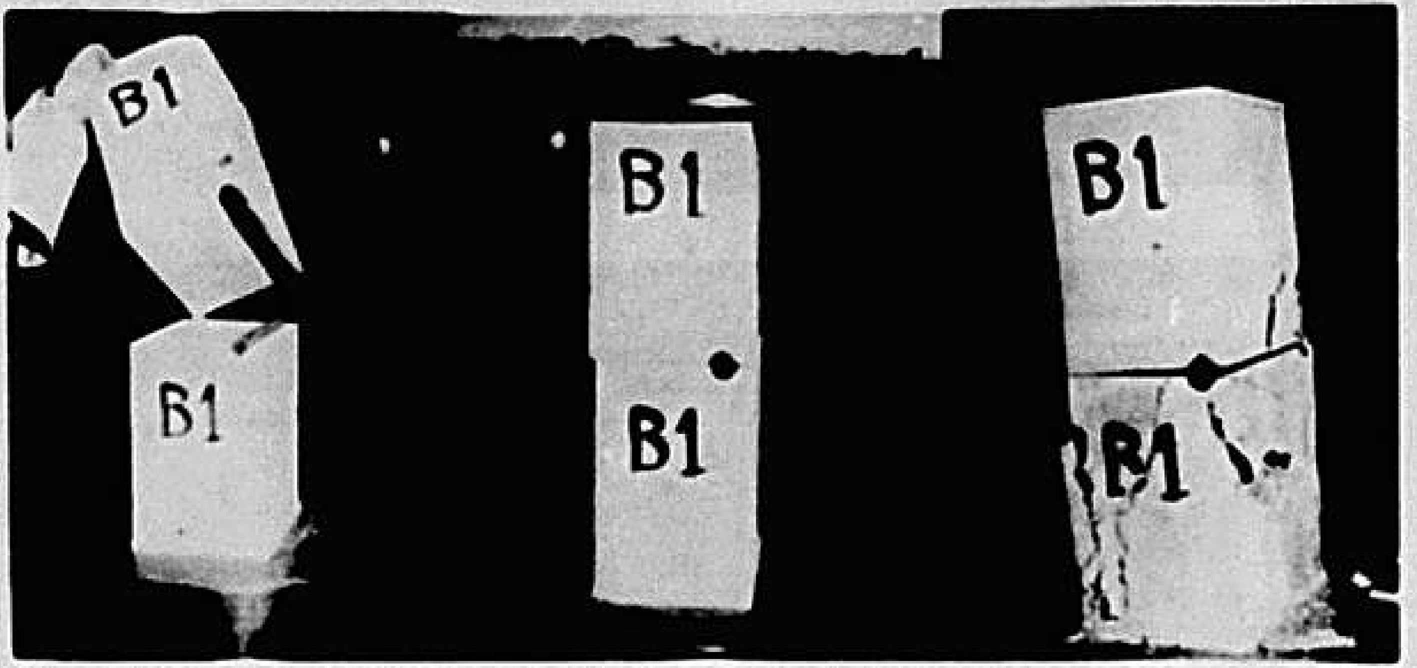


FIGURE 5-47. JOINT TESTS ON "B" SPECIMEN HAVING RUBBER GASKET IN GROOVE

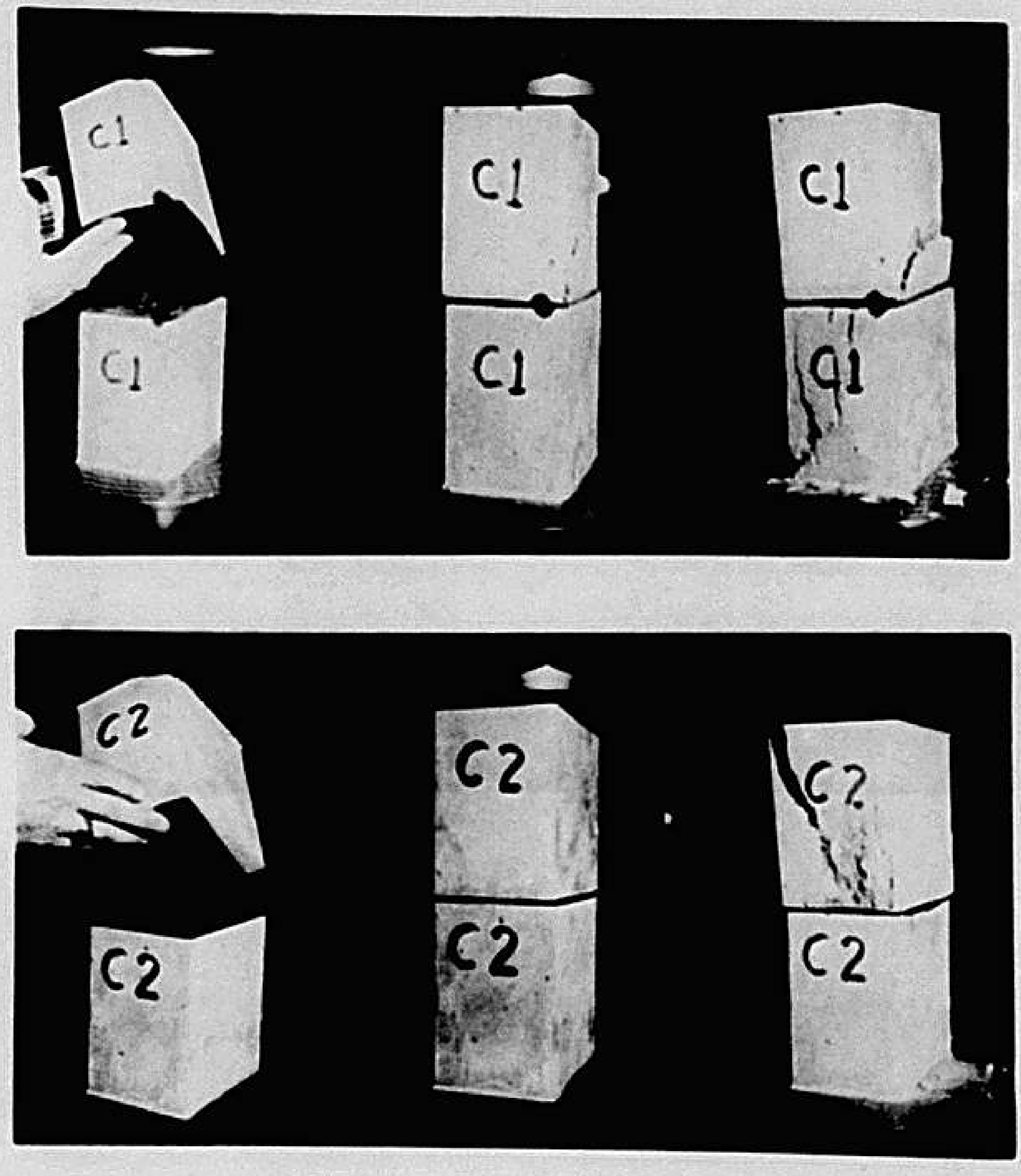


FIGURE 5-48. JOINT TESTS ON "C" SPECIMENS HAVING RUBBER GASKET IN GROOVE AND SHEET RUBBER OVER ENTIRE JOINT

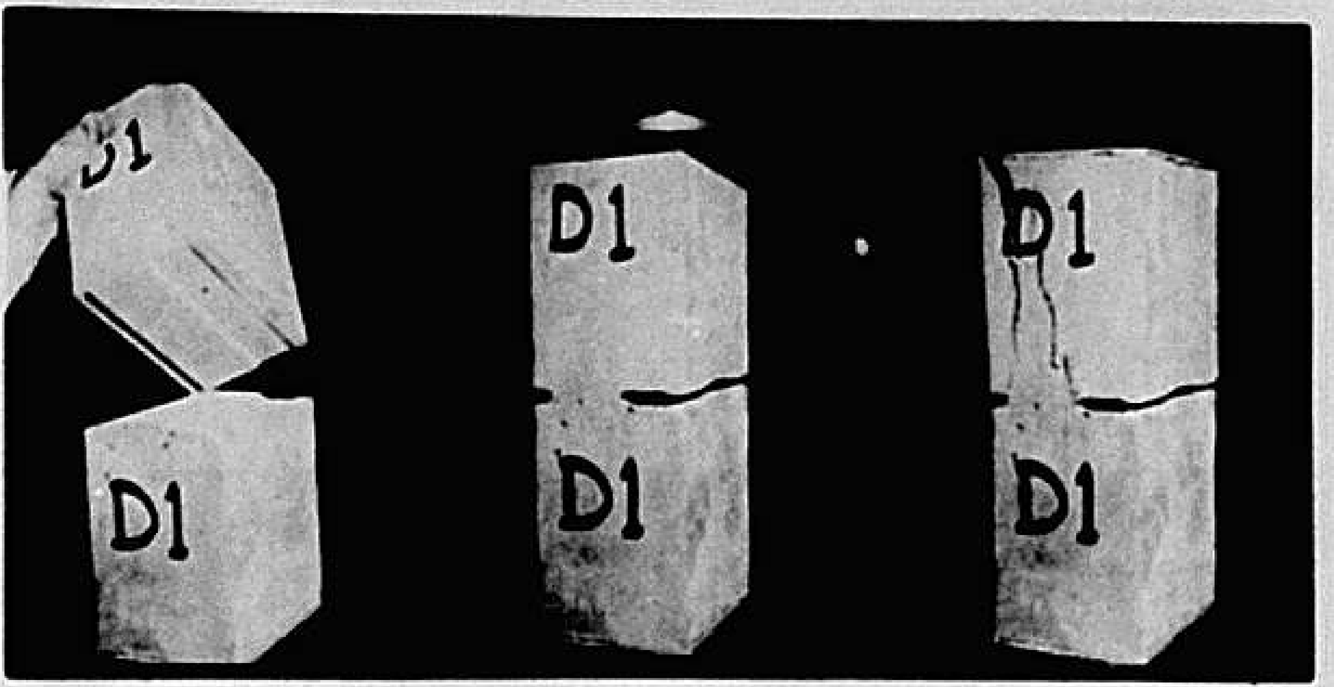


FIGURE 5-49. JOINT TESTS ON "D" SPECIMEN HAVING NO GASKET OR SEALANT, BALTIMORE TUNNEL CONFIGURATION

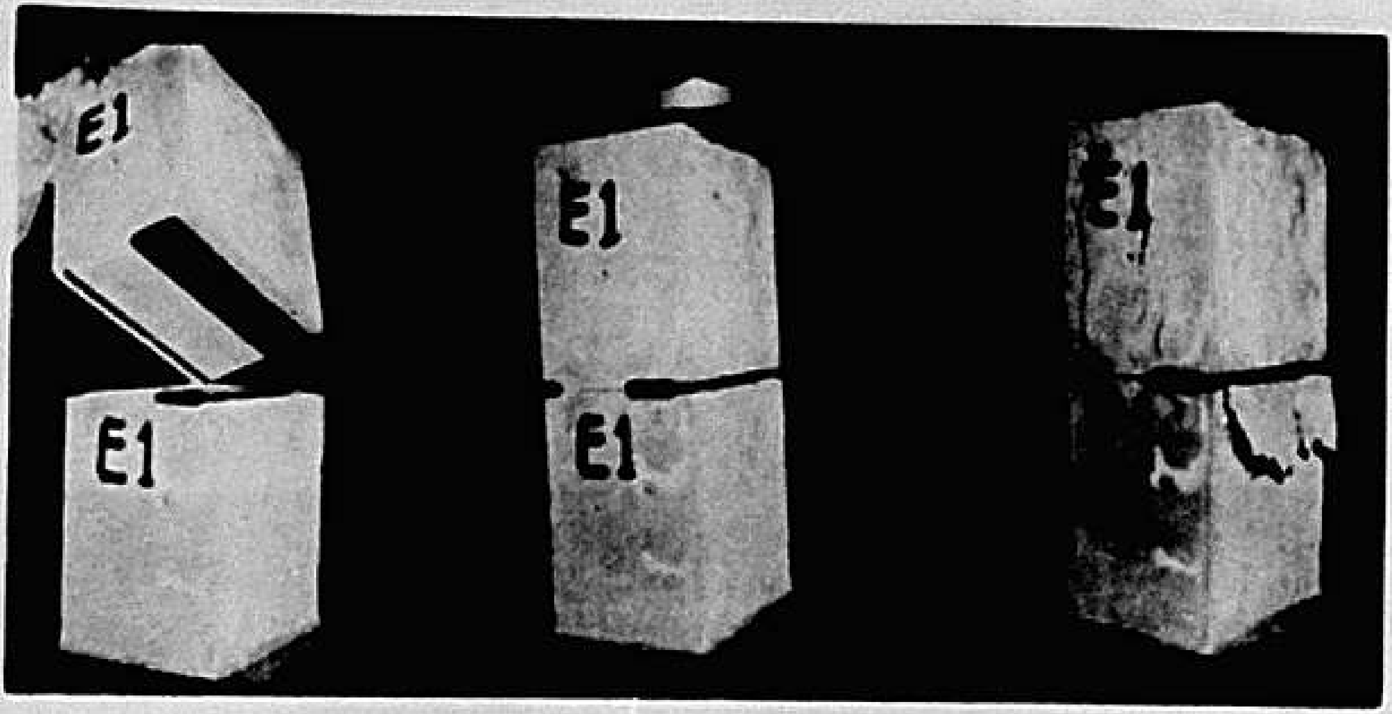


FIGURE 5-50. JOINT TESTS ON "E" SPECIMEN HAVING RUBBER GASKET IN GROOVE, BALTIMORE TUNNEL CONFIGURATION

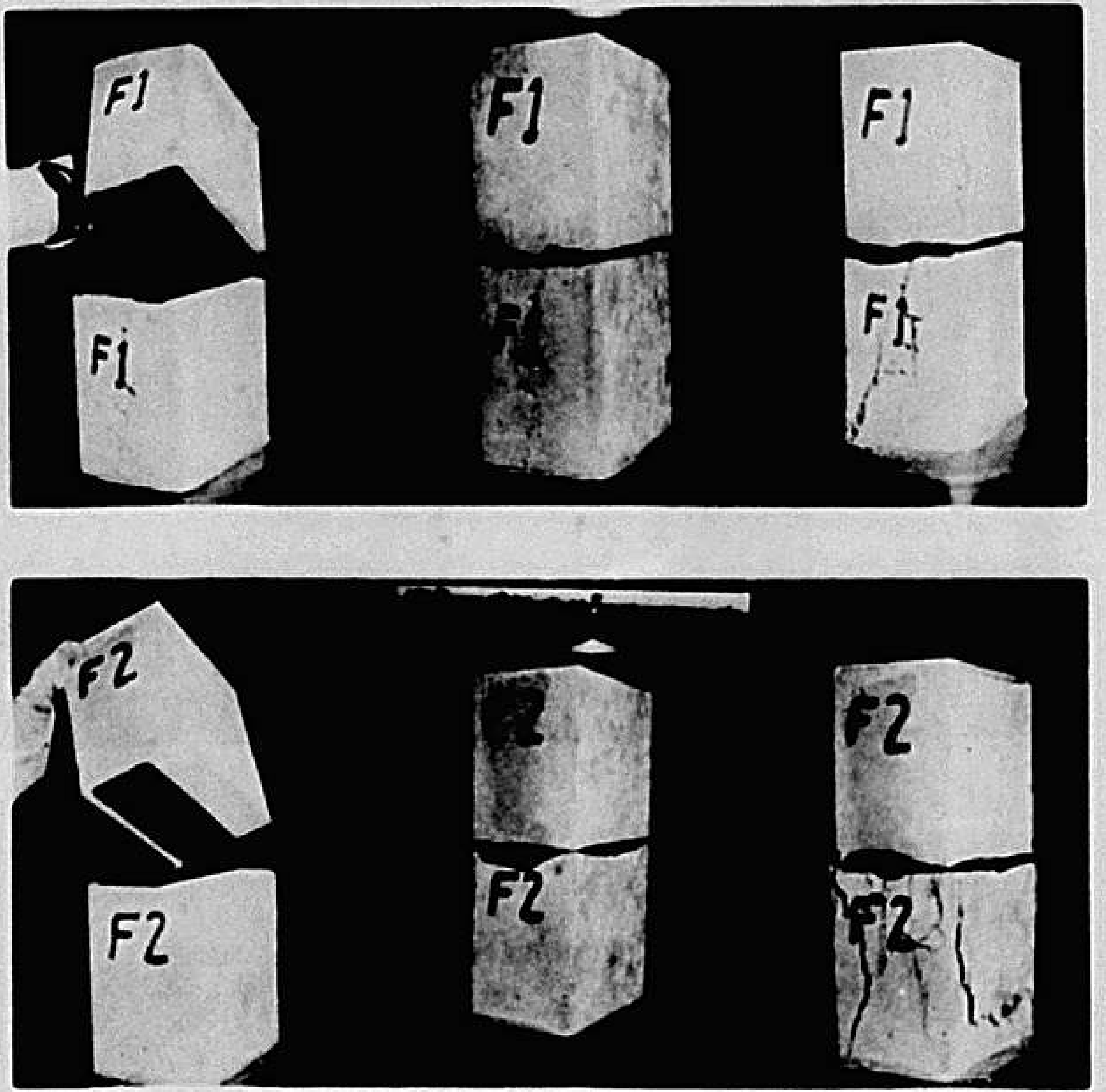


FIGURE 5-51. JOINT TESTS ON "F" SPECIMENS HAVING RUBBER GASKET IN GROOVE AND 2-INCH-WIDE STRIP OF BITUTHENE ON BEARING SURFACE, BALTIMORE TUNNEL CONFIGURATION

TABLE 5-5. COMPARATIVE DATA FOR JOINT SYSTEMS WITH PLAIN AND POLYMER-IMPREGNATED CONCRETE.

Compression tests

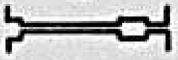
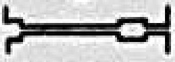
	Joint No. and configuration	Test load kips	Day tested	Mean test load kips	6 x 12 std. cyl. kips	Day tested	Mean 6 x 12 $\mathrm{lb/in}^2$
Plain concrete	A 	480 420 450	94 96 98	450	209 209	96 96	7390
	AC 	695 775 777	94 96 98	749	208 211	96 96	7410
Polymer impregnated face	B 	575 455 520	94 96 98	517	245 245	100 100	8670
	BC 	850 830 827	94 96 98	835	247 244	100 100	8680
Plain concrete plywood	C 	430 485 474	94 96	463	204 205	96 96	7230
	CC 	710 738 763	94 98 98	737	208 212	96 96	7430
Polymer impregnated face plywood	D 	600 550 623	94 98 98	591	248 262	100 100	9020
	DC 	940 875 905	94 98 98	907	261 264	100 100	9290

TABLE 5-5. COMPARATIVE DATA FOR JOINT SYSTEMS WITH PLAIN AND POLYMER-IMPREGNATED CONCRETE (CONTINUED)

Compression tests

	Joint No. and configuration	Test load kips	Day tested	Mean test load kips	6 x 12 std. cyl. kips	Day tested	Mean 6 x 12 lb/in^2
Plain Concrete spring felt	E 	310	95	289	198	96	7180
		244	98		208	96	
		313	98				
	EC 	495	95	496	209	96	7290
		483	98		203	96	
		510	98				
Polymer impregnated face spring felt	F 	365	95	392	257	100	9200
		398	98		263	100	
		413	98				
	FC 	520	95	552	264	100	9460
		525	98		271	100	
		610	98				
Plain concrete cushion tape WFT-1	G 	440	95	370	207	96	7270
		333	98		204	96	
		337	98				
	GC 	*			210	96	7390
		*			208	96	
		*					
Polymer impregnated face cushion tape WFT-1	H 	440	95	395	252	100	9050
		350	98		260	100	
		*					
	HC 	*			257	100	9160
		*			261	100	
		*					

* Not tested - insufficient tape

or increases the joint strength. The plywood provides a more uniform bearing area and crushes without the lateral flow characteristic of other sealants and fillers. The lateral flow in a joint under compression transfers some of the vertical force to a lateral force that can result in tensile forces at the joint faces, thus reducing the load-bearing ability of the joint.

Polymer impregnation of the joint surfaces may be useful to increase the joint strength in instances where heavy jacking loads damage segments during construction. The technique would be most useful where a large number of segments had been manufactured. These could be modified by polymer impregnation to salvage them. Special techniques would be needed case by case, and substantial costs could be expected as the process is not low cost.

5.7. Single Segment Tests

Two types of single segment tests were run. Arch load tests were run on two types of similar-size segments and simulated jacking tests were run on two types of segments with three types of bearing surfaces.

5.7.1. Two-hinged Arch Tests

Single segments of reinforced concrete and PIC, 2 inches and 4 inches thick, were tested as two-hinged arches as shown in Figure 5-52. The end supports were rigid steel bars machined to fit the end of the segments and mounted on horizontal and vertical load cells and locked into a stiff frame.

A uniform line load, distributed over the width of the segment, was applied at the center of the arch span. Some horizontal and all vertical components of the reactions were monitored with the load cells. After finding that the horizontal

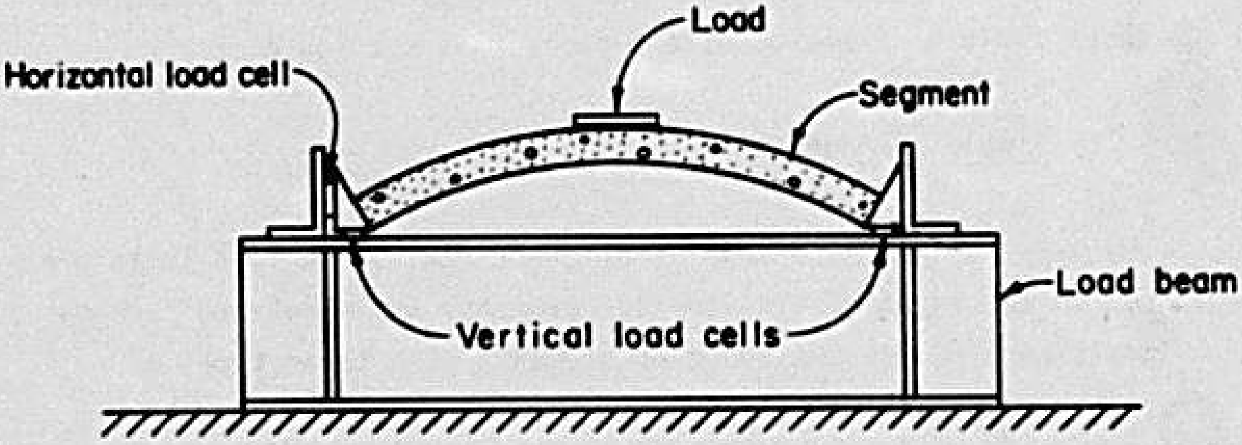


FIGURE 5-52. SINGLE SEGMENT TEST SETUP

component of the applied load was exceeding the capacity of the horizontal load cell, the load cell was bypassed by inserting a solid steel block in its place.

The initial failure mode for all segments tested was signified by a tension crack forming on the inner surface of the arch at the point of the applied load. The cracked section acted as a crown hinge in the arch, and the arch continued to support increasing load until the arch completely failed.

The 2-inch-thick reinforced concrete segments developed tension cracks at a load of 9,800 lb, and arch failures occurred at 23,750 lb. The PIC segments developed tension cracks at similar loads of 9,600 lb, but arch failure did not occur until the load exceeded 41,400 lb. The 4-inch-thick concrete segments developed first tension cracks at a load of 21,800 lb, with failure occurring at 27,400 lb. The 4-inch-thick PIC segments were not loaded to failure because the anticipated reactions were beyond the load capacity estimated for the test frame welds. Failure loads were expected to exceed 51,700 lb. The 4-inch-thick PIC segments developed tension cracks at loads of 23,200 lb. The data from these tests are shown in Table 5-6. The results show again that PIC has higher strength than conventional concrete.

5.7.2. Simulated Jacking Tests

Two types of segments were subjected to tests designed to simulate machine jacking loads against the edge of the panels. The first type of segment was representative of a four-segment-per-ring unbolted liner, 5 inches thick and [illegible] feet wide, for a tunnel 8 feet 3 inches in diameter, except that the shiplap transverse joint was not included. For these tests, the joint surfaces were flat. The second type of segment was from the

TABLE 5-6. RESULTS OF SINGLE SEGMENT-LOAD TESTS

Compression tests

Specimen No.	Load at tension crack, lb	Average load, lb	Ultimate load, lb	Average load, lb
2-inch segments				
102-77	9,450	9,820	25,630	23,750
771-77	9,000		20,000	
104-77	11,000		25,630	
1139-77 (PIC)	7,200	9,600	38,000	41,430
118-77 (PIC)	9,000		43,600	
2139-77 (PIC)	12,600		42,700	
4-inch segments				
1344-77	20,900	21,800	26,100	27,400
2344-77	20,240		28,100	
3344-77	24,280		28,100	
14-78 (PIC)	24,730	23,240	*	
17-78 (PIC)	22,500		*	
27-78 (PIC)	22,500		*	

* Not tested; estimated to be more than 51,700 lb.

test model ring (Section 5.8.). These were waffle-grid-type segments, six per ring, for a bolted liner 4 inches thick and 16 inches wide. The model was designed to be one-half scale of a 5-meter-diameter tunnel; consequently, the rings were designed to be 2.5 meters in diameter, or 8.2 feet.

For the tests, loads were applied to the transverse joints in a large testing machine. Three variations in load bearing were evaluated: (1) with three jacking pads 10 inches in diameter positioned at the 1/6, 1/2, and 5/6 points of the joint edge; (2) with uniform distribution of load applied directly to the joint surface; and (3) with load distribution through a jacking ring on the joint surface.

The test results are shown in Table 5-7. The data show that the segments can withstand jacking loads up to near the ultimate strength of the concrete; however, the total force that can be applied is dependent on the bearing area.

Inside and outside views of the segments after test are shown in Figures 5-53 through 5-55. Figure 5-56 is an inside view of the test model segment.

5.8. One-half Scale Tunnel Model

The primary purpose of the one-half scale model test was to demonstrate the watertightness of the candidate joint sealant systems. In order to obtain representative performance of the sealant systems, the structural behavior of the model must simulate underground conditions. The ground loading and ground/liner reaction was approximated in the model by active loads applied through flat jacks. The model was designed and built with six segment rings in order to increase the number of joints. In addition, segments spanning 60° are about as wide as can be cast

TABLE 5-7. RESULTS OF SIMULATED JACKING TESTS

Compressive loads

Segment type	Load method	Bearing area in^2	Total force kips	Jacking load lb/in^2	Concrete strength lb/in^2 1/
Unbolted	Jacking pads	2/ 176.7	985	5,570	5,720
Unbolted	Uniform	408.4	2,330	5,710	5,720
Unbolted	Jacking ring	408.4	1,975	4,840	5,780
Bolted	Uniform	3/ 351	540	7,530	7,330
		3/ 351	500	6,970	6,695
		3/ 351	490	6,830	7,195

1/ From 6- by 12-inch cylinder tests
2/ Contact area of pads and segment
3/ Total cross-sectional area of the segment ribs from inside to outside surfaces.

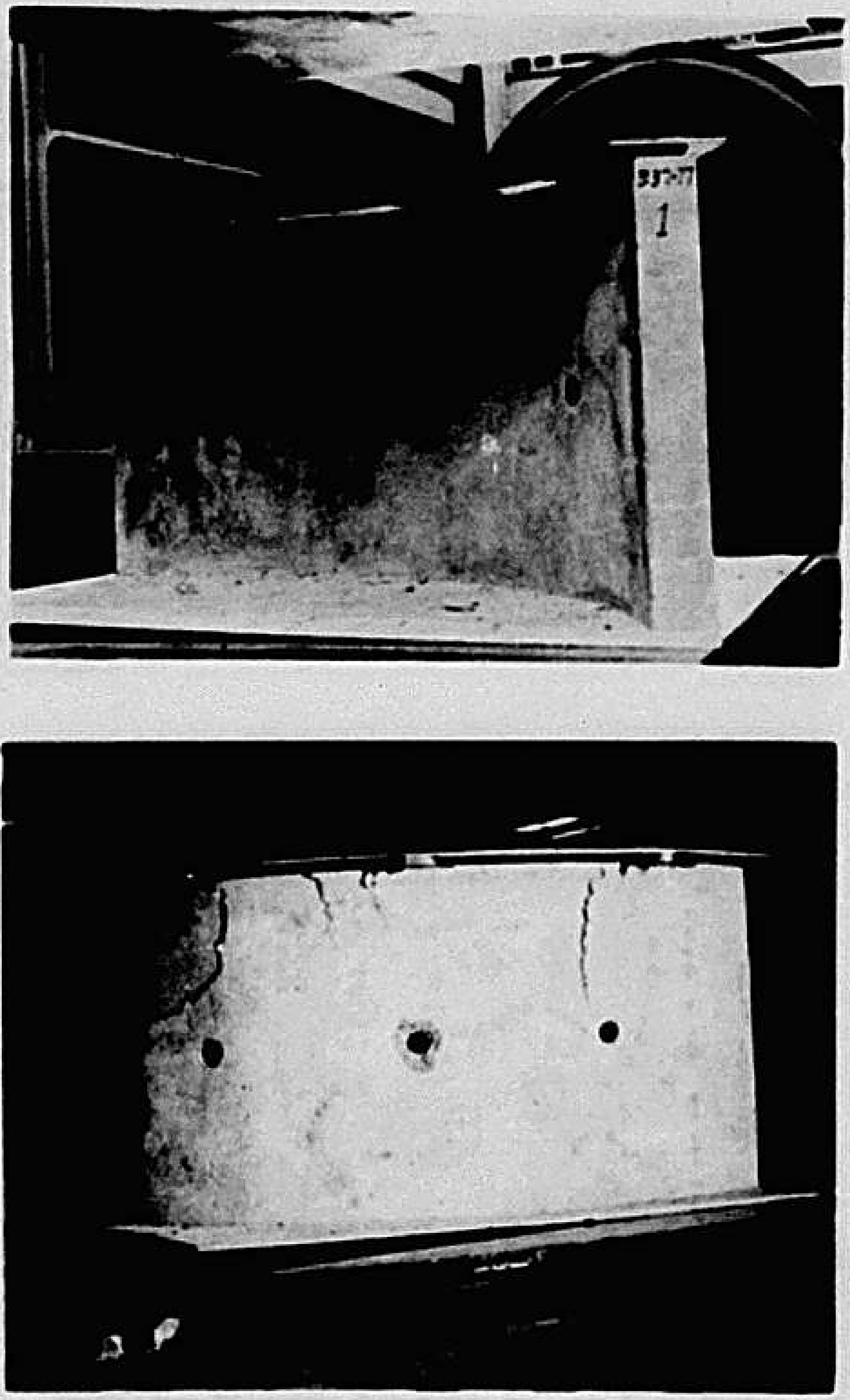


FIGURE 5-53. SIMULATED JACKING TEST - FAILURE AT 985,000 LBS. JACKING PADS LOCATED AT THE 1/6, 1/2, AND 5/6 POINTS ON TOP SURFACE

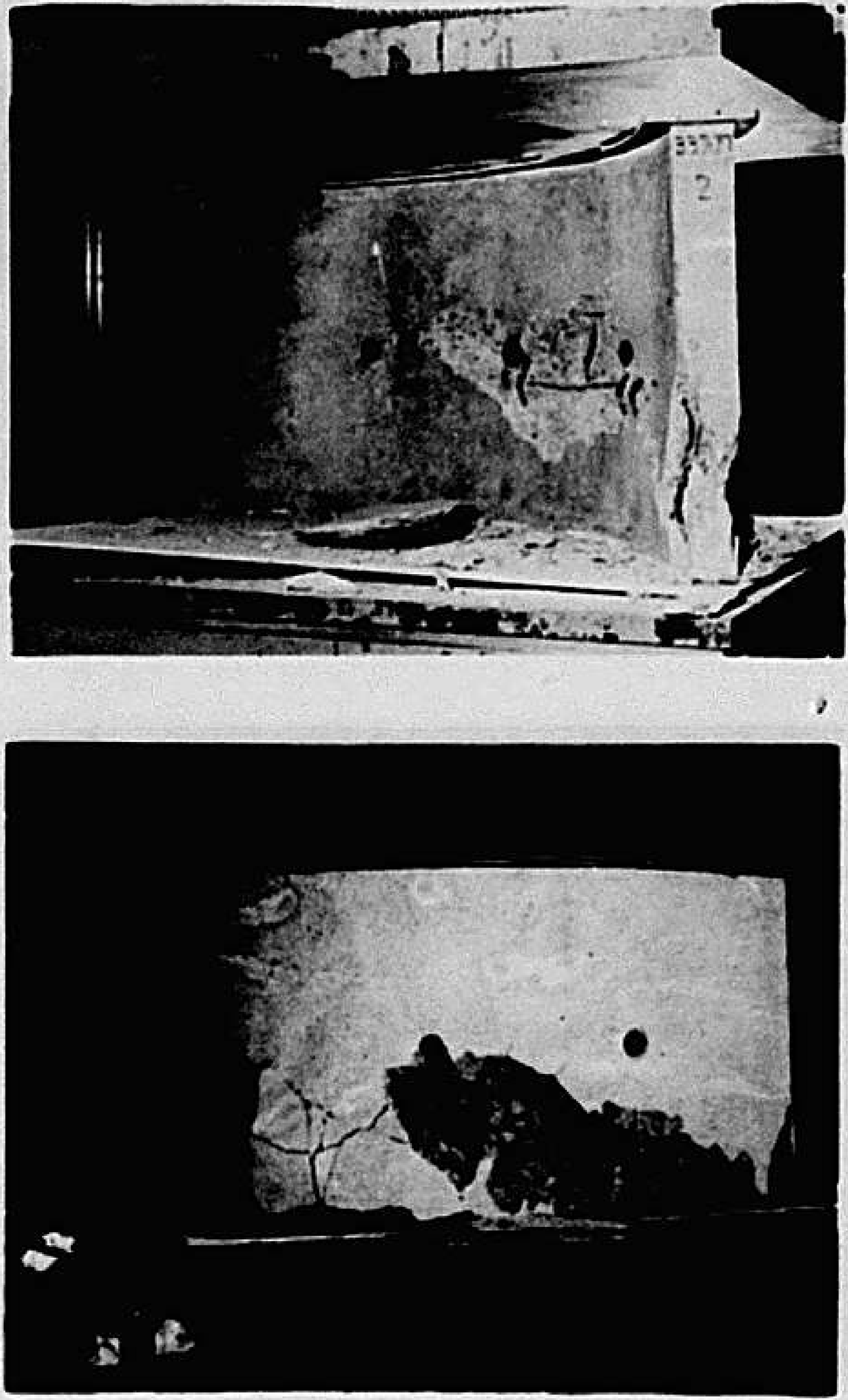


FIGURE 5-54. SIMULATED JACKING TEST - FAILURE AT 2,330,000 LBS.
UNIFORM BEARING ON TOP SURFACE

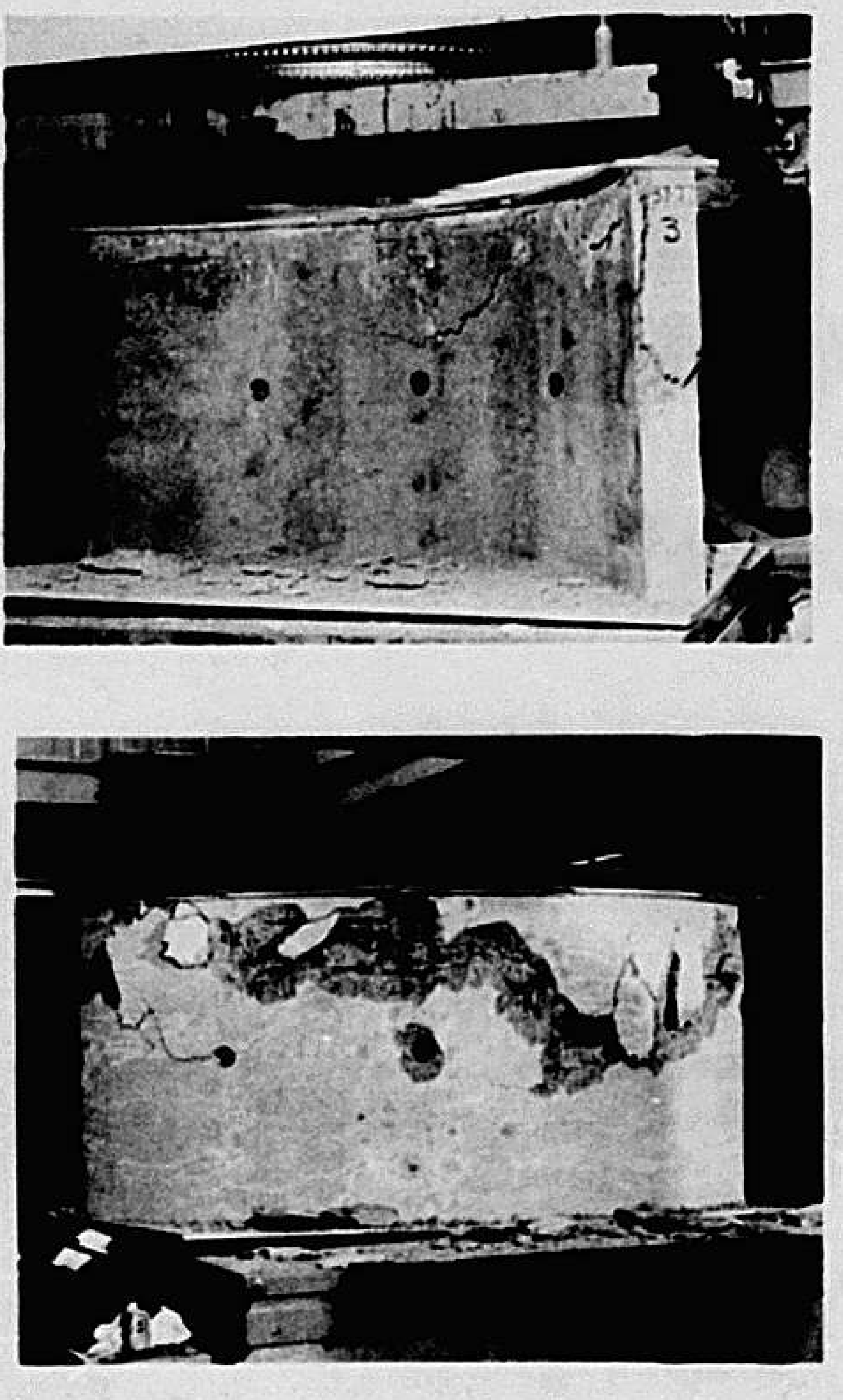


FIGURE 5-55. SIMULATED JACKING TEST - FAILURE AT 1,975,000 LBS.
"JACKING RING" BEARING ON TOP SURFACE

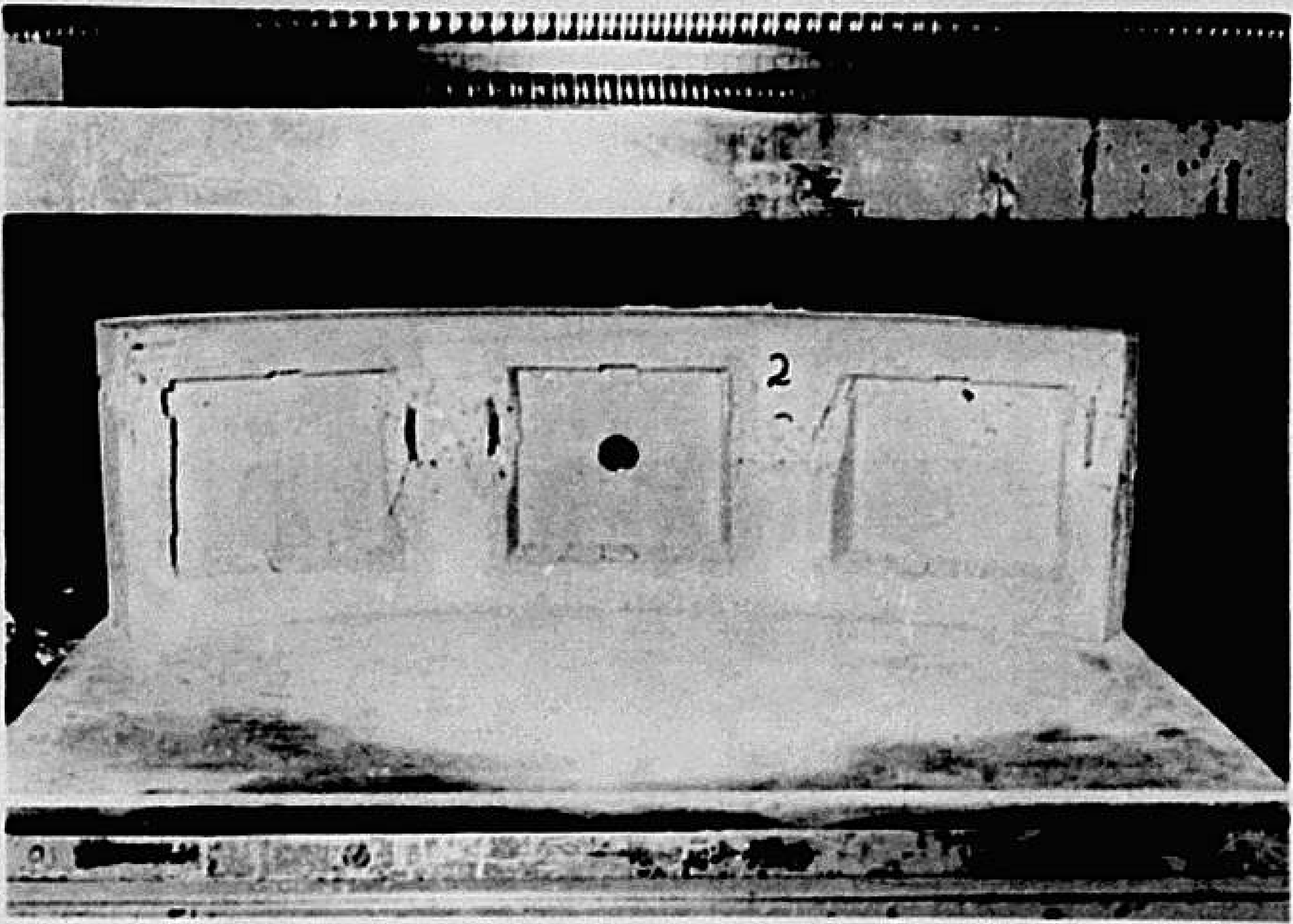


FIGURE 5-56. SIMULATED JACKING TEST - FAILURE AT 500,000 LBS.
UNIFORM BEARING ON TOP SURFACE

without forming at the ends for the exterior surfaces, ninety degree segments require forming. The model was designed with discontinuous longitudinal joints to eliminate four-corner intersections and to minimize hinge reaction under load (Section 5.8.2.).

The model was designed in metric units. It was intended to be one-half scale of a 5-meter tunnel. The segments were designed and fabricated with metric dimensions as shown on Figure 5-57. However, in order to be consistent with other data in this report, further discussion regarding the model will be in English units. The model also included a system to apply hydrostatic head to simulate ground-water pressure.

5.8.1. Model Liner

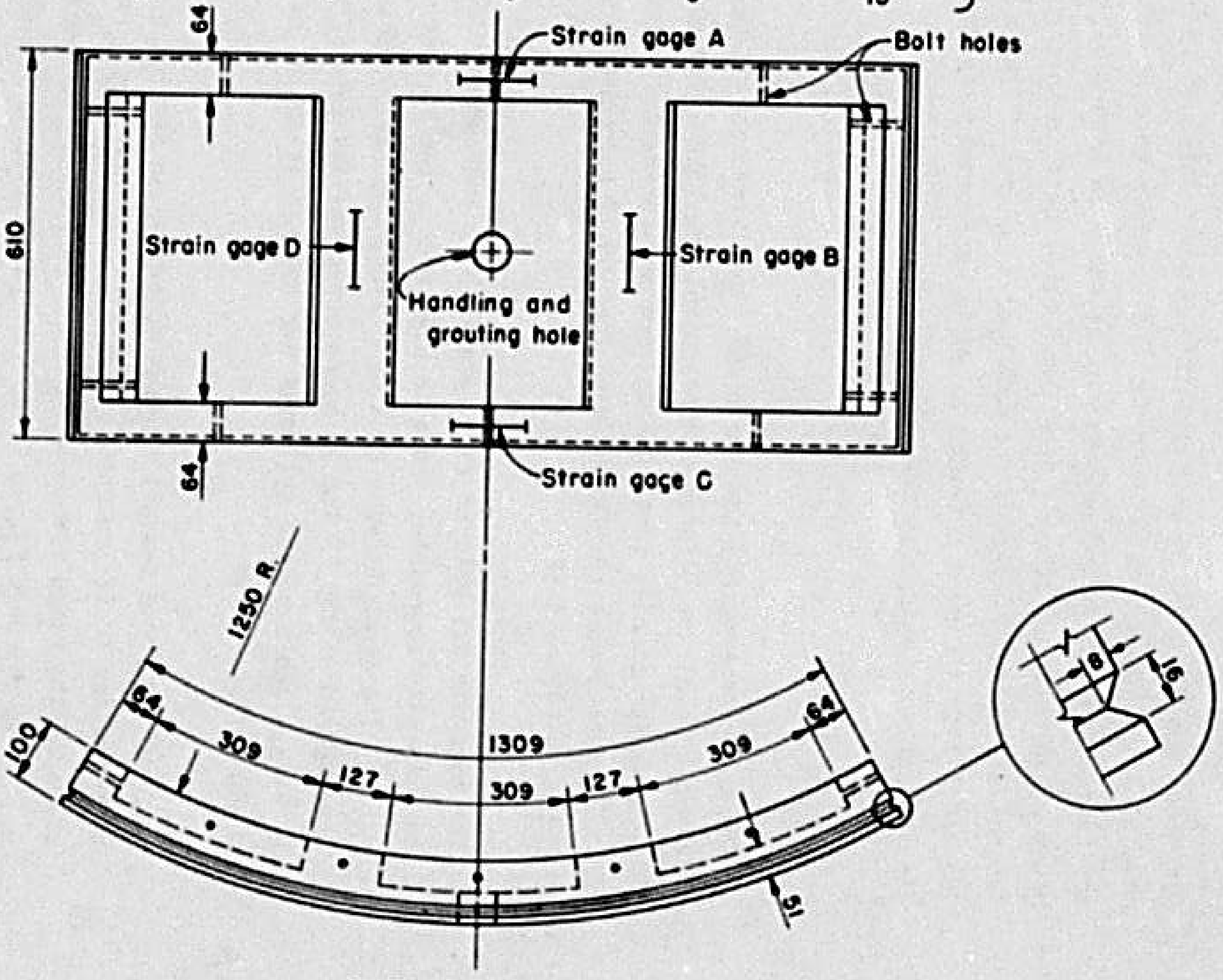
The concrete segments for the model liner were cast in reusable forms to evaluate tolerance reproducibility. Numerous segments were satisfactorily cast in each form and tolerances maintained. The segments were reinforced with four No. 3 deformed bars as shown in Figure 5-58.

The concrete was batched with Type II portland cement, 3/4-inch-maximum-size aggregate, and with 0.43 w/c (water to cement) ratio. The segments were cast on a vibrating table and were steam-cured at 155 °F for 39 hours after initial set. Companion 6- by 12-inch concrete cylinders had nominal strengths of 6,600 lb/in^2.

Each of the three sealant systems described in Section 5.1.1 were applied to 12 segments by adhesive bonding. This, then, provided the rings for each system. The bonded elastomeric gasket is shown in Figure 5-59. The other systems included in the model were the crushable compression seal and the local compression seal.

Gage Position In Segment	Segment A	Segment B	Segment C	Segment D
A	2	6	10	14
B	4	8	12	16
C	3	7	11	15
D	1	5	9	13

Gage numbers for segments for 4th ring only



(DIMENSIONS IN mm)

FIGURE 5-57. MODEL SEGMENT

FIGURE 5-58. SEGMENT FORM WITH REINFORCEMENT IN POSITION

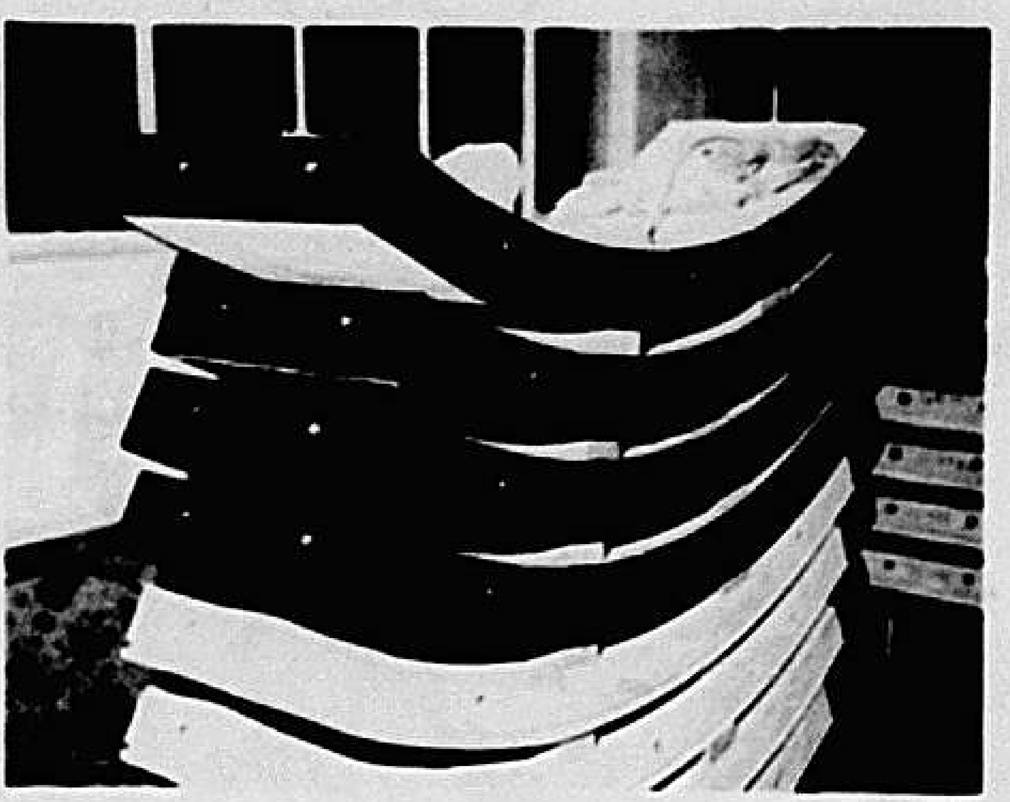


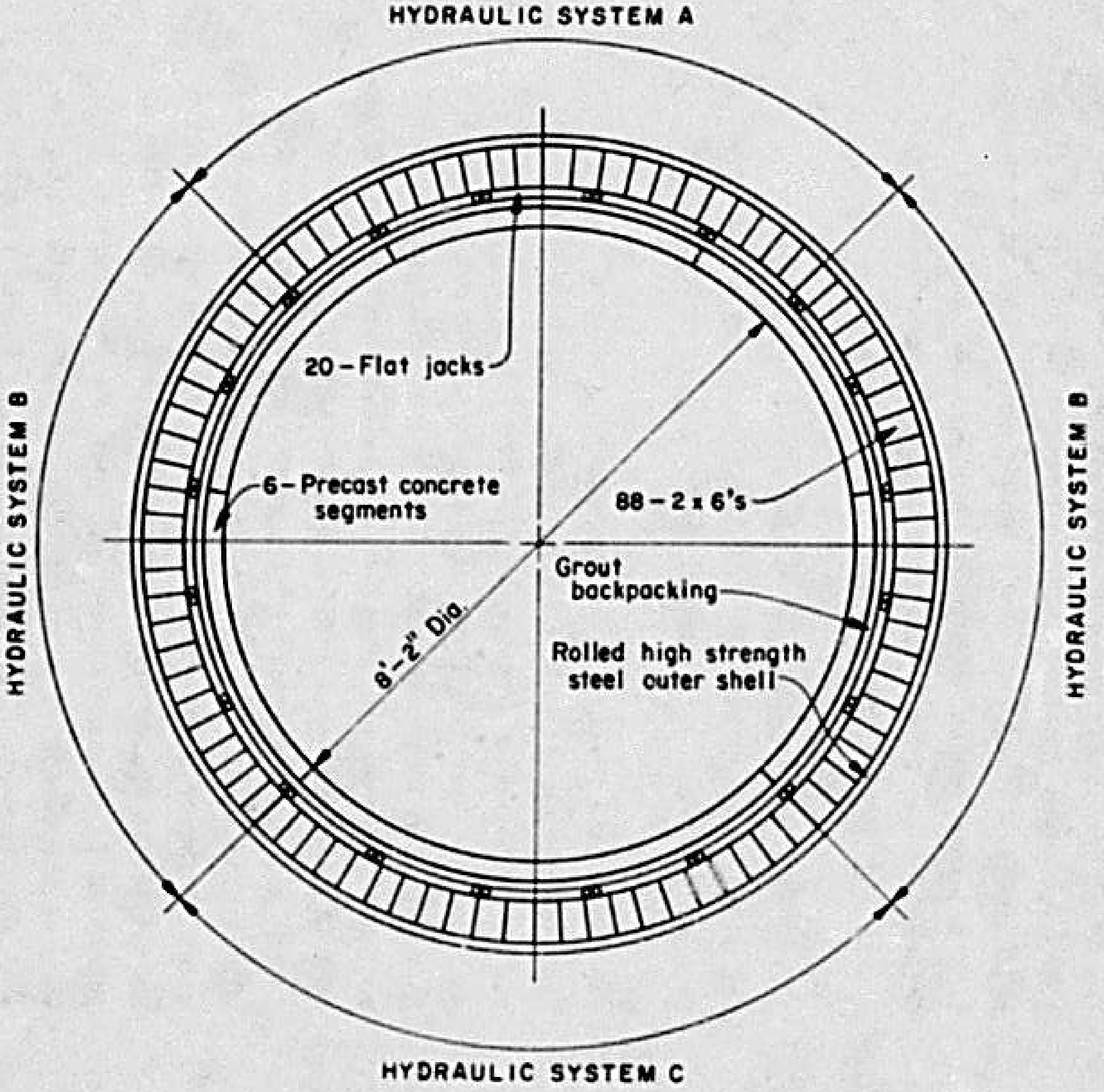
FIGURE 5-59. VIEW OF ELASTOMERIC GASKET MATERIAL BONDED TO TEST MODEL SEGMENTS

5.8.2. The Model Configuration

The model section is shown in Figure 5-60. The outer shell was a high-strength steel cylinder, 10 feet 4 inches inside diameter, 1-1/2 inches thick, with a stiffening ring welded at each end of its 8-foot length. The inner shell was the model liner. Between the two were a laminated wooden filler, padded flat jacks, and portland cement grout backpacking.

Twenty flat jacks were used in the model, and these were installed in three hydraulic systems, A, B, and C, as shown in Figure 5-60. Each jack was calibrated before installation.

The rings were erected using a specially designed segment handling device attached to a forklift. Starting with ring no. 3, installation began with the invert segment being positioned. Next the lower wall segments were put in place and bolted to the invert segment. This operation continued until the complete ring was installed and bolted together. The crown segment consisted of a two-piece wedge segment for ease of installation. The invert of the next ring was positioned in such a manner that the longitudinal edge was at the one-third point of the adjacent invert segment. The ring was completed and bolted to the adjacent segments. Each succeeding ring was assembled in the same manner such that the longitudinal joints were at the one-third point of the previously installed adjacent ring segment. This resulted in every fourth ring having the longitudinal joints in the same location. Mud was splattered on the segments and sealant systems, as shown in Figure 5-61 and as discussed in Section 5.1.2. to simulate dirty working conditions in an actual tunnel. Figure 5-62 shows installation of the last segment in the model. After all 36 segments had been installed, a plywood bulkhead was bolted to one end of the model. At the other end, a bulkhead fabricated from two



SCALE : $\frac{1}{2}$" = 1'

FIGURE 5-60. MODEL SECTION

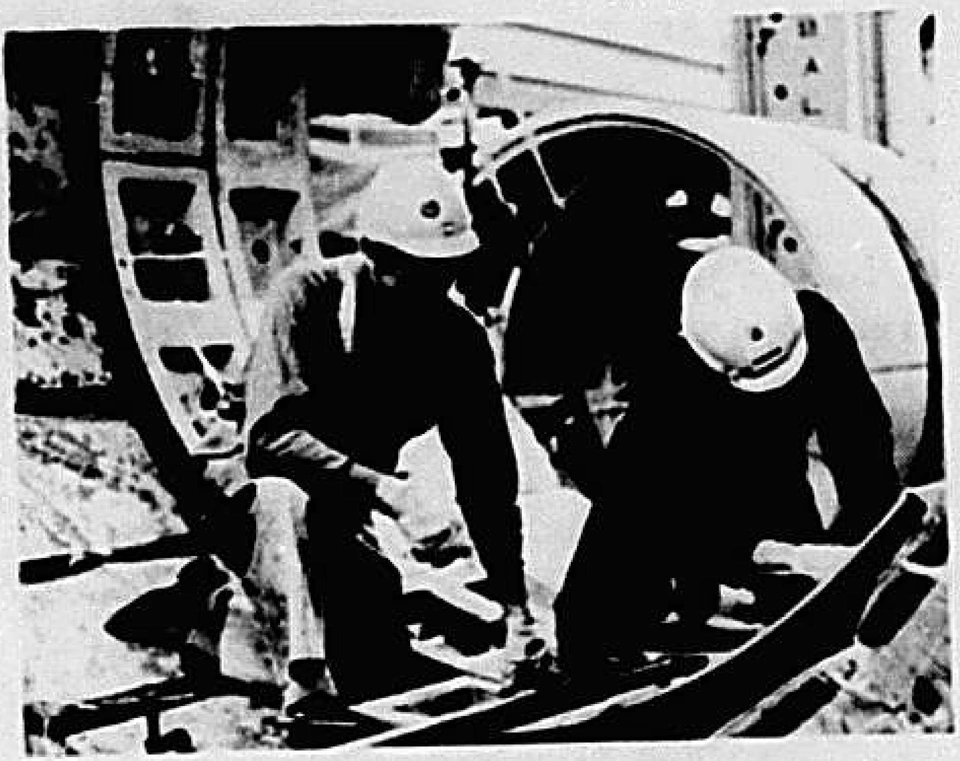


FIGURE 5-61."DIRTY"CONDITIONS BUILT INTO THE MODEL

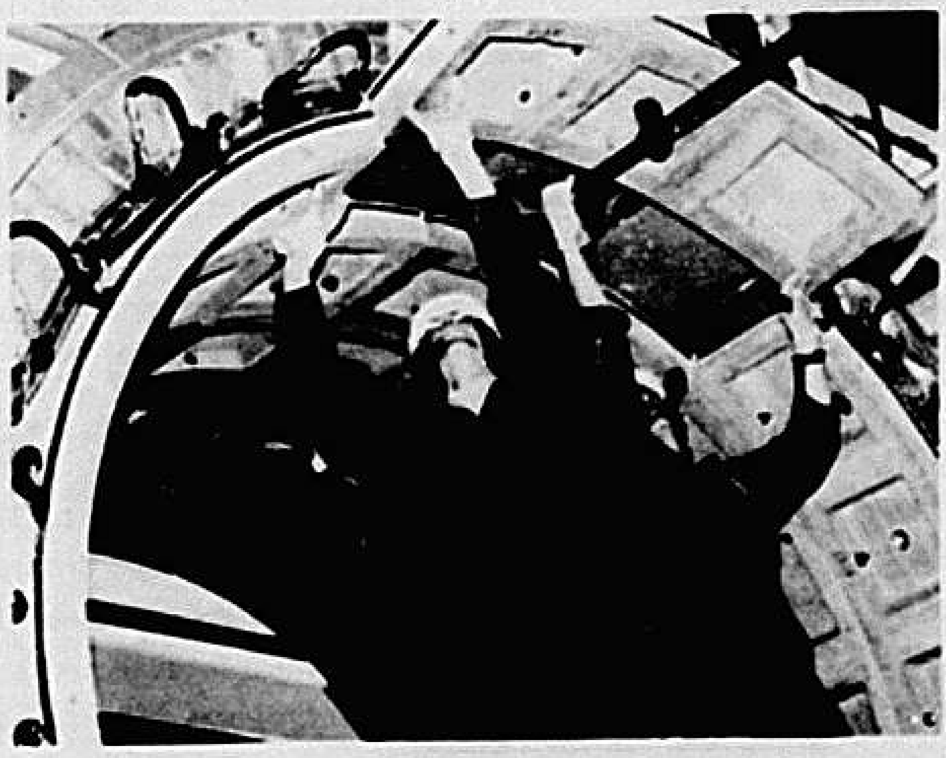


FIGURE 5-62. INSTALLATION OF THE LAST SEGMENT

rolled 4-inch angles and 1/4-inch steel plate was installed. This bulkhead was built to accommodate the hydraulic oil lines for the flat jack systems. Closed cell sponge rubber (3/8-inch neoprene) was used as gasket material to form a watertight seal between the two bulkheads and the test chamber.

Backfill grout was then pumped from bottom to top through the grout hole located in the center of the segments to fill the void between flat jacks and the liner.

5.8.3. Instrumentation Scheme

A reference frame was fabricated coincidental with the longitudinal axis of the model on which was mounted a multiarmed fixture holding eight radial displacement sensing LVDT's (linear variable differential transformers) as shown in Figure 5-63. Sixteen strain gages were embedded in four segments during fabrication. These were to monitor the applied loads on the liner. This instrumentation was located in ring no. 4 near the center of the model on one side only as shown in Figure 5-64. The loads were applied in a symmetrical manner; therefore, deflections and strains needed to be monitored on one side only.

Three pressure transducers were installed, one each in the three separate hydraulic-pressure regulating systems. The voltage signals from the pressure transducers and from the LVDT's and strain gages were input to a computer-controlled data logging system which supplied both printed paper and magnetic tape output. This magnetic tape was later used as input to a large computer for data reduction and printed and/or plotted output.

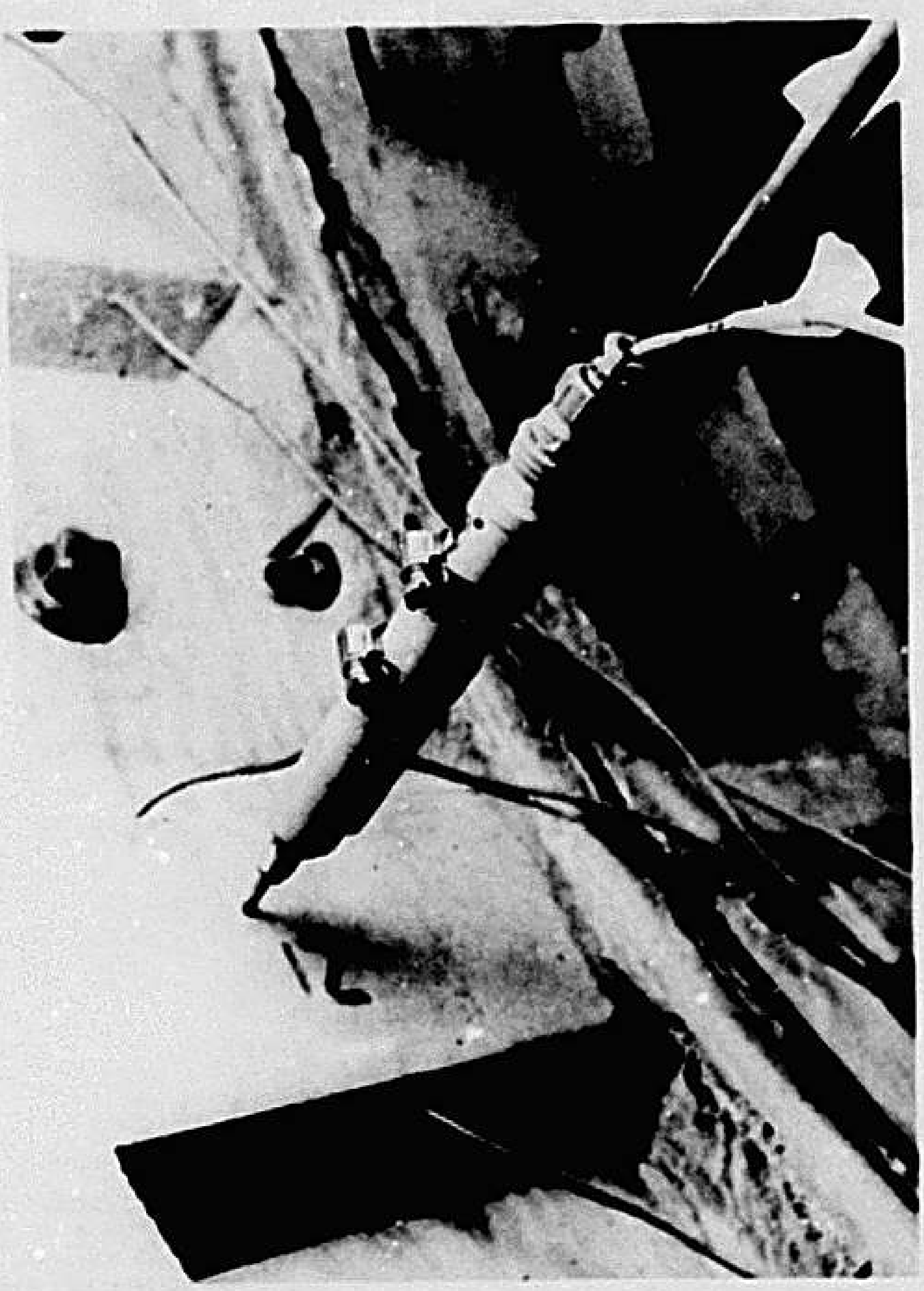


FIGURE 5-63. FIXTURE HOLDING LVDT IS SHOWN (AN ARRAY OF EIGHT SUCH INSTRUMENTS WAS USED TO MEASURE DEFLECTIONS)

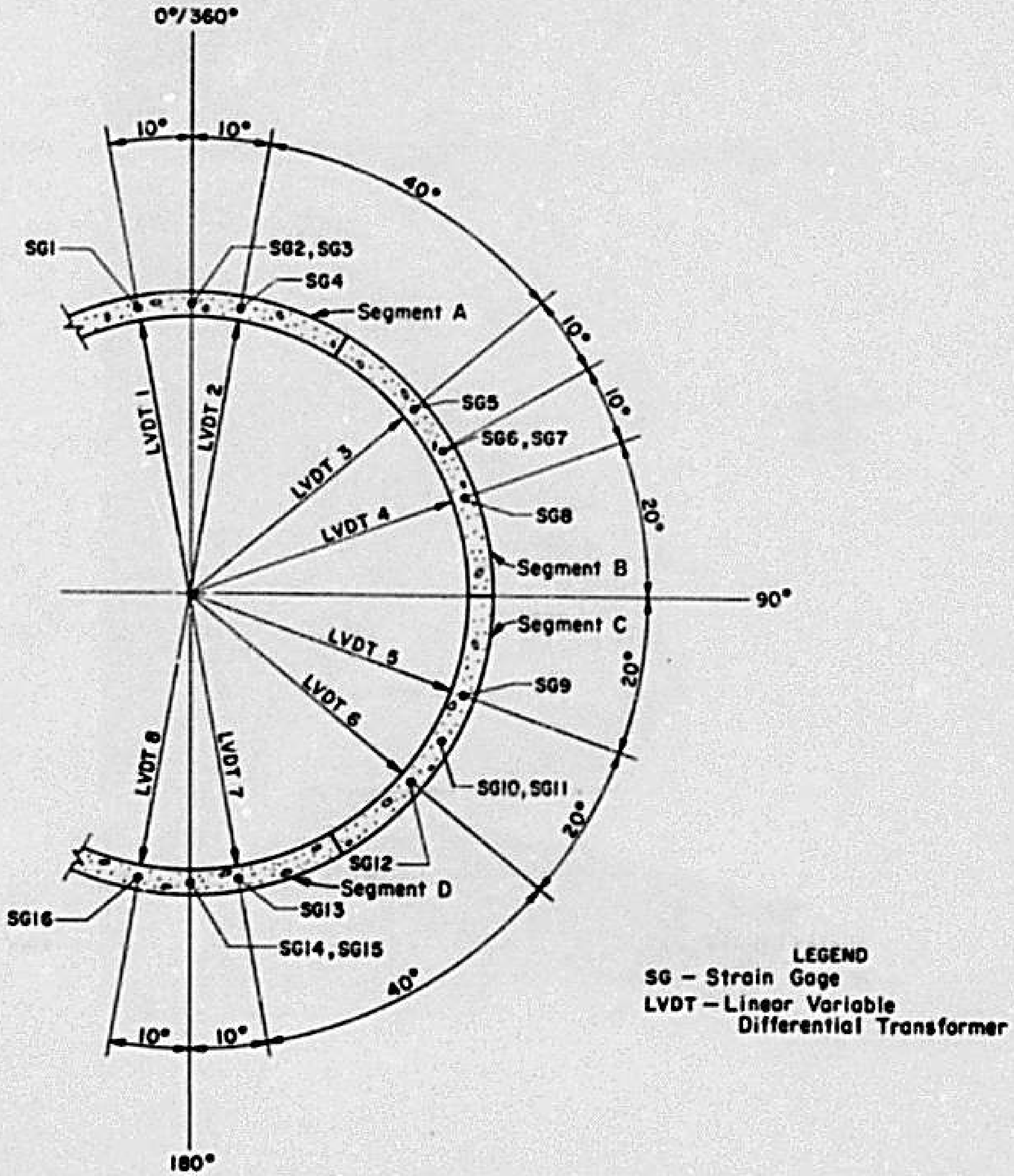


FIGURE 5-64. TEST RING INSTRUMENTATION

The hydraulic pressure system consisted of a 2,000-lb/in^2 maximum pressure, 100-gallon oil reservoir supply pump which was connected in series to a 3,000-lb/in^2, 10-gallon reservoir control pump. The pressures to the 20 flat jacks were supplied from three pressure-regulated systems. System A supplied 5 flat jacks in the crown of the model. Five jacks in each wall were connected in parallel to System B. System C supplied pressure to 5 jacks in the invert. These three systems are identified in Figure 5-60.

5.8.4. The Model Test

Water was introduced into the model between the outer steel shell and the liner through a hole in the top of the model. Initially, the space was vented to exhaust contained air. After venting, a water tank was attached to the model with a 1-inch-diameter hose and placed to provide a 5-foot head on the fluid. This was held for 14 days when the tank was raised to provide a 15-foot head. This again was held for 14 days, at which time the tank was raised to provide a 60-foot head. The system was intended to simulate ground-water pressure. The head was increased incrementally to determine if leakage would occur at these low pressures. After 14 days at 60-foot head (26 lb/in^2), leakage did not occur. At that point, the system was connected to a city waterline at a pressure of 65 lb/in^2. Some leakage did occur at that pressure so the system was returned to 60-foot head. The leaks were repaired as discussed in Section 5.3.2. However, part of the leakage between the crushable compression seal and the full surface preformed elastomeric gasket was not repaired to observe what would occur with subsequent pressure increases.

The hydrostatic pressure was monitored during this period by reading the embedded strain gages and converting the data to stress. Deflections were not monitored as the LVDT's were not installed at this time.

When all of the instrumentation was installed and scaled to zero readings, simulated ground pressures were induced through the flat jack systems. Uniform pressures were applied in 50-lb/in^2 increments. All gages were read three times at each pressure at 5-minute intervals. Following the third set of readings, the pressure was increased to the next level and the sequence repeated. This continued until the liner failed.

5.8.5. Test Results

As discussed in Section 5.8, the principal purpose of the one-half scale model was to demonstrate the performance of the candidate joint sealant systems under simulated underground conditions. The performance of the three sealant systems used in the model is discussed in Section 5.1.1. All of the systems were generally satisfactory in the model. The model, however, did not perform as expected. Controlled pressure regulation, as planned, was not achieved. When the data from the strain gage readings taken during the water filling and ground-water simulation were plotted gage by gage, it was evident that nonuniform pressures were being exerted on the lining. These pressures ranged from a low of 322 lb/in^2 to a high of 3,288 lb/in^2. The data are plotted and shown in Figures 5-65 through 5-80. The gage identifications used on these plots are shown in Table 5-8. Gage nos. 12, 13, and 16 apparently were malfunctioning.

It is presumed that these nonuniform pressures resulted from swelling of the wooden filler used in the model when water was introduced. Wood, when wetted, swells transversely and, with the close fit of the components between the outer shell and the

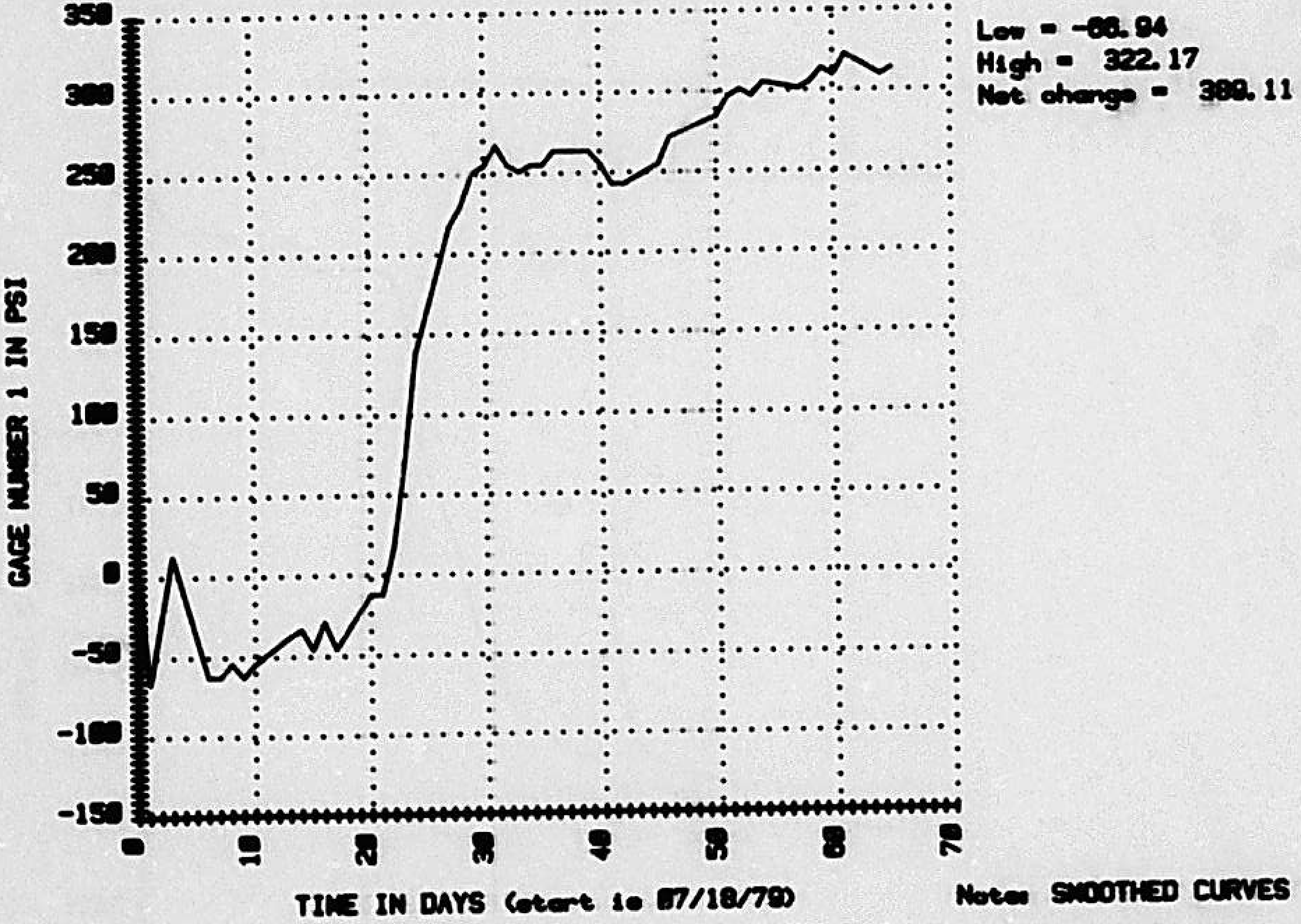


FIGURE 5-65. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 1.

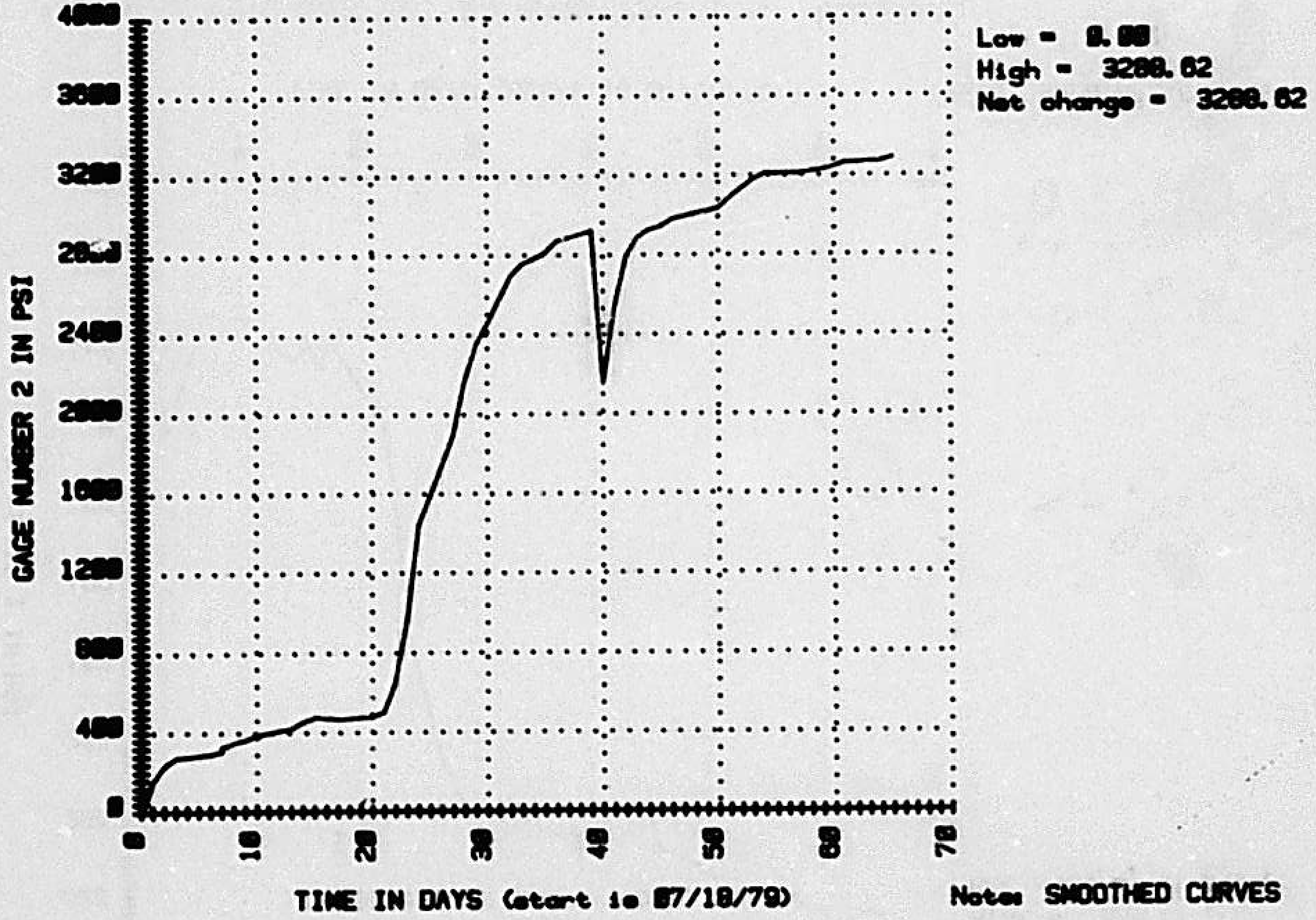


FIGURE 5-66, DOT/TSC TUNNEL TEST, GAGE READINGS BEFORE TESTING - GAGE NUMBER 2.

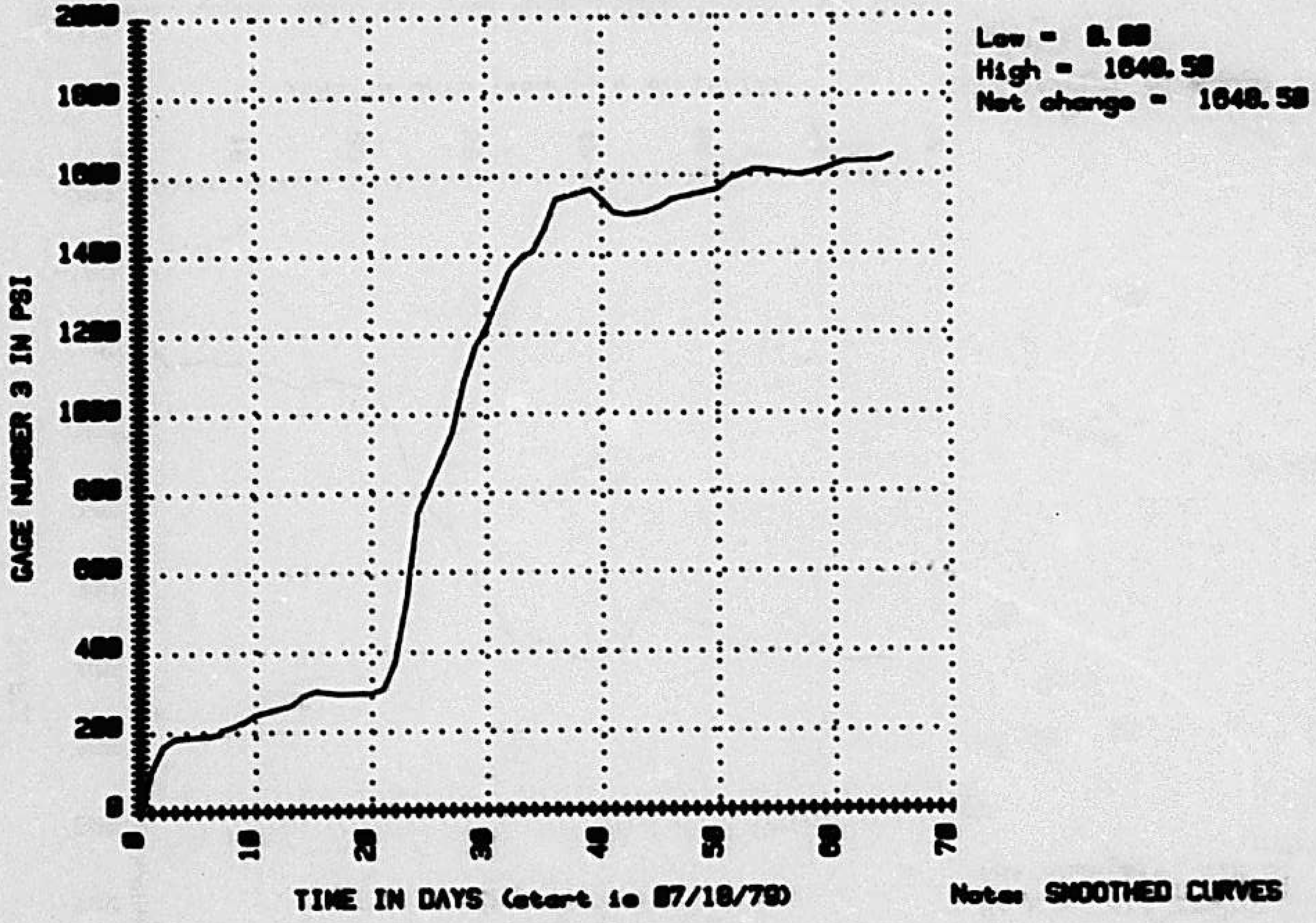


FIGURE 5-67, DOT/TSC TUNNEL TEST, GAGE READINGS BEFORE TESTING, GAGE NUMBER 3.

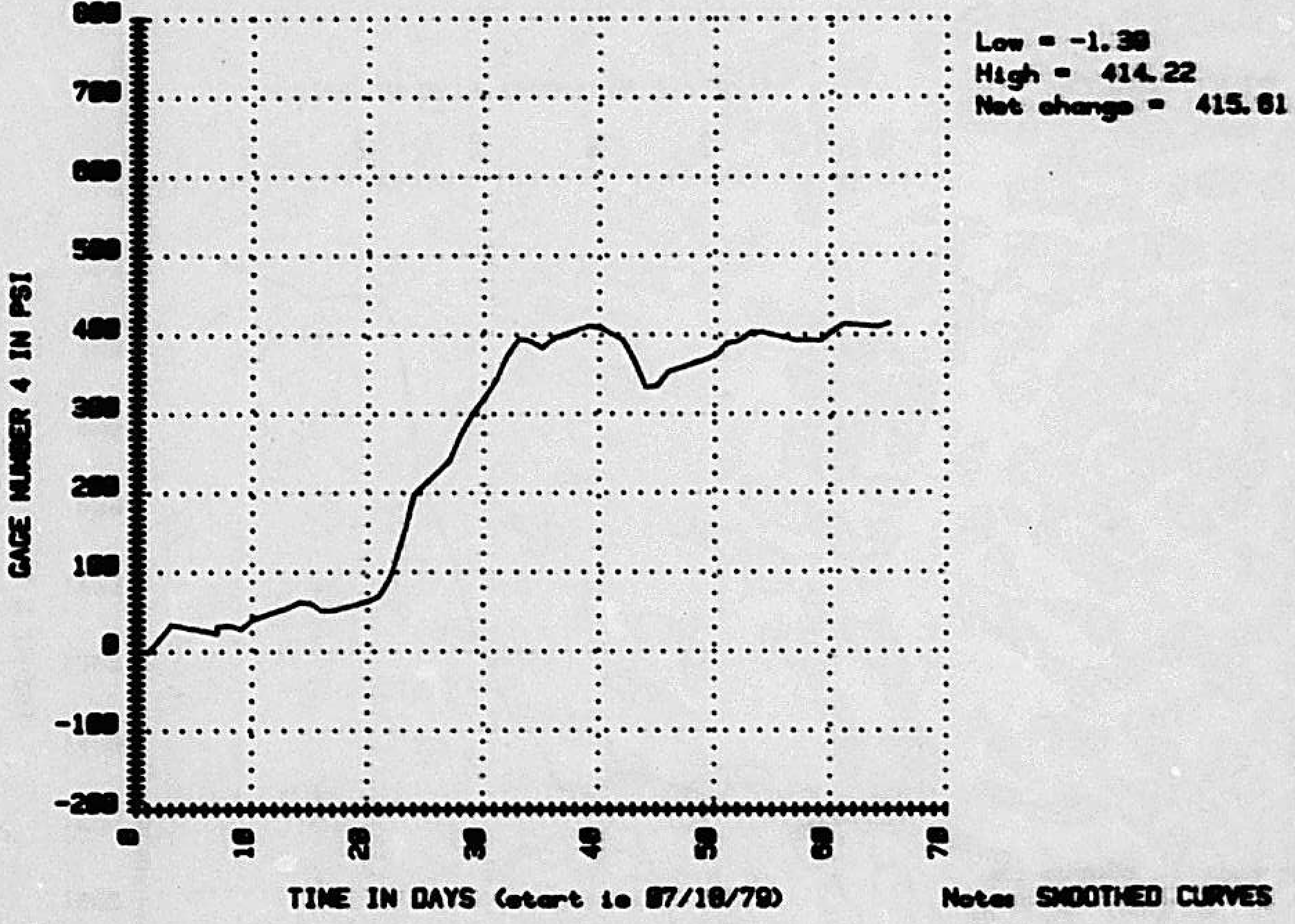


FIGURE 5-68. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 4.

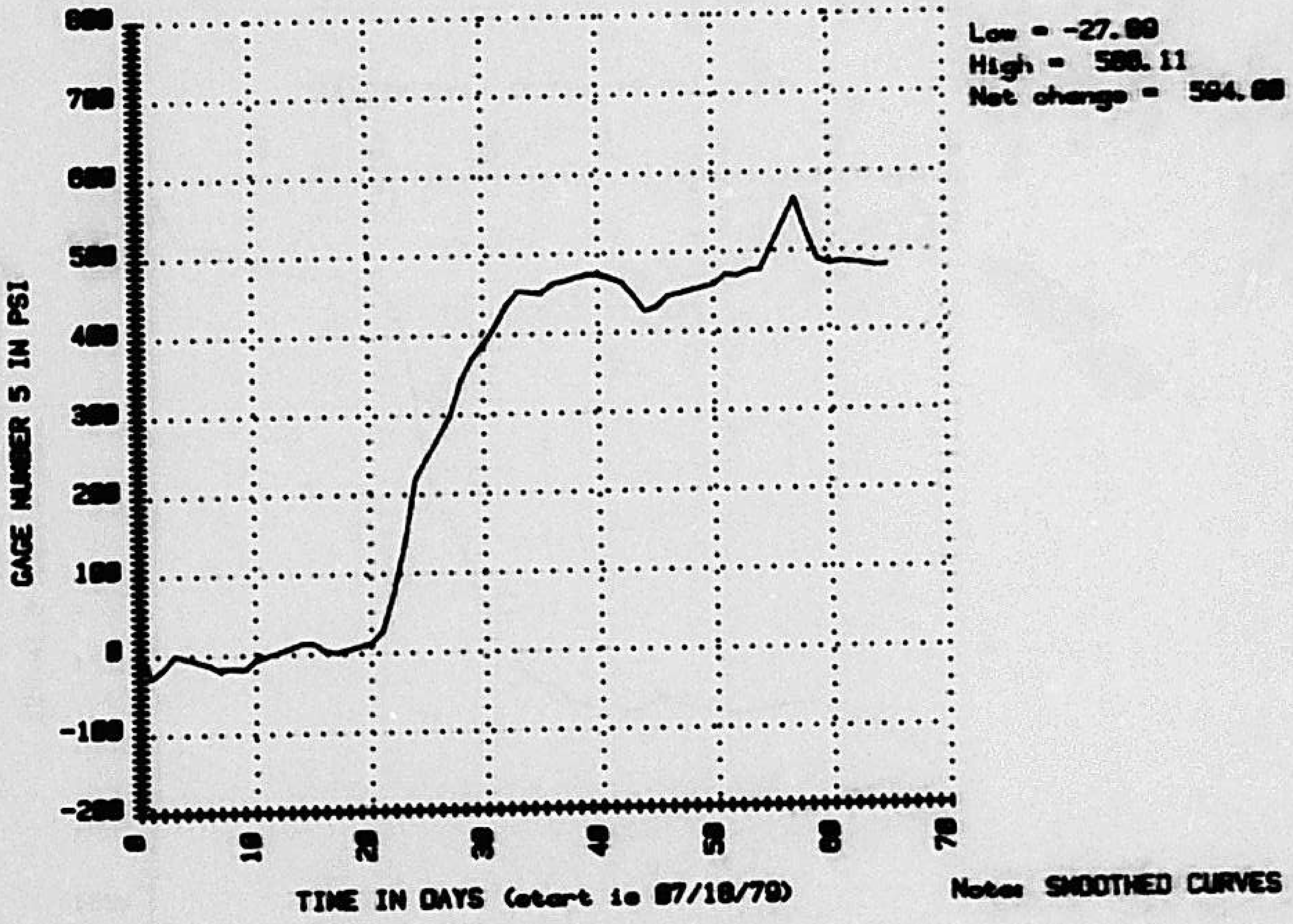


FIGURE 5.69, DOT/TSC TUNNEL TEST, GAGE READINGS BEFORE TESTING - GAGE NUMBER 5.

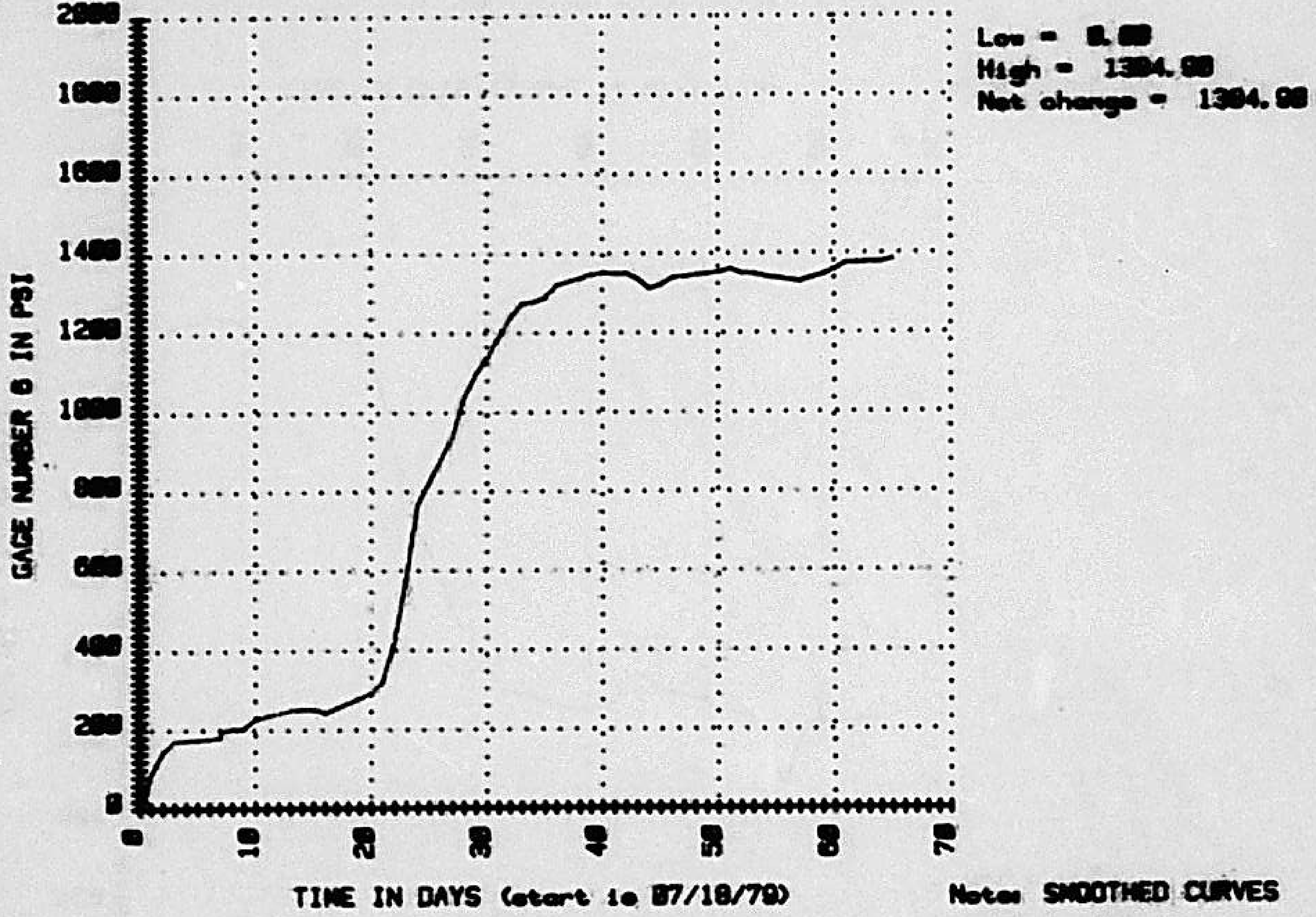


FIGURE 5-70. DOT/TSC TUNNEL TEST GAGE READINGS BEFORE TESTING - GAGE NUMBER 6.

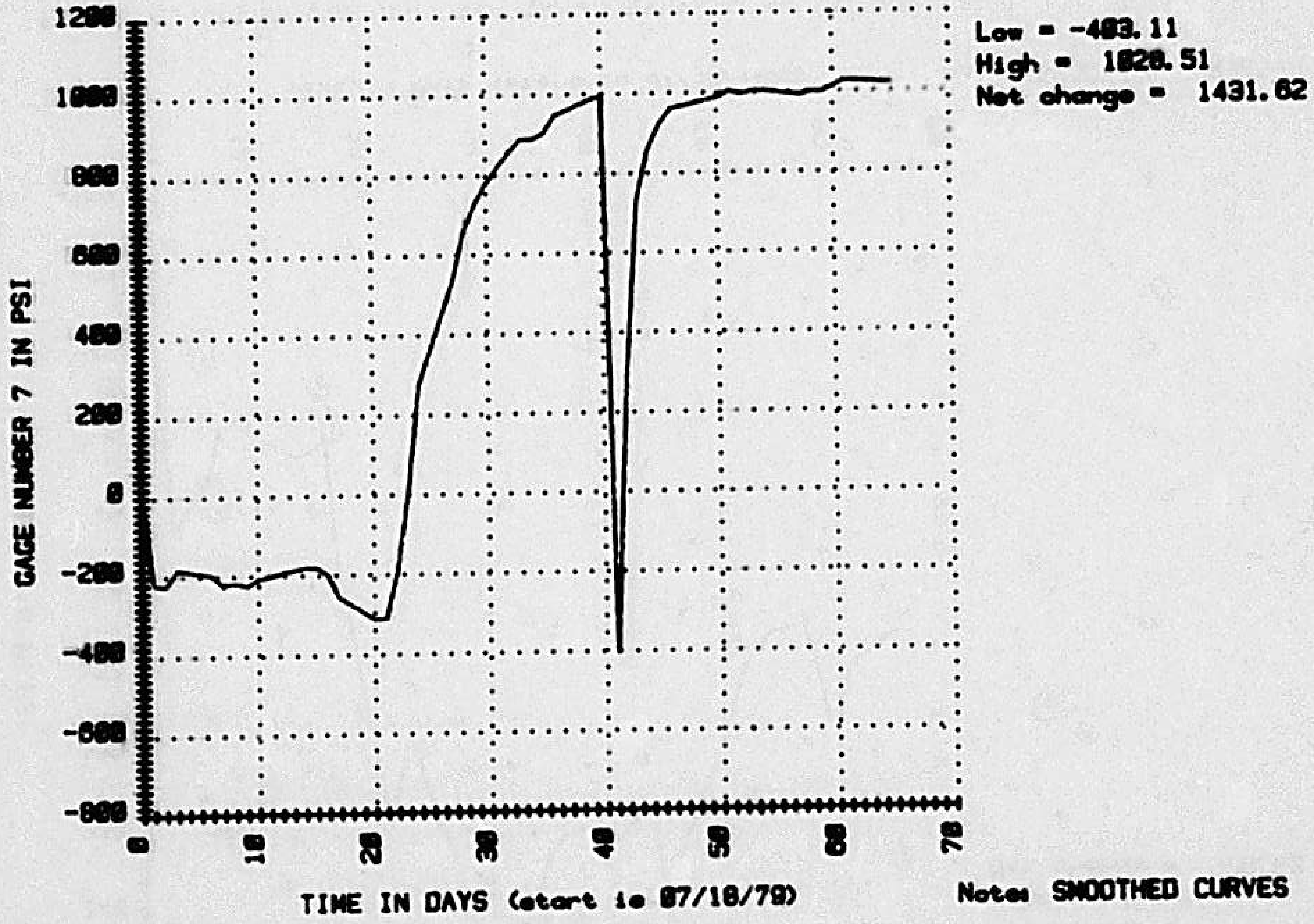


FIGURE 5-71. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 7.

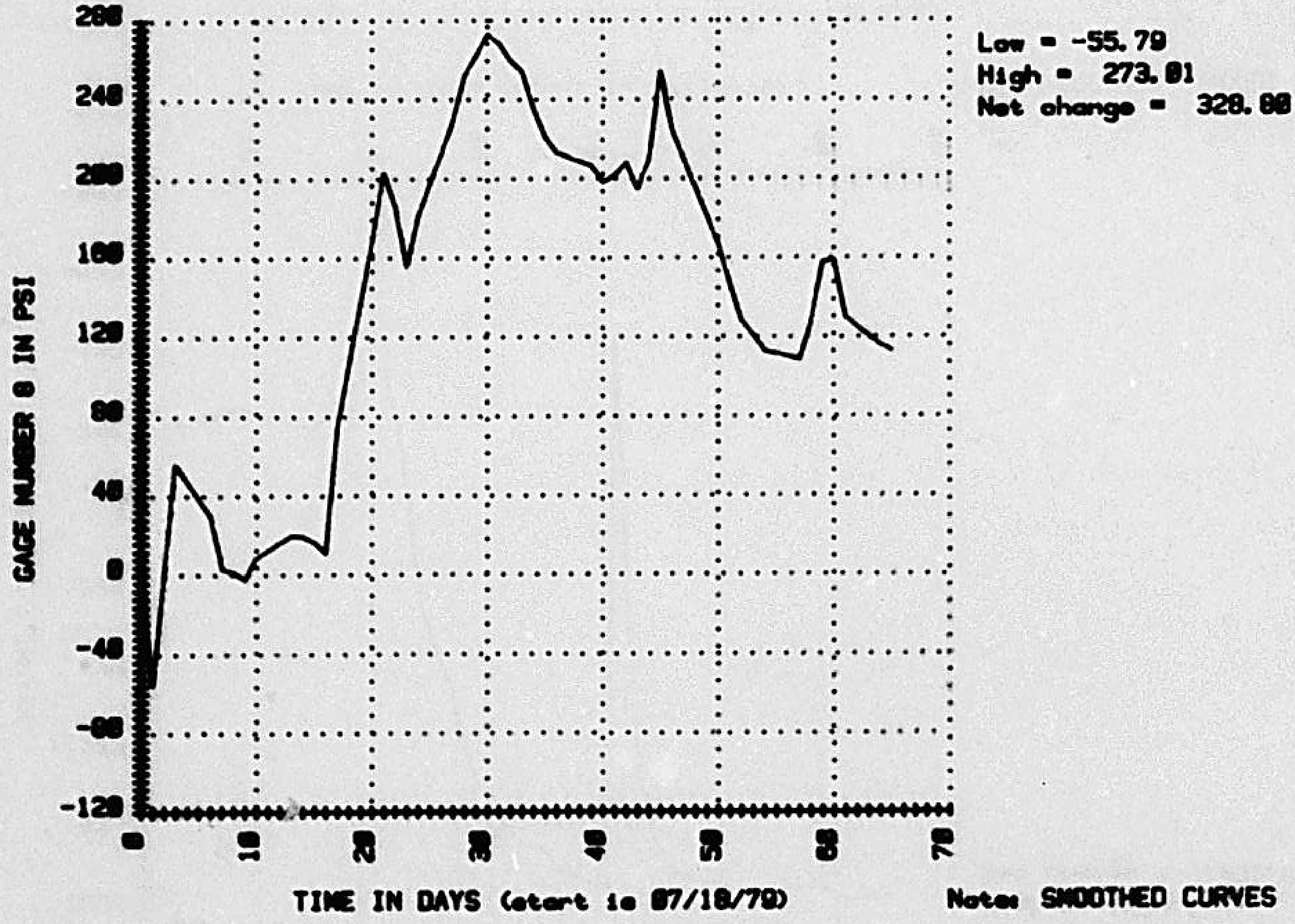


FIGURE 5-72. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 8.

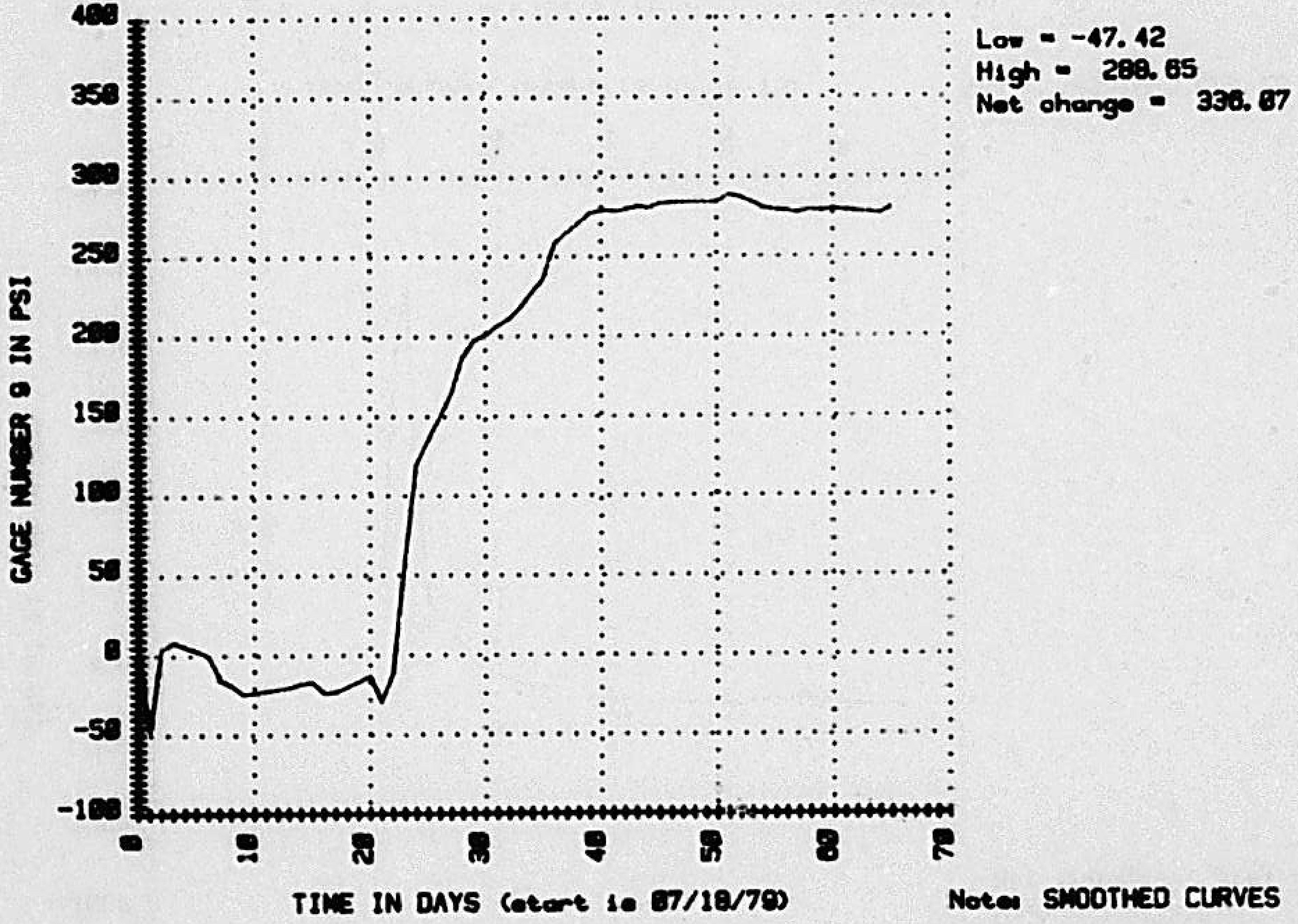


FIGURE 5-73. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 9

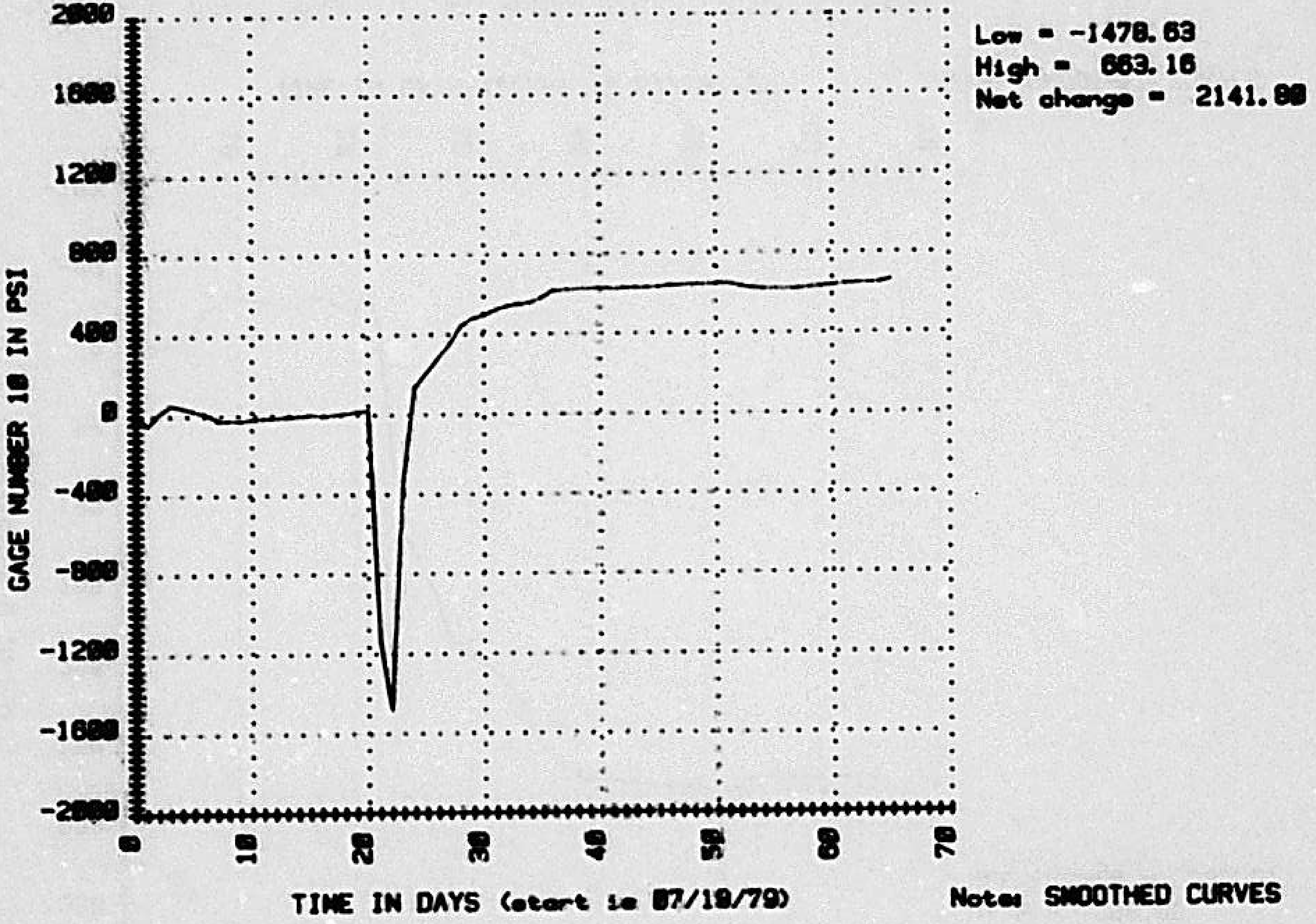


FIGURE 5-74. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 10.

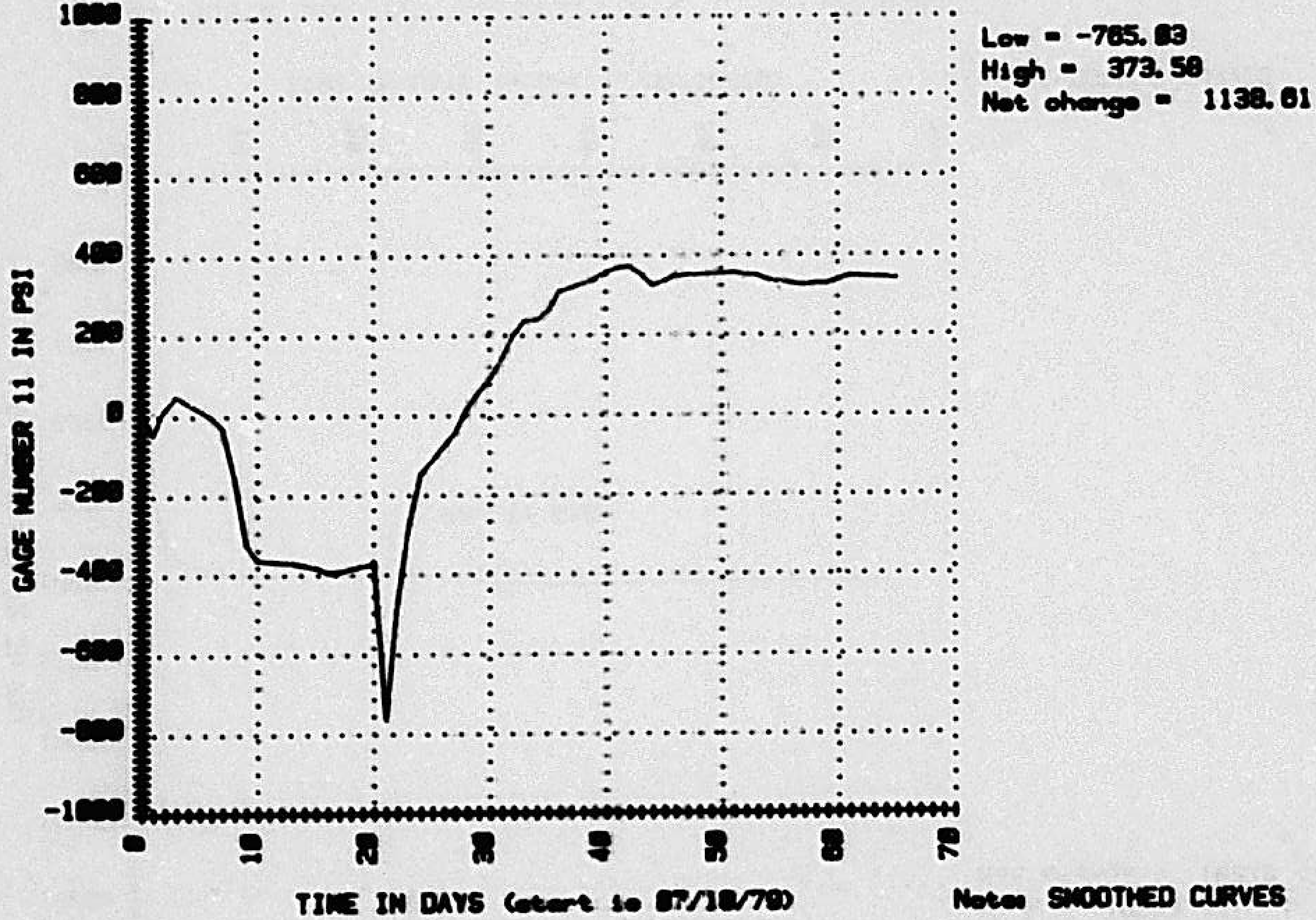


FIGURE 5-75. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 11.

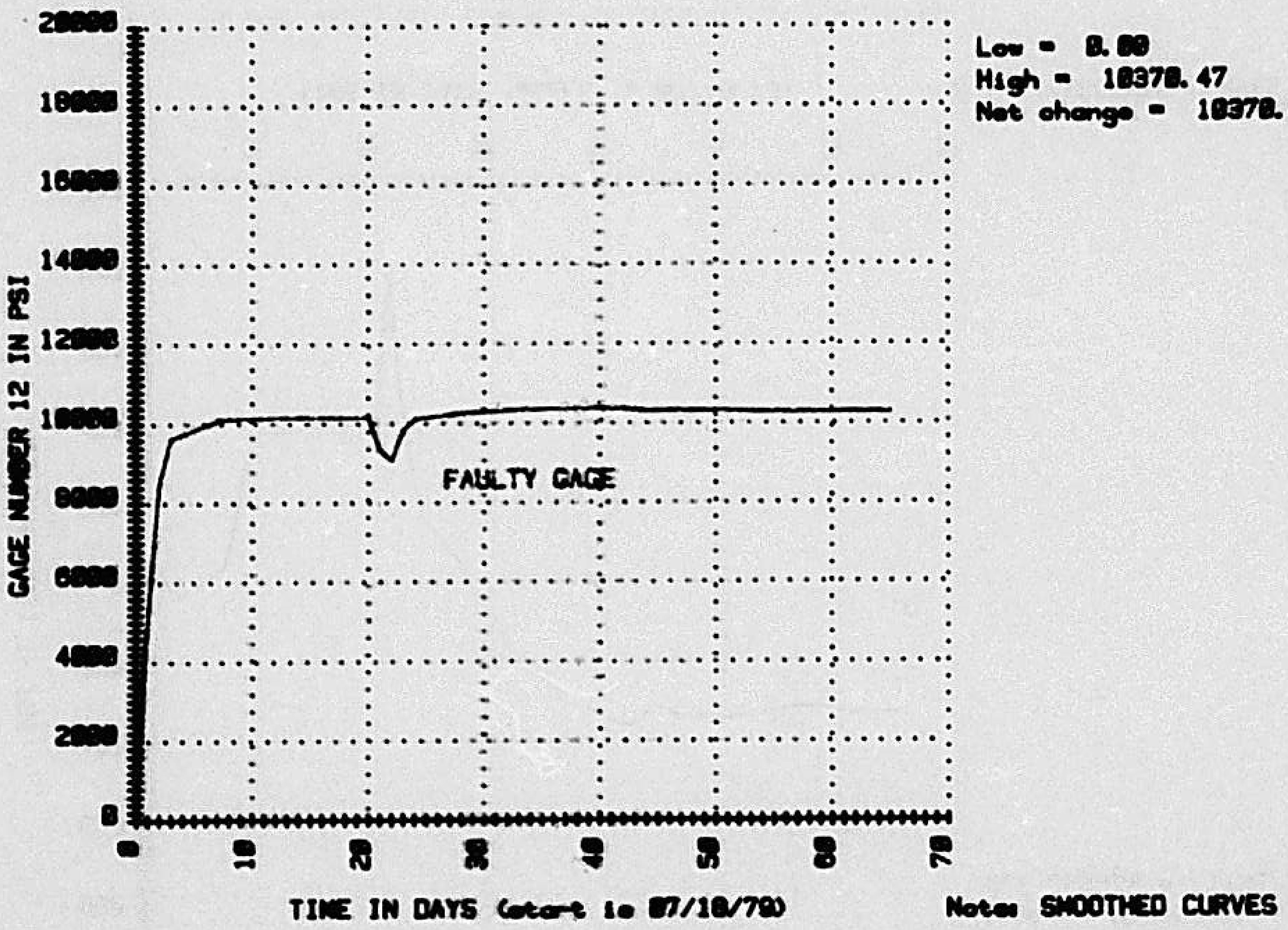


FIGURE 5-76. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 12.

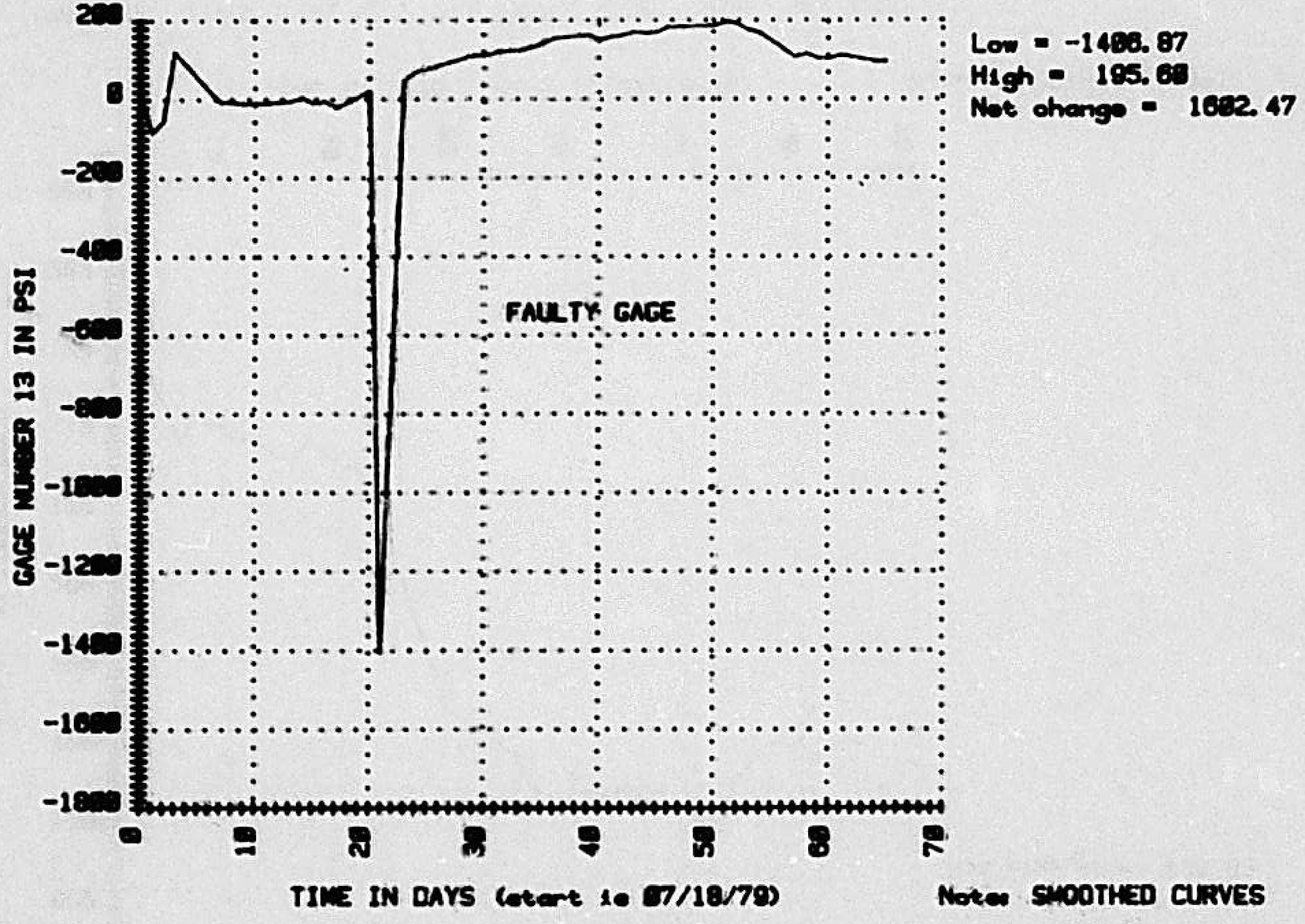


FIGURE 5-77. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 13.

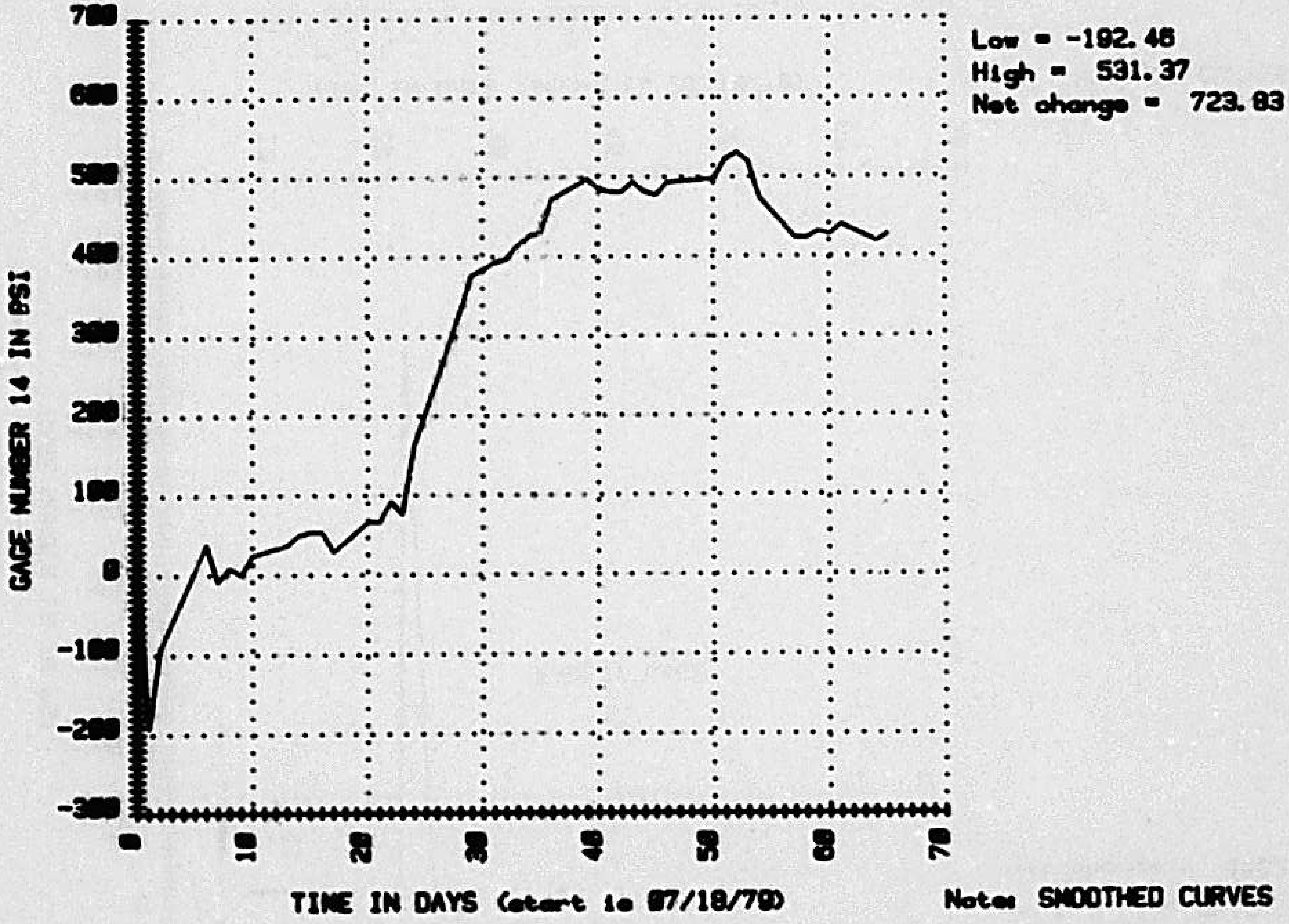


FIGURE 5-78. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 14.

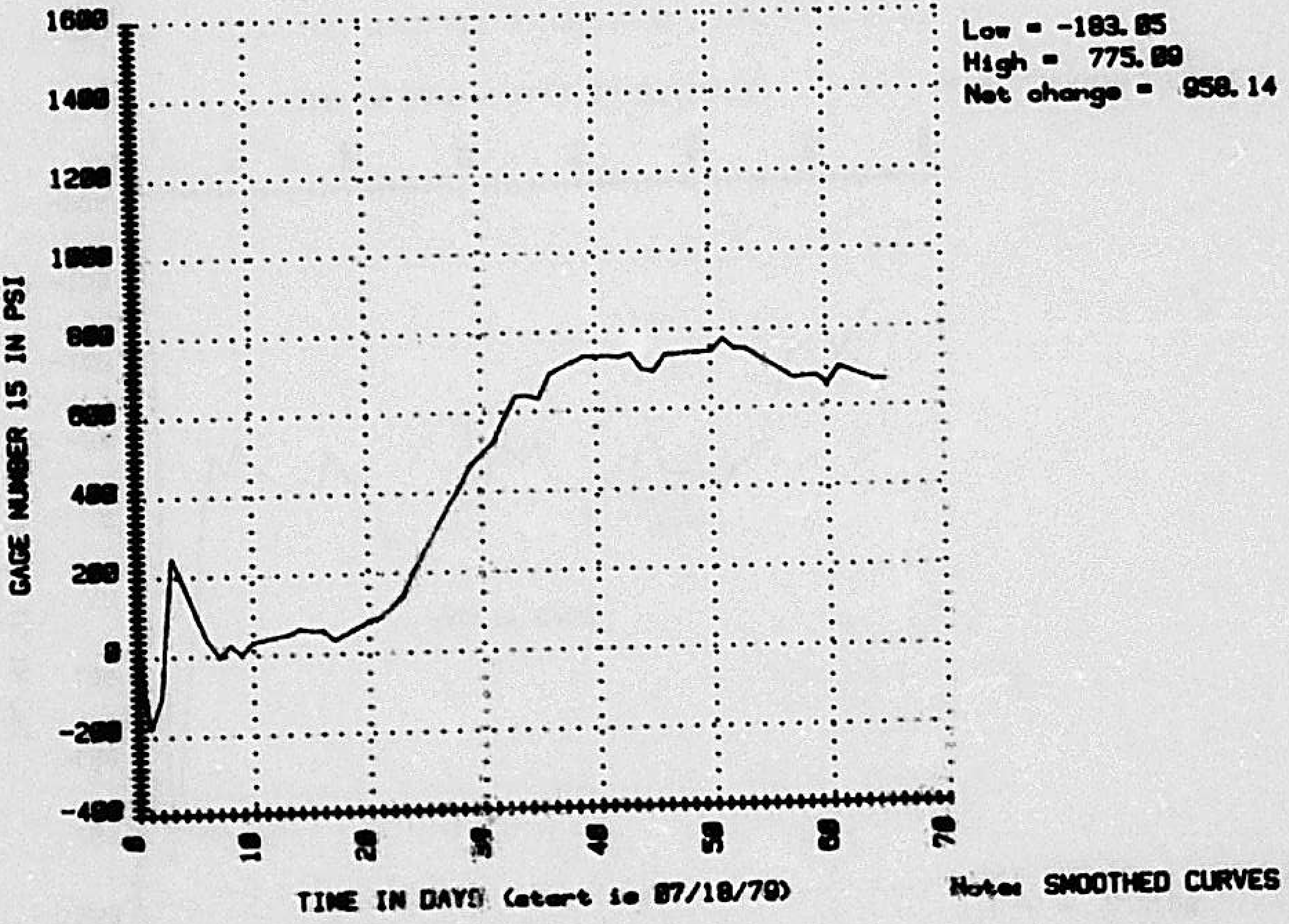


FIGURE 5-79, DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 15.

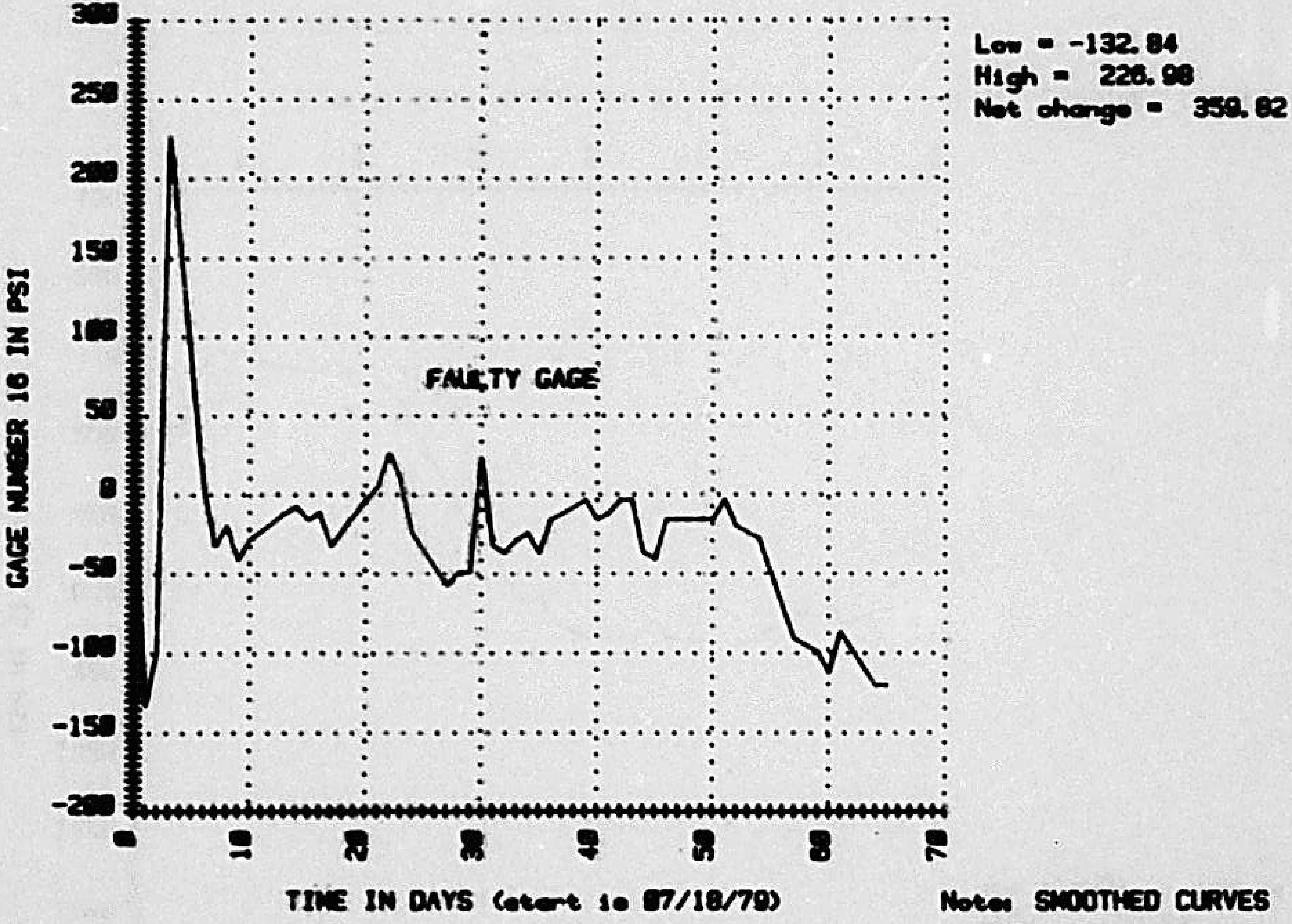


FIGURE 5-80. DOT/TSC TUNNEL TEST. GAGE READINGS BEFORE TESTING - GAGE NUMBER 16.

TABLE 5-8. GAGE IDENTIFICATION

Strain gages

Label	Strain gage No.
IPAAD	1
IPABA	2
IPABC	3
IPACB	4
IPBDD	5
IPBEA	6
IPBEC	7
IPBFB	8
IPCGD	9
IPCHA	10
IPCHC	11
IPCIB	12
IPDJD	13
IPDKA	14
IPDKC	15
IPDLB	16

LVDT's

Label	LVDT No.
LIAA*	1
LIAC*	2
LIBD	3
LIBF*	4
LICG*	5
LICI*	6
LIDJ*	7
LIDL*	8

Hydraulic System Pressure Transducers

Label	System
PLAB*	A
PLBM*	B
PLDK*	C
PLEN*	D

liner, resulted in increasing pressures. The nonuniformity results from differences in the degree of swelling from board to board and the tightness of the fit. When the model was designed, swelling of the wooden filler was not seriously considered as the wood for the filler was to have been waterproofed. The waterproofness must have been altered when the boards were planed and trimmed to fit the outer shell. As it turned out, these loads actually simulated variable, nonuniform ground loads with ground-water pressure rather than just hydrostatic loads from the water. This was not all bad, as it demonstrates the effectiveness of the liner and sealant systems under 60 feet of ground-water head and variable ground loads.

The coup de grace occurred shortly after the flat jack loads were applied to the liner. The loads were increased as discussed in Section 5.8.4. and were representative of further increasing ground loads. These data are plotted in Figures 5-81 through 5-84. Each plot shows all of the data from an instrumented segment as shown in Figure 5-64. The four figures show stress in pounds per square inch computed from the strain readings, deflection in inches as measured with the LVDT's, and loads in pounds per square inch from the flat jacks for segments A, B, C, and D, respectively.

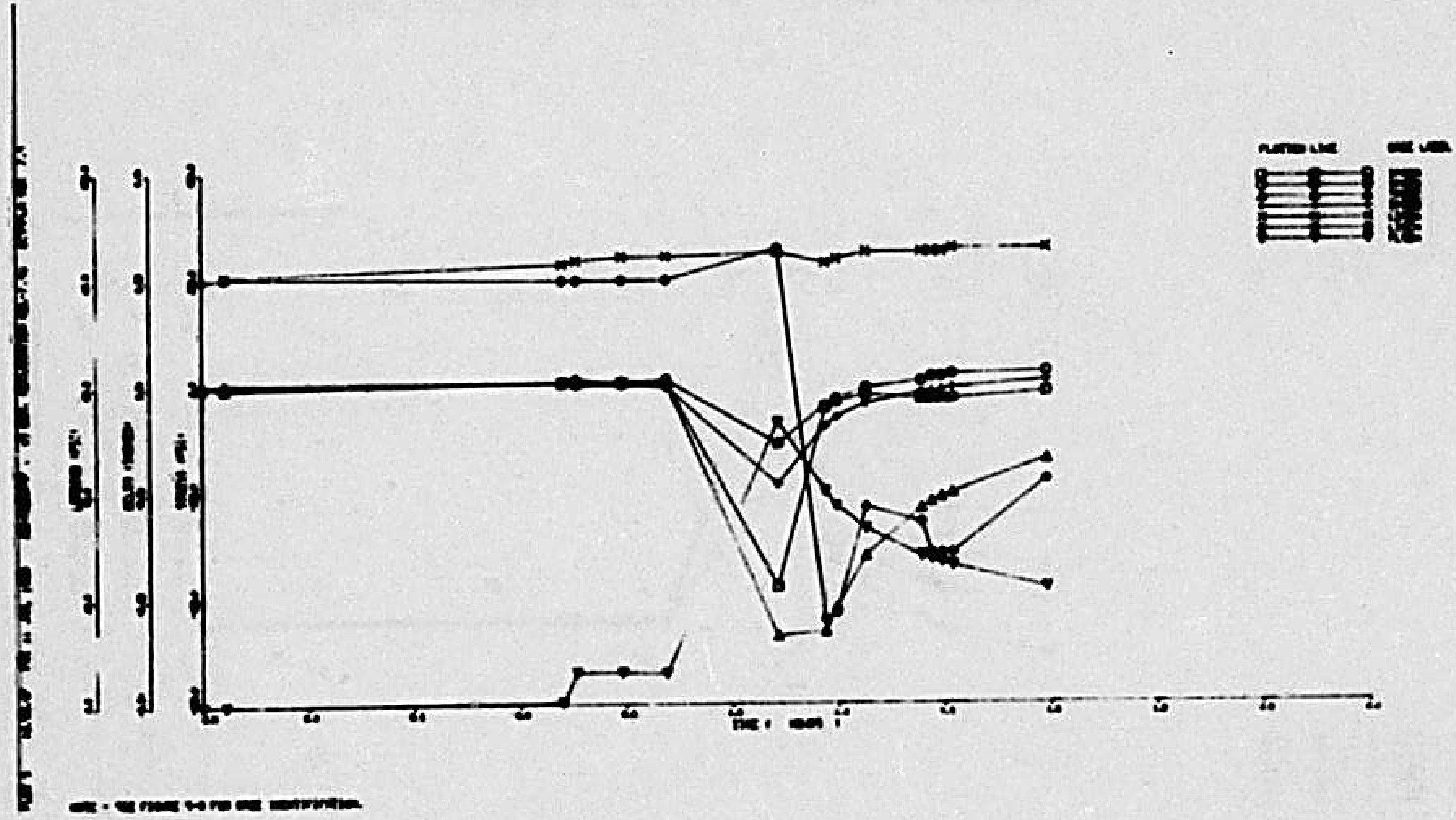


FIGURE 5-81. TUNNEL SEGMENT TEST - SEGMENT A (TOP).

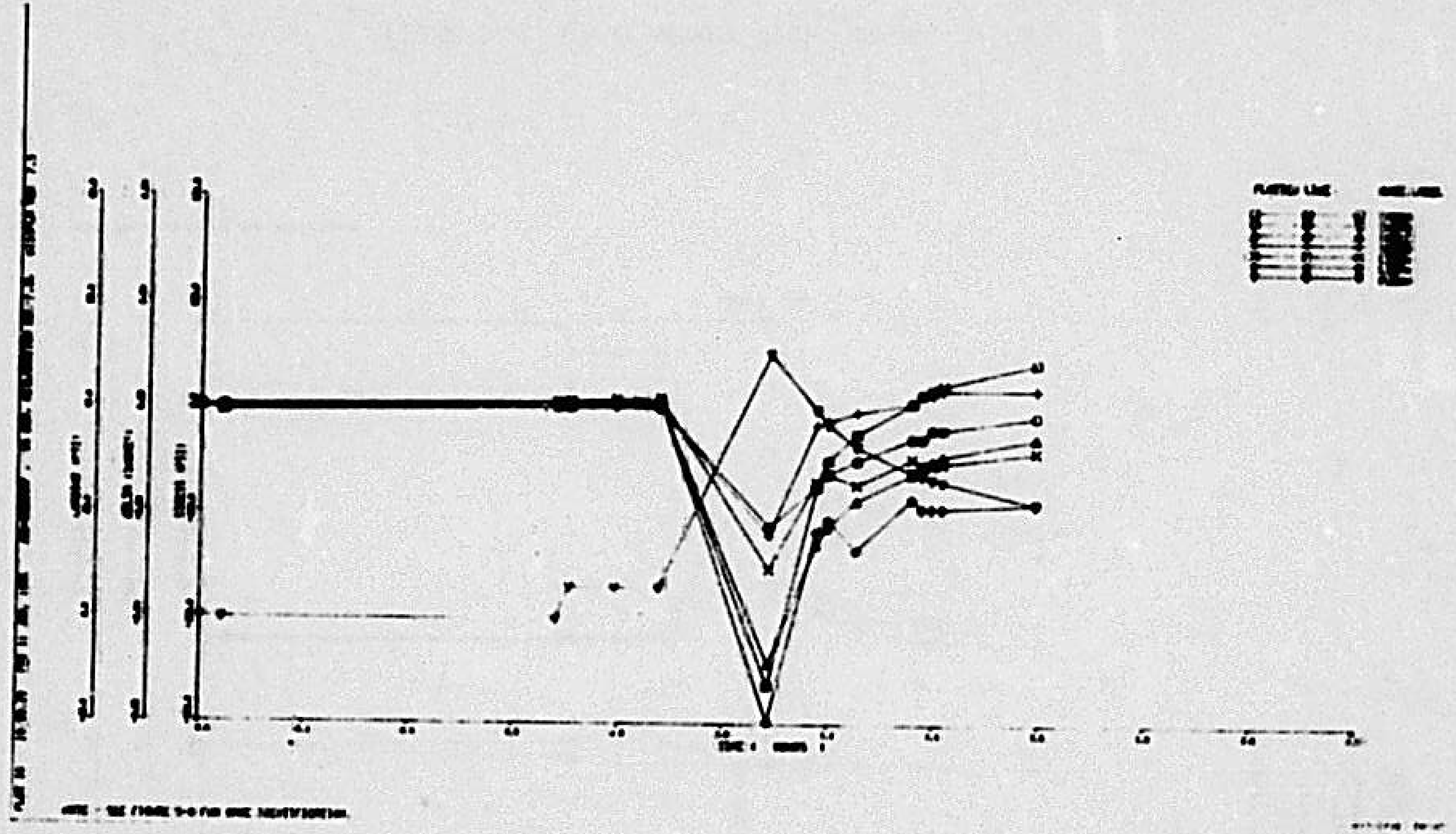


FIGURE 5-82. TUNNEL SEGMENT TEST - SEGMENT B (UPPER RIGHT).

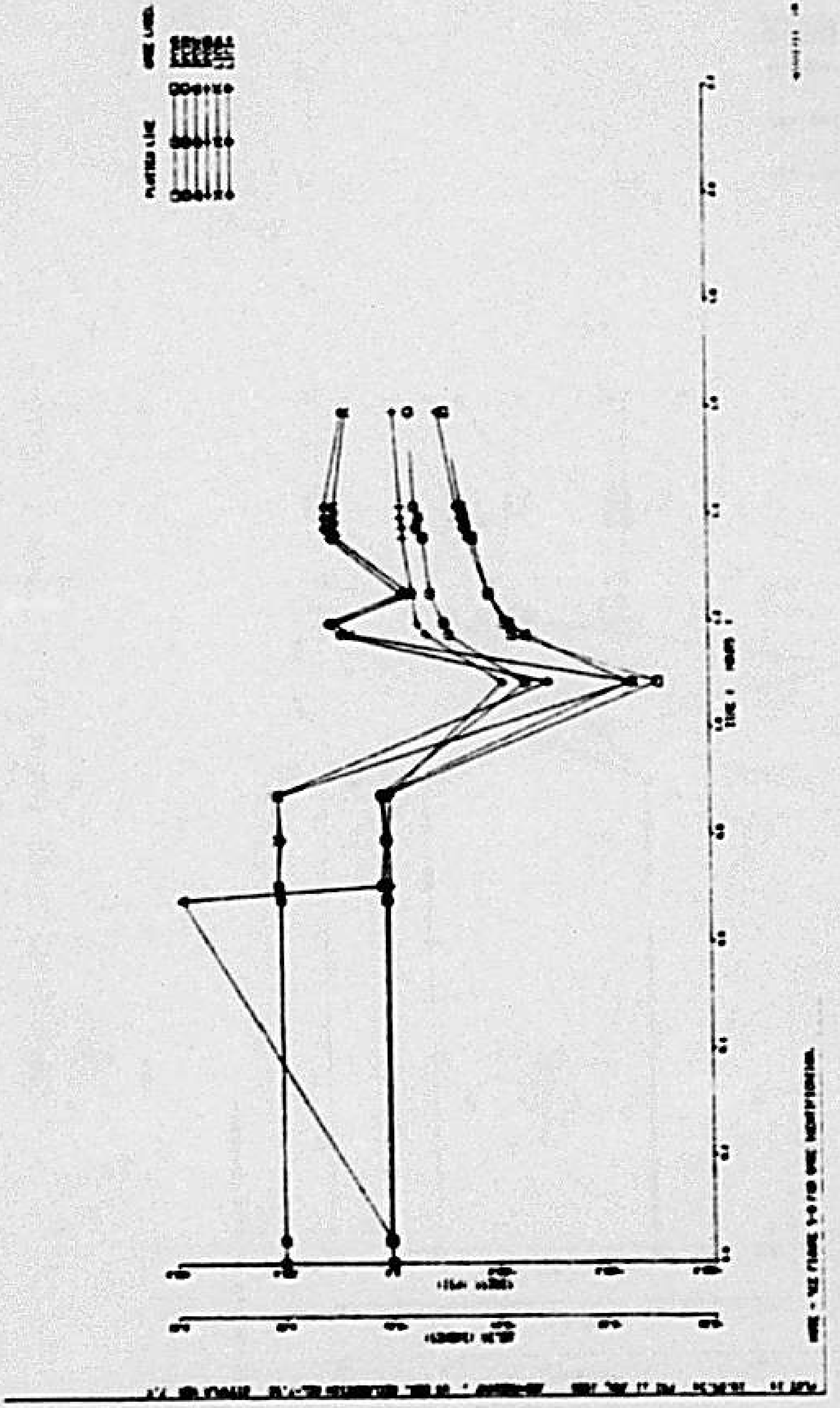


FIGURE 5-83. TUNNEL SEGMENT TEST - SEGMENT C (LOWER RIGHT).

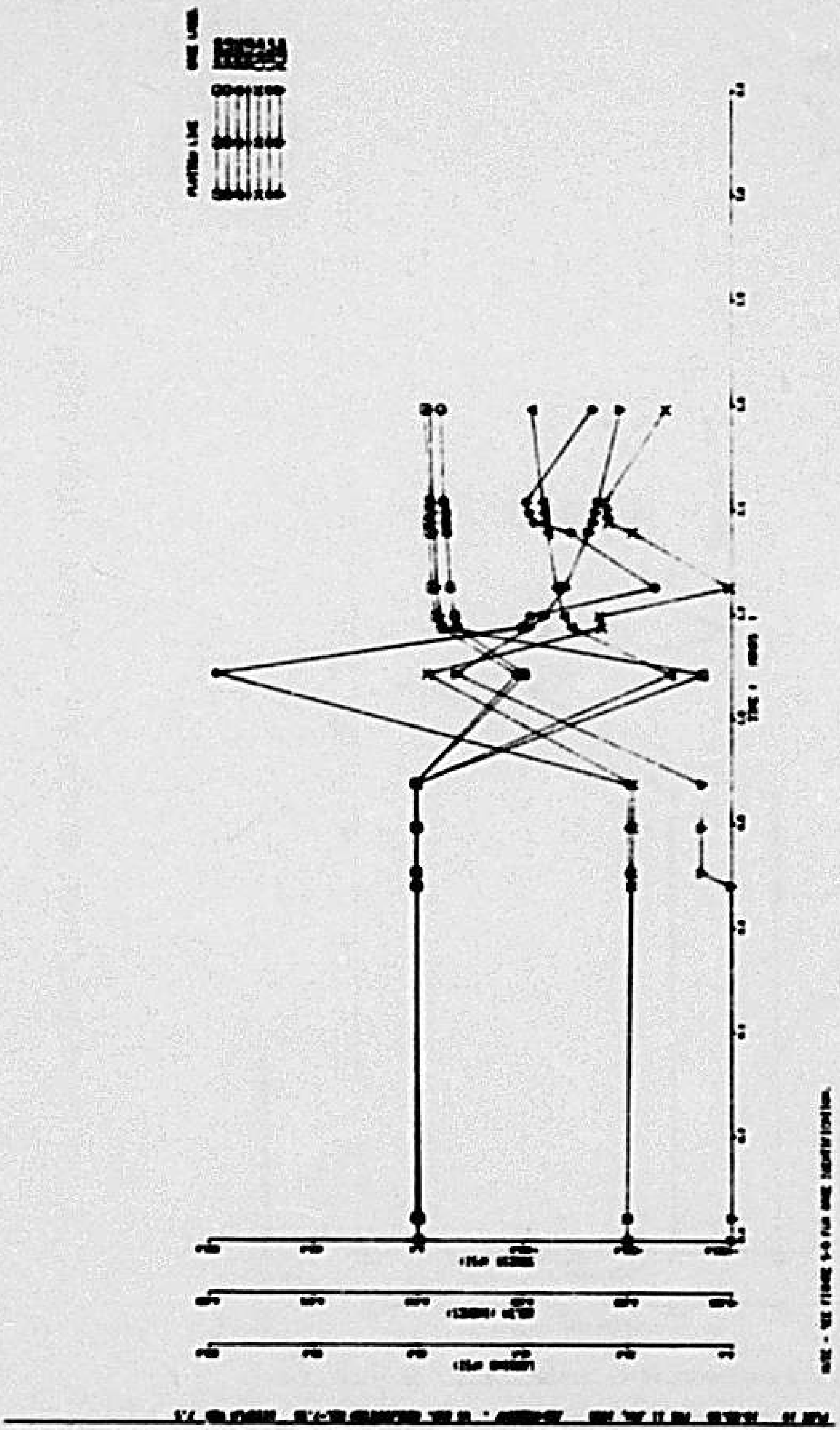


FIGURE 5-84. TUNNEL SEGMENT TEST - SEGMENT D (BOTTOM)

The principal damage to the model after failure is shown in Figure 5-85. The failure mechanism appears to be a wedging or punching shear stress at the bolted connections between segments in adjacent rings. The failure was brittle and sudden in nature. The fact that little warning was given prior to failure should be considered when designing the connections for segmented liner systems.

The sealant systems remained watertight under the increasing loads up to the point of failure.

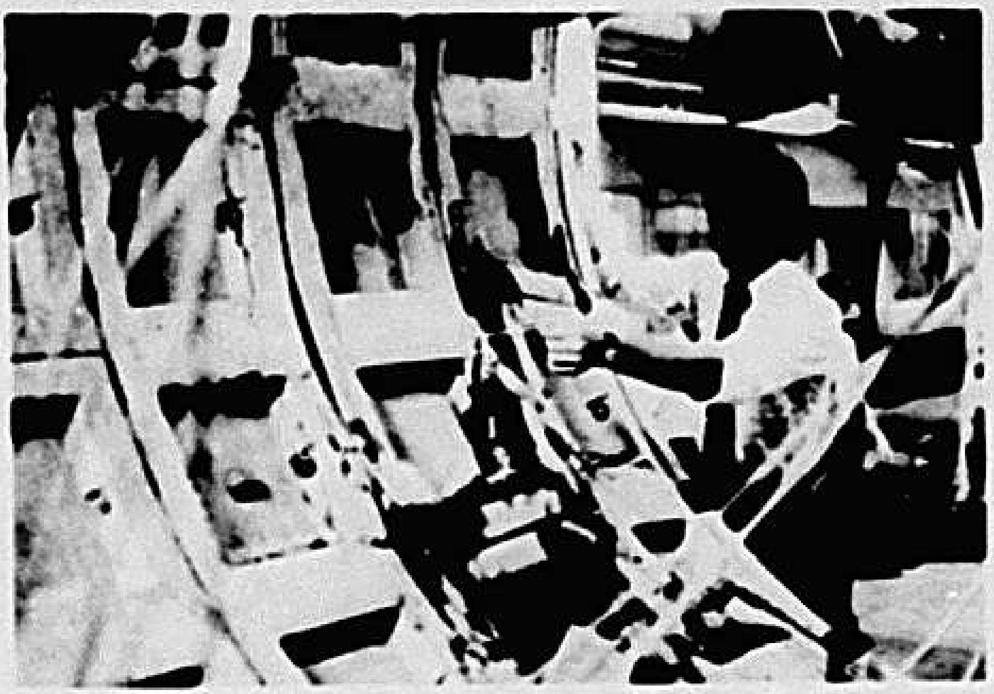


FIGURE 5-85. PRINCIPAL DAMAGE TO THE MODEL IS SHOWN (SHEAR FAILURE BETWEEN ADJACENT RINGS APPEARS TO BE THE CAUSE)

6. PHASE 5 - DEVELOPMENT OF DESIGN AND CONSTRUCTION SPECIFICATIONS

During the course of this study, numerous segments were designed and cast in the laboratory, ranging in size from the one-eighth scale minitunnel segments to full-size Stillwater Tunnel segments 8 feet 3 inches in diameter. Reusable forms were designed to evaluate reproducibility of the segments and maintenance of tolerances. The forms were made from plywood and sheet metal and were generally satisfactory for casting three to five segments. Reproducibility of the forms was also demonstrated with replicate forms being constructed by shop craftsmen. It was evident that even under closely controlled laboratory conditions, close inspection was necessary throughout each step of the segment fabrication to maintain desired quality.

As previously mentioned, Buckskin Mountains and Stillwater Tunnels were under construction during the course of this study. At Buckskin Mountains Tunnel, more than 28,800 segments were cast using trains of six forms each, utilizing eight trains at a time. Segments were cast in one train, cured in a second in a steam chamber, and stripped from a third; the forms were subseqently cleaned and prepared for the next use. At Stillwater, the contractor set up a casting yard of approximately 300 forms with concrete bases and steel sides. Moist curing was utilized. Sequential operations progressed through all forms from start to finish in casting the segments in daily cycles. In general, satisfactory reproducibility was achieved in both cases; however, very close inspection was required.

Many segments were damaged in casting, handling, curing, and transporting, and it was necessary to establish repair procedures and criteria to reduce the number of rejected segments. Epoxy resins were used at both of the previously mentioned tunnels. Although repair of damaged segments was not part of this study, it is critical to obtain an acceptable construction job. New, commercially available, polymethacrylate polymer concretes should be considered in any repair program.

In each instance of tunnel construction, the contractor should be required to demonstrate his capabilities in manufacturing and installation, using test assemblies. This will demonstrate initial conformance to specified quality and tolerance.

The paragraphs that follow are guide paragraphs for a segmented lining and for its installation.

6.1. Guide Paragraphs for Precast Concrete Segment Tunnel Lining

6.1.1. General

This section includes specifications for the fabrication of precast segmented straight and tapered concrete rings for tunnels. Installation shall be as specified in paragraph 6.2.

6.1.2. Concrete

Concrete for precast concrete segments shall conform to the requirements of paragraphs ___, ___, ___, except for the following provisions:

(1) The compressive strengths of the concrete in precast concrete segments shall be 5,000 lb/in^2 at 28 days' age, as determined in accordance with subparagraph d.

(2) The maximum size coarse aggregate shall be 3/4 inch.

(3) The slump of the concrete shall not exceed 2 inches.

(4) The concrete shall contain not less than 564 pounds of cement per cubic yard of concrete.

(5) Use of a water-reducing, set-controlling admixture (WRA) will not be required. If the contractor elects to use a WRA, the WRA shall conform to ASTM: C 494, Type A or D.

(6) The concrete shall contain an air-entraining agent conforming to ASTM: C 260. The percentage of air entrained in the concrete as discharged from the mixer shall be 4 plus or minus 1 percent, by volume of concrete. The use of an air-entraining agent will not be required if the specified percentage of air in the concrete is obtained by use of WRA.

6.1.3. Reinforcement

Reinforcement for precast concrete segments shall conform to paragraph ___. Dimensions of precast concrete segments shall be as shown on the drawings.

6.1.4. Test Assemblies

(1) Assemble and bolt together in a horizontal position, three rings each from the first segments manufactured for straight rings and for tapered rings.

(2) During the manufacture of the segments, prepare three additional test assemblies of rings with straight and tapered faces. The periods of testing will be designated by the engineer.

(3) If ring measurements do not meet the requirements, halt the manufacturing process and resume only when the cause for failure has been found and corrected, as determined by subsequent test assemblies.

(4) Furnish all necessary facilities to perform the required assemblies and tests, at no additional cost to the contracting officer.

6.1.5. Quality Assurance

(1) Notify the contracting officer in writing at least 30 days prior to the beginning of work at the casting yard where the precast concrete segmented rings are to be manufactured and make arrangements for inspection by the engineer.

(2) Provide free access for the engineer to all work areas at all times and provide sufficient office space, workmen, and equipment for the performance of inspection.

(3) Provide and make available, at all times, master and working templates, gages, calipers, and other equipment to adequately determine the accuracies and tolerances in the fabrication.

6.1.6. Tolerances

(1) As shown on drawing No. ________.

(2) Manufacture similar segments with such accuracy and uniformity in dimensions that they will be entirely interchangeable not only in individual rings but with similar segments of other rings. Space bolt holes accurately so that any two rings can be bolted up in any relative position with the same size bolts in every bolt hole.

(3) Ensure the planeness of joint faces to satisfy the watertightness requirements specified in paragraph ___.

(4) Replace any segment which does not comply with the tolerances indicated.

6.1.7. Submittals

(1) Shop drawings: Submit shop drawings in accordance with paragraph ___, for:

- (a) Formwork
- (b) Each size and type of segment
- (c) Reinforcement and other embedded items

(2) Data: Submit to engineer for approval, concrete mix proportions including all ingredients, trial mixes, and results of all tests on concrete.

(3) Casting yard: Submit to engineer, drawings showing layout of facilities for casting, curing, coating, and storing segments.

(4) Samples: Submit to the engineer for approval, three samples of each of the following:

- (a) Segment Liner Gasket: Complete ring
- (b) Calking: Each sample 1 gallon

6.1.8. Delivery, Storage, and Handling

(1) Use supports to store segments in order to avoid damage or undue strains.

(2) Prevent damage to the segments and gaskets during storage and delivery. Keep wire ropes, chains, or hooks from direct contact with gaskets.

(3) Ship tapered segments in units of complete rings, properly identified.

(4) Inspect segments prior to shipping.

(5) Install liner gaskets and attach with epoxy adhesive furnished by and in accordance with the gasket manufacturer's recommendations.

(6) Segments must have attained the specified 28-day compressive strength prior to shipping.

6.1.9. Quality Control

(1) Formwork: Check the dimensions of the first segment cast from each form and, where required, make the necessary adjustments to the form. Thereafter, check 2 percent of each type segment produced each day but not less than one segment of each type produced each day.

(2) Concrete Test Cylinders: As required by paragraph ___.

6.1.10. Replacement Segments

(1) Cast a sufficient number of segments to replace loss by breakage or other causes, but not less than the following quantities over the theoretical amount required (amount based on length of tunnel and experience).

6.1.11. Segment Identification

(To suit the requirements of the owner)

6.1.12. Sealant System

(1) Crushable Compression Seal. - Nonbituminous fiberboard shall conform to the physical requirements of ASTM: D 2828-71 and all requirements of ASTM: D 1751 except that it shall contain no asphalt or other bitumen and shall be otherwise equal to Homex 300 (G-30) expansion joint filler manufactured by the Daton Sure-Grip and Shore Company, Miamisburg, Ohio 45342.

(2) Sprayed Elastomer. - Sprayed elastomer or preformed tape shall conform to Service Tentative Specifications for Precast Concrete Tunnel Liner Segments, revised December 5, 1971 (appendix D).

(3) Rubber Compression Gaskets. - Full face and local rubber compression seals shall conform to the gasket requirements of ASTM: C 361-78.

6.1.13. Measurement and Payment

The work under this section will not be measured nor paid for separately. Precast concrete segment rings of various types specified in this section and indicated on the drawings are considered incidental materials required in construction of specific items of work that will be measured and paid for under the contract items listed in the schedule under paragraph ___.

Progress Payment:

(Progress payments are usually allowed according to the requirements of the owner.)

6.2. Guide Paragraphs for Installation of Precast Concrete Segment Tunnel Lining

6.2.1. General

Install the precast concrete tunnel liners to the tolerances for line and grade specified in paragraph ___ and to the limits shown on the drawings. Install liners in a manner that will not damage the segment or joint sealant. The contractor may submit other designs for furnishing and installing precast concrete segments for consideration. If other designs are approved, they shall be furnished and installed at no additional cost to the ___________.

6.2.2. Assembly

Assemble the segments on a fitting ring to form a circular section before connection to the previously installed liner. Assemble and install the ring of precast concrete segments inside a tunneling shield. Clean the surfaces of segments which will be in contact with each other. At the time of erection, such surfaces shall be free of all material which could interfere with proper bearing and watertightness. (Other contractor proposals will be considered.)

6.2.3. Bolting Segments

(1) Provide bolt assemblies as shown on the drawings.

(2) Before a ring is erected, inspect the previously installed ring and repair or replace all damaged parts.

(3) Fully bolt each ring and retighten bolts in the preceding two rings before shoving the shield for further excavation.

(4) Tighten longitudinal bolts to ___ percent of proof load as specified in AISC Specification for Structural Joints.

(5) Tighten transverse bolts to a tension of___ pounds.

6.2.4. Grouting

Backfill spaces between the excavated surfaces and each completed ring of precast concrete segments with grout before jacking loads are allowed to act on the segments. Backfill grouting shall proceed from the bottom holes to the top holes of the segment rings. Use bulkheads as necessary to ensure complete filling of the space outside the segments. Regrout in areas that are found to have voids remaining behind the segments. Backfill grouting shall conform to the provisions of paragraph ___.

6.2.5. Bracing

Support the last installed ring by means of a horizontal tie rod or stiff internal fitting ring inserted before the shield is advanced. Keep the support in place until the grouting around the lining has been completed and the grout has set.

6.2.6. Jacking

Ensure jacking loads are applied only at the liner jacking ribs or that the jacking thrust is evenly distributed around the liner.

6.2.7. Calking

Calk all tunnel liners. Clean the calking groove by means of air or water jet prior to calking.

6.2.8. Changes in Alinement and Grade

Use tapered rings on horizontal and vertical curves and elsewhere as required to maintain tolerances.

6.2.9. Special Segments

Use extra strength rings at locations specified on the drawings.

6.2.10. Inspection

Precast concrete segments will be inspected by the engineer before being taken into the tunnel. Damaged segments that can be repaired, as determined by the engineer, shall be repaired by the contractor in accordance with paragraph ___.

6.2.11. Utility Lines

Utility lines necessary for construction of the tunnel may be suspended from the installed precast concrete segments. Cast-in holes or embedded anchorages may be used for this purpose. Drilling of additional holes for securing the utility lines shall be approved by the contracting officer.

6.2.12. Repairs

After the precast concrete segment tunnel lining is installed, all holes used for installing precast concrete segment tunnel lining and suspending utility lines and all spalled or chipped joints shall be filled or repaired in accordance with paragraph ___.

6.3. Cost Analysis

The total construction cost for tunnels of three different lengths was estimated. A summary of those estimates is shown in Appendix E. It is evident from these estimates that the segment joint sealant system cost does not influence the total construction cost significantly.

The total cost for creating a watertight lining for the tunnel varies with the sealing system chosen and the linear feet of joint which must be sealed. For longer tunnels, economies of scale may result in lower sealant costs per linear foot of tunnel. If we assume the tunnel is long enough to allow the contractor to order sealant in economic quantities, the cost of waterproofing is proportional to the number of segments per ring and the total length of the tunnel, and inversely proportional to the length of the segment ring. Figure 6-1 shows this simple relationship.

The cost per foot of joint for sealant system depends on the details of the system, the cost of materials, and the geometry of the joint. The cost of installation may vary between systems. As more experience is accumulated, the installed cost of calking and the installed cost of gasket material should be substituted for the simple material cost used in the example shown on Figure 6-2. The system shown on Figure 6-2 was chosen for illustration of the cost calculation only, and shows a calculation for:

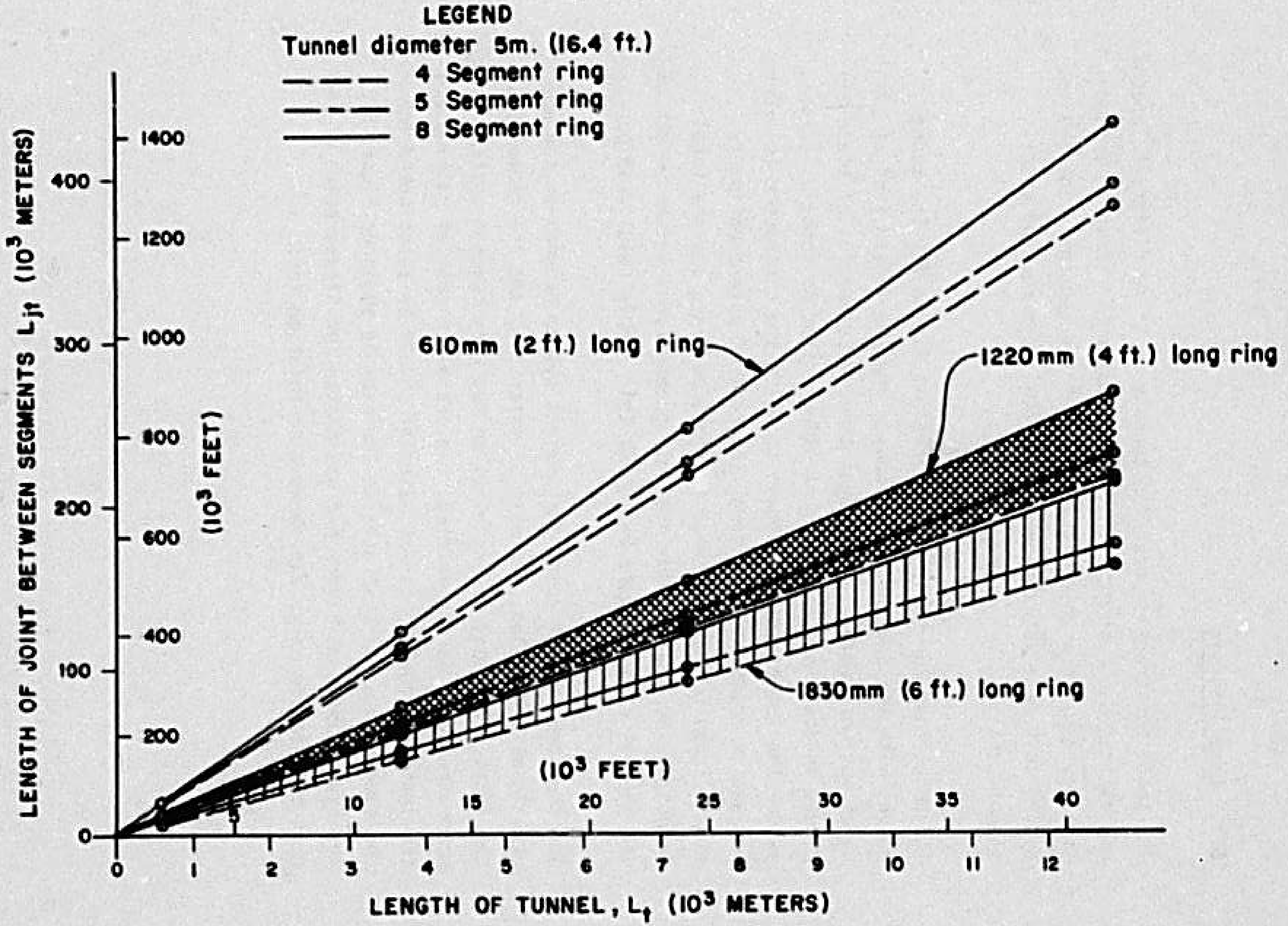
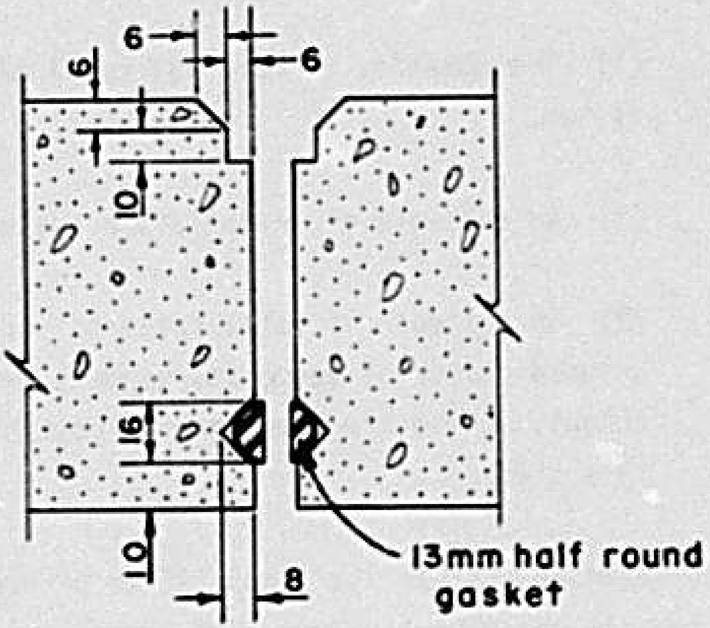


FIGURE 6-1. LENGTH OF JOINT BETWEEN SEGMENTS FOR A 5m. DIAMETER TUNNEL



JOINT DETAIL
(For illustration only)

Calking volume, V_c per meter
V_c = (1+ waste) 2 (6)10(1,000) ÷ 1000 mm³/mL
Assume waste = 60%
V_c = 1.6(120) = 192 mL/m

Cost of calk \$20/gal (\$5.30/L)
C_c = 0.192 (5.30) = \$1.00/m

Cost of gasket \$0.50/ft (\$1.64/m)
C_g = 2(1.64) = \$3.30/m

Cost per foot of joint
C_{jt} = 1.00 + 3.30 = \$4.30/m

For a tunnel 3658 m long (12,000 ft)
4 segments + a key segment
1.22 m (4-ft long ring)

L_{jt} + 5(3658) + π(5) 3658/1.22

= 65390 m

Cost of sealant 65390 (4.3) = \$281,000

Tunnel construction cost, 1978, was estimated to be \$32 million.

FIGURE 6-2. COST OF JOINT SEALANT SYSTEM

(1) The quantity of material required for a given sealant system.

(2) An estimate of installation waste.

(3) An estimate of total sealant system costs based on an assumed number of segments, segment width, and length of tunnel. Costs are based on the cost of material purchased for this study.

A detailed cost analysis has little permanent value in today's rapidly changing economy. For example, a year ago coal-tar modified polysulfide canal sealant (Sample no. 2) was selling for approximately $5 to $6 per gallon, and two-component urethane building sealants were commonly priced at $17 or more. Today, the same polysulfide has risen to $10.50 per gallon, with the polyurethane being priced as low as $11. Further, it has not been uncommon to find the material price paid by a contractor considerably different than that quoted in a cost survey. Another reason that there is some risk in consumer decision making based on materials cost estimates is that application costs have been found to vary widely from one contractor to another. When application costs are a significant part of the system cost, such variations can quickly change the relative merits of otherwise closely valued systems.

With these caveats in mind, some general comparisons can be made to see if some system appears to be hopelessly outpriced, and to see where possible economies can be looked for in changing conditions.

Figure 6-3 shows cost of sealant materials and provides a method of quickly estimating cost of completed work for sealant materials

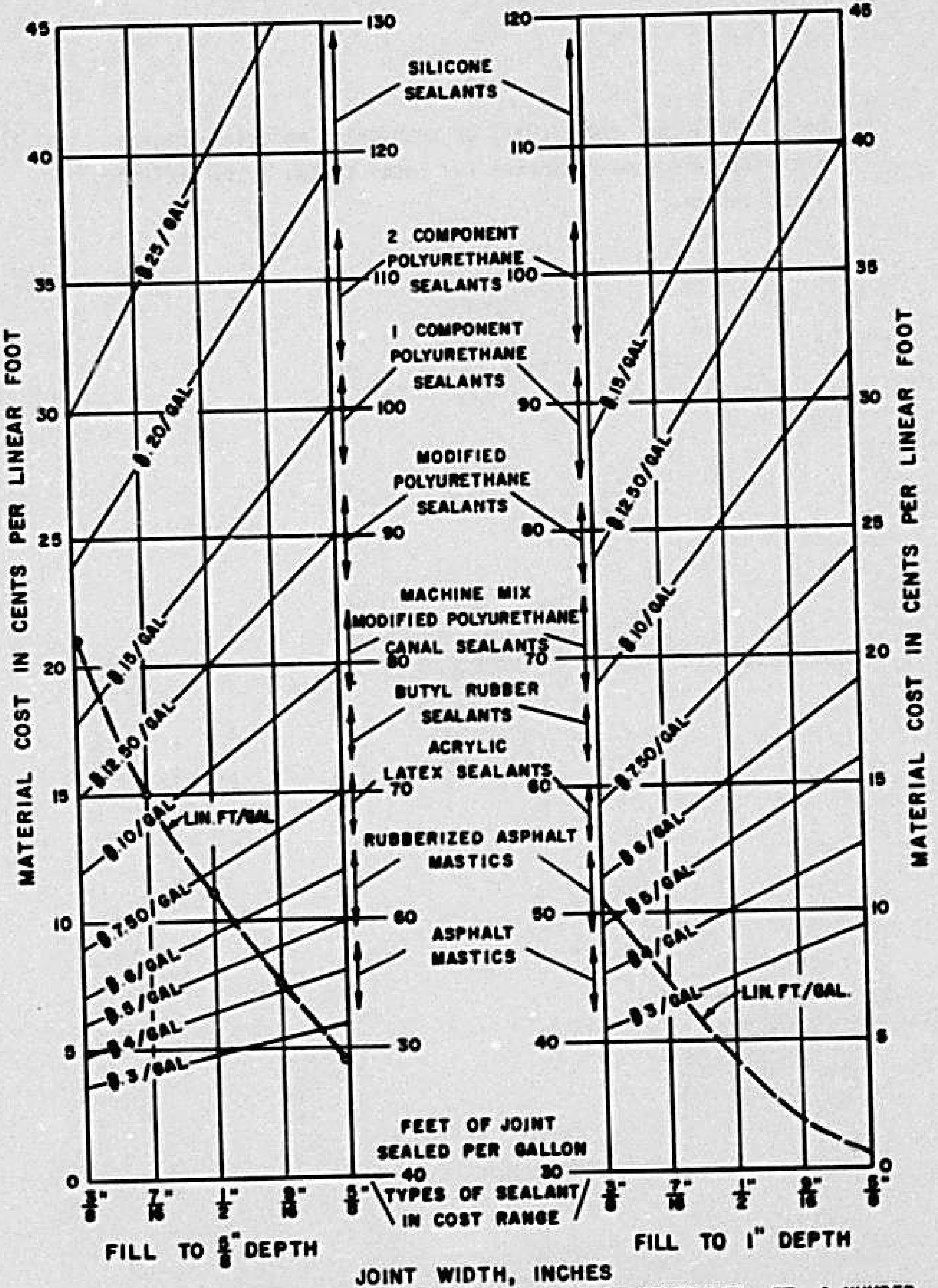


FIGURE 6-3. COST OF JOINT SEALING MATERIAL IN CENTS/LIN. FT. & NUMBER OF FEET WHICH CAN BE SEALED PER GALLON OF JOINT SEALANT

only. Table 6-1 shows costs of cushioning material, gasket material, and some estimates for total system costs including installation.

TABLE 6-1. SEALANT SYSTEM COSTS

Cents per lineal foot of joint

Material identification	Material cost ($)	Applied system and alternate for poor fit*							
		1	1A	2	2A	3	3A	4	4A
Half round 1/2-in-diameter rubber gasket	50							65	100
Lower middle cost sealant ($12.00/gal) - 1/4-in fillet	5							25	25
- 1/2-in-sq. section	18		50				50		50
Full face 1/16-in rubber sheet with sealing bulb	80					100	100		
Full face sprayed elastomer, 1/16-in thick at $20/gal.	100			120	150				
Fiberboard cushion 1/2-in thick at $0.35/ft^2	23	50	50						50
Treated plywood 1/2-in thick at $0.40/ft^2	27								
Polyurethane foam 12 lb/ft^3 density 1/2-in thick at $0.50/ft^2	34								
Good fit total		50		120		100		90	
Bad fit total			100		150		150		225

* System nos. 1 through 4 correspond to numbers of systems in Section 5. Applied costs include estimate for waste but not for contractors overhead and profit. Treated plywood and polyurethane foam could be used interchangeably with fiberboard for cushioning if obtainable at a lower price or if other advantages were seen.

7. CONCLUSIONS

7.1. General

It can be concluded from this study that a precast concrete segment liner with bolted connections between segments and rings is a viable alternative to be considered when designing soft ground transportation tunnels. A sealant system comprised of a crushable compression seal and a fluid-applied sealant which will provide watertight joints in the liner and which results in a minimum loss in joint strength between segments and rings in the assembled structure has been identified.

Reproducibility and maintenance of tolerances in the segments can be achieved with reusable and replicate forms. Close inspection, however, is required to maintain a high level of accuracy. It is inevitable that some segment damage will occur in handling and installation, and repair procedures must be developed.

It appears that four segments per ring is the best number to use. The length of the ring should be the longest that can be handled by the installation equipment within the tail shield. The installation equipment should be ancillary to and an integral part of the TBM and the sequence of operations so designed to produce minimum delays in the TBM advance rate.

The segments can be designed to withstand jacking loads near the ultimate strength of the concrete. The actual design of the segments will vary from project to project. In some instances, a two-part segment may be designed to include a wedge-shape portion for the final fit. Backpacking and grouting behind the liner should be accomplished before jacking loads are applied to the segments.

A number of specific conclusions related to the sealant materials, sealant systems, and joint configurations can be drawn from this study.

7.2. Sealant Materials

a. Any candidate sealant should be able to withstand 10 percent initial strain as a minimum.

b. Water immersion is the most damaging environment, either to polymer degradation or to adhesion deterioration.

c. The addition of hydrostatic pressure to the water immersion environment markedly increases the deterioration of sealant adhesion as compared to immersion only.

d. Ozone deterioration is not a problem since selected polymers have good resistance to ozone and there is minimum strain on the sealant in service.

e. Fire resistance is not an important property since the ratio of sealant area to concrete area is small, and heat sink characteristics of concrete, grout, and ground tend to slow the deterioration rate. However, softening under heat can cause displacement of the sealant and should be evaluated.

f. Limited oxygen index classification test is a reliable specifications tool for controlling burning characteristics of sealants once their burning properties have been established.

7.3. Sealant Systems

a. Fluid-applied sealant must be part of any sealant system.

b. A neoprene compression gasket, a urethane sealant, an epoxy-modified urethane sealant, and a fiberboard gasket were satisfactory as joint cushioning materials. If loads near the ultimate joint strength are anticipated, only the fiberboard or equivalent should be used.

c. Provision for maintenance of sealing capability of all sealing systems is necessary. The simplest means for this is to provide a calking groove on the interior surface at all seams. The effectiveness of calking is dependent upon the bolt seals which should be replaceable for system maintenance.

d. Satisfactory sealant system repairs can be made with a polymer gel-bentonite grout injected behind the sealant system. Temporary repairs can be made with polymer injection alone. At the present state of development, polyurethane foams for injection are not satisfactory.

7.4. Joint Configuration

a. Near full joint strength can be maintained with a full surface crushable compression seal. This is reduced proportionally by providing 1/2-inch less in width to form a sealant groove at the inner surfaces.

b. A 1/2-inch-wide joint is satisfactory for expansion, contraction, and shear and provides proper width for a 1/2-inch sealant depth. The one-half by one-half sealant section is required to maintain hydrostatic resistance.

c. Shear appears to be the controlling factor, not only in the joint design and connections, but also in the performance of the sealant material. Extension of sealant from joint rotation or from temperature change is not considered significant.

8. RECOMMENDATIONS

As part of the original study plan, a section identified as Part 2 was included. The purpose of this part was to propose implementation of the research results of this study in an actual installation of a segmented concrete lining system in a tunnel to be designated by TSC. It also proposed additional studies, as deemed necessary, to accomplish the implementation and continued research on newly developed materials to improve the liner system and/or to lower costs.

Therefore, it is recommended that Part 2 be implemented by developing a test program for an actual soft ground transportation tunnel. The tunnel should be designed with four segment rings, bolted segment to segment and ring to ring. The design should follow the general tenets presented in the design example, Appendix C. The joint system should contain a 1/2-inch-thick crushable compression seal, essentially full surface, except for 1/2-inch less width to provide for a calking groove at the inner surfaces.

If field testing, other than implementation of the principal system, is desired, then it is further recommended that a portion of the segmented liner be sealed with the following systems:

a. Full surface sprayed elastomer

b. Full surface preformed elastomeric gasket with provision for calking sealant

c. Local compression seal with provision for calking sealant

In each case, the calking sealant should be one of the five top-rated sealants. These would be single- or two-component urethanes or epoxy-modified urethane sealants.

The specifications should follow the general guide paragraphs presented in Sections 6.1 and 6.2.

The value of the minitunnel test device was demonstrated in a single test using a local preformed gasket. The minitunnel incorporates all of the features of a large segment joint system in a small scale model and is easy to handle and operate. It is further recommended that TSC consider additional testing with this equipment on other candidate sealant systems. The apparatus was designed to include fire on the inside of the tunnel so that fire tests could be run with hydrostatic pressure on the joint sealant system. Tests under these conditions certainly would be of value.

It is recommended that a program be initiated to identify repair procedures for damaged concrete segments. The program should include new commercially available polymer concretes that have the potential for low cost, very quick, high strength repairs.

Finally, it is recommended that a continuing screening program be initiated to evaluate new developments in sealant materials. Although many sealants are offered for tunnel use by the manufacturers, few are suitable, as judged by careful screening. Hydrostatic pressure tests, as presented in this report (Section 5.2), should be part of any evaluation program.

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APPENDIX A

CITATIONS

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
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15. Supplementary Notes

16. Abstract A fundamental investigation of soft-ground tunneling operations was made to identify and assess the potential technical and economic feasibility of new tunneling system concepts. Quantitative estimates were made of costs and rate of advance of different candidate system concepts relative to an assumed set of tunneling conditions. The magnitude of R&D effort required to achieve cost reductions and performance improvements over the 1970 to 1985 time period was estimated.

The study concludes that the major restraints to reducing costs and increasing performance in soft ground tunneling over the 1970 to 1985 time period will result from the lack of any effective method forhandling bouldery ground and from the lack of a method for rapid installation of the permanent tunnel liner continuously and concurrently with the advance of the face. With a 15-year R&D effort of $35 to $70 million, these problems could be substantially overcome and current tunneling costs could be expected to decrease by 40-65% and advance rates could be expected to increase by a factor of from 4 to 8.

Cost differences among the more promising alternative system concepts were found to be small relative to the range of uncertainty associated with the cost forecasts. The most promising areas of new technology were judged to be the dredgehead for excavation; soil-water balance, air-on-face, synthetic resins, and cryogenic freezing for ground control; modular vehicle and hydraulic pipeline for materials handling; and shotcrete and fast setting poured-in-place concrete for tunnel wall support.

17. Key Words
SYSTEMS ANALYSIS, SOFT GROUND TUNNELING, TUNNELING, SYSTEMS STUDY

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Polymer-Impregnated Concrete Tunnel Support and Lining

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16. ABSTRACT

The development of precast polymer-impregnated concrete (PIC) tunnel support-liner systems is reported. Investigations included: (1) Full-scale tests of conventional concrete and PIC segments with concrete backfill as well as PIC segments with sand backfill; (2) economic studies to compare precast conventional concrete and PIC systems; (3) the effects of joint configuration, elastomeric joint sealer, and segment material on the support-lining system strength determined by laboratory tests and statistical inference; (4) heat transfer analysis employing finite differences to determine temperature distribution in the PIC lining caused by transportation tunnel fires; (5) effects of elevated temperature on the compressive strength and the heat transmission characteristics of PIC; and (6) determination of flame spread, fuel contribution, smoke developed, the combustion gases, and visual damage of PIC resulting from exposure.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS--/ precast con ete/ concrete properties/ *polymer concretes/ *materials tests/ structural models/ tunnel linings/ *economi feasibility/ tunnel supports/ transverse joints/ longitudinal joints/ *loading tests/ backfills/ *heat transfer/ fl mmability/ impregnation/ hazards/ polymerization/ monomers/ fires

b. IDENTIFIERS--/ concrete-polymer materials

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Kendall Square
Cambridge MA 02142

16. Abstract

This study addresses precast concrete lining systems. Existing precast concrete systems designed or constructed in Europe, Japan, and the United States are evaluated. With these as a point of departure, designs for lining systems applicable to the specific conditions encountered in the United States are developed. A comparative cost analysis is made between the linings designed in the study, one existing precast concrete design and two in fabricated steel. Appreciably lower costs are found for all of the concrete liner designs when compared to those in fabricated steel. Water sealing systems are discussed and recommendations for the development and testing of sealing details are made. Guidelines for dissemination of information about, and for the implementation of the systems, are presented.

17. Key Words
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Lining Systems
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Tunnel Supports
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Boltless Segmented Tunnel Lining Backed with Polyurethane Foam

Department of the Interior, Washington, D.C.   (109 950)

Patent Application
AUTHOR: Tiedemann, Henry R.
C5245L1   FLD: 13B, 50, 90   USGRDR7522
Filed 7 Aug 74   12p
REPT NO: PAT-APPL-495 351, DOCKET/MIN-2107
MONITOR: 18
Government-owned invention available for licensing. Copy of application available NTIS.

ABSTRACT: The patent application relates to a light weight, tough, impermeable tunnel lining made of modular segments that are joined inside a tunnel and contain a separate polyurethane foam backing subsequently forced in unfoamed condition into the cavity between the earth and the segmented lining. The modular segments are provided with flanged connections which do not require bolting and which contain means through which foamable polyurethane compositions may be injected to complete the tunnel lining.

DESCRIPTORS: *Tunnel linings, *Patent applications, Polyurethane resins, Segmented elements, Joints(Junctions)

IDENTIFIERS: NTISGPINT

PB-243 965/1ST   NTIS Prices: PC$3.25/MF$2.25

TITLE	EFFECT OF STRESS PATH ON AXIAL AND VOLUMETRIC STRAINS OF A NORMALLY CONSOLIDATED CLAY
INVESTIGATORS	GANGOP/"HYAY CR; DAS S
PERFORMING ORGANIZATION	JADAVPUR UNIVERSITY, CIVIL ENGINEERING, CALCUTTA, WEST BENGAL, INDIA
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

IN THIS STUDY, LABORATORY SIMULATED IN-SITU SAMPLES AND ISOTROPICALLY CONSOLIDATED SAMPLES ARF BEING TAKEN THROUGH DIFFERENT STRESS PATHS TO STUDY THE RELATIONSHIP BETWEEN AXIAL AND VOLUME STRAINS DURING CONSOLIDATION FOR SETTLEMENT ANALYSIS. /IRF/ (CONVENTIONAL AND/OR POLYMER CONCRETE); (C) MAKE ANALYTICAL STUDIES OF VARIOUS JOINT AND SEGMENT CONFIGURATIONS INCLUDING LARGER DIAMETERS THAN THE FULL-SCALE TEST AND SHAPES OTHER THAN CIRCULAR; (D) DEVELOP METHODS AND TECHNIQUES TO DETECT THE PRESENCE OF VOIDS BEHIND TUNNEL SUPPORT AND LINING SYSTEMS. (E) INVESTIGATE HELIX TUNNEL SUPPORT AND LINING SYSTEMS. 3DKFAMA BUREAU OF RECLAMATION /US/

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ACCESSION NO.	Pb-231 912/7
TITLE	Testing and Evaluating of Prototype Tunnel Support Systems.
TITLE NOTE	Final rept. Oct 71-Oct 72
AUTHORS	Parker, H. w.; Deere, D. u.; Peck, R. b.; Birkemoe, P. c.; Semple, R. m.
CORPORATE SOURCE	Illinois Univ., Urbana. Dept. of Civil Engineering.
PAGINATION/DATE	1 Aug 73; 338p
NTIS PRICES	pc $7.50/Mf $1.45
CATEGORY CODES	13B; 13C; 50B; 50C
DESCRIPTORS	*tunnels; *supports; Tunnel linings; Precast concrete; Addition resins; Slip forms; Mixtures; Reinforced concrete
IDENTIFIERS	*polymer concrete; Fra
SPONS. AG. ACRONYM/NO.	Fra-Ord/d-74-11
ANNOUNCEMENT PUBLICATION	U7413
REPORT NOS.	Uilu-Eng-73-2013
CONTRACT/GRANT NOS.	Dot-Fr-20020
ABSTRACT	The report presents the results of engineering studies related to the development of new and improved tunnel support systems. Steel fiber reinforced regulated-set concrete has been proposed for use as a slipformed concrete lining which can be placed immediately behind a tunnel boring machine. Mix design studies and field pumping tests for this new concrete are described. The results of a cooperative research effort carried out with the U.s. bureau of Reclamation on precast polymer concrete segmented tunnel support systems include an evaluation of the structural aspects of the system, an analysis of potential heat and fire hazards, and an evaluation of the cost of the promising new support system. (modified author abstract)

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ACCESSION NO.	Ad-762 080
TITLE	The Effects of Composition, Environment and Stress on the Durability of Composite Bonds.
TITLE NOTE	Final rept. 10 Mar 71-10 Mar 72
AUTHORS	Patrick, R. L.; Brown, J. A.; Dunbar, L.
CORPORATE SOURCE	Alpha Research and Development Inc Elverson Pa
PAGINATION/DATE	10 Mar 72; 45p
NTIS PRICES	pc $3.00/Mf $0.95
CATEGORY CODES	13E; 69C
DESCRIPTORS	(*bonded joints, Epoxy plastics); Curing agents; Amines; Filling; Silicates; Aluminum compounds; Zirconium compounds; Stress corrosinn; Aluminum; Effectiveness
IDENTIFIERS	Phenylenediamines; Fillers; Additives; N
ANNOUNCEMENT PUBLICATION	U7315
CONTRACT/GRANT NOS.	N00019-71-C-0277
ABSTRACT	It was shown that a single recrystallization of m-phenylenediamine (mpda) was most effective in generating optimum G values in the Mpda cured epoxy system. It was also shown that stoichiometric quantities (14.5 phr) of Mpda provided the highest G values. Fillers were examined and a flat platelets (aluminum silicate) and rounded, granular (zirconium silicate) particles were utilized at various particle sizes and concentrations. The highest G value was obtained at .50 phr with the 1.5 micron aluminum silicate. As the size of the filler particles increased, G sub 1a approached G sub 1c indicating that large particles were more effective as crack stoppers in filled adhesive systems. (author)

ACCESSION NO.	Pb-223 255/1
TITLE	Component Building and the Organization of the Building Process: a study of Joints and Jointing. Abstracts 1959-1971. Component Two: Information System Volume 1.
CORPORATE SOURCE	Washington Univ., St. Louis, Mo. Building Industrial Research and Development Group.
PAGINATION/DATE	1971; 229p
NTIS PRICES	pc $13.50/Mf $1.45
CATEGORY CODES	13M; 13E; 13H; 60H; 89F; 69B; 69C; 94G
DESCRIPTORS	(*prefabrication, *construction management); (*joints(junctions), construction management); (*joining, Construction management); Buildings; Abstracts; Construction; Structural members; Fasteners; Subassemblies; Standards; Quality control; Joint fillers; Installing
IDENTIFIERS	Nsf
NOTES	See also Pb-223 256 and Pb-223 254.
ANNOUNCEMENT PUBLICATION	U7322
CONTRACT/GRANT NOS.	Nsf-Gk-4526
ABSTRACT	A collection of abstracts is presented covering an industrial survey of existing work and practices in the field of joints and jointing in component building. Included are recommendations for component design and implementation of joints and joint standardization. It is organized by the keyword system.

ACCESSION NO.	Pb-223 256/9
TITLE	Component Building and the Organization of the Building Process: a study of Joints and Joining (abstracts 1959-1971). component Two: Information System Volume 2.
CORPORATE SOURCE	Washington Univ., St. Louis, Mo. Building Industrial Research and Development Group.
PAGINATION/DATE	1971; 208p
NTIS PRICES	pc $12.50/Mf $1.45
CATEGORY CODES	13M; 13E; 13H; 60H; 89F; 89G; 69B; 69C; 94G
DESCRIPTORS	(*prefabrication. *construction management); (*joints(junctions). construction management); (*joining. Construction management); Buildings; Abstracts; Construction; Structural members; Fasteners; Subassemblies; Standards; Quality control; Joint fillers; Installing
IDENTIFIERS	Nsf
NOTES	See also Pb-223 254 and Pb-223 255.
ANNOUNCEMENT PUBLICATION	U7322
CONTRACT/GRANT NOS.	Nsf-Gk-4526
ABSTRACT	A collection of abstracts is presented covering an industrial survey of existing work and practices in the field of joints and jointing in component building. Included are recommendations for component design and implementation of joints and joint standardization. It is organized by the keyword system.

ACCESSION NO.	Pb-188 464
TITLE	Study of preformed open cell neoprene joint sealer for use in transverse weakened plane sawed joints.
TITLE NOTE	Final rept.
CORPORATE SOURCE	Colorado State Dept. of Highways. Planning and Research Div.
PAGINATION/DATE	Nov 69: 45p
NTIS PRICES	hc $6.00 Mf $0.95
CATEGORY CODES	11A: 13B: 903
DESCRIPTORS	(*roads. Pavements): (*pavements. Expansion joints): (*expansion joints. *sealing compounds): (*rubber seals. Performance(engineering)): Synthetic rubber: Plastic seals: Bonded joints: Concrete: Cements: Asphalt: Epoxy plastics: Costs. Foundations(structures): Moisture: Deterioration. Failure(mechanics): Specifications
IDENTIFIERS	*construction joints: Precast concrete: Portland cements: Subgrades: Evaluation
NOTES	Prepared in cooperation with Bureau of Public Roads. Washington. D.c.
ANNOUNCEMENT PUBLICATION	U7004
ABSTRACT	Various highway jointing patterns and joint sealants were evaluated. The test sections are on both a lime-treated and untreated swelling subgrade. Unsealed joints are compared to those containing preformed neoprene. standard rubberized asphalt. and rubberized epoxy. Random joint spacings were also tried. Joint movements were measured and detailed visual observations of the joints were noted. Difficulties were experienced during construction which may have led to some controversial results. It was concluded that joints sealed with the asphalt were cheaper to construct and performed better than the preformed neoprene in that they had less infiltration. spalling. and adhesion failures. It was also concluded that unsealed joints were better than those sealed. This could be a reflection of the unusually dry climatic conditions. (bpr abstract)

ACCESSION NO.	Pb-194 591
TITLE	Contraction joint sealing systems - San luis drain, central valley project.
TITLE NOTE	Technical rept.
AUTHORS	Johns, Henry
CORPORATE SOURCE	Bureau of Reclamation, Denver, Colo. Office of Chief Engineer.
PAGINATION/DATE	Aug 70; 32p
NTIS PRICES	hc $3.00 Mf $0.65
CATEGORY CODES	11A; 13C; 71B; 60C
DESCRIPTORS	(*canal linings, *control joints); (*concrete construction, *sealers); (*polysulfide resins, *sealing compounds); (*polyvinyl chloride, Sealing compounds); Joint fillers; Field tests; Contraction; Bonding; Extruding; Elastomers; Waterproofing
ANNOUNCEMENT PUBLICATION	U7023
REPORT NOS.	Rec-Oce-70-35
ABSTRACT	Extension tests and visual examinations were made of specimens cored from an experimental sealer installation in a concrete canal lining. Three sealing systems were employed: preformed polysulfide strip, machine-applied polysulfide sealant, and Pvc contraction joint forming waterstop. Conclusions are that: (1) a properly installed preformed strip will bond to fresh concrete, thereby forming and sealing a contraction groove; (2) the strip is effective in forming a weakened plane in the concrete lining; (3) some cost savings may be realized if forming and cleaning of contraction grooves can be eliminated by the strip; (4) use of the strip eliminates mixing and proportioning problems encountered using extruded sealant; (5) sealant in the strip would probably be more uniform in quality and dimension than field-extruded liquid sealant; (6) surface tooling of field-extruded polysulfide would have improved contact between sealant and concrete, thereby enhancing bond; (7) application of extruded polysulfide sealant at a later age of the concrete would have improved bond; (8) visual examination of cores indicated that the Pvc strip application was generally well done; and (9) lining thickness control was excellent. (author)

ACCESSION NO.	Ad-732 419
TITLE	Tests on Concrete Sheet Piles with Plastic Interlock.
TITLE NOTE	Final rept. 10 Oct 68-27 Jan 69
AUTHORS	Orenstein, Gleen S.; Calenzo, Peter A.
CORPORATE SOURCE	Army Engineer Waterways Experiment Station Vicksburg Miss
PAGINATION/DATE	Mar 69; 47p
NTIS PRICES	pc $3.00 Mf $0.95
CATEGORY CODES	11A; 13M; 71B; 60G
DESCRIPTORS	(*foundations(structures), *plastic seals), Beams(structural); Moistureproofing; Polyethylene plastics; Joints; Mechanical fasteners
IDENTIFIERS	*concrete piles
ANNOUNCEMENT PUBLICATION	U7201
REPORT NOS.	Aewes-Misc-Paper-C-69-2
ABSTRACT	Tests were conducted on concrete sheet piles incorporating a newly developed plastic interlock-waterstop. The purpose of the tests was to determine the structural limitations of the interlock so as to enable a determination of the feasibility of its use on various U. S. Army Engineer Division, Lower Mississippi Valley projects as a substitute for steel sheet piling. (author)

ACCESSION NO.	Ad-755 926
TITLE	A guide for Pressure Grouting Cracked Concrete and Masonry Structures with Epoxy Resins.
TITLE NOTE	Final draft rept.
AUTHORS	Fuller, J. O.; Kriegh, J. D.
CORPORATE SOURCE	Arizona Univ Tucson Dept of Civil Engineering
PAGINATION/DATE	Feb 73; 45p
NTIS PRICES	pc $3.75/Mf $0.95
CATEGORY CODES	13C; 11A; 89G; 7'9; 60C
DESCRIPTORS	(*concrete, *maintenance); (*grout, *epoxy plastics); Handbooks; Expansion joints; Viscosity; Cracks; Sealing compounds; Safety; Cleaning; Test methods

ACCESSION NO.	Pb-218 355/6
TITLE	Rigid Pavement Investigations Growth Characteristics and Blowups and Performance of Transverse Joints and Joint Sealing Materials.
TITLE NOTE	Interim rept. 1971-72
AUTHORS	Stromberg, Francis J.
CORPORATE SOURCE	Maryland State Highway Administration, Brooklandville. Bureau of Research.
PAGINATION/DATE	Oct 72; 34p
NTIS PRICES	pc $3.00/Mf $0.95
CATEGORY CODES	13B; 11A; 71B; 60F
DESCRIPTORS	(*joint sealers, Performance evaluation); (*construction joints, Deformation); (*concrete pavements, Construction joints); Expansion joints; Shrinkage; Expansion; Control joints; Field tests
IDENTIFIERS	Fn:pr
ANNOUNCEMENT PUBLICATION	U7312
PROJECT NOS.	Fh-Aw-73-96-46
ABSTRACT	The main objectives of this investigation are to measure the 'field growth' of rigid pavements, so that better performing aggregate types can be determined and to determine the reasons for 'blowup' occurrences on rigid pavements. In the field investigation of concrete growth, the overall lengths of all test sites are increasing. The concrete in two stone contracts appears to be growing, whereas, the concrete on the one gravel concrete appears to be shrinking. The results at this time however are inconclusive. In the investigation of blowups, the results to date indicate that the probability of a blowup is considerably greater at an expansion joint than at a contraction joint. Also, the probability of a blowup is greater on a pavement built using gravel aggregate than one built using a stone or slag aggregate. Pavement age is also a significant factor in blowup occurrences. (author)

ACCESSION NO.	PB-219 199/7
TITLE	In Service Behavior of Preformed Neoprene Joint Seals.
TITLE NOTE	Interim rept. Fy 71-72
AUTHORS	Stromberg, Francis J.; Weisner, John
CORPORATE SOURCE	Maryland State Highway Administration, Brooklandville. Bureau of Research.
PAGINATION/DATE	Jul 72; 41p
NTIS PRICES	pc $3.00/Mf $0.95
CATEGORY CODES	13B; 11A; 60F; 71B
DESCRIPTORS	(*joint sealers, *chloroprene resins); (*concrete pavements, Joint sealers); Field tests; Life expectancy; Specifications; Visual inspection; Sealants; Moisture; Adhesives; Evaluation; Installing; Roads; Maryland
IDENTIFIERS	Fnapr
NOTES	Prepared in cooperation with Federal Highway Comission, Washington, D.C.
ANNOUNCEMENT PUBLICATION	U7312
PROJECT NOS.	Fha-Aw-72-102-46
ABSTRACT	The main objective of this investigation is to evaluate the performance of two different neoprene joint seal configurations under actual field conditions and using normal installation techniques. Six paving contracts were selected for this investigation. The Neoprene Chevron Compression Seal was installed on two contracts and the Neoprene Delastic Series 'A' was installed on four contracts. One contract using a standard hot-poured liquid sealing compound was used as a control. The installation of the neoprene seals was done in accordance with the Maryland Specifications. Subsequent to construction, two detailed examinations are made each year on each project. After two years, the general condition of the seals appears to be good with performance being generally satisfactory. The main causes of poor performance appear to be in the installation procedures. In contrast, the regular hot-poured material has performed poorly with a sealing life of less than two years on the one contract observed. (author)

ACCESSION NO.	PB-244 108/7SL
TITLE	Concrete Pavement Construction and Joints and Loader-Truck Production Studies
CORPORATE SOURCE	Transportation Research Board, Washington, D.C.
PAGINATION/DATE	1975; 104p*
NTIS PRICES	NTIS Prices: PC$4.20/MF$2.25
CATEGORY CODES	13B; 50A*
DESCRIPTORS	*Concrete pavements; *Highway bridges; *Construction; Joint sealers; Covering; Reinforcing steels; Computerized simulation; Bridge decks; Construction materials; Earthwork; Time studies; Optimization; Maintenance; Prestressed concrete; Design; Earth handling equipment; Photographic techniques
IDENTIFIERS	NTISNASTRB
ANNOUNCEMENT PUBLICATION	U7523
REPORT NOS.	TRB/TRR-535; ISBN-0-309-02386-6
ABSTRACT	;Contents: Development of a specification to control rigid pavement roughness; New York's experience with plastic-coated dowels; Concrete pavement jointing and sealing methods; Performance evaluation of Utah's concrete pavement joint seals; Some refinements in expansion joint systems; Prestressed pavement demonstration project; Depth of concrete cover over bridge deck reinforcement; The use of time-lapse photography and computer simulation for loader-truck production studies.

ACCESSION NO.	AD/D-000 047/1SL
TITLE	Module Connectors
TITLE NOTE	Patent
AUTHORS	Rosenberg, Edgar N.
CORPORATE SOURCE	Department of the Navy Washington D C
PAGINATION/DATE	Filed 2 Feb 73, patented 16 Oct 73; 8p
NTIS PRICES	NTIS Price: Not available NTIS
AVAILABILITY	Government-owned invention available for licensing. Copy of patent available Commissioner of Patents, Washington, D.C. 20231 $0.50.
CATEGORY CODES	13J; 47A; 90
DESCRIPTORS	*Floating bases; *Patents; Containers; Floats; Concrete; Joints; Sealing compounds
IDENTIFIERS	PAT-CL-114-0-5-T; NTISGPN
ANNOUNCEMENT PUBLICATION	U7505
REPORT NOS.	PAT-APPL-329 010; PATENT-3 765 353
ABSTRACT	An improved method of joining elongate bottle members into a floatation structure is disclosed in the patent. A plurality of the elongate bottle members are joined together at a point beneath the water line of the body of water in which they are floating. This joint is accomplished by dewatering a volume between adjacent, specially-configured sections on the lower end of the elongate bottle members and filling the dewatered joint with a mixture of plastic concrete. After the concrete is cured, the joint is placed in a compressional loading to insure a rigid and mechanically stable union.

ACCESSION NO.	Pb-219 232/6
TITLE	Evaluation of Combination Insert and Sealant for Concrete Pavements.
TITLE NOTE	Interim rept. no. 1
AUTHORS	Stromberg. Francis J.
CORPORATE SOURCE	Maryland State Highway Administration. Brooklandville. Bureau of Research.
PAGINATION/DATE	Sep 72; 21p
NTIS PRICES	pc $3.00/Mf $0.95
CATEGORY CODES	13B; 60F
DESCRIPTORS	(*highways. *joint fillers); (*concrete pavements. *sealers); Joints; Chloroprene resins; Installing; Inspection; Performance evaluation; Time; Maryland
IDENTIFIERS	Contraction joints; Sealing strips; Interstate highway 95; Fhapr
ANNOUNCEMENT PUBLICATION	U7311
PROJECT NOS.	Fh-Aw-73-119-46
ABSTRACT	The primary objective of investigation is to evaluate under actual field conditions the performance of a combination insert and sealant for concrete pavements manufactured by the R. J. company of Timonium. Maryland. In October. 1971. thirty transverse joints using this material were installed on a widening contract on I-95. north of Baltimore. No difficulties were encountered in installation. Visual observations were made in January and August of 1972. and the results are reported. After these experimental joints have been in for a few more years. final conclusions can be made as to their performance.

AN - Pb-194 769
TI - A systems study of soft ground tunneling.
TN - Final rept. Feb 69-May 70
AU - Brandt, C. t.; Stone, R. D.; Smith, A. r.; Willis, B. h.; Pastuhof, Alex
CS - Fenix and Scisson, Inc., Tulsa, Okla.
PD - May 70: 439p
PR - hc $3.00 Mf $0.65
CC - 13B; 8G; 60B; 64L; 85C
DE - (*tunnels, *subsurface investigations); Subways, Tunneling(excavation); Underground surveys, Shields(tunneling); Underground supporting; Tunnel linings; Shotcrete; Reinforced concrete; Soil analysis; Construction equipment; Construction materials; Construction costs; Cost comparison; Systems analysis
ID - *soft ground tunneling; Advanced planning
SA - Dot-Fra-Onsgt-231
NO - Prepared in cooperation with Little (arthur D.), Inc., Cambridge, Mass.
AP - U7023
CG - Dot-Fr-9-0034
AB - A fundamental investigation of soft-ground tunneling operations was made to identify and assess the potential tedchnical and economic feasibility of new tunneling system concepts. Quantitative estimates were made of costs and rate of advance of different candidate system concepts relative to an assumed set of tunneling conditions. The magnitude of R and D effort required to achieve cost reductions and performance improvements over the 1970 to 1985 time period was estimated. The study concludes that the major restraints to reducing costs and increasing performance in soft ground tunneling over the 1970 to 1985 time period will result from the lack of any effective method for handling bouldery ground and from the lack of a method for rapid installation of the permanent tunnel liner continuously and concurrently with the advance of the face. With a 15-year R and D effort of $35 to $70 million, these problems could be substantially overcome and current tunneling costs could be expected to decrease by 40-65% and advance rates could be expected to increase by a factor of from 4 to 8. Cost differences among the more promising alternative system concepts were found to be small relative to the range of uncertainty associated with the cost forecasts. (author)

TITLE	EARTH PRESSURES AND STRESSES INDUCED IN THE LININGS OF A TUNNEL UNDER CONSTRUCTION FOR THE MADRID SUBWAY (METRO)
INVESTIGATORS	ESCARIO V ; SAGASETA C
PERFORMING ORGANIZATION	MINISTRY OF PUB. WORKS. TRANSP & SOIL MECH LAB. MADRID. SPAIN
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

EARTH PRESSURES AND STRESSES INDUCED IN THE LINING OF THE TUNNEL WILL BE MEASURED BY MEANS OF VENTILGEBER GLOETZEL CELLS EMBEDDED IN THE CONCRETE AND BY OTHER METHODS. EXTENSOMETERS WILL ALSO BE PLACED IN BOREHOLES BETWEEN THE SURFACE AND THE TUNNEL LINING. PERIODICAL MEASUREMENTS ARE BEING MADE OF THE SURFACE SUBSIDENCE AT VARIOUS POINTS. /IRRD-IRF/ SUPERSEDES IRRD 44539.

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SPONSORING ORGANIZATION	SPANISH GOVERNMENT
SPONS. ORG. CONTROL NO.	2R63066822 (HRB NO.)
SSIE ACCESSION NO.	GB 66822

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FUNDING	$15,030
SPONSORING ORGANIZATION	U.S. DEPT. OF TRANSPORTATION, FEDERAL HIGHWAY ADMINISTRATION
SPONS. ORG. CONTROL NO.	2R32234103 (HRB NO.)
SSIE ACCESSION NO.	GB 234103

TITLE	TUNNEL LINER FOR GEO MASSEY EXPERIMENTAL SECTION
INVESTIGATORS	KERR JW; DARBY RO
PERFORMING ORGANIZATION	BRITISH COLUMBIA DEPT. HIWYS., VICTORIA. BRITISH COLUMBIA, CANADA
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

TO INCREASE THE AVAILABLE LIGHT LEVEL FOR A TELEVISION TRAFFIC MONITOR WITHIN THE TUNNEL. SOME FORM OF REFLECTIVE SURFACE OVER THE CONCRETE IS NEEDED. LARGELY BECAUSE OF THE EASE OF ERECTION AND MAINTENANCE, PREFABRICATED FIBERGLASS PANELS WERE CHOSEN INSTEAD OF TILING OR EPOXY PAINT LINING. FIVE PANELS HAVE BEEN INSTALLED AS A TEST SECTION. THE FASTENING ASSEMBLY, RESISTANCE TO ABRASION, RETENTION OF REFLECTIVITY, ETC. WILL BE EVALUATED. /RATAOC/

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SPONSORING ORGANIZATION	BRITISH COLUMBIA GOVERNMENT
SPONS. ORG. CONTROL NO.	2R34050869 (HRB NO.)
SSIE ACCESSION NO.	GB 50869

TITLE	SLIDING FORMS FOR CONSTRUCTING MONOLITHIC PRESSED CONCRETE LININGS IN SHIELD TUNNELING.
AUTHORS	Skulbin, F. T.; Dushenko, E. F.; Korol'kov, V. N.
SOURCE REFERENCE	Soil Mech Found Eng v 9 n 2 Mar-Apr 1972 p 112-115
SUBJECT HEADING	CONCRETE CONSTRUCTION--Forms
CROSS REFERENCE	TUNNELS--Lining
FREE-LANGUAGE TERMS	SHIELD TUNNELING
ABSTRACT NUMBER	73-000782
ABSTRACT	To eliminate the shortcomings of rigid formworks the Scientific-Research Institute of Bases and Underground Structures developed and manufactured a pliable sliding form. The pliancy of the formwork in transverse and longitudinal directions is accomplished by installing spring elements in the joints between the segments and sections of the formwork. The formwork consists of three main parts: rigid, intermediate and pliant. The concrete mix is pressed within the first section at the time of advancing the shield. The segments in it are connected by bolts, which permit their assembly and disassembly directly in the tunnel. 6 refs.
CARD ALERT CODES	401; 405
JOURNAL CODEN	SMFEAF

TITLE	SPECIAL CONCRETES AND MORTARS
INVESTIGATORS	PAILLIERE : DELUDE P: BUS : BERISSI : CHAMPION : MENOU J
PERFORMING ORGANIZATION	LAB. CENT. DES PONTS CHAUSSEES, PARIS, FRANCE
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

SOME CONCRETES AND MORTARS CANNOT BE CONSIDERED AS CONVENTIONAL MATERIAL BECAUSE OF THEIR COMPOSITION. THEY CONTAIN INGREDIENTS OTHER THAN CEMENT AND NATURAL AGGREGATES, AND THEIR APPLICATION TECHNIQUES ARE QUITE SPECIAL. THIS RESEARCH IS CONCERNED WITH THE MIX-DESIGN, CHARACTERISTICS, MANUFACTURE, APPLICATION AND CONTROL OF CONCRETE FOR CAST-IN SITU PILES AND WALLS, TUNNEL LININGS (NON-STANDARD USE), CONCRETE AND MORTARS CONTAINING RESIN (BINDERS OF UNCONVENTIONAL USE), LIGHTWEIGHT CONCRETE (NON-STANDARD AGGREGATES), AND PUMPED CONCRETE. /IRRD/

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FUNDING	$147,200
SPONSORING ORGANIZATION	UNITED KINGDOM GOVERNMENT
SPONS. ORG. CONTROL NO.	2R32068169 (HRB NO.)
SSIE ACCESSION NO.	GB 68169

TITLE	POLYMER CONCRETE TUNNEL SUPPORT AND LINING TEST PROGRAM
INVESTIGATORS	DIKEOU
PERFORMING ORGANIZATION	U.S. DEPT. OF THE INTERIOR, BUREAU OF RECLAMATION, DENVER FEDERAL CTR., BLDG. 67, DENVER, COLORADO, 80225
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

THIS PROJECT WILL DEVELOP AND TEST LOW COST, HIGH STRENGTH PRECAST POLYMER IMPREGNATED CONCRETE FOR THOSE TUNNEL SUPPORT AND LINING SYSTEMS THAT UTILIZE THE UNIQUE CHARACTERISTICS OF POLYMER CONCRETE MATERIALS. /FHWA/

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SPONSORING ORGANIZATION	U.S. DEPT. OF TRANSPORTATION, FEDERAL HIGHWAY ADMINISTRATION
SPONS. ORG. CONTROL NO.	3584064: 2R34234683 (HRB NO.)
SSIE ACCESSION NO.	GB 234683

ACCESSION NO.	PB-242 968/6SL
TITLE	Field Evaluation of Joint Seal Materials
TITLE NOTE	Final rept. on Phase 5
AUTHORS	Wolters, R. O.
CORPORATE SOURCE	Minnesota Dept. of Highways, St. Paul. Office of Research Coordination.
PAGINATION/DATE	1974; 29p
NTIS PRICES	NTIS Prices: PC$3.75/MF$2.25
CATEGORY CODES	11A; 13C; 71B; 50A; 50C
DESCRIPTORS	*Concrete pavements; *Joint sealers; Performance evaluation; Field tests; Highways
IDENTIFIERS	DOT/4CZ/CA; DOT/4BZ/BF; NTISDOTFHA
ANNOUNCEMENT PUBLICATION	U7519
REPORT NOS.	MN-HW-S-180-75-2; Investigation-168
ABSTRACT	At the time of construction of a PCC pavement in 1969, transverse contraction joints perpendicular to centerline were sealed using liquid seals and preformed compression-type seals. Test sections were established for each material under study to evaluate

ACCESSION NO.	Pb-210 311
TITLE	Acceptance Criteria for Preformed Transverse Joint Sealers.
TITLE NOTE	Final rept.
AUTHORS	Hiss, J. G. Fred Jr
CORPORATE SOURCE	New York State Dept. of Transportation, Albany. Engineering Research and Development Bureau.
PAGINATION/DATE	Apr 72; 38p
NTIS PRICES	pc $3.00/Mf $0.95
CATEGORY CODES	11A; 13B; 71B; 60F
DESCRIPTORS	(*joint sealers, *concrete pavements); Polychloroprene; Acceptability; Tests
ANNOUNCEMENT PUBLICATION	U7216
REPORT NOS.	Rr-72-7
PROJECT NOS.	Hpr-2-5
ABSTRACT	Transversr joints are constructed in rigid pavements to allow for expansion and contraction of portland cement concrete. After these joints are constructed, they must be sealed to keep out incompressible materials and water. The ultimate goal of the investigation was twofold: (1) to determine the laboratory tests that would best predict the field serviceability of preformed polychloroprene joint sealers, and (2) then to determine minimum specification limits ensuring adequate service.

ACCESSION NO.	Pb-194 405
TITLE	Polysulfide canal contraction joint sealer. laboratory tests to determine effect of early immersion on coal-Tar extended polysulfide sealer placed in fresh concrete
AUTHORS	Uyeda. Harry K.
CORPORATE SOURCE	Bureau of Reclamation. Denver. Colo. Office of Chief Engineer.
PAGINATION/DATE	1970: 18p
NTIS PRICES	hc $3.00 Mf $0.65
CATEGORY CODES	11A: 13C: 71B: 60C
DESCRIPTORS	(*polysulfide resins. *sealers): (*joint sealers. Polysulfide resins): (*concretes. Joint sealers): (*canals. Joint sealers): Submerging: Tension tests: Degradation
ANNOUNCEMENT PUBLICATION	U7022
REPORT NOS.	Rec-Oce-70-29
ABSTRACT	Laboratory tests show the effect of early immersion on the performance of polysulfide sealer extruded into the fresh concrete of contraction joint grooves. Tensile test results indicate that sealer-concrete bond is a function of the cure time prior to immersion. Although one-day cure time was found to be the minimum acceptable in these tests. several days' curing before immersion improved performance significantly. (author)

TITLE	EXPERIMENTAL LINER FOR SAILOR BAR VEHICULAR TUNNEL
INVESTIGATORS	KERR JW; NESBITT MC; DARBY RO
PERFORMING ORGANIZATION	BRITISH COLUMBIA DEPT. HIWYS., VICTORIA, BRITISH COLUMBIA, CANADA
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

LEAKS IN THE CONCRETE LINING OF A 950 FOOT LONG TUNNEL IN THE FRASER CANYON CAUSE INTENSE ICING TO OCCUR DURING THE WINTER. GROUTING WITH CEMENT AT HIGH PRESSURES AND A.M. 9 AT MODERATE PRESSURES FAILED TO COMPLETELY STOP THE LEAKS. THREE TEST SECTIONS WERE ERECTED TO INVESTIGATE THE BEHAVIOUR OF ICE BEHIND A PROPOSED LINING TO ASSESS THE VALUE OF INSULATION AND TO COMPARE THE DURABILITY OF ALUMINUM, GALVANIZED CORRUGATED METAL AND ASBESTOS CEMENT TILE. CONTINUOUS RECORDING THERMOMETERS WERE PLACED IN THE AIR, SIX INCHES AND 18 INCHES INTO THE CONCRETE. OTHER THERMOCOUPLES WERE PLACED AT OTHER POINTS TO FIND THE SPACIAL VARIATION OF TEMPERATURE. RESULTS IN THE 1964-5 WINTER SHOWED THAT TEMPERATURES FELL BELOW FREEZING 18 INCHES INTO THE CONCRETE. CALCULATIONS SHOWED THAT EFFECTIVE INSULATION WOULD BE VERY COSTLY. OBSERVATIONS SINCE HAVE SHOWN NO PROBLEMS WITH ICE CAUSING BULGING OF THE LINING. THE SELECTED DESIGN CONSISTS OF A CURVED CORRUGATED ASBESTOS CEMENT LINER ANCHORED DIRECT TO THE CONCRETE OF THE TUNNEL. THE LINER EXTENDS DOWN TO A HEATED GUTTER AT THE ROAD LEVEL. THERE IS PROVISION FOR HEATING CABLES TO BE INSTALLED AT POINTS WHERE ICE ACCUMULATION IS EXCESSIVE. A CONTRACT HAS BEEN LET FOR 1440 FEET OF LINING./RATAOC/

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SPONSORING ORGANIZATION	BRITISH COLUMBIA GOVERNMENT
SPONS. ORG. CONTROL NO.	2R10050085 (HRB NO.)
SSIE ACCESSION NO.	GB 50085

TITLE	SEGMENTED CONCRETE LINER STUDY
INVESTIGATORS	UNKNOWN
PERFORMING ORGANIZATION	BECHTEL CORPORATION, 50 BEALE ST., SAN FRANCISCO, CALIFORNIA, 94119
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

The U.S. Department of Transportation is interested in conducting a systems study of prefabricated, portland cement concrete, tunnel liners for use as both primary and secondary tunnel support on a wide range of ground conditions. The study is intended to establish the preliminary work required to develop standard concrete liner segments, incorporating the innovations necessary to provide efficient liners applicable primarily for excavation with tunneling machines. A system of liners will be developed for both single and double track transit tunnels.

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FUNDING	$140,265, CONTRACT
SPONSORING ORGANIZATION	U.S. DEPT. OF TRANSPORTATION, OFFICE OF THE SECRETARY
SPONS. ORG. CONTROL NO.	048773 (TRAIS NO.)
SSIE ACCESSION NO.	GZ 48773

TITLE	DEVELOPMENT AND TESTING OF NEW TUNNEL SUPPORTS
INVESTIGATORS	PECK RB
PERFORMING ORGANIZATION	UNIV. OF ILLINOIS. SCHOOL OF ENGINEERING. CIVIL ENGINEERING. 2527 HYDROSYSTEMS LAB.. URBANA. ILLINOIS. 61801
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

The University will investigate and test new concepts in rational tunnel design. new materials and techniques for shot crete support of tunnels and new materials and improved structural design for segmented tunnel linings.

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SPONSORING ORGANIZATION	KAJIMA CORPORATION
SPONS. ORG. CONTROL NO.	2R63602370 (HRB NO.)
SSIE ACCESSION NO.	GB 602370

TITLE	TUNNELS
INVESTIGATORS	BRUSER DM; BURCHAND JB; WARD WH
PERFORMING ORGANIZATION	UNKNOWN INST. OR INDIV. GRANT, WINNIPEG. CANADA
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

THEORETICAL AND FIELD INVESTIGATIONS ARE MADE OF THE BEHAVIOUR OF THE GROUND, BOTH SOIL AND ROCK, DUE TO TUNNELLING. THE PERFORMANCE OF VARIOUS TYPES OF TUNNEL LINING IN A VARIETY OF GROUND CONDITIONS IS STUDIED. THE OBJECTIVE IS TO REDUCE THE COST OF WATER TUNNEL CONSTRUCTION WHILE MAINTAING SUITABLE STANDARDS OF PERFORMANCE. FIELD STUDIES ARE DONE OF THE PERFORMANCE OF TUNNEL LININGS, PARTICULARLY SPRAYED CONCRETE LININGS AND ROCK BOLTING, FOR THE PROPOSED TYNE-TEES WATER SUPPLY TUNNEL WHICH WILL RUN THROUGH A WIDE VARIETY OF CARBONIFEROUS ROCKS. THE RESULTS WILL APPLY BOTH TO THE TYNE-TEES TUNNEL AND TO SIMILAR FUTURE TUNNELS. /IRRD-IRF/

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SPONSORING ORGANIZATION	UNITED KINGDOM GOVERNMENT
SPONS. ORG. CONTROL NO.	2R63601463 (HRB NO.)
SSIE ACCESSION NO.	GB 601463

TITLE	PIPELINE AND TUNNEL HYDRAULICS
INVESTIGATORS	DEXTER RB
PERFORMING ORGANIZATION	U.S. DEPT. OF THE INTERIOR, BUREAU OF RECLAMATION, HYDRAULICS BRANCH, DENVER FEDERAL CTR., BLDG. 67, DENVER, COLORADO, 80225
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

New materials and construction methods are being developed for long large-diameter pipelines and water conveyance tunnels under other research projects. These efforts will result in the use of flow surfaces that have not been evaluated for hydraulic resistance. Future aqueduct and pipelines may be constructed of reinforced plastic mortar, asbestos-cement, or various designs of precast concrete pipe sections. Joint designs and joint alignment, that may significantly effect hydraulic resistance, will vary with pipeline and tunnel lining materials. Current emphasis on rapid tunnel excavation by boring machine and use of precast segmental lining sections will result in tunnels with closely spaced transverse joints in the lining. Also, both machine bored and drilled-and-blasted tunnels may be lined with shotcrete resulting in relatively rough flow surfaces.

A need will exist to evaluate the hydraulic performance of the new conduits so the most economic designs of subsequent conduits can follow. The performance of full size operational conduits is the most reliable guide for prediction of hydraulic performance of future designs. Emphasis will be placed upon design and construction of hydraulic test facilities in new water conveyance conduits for future tests.

FUNDING	$5,000
SPONSORING ORGANIZATION	U.S. DEPT. OF THE INTERIOR, BUREAU OF RECLAMATION
SPONS. ORG. CONTROL NO.	DR-186
SSIE ACCESSION NO.	ZUF 2810

TITLE	STUDY OF TUNNEL LININGS SUPPORTS AND REINFORCEMENT
INVESTIGATORS	MORRIS JW
PERFORMING ORGANIZATION	U.S. DEPT. OF THE INTERIOR, BUREAU OF RECLAMATION, HYDRAULICS STRUCTURES BR. DENVER FEDERAL CTR., BLDG. 67, DENVER, COLORADO. 80225
PERIOD OF PERFORMANCE	7/73 TO 6/74
FISCAL YEAR	74
TECHNICAL SUMMARY (AB)	

The determination of tunnel lining, support and reinforcement requirements is a matter of continuing concern to planners and designers of water development projects.

Studies are being made using the finite element method of analysis to predict stresses and displacements around tunnel openings in rock.

Measurements from instrumentation installed in both drilled and blasted and machine bored prototype tunnels will be analyzed to obtain a better understanding of movements and stresses in the rock surrounding the excavated section.

Studies are also being made to compare the practicality and adequacy of steel liner plate alone, compared to steel rib and liner plate in combination, as support for soft ground tunnels over a range of diameters.

Studies are being continued in the evaluation of various methods of design for rock bolt support systems and to develop criteria to be used to design Bureau of Reclamation tunnels.

FUNDING	$5,000
SPONSORING ORGANIZATION	U.S. DEPT. OF THE INTERIOR, BUREAU OF RECLAMATION
SPONS. ORG. CONTROL NO.	DD-70
SSIE ACCESSION NO.	ZUF 16410

TITLE	DEVELOPMENT AND TESTING OF NEW TUNNEL SUPPORTS
INVESTIGATORS	PECK RB
PERFORMING ORGANIZATION	UNIV. OF ILLINOIS. SCHOOL OF ENGINEERING. CIVIL ENGIN. 2527 HYDROSYSTEMS LAB., URBANA. ILLINOIS. 61801
PERIOD OF PERFORMANCE	7/74 TO 6/75
FISCAL YEAR	75

• TECHNICAL SUMMARY (AB)

The University will investigate and test new concepts in rational tunnel design. new materials and techniques for shot crete support of tunnels and new materials and improved structural design for segmented tunnel linings.

Document provided to S.S.I.E. by the T.R.A.I.S.

FUNDING	$399.743. CONTRACT
SPONSORING ORGANIZATION	U.S. DEPT. OF TRANSPORTATION. FEDERAL RAILROAD ADMIN.. HIGH SPEED GROUND TRANSP. OFF.
SPONS. ORG. CONTROL NO.	038648 (TRAIS NO.)
SSIE ACCESSION NO.	GZE 294 1

TITLE	Structural design data for unreinforced concrete tunnel linings
AUTHORS	DIXON, JD
AUTHOR AFFILIATION	DENVER MINING RESEARCH CENTER, COLO
SOURCE REFERENCE	U S Bur Mines- Report Investigations 7297 Sept 1969, 43 p
SUBJECT HEADING	TUNNELS--Lining
CROSS REFERENCE	TUNNELS--Stresses; MINES AND MINING--Tunneling; ROCK MECHANICS
ABSTRACT NUMBER	70-24725
ABSTRACT	Structural design data for unreinforced concrete tunnel linings in the form of stress and deflection coefficients from which bending, axial, shear, and boundary stresses, moments, thrusts, and shear forces, and structural deflections can be determined at any point on the lining were developed. The tunnel configurations include three basic shapes, circular, rectangular, and horseshoe, with dimensions based on designs evolved by the mining industry. These analyses were made by the direct stiffness matrix method, a computer-oriented procedure.
CARD ALERT CODES	401

TITLE	Use of thin- walled prefabricated, reinforced concrete ring segments for lining of tunnels end adits
ORIGINAL TITLE	Die Verwendung duennschaliger Betonfertigteile beim Ausbau von Tunneln und Stollen
AUTHORS	BENDA, V
SOURCE REFERENCE	Rock Mech, Felsmech, Mec Roches v 2 n 4 Dec 1970 p 229-41
SUBJECT HEADING	TUNNELS--Lining
CROSS REFERENCE	CO'CRETE CONSTRUCTION--Reinforcement: CONCRETE CONSTRUCTION--Prefabricated: TUNNELS--Stresses
ABSTRACT NUMBER	72-15789
ABSTRACT	Success of ttle technique, which is described in detail and has been employed in many instances in tunnels, mines etc, depends on proper execution of joints, between individual segments as well as on complete filling with rock, cement, etc of empty spaces between the lining and rock, thus assuring uniform distribution of rock pressure. 10 refs. In German with English abstract.
CARD ALERT CODES	401: 405: 408

TITLE	Lining of tunnels and galleries with concrete ring construction by the Bernold system
ORIGINAL TITLE	Der Tunnel- und Stollenausbau nach der Betonschalenbauweise System Bernold
AUTHORS	WOEHLBIER, G; NATAU, O
AUTHOR AFFILIATION	TECHNISCHE UNIVERSITAET CLAUSTHAL, WEST GERMANY
SOURCE REFERENCE	Large Permanent Underground Openings, Proc Int Symp, Sept 23-25 1969, Oslo, Norway, Int Soc Rock Mech, 1970, p 215-25
SUBJECT HEADING	TUNNELS--Lining
CROSS REFERENCE	ROCK MECHANICS
ABSTRACT NUMBER	72-20362
ABSTRACT	6 refs. In German.
CARD ALERT CODES	401; 483; 502

TITLE	Precast concrete tunnel linings for Toronto subway
AUTHORS	BARTLETT, JV; NOSKIEWICZ, TM; RAMSAY, JA
AUTHOR AFFILIATION	MOTT, HAY & ANDERSON, SURREY, ENGLAND
SOURCE REFERENCE	ASCE J Constr Div v 97 n CO2 Nov 1971 paper 8498 p 241-56
SUBJECT HEADING	TUNNELS--Lining
CROSS REFERENCE	SUBWAYS--Costs; CONCRETE CONSTRUCTION
ABSTRACT NUMBER	72-24188
ABSTRACT	Precast concrete tunnel linings were used in the Toronto subway system in a wide range of soils conditions. This has resulted in a significant cost saving as compared with the conventional cast iron lining. The linings are 16- ft ID and are without secondary lining. They are interchangeable with cast iron linings which are also used on the project.
CARD ALERT CODES	401; 405; 681; 911
JOURNAL CODEN	JCCEA

TITLE	Novel shape of reinforced concrete lining for shield driven tunnels
AUTHORS	APEL, F
AUTHOR AFF.LIATION	VOI, ESSEN-BURGALTENDOR, WEST GERMANY
SOURCE REFERENCE	Tunnels Tunnelling v 3 n 2 Mar-Apr 1971 p 108-11
SUBJECT HEADING	TUNNELS--Lining
CROSS REFERENCE	CONCRETE CONSTRUCTION--Reinforced
ABSTRACT NUMBER	72-21278
ABSTRACT	Article describes a novel tunnel lining in soft ground technique that uses reinforced concrete T- beams, called rib liners. To facilitate the connection of the radial joints the ribs are fitted with inserts at the top of the liners which will take straight or slightly bent steel bolts. If a yielding to ground pressure construction is desired these bolts serve only for the erection of the rings and are then recovered. When a stiff, elastic construction is desired, they remain in place and are tensioned in accordance with the structural requirements. The sealing of the joints is achieved by painting the contact surfaces of the liners with plastic and filling the sealing recesses with a plastic filler.
CARD ALERT CODES	401; 405

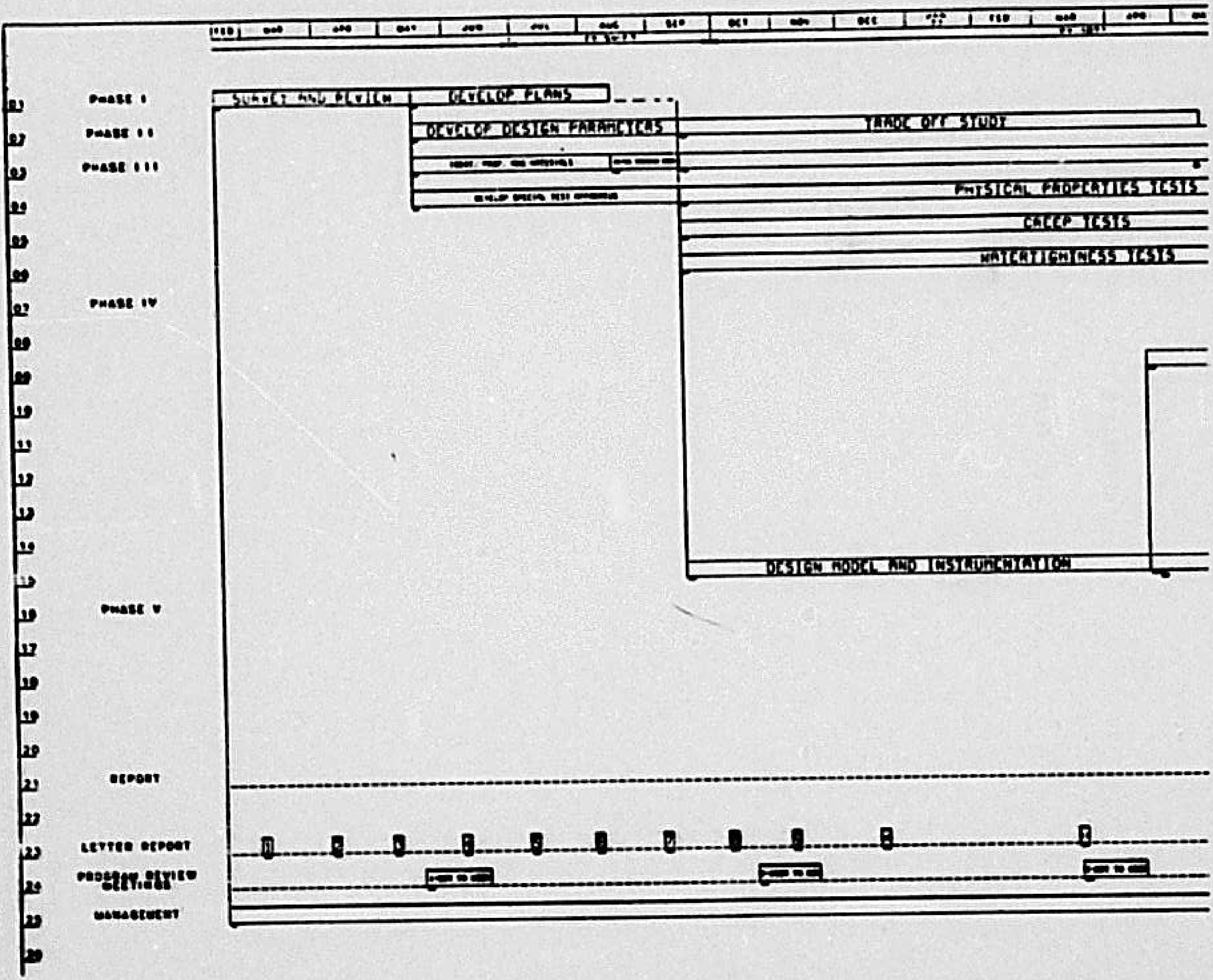
TITLE	Calculation of Reinforced Concrete Lining in the Heitersberg, Los West Tunnel.
ORIGINAL TITLE	BERECHNUNG DER STAEHLBETONTUEBBINGE FUER DEN HEITERSBERGTUNNEL, LOS WEST.
AUTHORS	Andraskay, E.; Hofmann, E.; Jemelka, P.
AUTHOR AFFILIATION	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE, ZURICH, SWITZ
SOURCE REFERENCE	Schweiz Bauztg v 90 n 36 Sep 7 1972 p 864-868
SUBJECT HEADING	TUNNELS--Lining
CROSS REFERENCE	COMPUTER SYSTEMS PROGRAMMING
ABSTRACT NUMBER	73-005163
ABSTRACT	The tunnel described was lined with precast reinforced concrete elements. Using STRESS computer program, it was possible to vary the soil properties in the analysis and thus to determine their influence on the structural system consisting of linear and surrounding soil. Application of plastic design methods led to a flexible and economic liner. In spite of modern computational means, it is still the responsibility of the engineer to decide the selection of material properties, to assume on load-distribution and to interpret the results. The stresses in the liner due to shield-driving forces can be approximately determined by constant observation. 7 refs. In German.
CARD ALERT CODES	401; 723
JOURNAL CODEN	SCBABG

TITLE	REPORT ON APPLICATION OF A LARGE EXCAVATOR SHIELD TUNNELING SYSTEM AND PRECAST CONCRETE SEGMENT FINAL LINING FOR THE CASTIGLIONI TUNNEL, ITALY.
AUTHORS	Tarsitani, Alberto
AUTHOR AFFILIATION	CONSORZIO FERROFIR, ROME, ITALY
SOURCE REFERENCE	Rapid Excavation and Tunneling Conf. Proc. San Francisco, Calif, Jun 24-27 1974 v 2 p 16'1-1650. Publ by Soc of Min Eng of AIME, New York, NY, 1974
SUBJECT HEADING	TUNNELS--Construction
CROSS REFERENCE	EXCAVATION; CONCRETE CONSTRUCTION--Prefabrication; CONSTRUCTION EQUIPMENT
FREE-LANGUAGE TERMS	HYDRAULIC EXCAVATOR SHIELD; SOFT GROUND TUNNELING
ABSTRACT NUMBER	75-077756
ABSTRACT	Of the three possible methods of excavation considered, the method chosen includes full section excavation using an hydraulic excavator end shield with a conveyor belt and a mechanical system to position a precast segmented final lining. This technology could be used both in the clay and in the sands. It was chosen because of the uniformity of ground, the excavation speed predicted by the manufacturer, labor required, safety of the work, and the new important experience that the form could get through the operation of a machine to drive a full face tunnel. The tunneling machine is a Robbins Model 3615-143. Static problems and a careful analysis of the assembly time were evaluated to determine the best lining method. The lining chosen is composed of rings with six concrete segments whose weight is about 13 tons each, plus a key element weighing about 800 kg.
CARD ALERT CODES	401; 405

ACCESSION NO.	ad-697 281
TITLE	Twofold joint photocount statistics for mixed thermal & coherent radiation (REPRINT)
AUTHORS	Fillmore, Gary L.
CORPORATE SOURCE	Pennsylvania State Univ University Park Dept of Electrical Engineering
PAGINATION/DATE	20 Jan 69: 6p
AVAILABILITY	Pub. in The Physical Review, v182 n5 p1_84-1386, 25 Jun 69.
CATEGORY CODES	20F: 930
DESCRIPTORS	(*photons, Counting methods): Coherent radiation; Thermal radiation; Distribution functions; Polynomials
SPONS. AG. ACRONYM/NO.	Arod-5659:9-E
ANNOUNCEMENT PUBLICATION	U7002
CONTRACT/GRANT NOS.	Da-31-124-Aro(d)-383
PROJECT NOS.	Da-2-0-061102-B-31-E
ABSTRACT	The conventional model of the photodetection process and the short-time approximation are used to obtain the factorial moment generating function for the N-fold detection of mixed thermal and coherent radiation. This generating function is then used to obtain the photocount distribution for twofold joint photodetection. The photocount distribution is expressed as a threefold summation over Laguerre polynomials. The distribution is examined for the limiting cases of purely thermal radiation and uncorrelated fields. (author)

APPENDIX B

STUDY PLAN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SURVEY AND REVIEW
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DEVELOP DESIGN PARAMETERS
TRADE OFF STUDY
PHYSICAL PROPERTIES TESTS
CREEP TESTS
WATERTIGHTNESS TESTS
DESIGN MODEL AND INSTRUMENTATION
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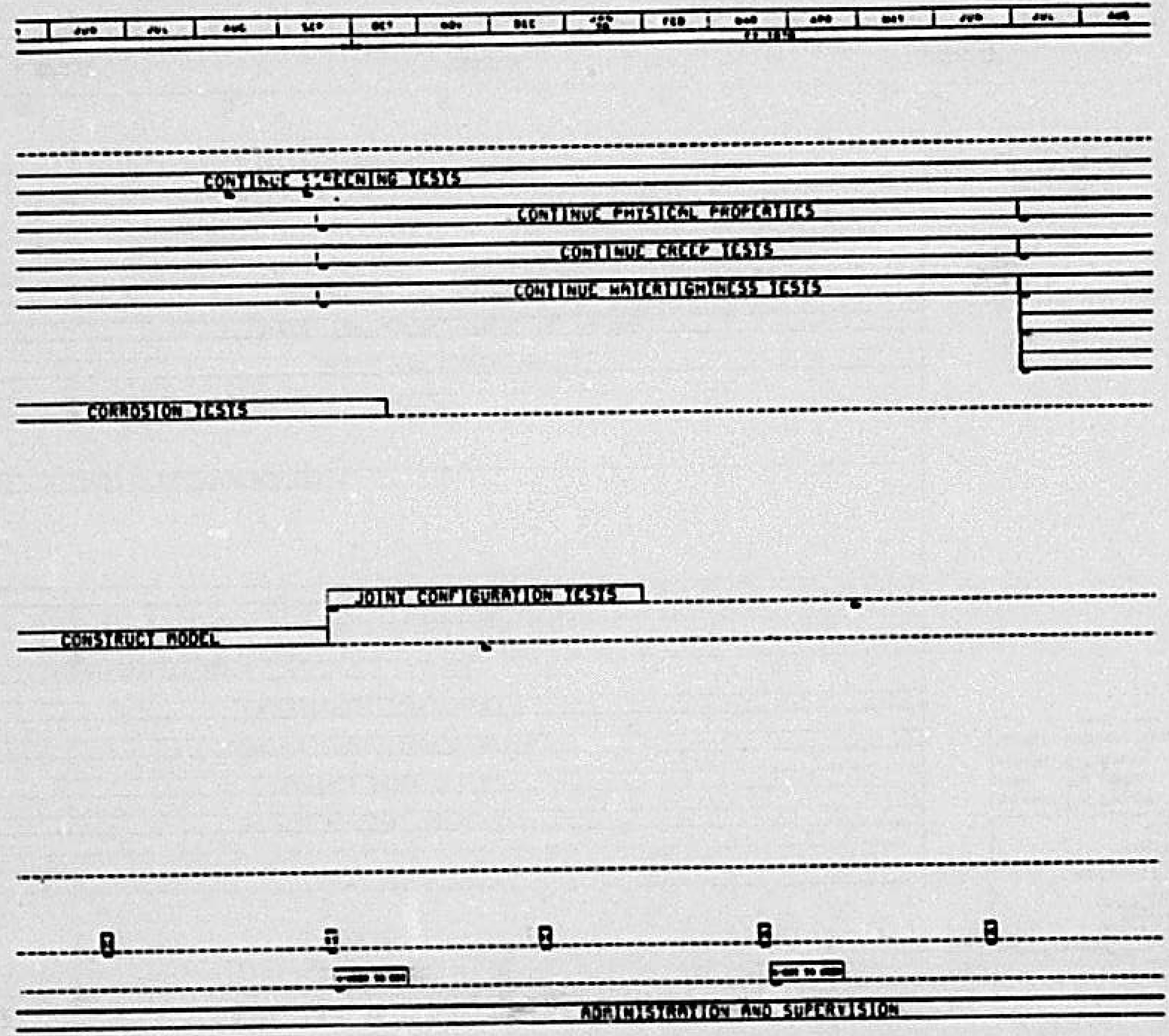
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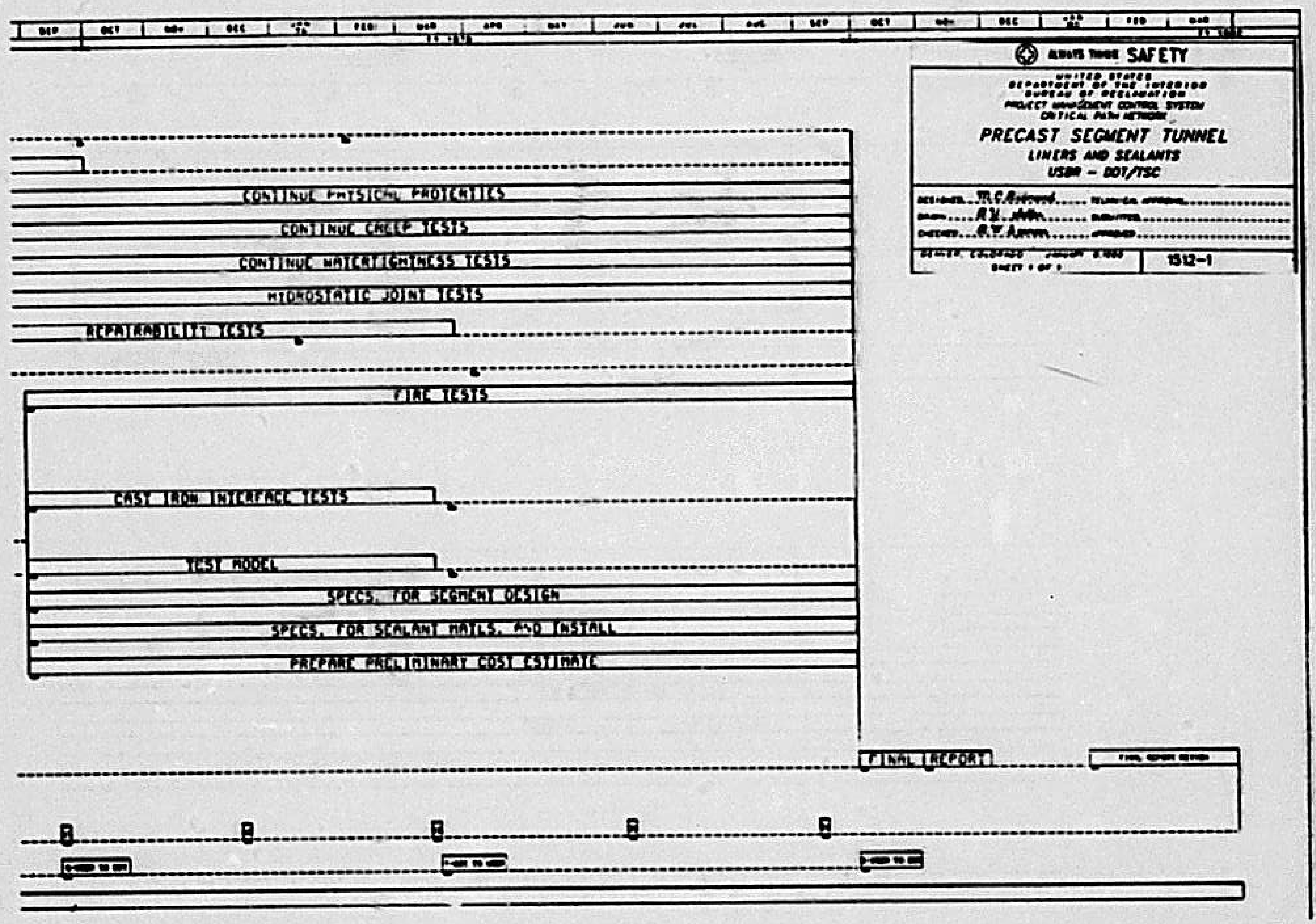
CONTINUE PHYSICAL PROPERTIES
CONTINUE CREEP TESTS
CONTINUE WATERTIGHTNESS TESTS
CORROSION TESTS
JOINT CONFIGURATION TESTS
CONSTRUCT MODEL
ADMINISTRATION AND SUPERVISION

SEP
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ALWAYS THINK SAFETY
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PROJECT MANAGEMENT CONTROL SYSTEM
CRITICAL PATH NETWORK
PRECAST SEGMENT TUNNEL
LINERS AND SEALANTS
USBR - DOT/TSC
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SUBMITTED
APPROVED
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CONTINUE PHYSICAL PROPERTIES
CONTINUE CREEP TESTS
CONTINUE WATERTIGHTNESS TESTS
HYDROSTATIC JOINT TESTS
REPAIRABILITY TESTS
FIRE TESTS
CAST IRON INTERFACE TESTS
TEST MODEL
SPECS. FOR SEGMENT DESIGN
SPECS. FOR SEALANT MATLS. AND INSTALL
PREPARE PRELIMINARY COST ESTIMATE
FINAL REPORT

APPENDIX C

DESIGN EXAMPLE

APPENDIX C - DESIGN EXAMPLE

Introduction

The purpose of this example is to determine a preliminary precast concrete segment thickness for a 5-m (16.4-ft) inside diameter subway tunnel.

Two approaches to the selection of a preliminary segment thickness are illustrated. In part 1 the method suggested by Deere, Peck, Monsees, and Schmidt is applied to the tunnel where height of cover over the tunnel is five diameters. In part 2, the tunnel is located so the cover over the tunnel is less than three diameters. A vertical loading is applied to the ring with supporting ground reactions based on a modulus of subgrade reaction for the surrounding earth. The ground liner interaction is analyzed through the use of the U. S. Army Corps of Engineers "TUNNEL" computer program.

Notation

A_g - Area of gross concrete section

A_s - Area of steel reinforcement

D - Inside tunnel diameter

  ΔD - change in tunnel diameter

E - Modulus of elasticity

  E_c - of the concrete

  E_s - of the reinforcement

I - Moment of inertia

  I_g - of the gross concrete section

  I_{se} - of the reinforcement about the centroidal axis of the gross concrete section

K - Modulus of subgrade reaction

M - Moment

  M_u - factored ultimate moment

  M_n - nominal moment capacity

  M_b - balanced condition moment

P - Thrust

  P_u - factored ultimate axial load

  P_n - nominal axial load capacity

  P_b - balanced condition axial load

V - Shear

  V_u - factored ultimate shear

  V_n - nominal shear capacity

  V_c - shear capacity of concrete

b - Width of cross section

c. - Depth to neutral axis from extreme compression fiber

d - Depth to centroid of tension reinforcement from extreme compression fiber

f - Stress

  f_a - due to axial load

  f_b - due to bending

f'_c - Specified compressive strength of concrete (stress)
t - Segment thickness
- Density
γ_d - dry
γ_{sat} - saturated
e - reinforcement ratio $A_s \div bd$
ϕ - Strength reduction factor

Design example part 1

Design criteria

Loading from "Design of Tunnel Liners and Support Systems," the following design steps are required:

1. Provide for ring thrust
2. Provide for anticipated distortions
3. Consider the possibility of buckling
4. Make allowance for other external conditions

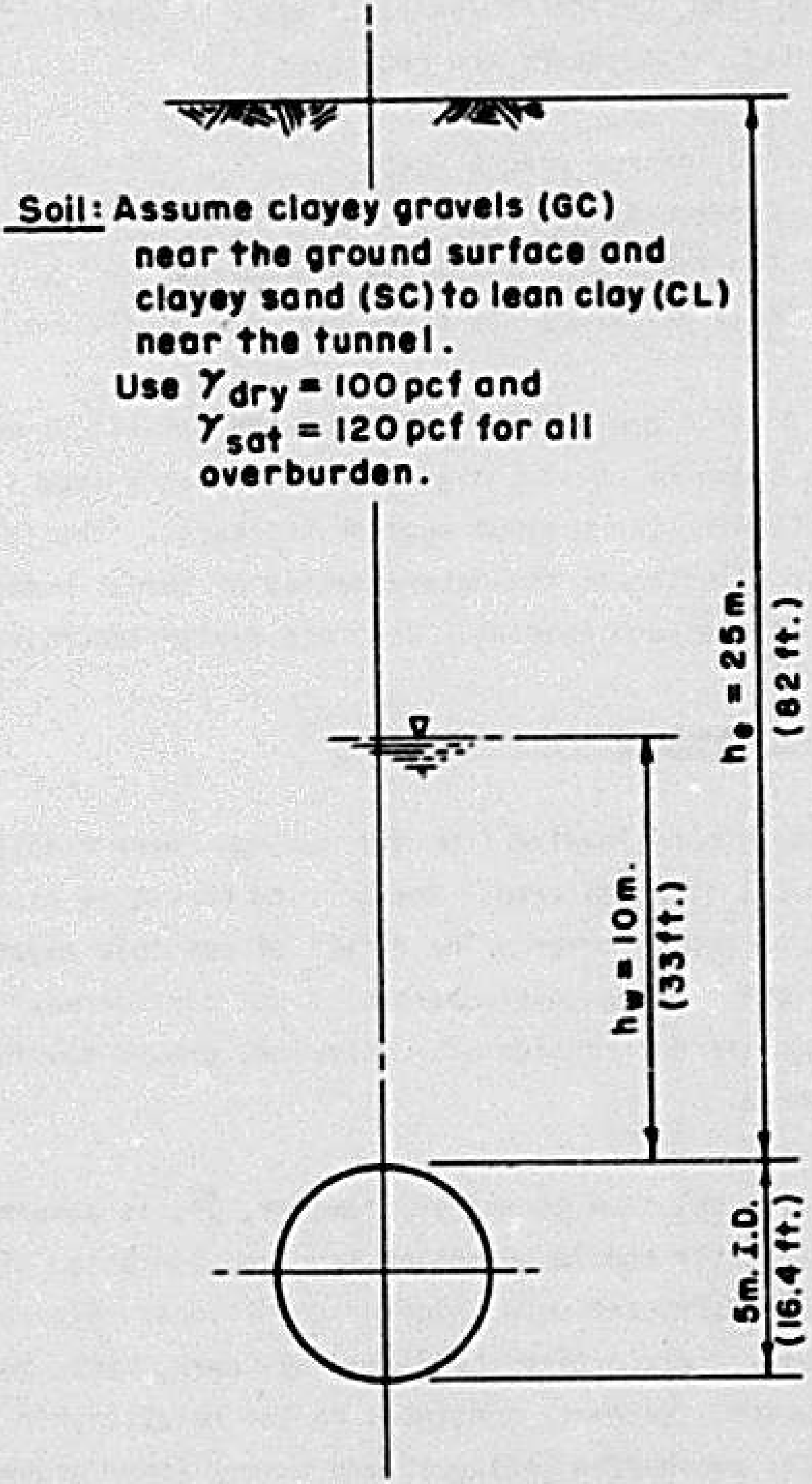
Steps 3 and 4 are site-specific and are not illustrated in this design example. Nevertheless, considerations from steps 3 or 4 may determine the minimum segment thickness. The following example illustrates the determination of thrust moment and shear due to the ground loading. Concrete design according to ACI 318-77.

Design parameters and assumptions

Only the ground loading from the maximum cover condition shown on Figure C-1 is considered. Design ring thrust is based on the full height of ground cover. The effect of possible adjacent tunneling and/or other ground disturbances is not considered. Surface loadings are not considered. Likewise, ground subsidence is not considered.

The design relative change in diameter, $\frac{\Delta D}{D}$, is assumed to be 0.005. This parameter should be chosen from consideration of similar tunnels constructed under similar conditions. Figure C-2 shows the measured distortions tabulated by Deere, Peck, Monsees, and Schmidt. Research continues on the relationship between soil strength, overburden pressure, and tunnel liner/ground reaction; for illustration, a value of $\frac{\Delta D}{D} = 0.005$ appears to be reasonable.

Design example part I



Soil: Assume clayey gravels (GC) near the ground surface and clayey sand (SC) to lean clay (CL) near the tunnel.

Use γ_{dry} = 100 pcf and γ_{sat} = 120 pcf for all overburden.

FIGURE C-1. MAXIMUM DEPTH OF COVER OVER THE SUBWAY TUNNEL

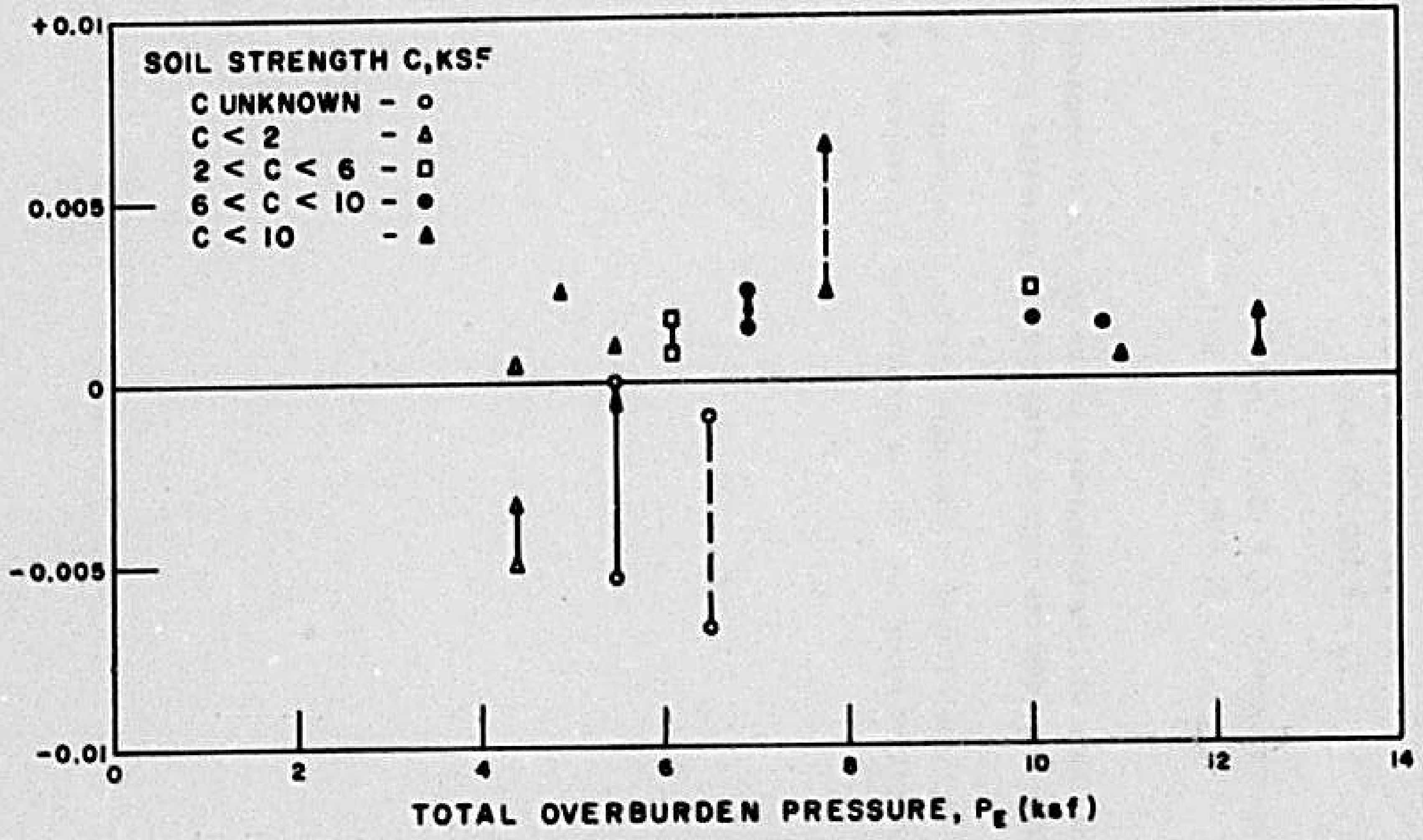


FIGURE C-2. DISTORTIONS OF TUNNEL LINING
(LINING DEFLECTIONS TAKEN FROM TABLE IV-4
DEERE, PECK, MONSEES, SCHMIDT, 1969)

Concrete: f'_c = 5,000 lb/in^2

γ = 145 lb/ft^3 in place

E_c = 4,100,000 lb/in^2

Reinforcement: f_y = 60,000 lb/in^2

E_s = 29,000,000 lb/in^2

Segments will be backpacked and/or grouted to completely fill the space between the segment ring and the excavated ground surface.

The tunnel lining is considered to be a continuous ring with the effective moment of inertia reduced for the cracked concrete.

General Summary

Thrust, Moment and Shear

Thrust is constant for a given depth according to the design method chosen; therefore, the stress due to thrust decreases with increasing segment thickness. For a given relative change in diameter, $\frac{\Delta D}{D'}$ moment and shear increase with increasing ring stiffness. Increasing the segment thickness produces a greater sectional moment of inertia and greater moment and shear. Algebraic expressions for thrust, moment and shear are shown on the following pages.

Figure C-3 shows the variation in maximum stress with segment thickness for linear elastic material with tensile strength equal to compressive strength. This figure does not predict the stresses in concrete segments; however, two implications of the expressions for thrust moment and shear are apparent:

(1) For a given depth of cover there is a minimum compressive strength of material for which the lining is adequate. That is increasing the thickness of lining does not reduce the stress in the lining material.

(2) For a given depth of cover and allowable lining material stress, there is a range of values for lining thickness which will produce acceptable stress levels in the lining. Lining thicknesses outside this range either thinner or thicker will produce unacceptable stress levels.

Table C-1 is a summary of the results of calculations used to produce Figures C-4 through C-6.

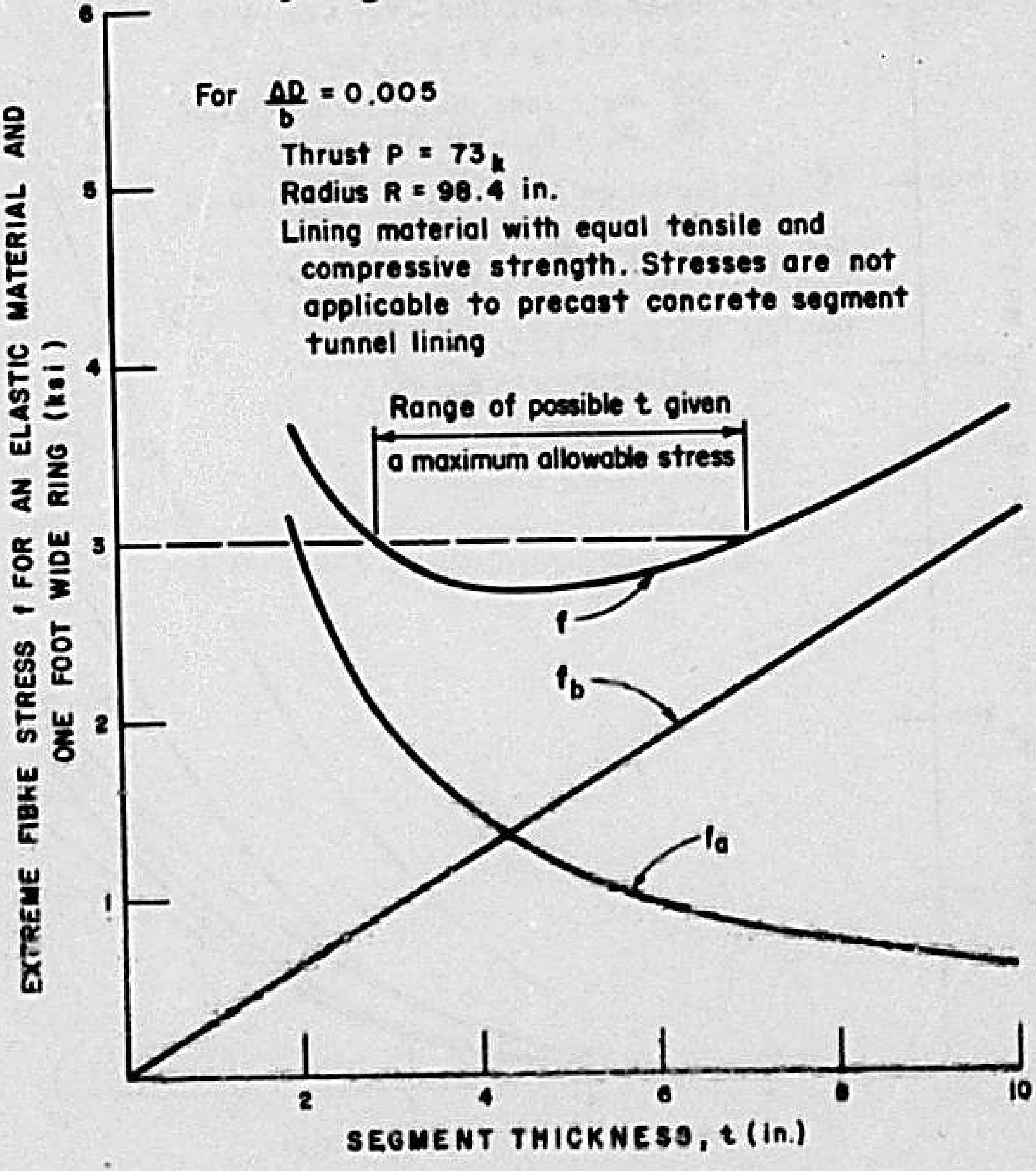
TABLE C-1. SUMMARY OF PRELIMINARY SEGMENT THICKNESS CALCULATIONS

	Flexure				Axial section				Flexure			Balance point		Axial load		Point on interaction		Shear		
t in	E_cI_g 1/ 10^6 k-in²	M_c in-k	EI 2/ 10^6 k-in²	M_c in-k	A_s in²	d_1 in	d_2 in	EI 3/ 10^6 k-in²	M_c in-k	EI 4/ 10^6 k-in²	M_c in-k	ϕM_b in-k	ϕP_b k	ϕP_0 k	P_{max} k	ϕM_n in-k	P_u k	V_u 2/ k	V_c 3/ k	ϕV_c k
4	262	71	106	30	0.20 0.60 0.16	2.00 2.00 2.00	— — —	52 52 52	14 14 14	71	19	52 52 52	22 9 27	154 166 149	123 133 119	28 28 28	83 81 83	1.5	0.6	2.9 2.9
5	513	138	295	55	0.40 1.10 0.20	3.75 3.63 3.75	1.25 1.38 1.25	128 189 121	35 50 33	138	38	125 174 118	58 36 60	200 264 194	160 211 155	55 55 55	138 192 131	2.9	1.1	5.4 5.3
6	886	299	394	96	0.30 1.30 0.20	4.75 4.50 4.75	1.25 1.50 1.25	266 355 270	67 96 59	216	59	200 279 161	76 51 78	245 320 233	196 256 186	96 96 96	164 227 151	5.0	2.0	6.8 6.5
7	1,420	300	563	152	0.52 1.60 0.28	5.60 5.50 5.75	1.51 1.50 1.25	427 667 164	115 180 98	377	102	294 442 257	92 73 96	290 379 272	232 304 217	152 152 152	400 274 167	8.0	3.2	8.2 7.9
8	2,100	567	840	227	0.86 1.97 0.32	6.69 6.44 6.75	1.31 1.56 1.25	705 1,380 900	193 297 151	619	167	420 657 346	110 104 113	339 440 310	271 352 248	277 277 227	215 324 181	11.0	4.7	9.6 9.3
10	4,500	1,107	1,640	443	1.03 2.53	8.63 8.38	1.38 1.62	1,600 2,500	432 674	1,440	380	733 1,114	143 132	437 554	349 444	443 443	259 386	23.0	9.2	12.4 12.0

1/ EI based on gross section.
2/ EI based on ACI (318-77), Eq. 10-10.
3/ EI based on ACI (318-77), Eq. 10-9.
4/ I based on ACI (318-77), Eq. 9-7.
E_c = 4300 k/in²
E_s = 29 000 k/in²
Notation according to ACI (318-77).

$$f = f_a + f_b \qquad f_a = \frac{73}{t(12)} = \frac{6.1}{t}$$

$$f_b = \frac{my}{I} = 0.00015\ EI\ \frac{t}{2I} = 0.308t$$



For $\frac{\Delta D}{b} = 0.005$

Thrust $P = 73_k$

Radius $R = 98.4$ in.

Lining material with equal tensile and compressive strength. Stresses are not applicable to precast concrete segment tunnel lining

FIGURE C-3. VARIATION IN MAXIMUM STRESS WITH LINING THICKNESS GIVEN DESIGN RELATIVE CHANGE IN DIAMETER AND THRUST

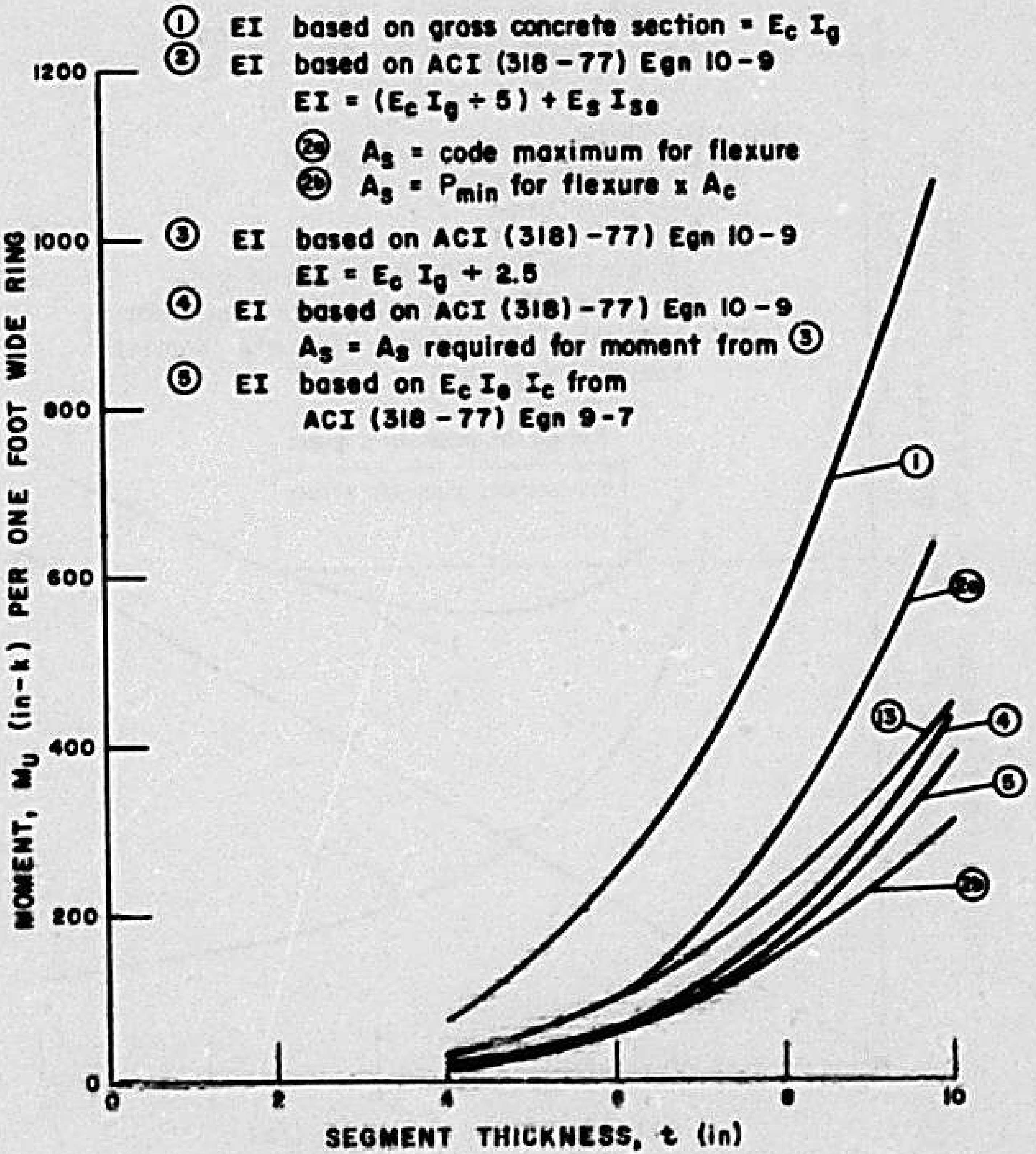
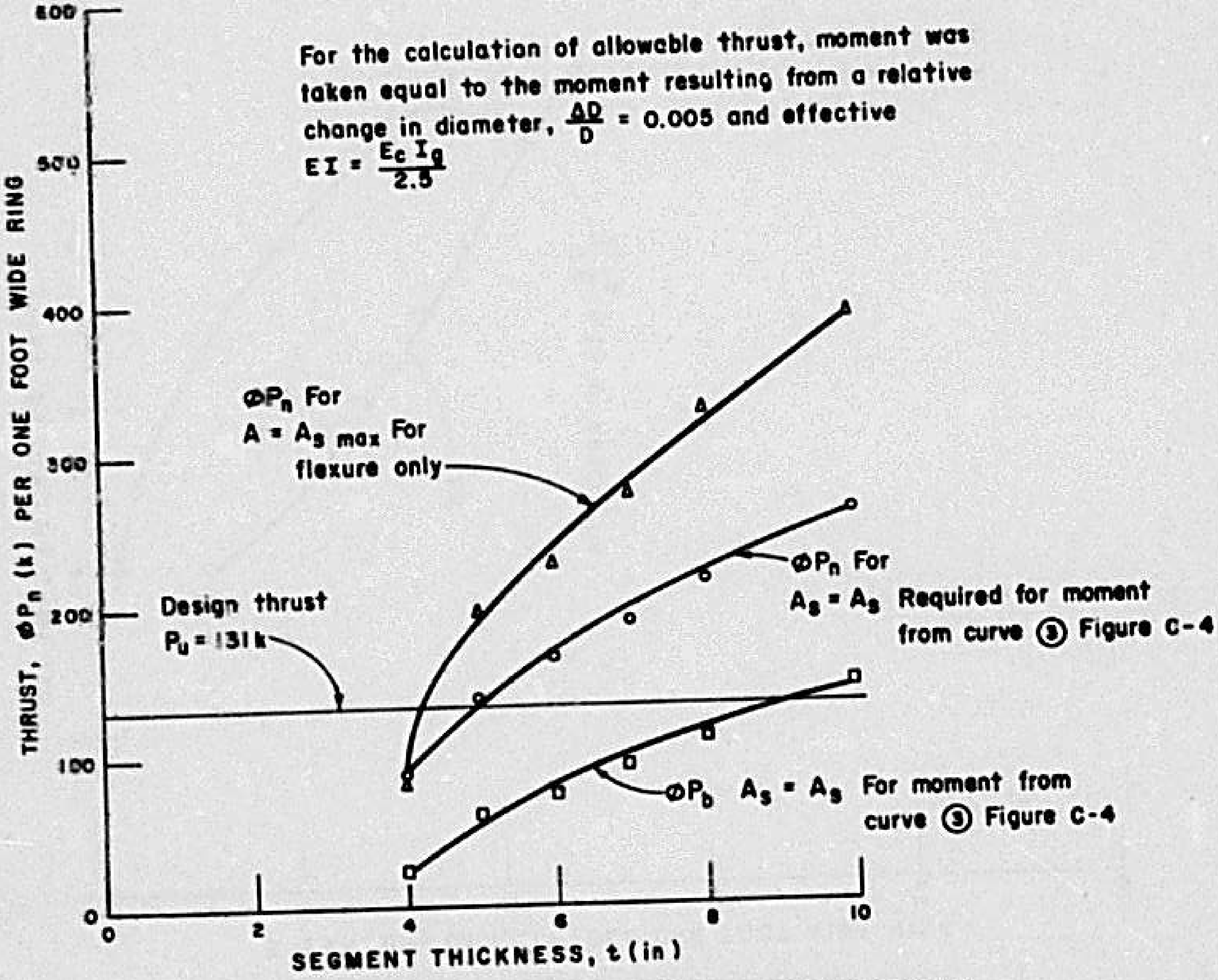


FIGURE C-4. MOMENTS DUE TO $\frac{\Delta D}{D}$ = 0.005 WITH VARYING ASSUMPTIONS FOR EFFECTIVE EI.



For the calculation of allowable thrust, moment was taken equal to the moment resulting from a relative change in diameter, $\frac{\Delta D}{D} = 0.005$ and effective $EI = \frac{E_c I_g}{2.5}$

FIGURE C-5. THRUST CAPACITY OF THE LINING FOR VARIOUS SEGMENT THICKNESSES AND REINFORCEMENT RATIOS

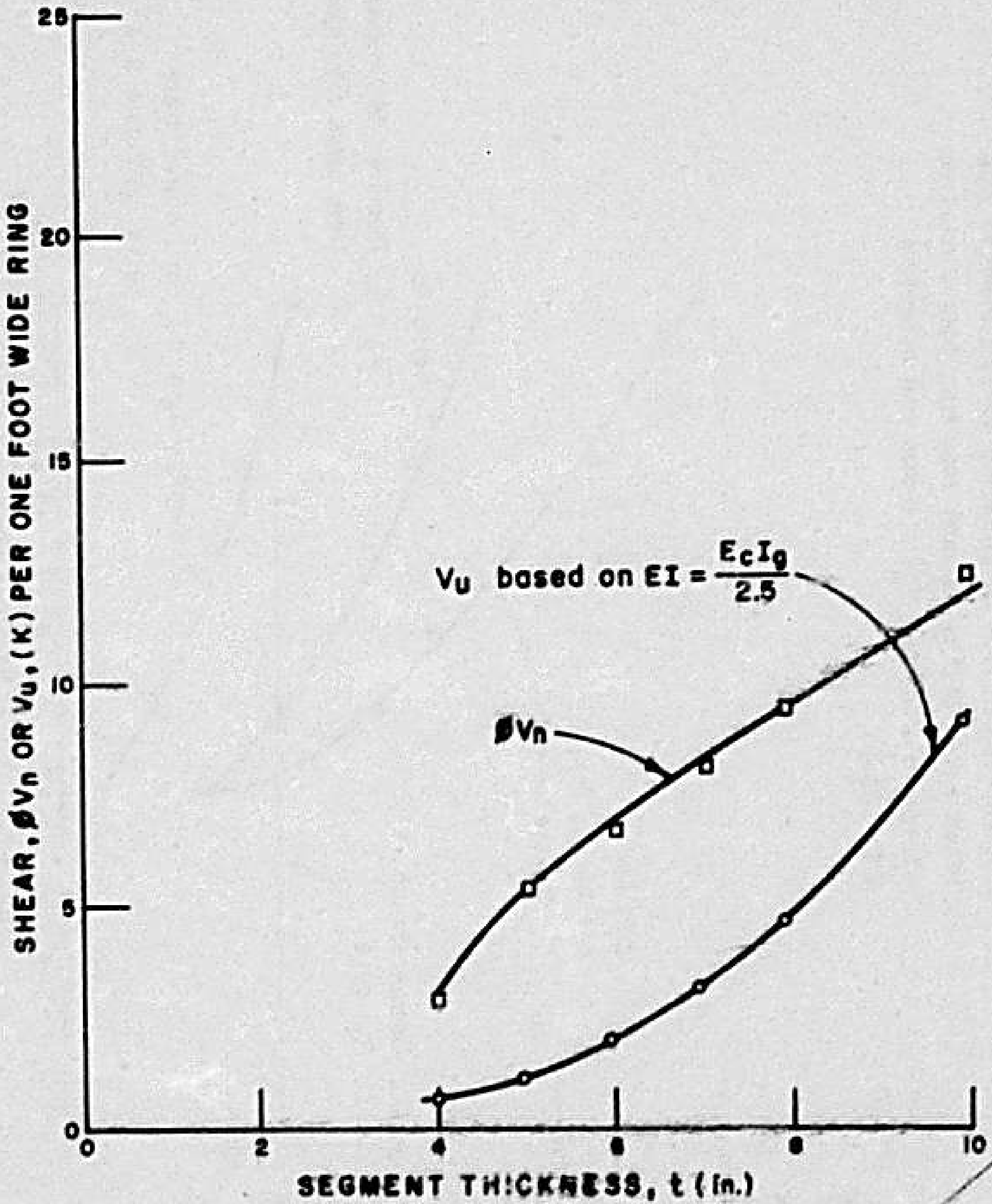


FIGURE C-6. SHEAR IN THE LINING DUE TO A RELATIVE CHANGE IN DIAMETER, $\frac{\Delta D}{D}$ = 0.005 AND SHEAR CAPACITY OF THE LINING

Moment

Figure C-3 shows the variation of moment with segment thickness. If the effective EI is assumed to be $E_cI_g \div 2.5$ and the section is reinforced for the moment indicated by curve 3 on Figure C-4 then the effective EI can be calculated using the assumptions of curve 4 or 5. The expected moment, shown by curve 4 or 5, can be compared with the moment for which the section was reinforced, curve 3. Figure C-4 shows that for the range of segment thicknesses considered, the expected moments are less than the design moments shown by curve 3. Therefore, the section reinforced for the design moment of curve 3 is adequate. Figure C-4 also shows the tendency of curves 4 and 5 to approach curve 3. It appears there is a maximum segment thickness for which the segment cannot be reinforced for moment.

Thrust

The minimum thickness of lining is determined from thrust considerations. Figure C-5 shows that a 5-inch-thick segment would just be able to carry the design thrust. The capacity of the section must be reduced for: (1) blockouts in the compressive zone of the concrete and (2) lower thrust capacity of the joints due to sealant systems (See Section 5.6).

Shear

Figure C-6 shows the variation of design shear, V_u, and shear capacity, ϕV_n with segment thickness. Shear based on the effective EI shown on the figure does not appear to limit the segment thickness over the range of thicknesses.

Thrust, P

radial pressure, P on the lining

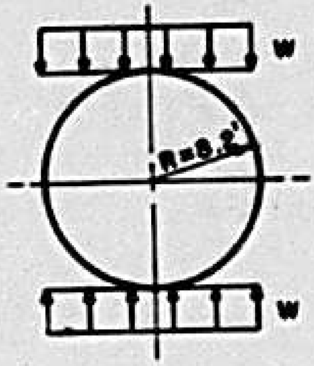
$$P = \gamma_d (h_e - h_w) + \gamma_s (h_w)$$
$$= 100 (82-33) + 120 (33) = 8860 \text{ psf} = 8.9 \text{ ksf}$$

Thrust

$$P = PR = 8.9 (8.2) = 73\text{k}$$
$$P_u = 1.8P = 1.8 (73) = \underline{131\text{k}}$$

Moment M

Provide for moment due to a design relative deflection $\frac{\Delta D}{D}$



$$\Delta D = \frac{wR^4}{6EI} \qquad \frac{\Delta D}{D} = \frac{wR^3}{12EI}$$

$$M_{max} = \tfrac{1}{4} wR^2$$

ref: Roark, R.J., Young, W.C., "Formulas for Stress and Strain", McGraw-Hill Book Co., New York, 1975.

for a design relative deflection, $\frac{\Delta D}{D}$

$$M_{max} = \frac{1}{4}\left(\frac{\Delta D}{D}\right)\left(\frac{12EI}{R^3}\right)R^2 = \left(\frac{\Delta D}{D}\right)\frac{3EI}{R}$$

$\frac{\Delta D}{D} = 0.005$, $R = 98.4$ in. $\qquad M_{max} = .00015\ EI$ in-k

$$M_u = 1.8\ M_{max} = \underline{0.00027\ EI \text{ in-k}}$$

Shear V

$$V_{max} = 0.5\ wR$$
$$= 0.5 \left(\frac{\Delta D}{D}\right)\left(\frac{12EI}{R^3}\right)R$$

$\frac{\Delta D}{D} = 0.005$, $R = 98.4$ in

$$V_{max} = .0000031\ EI$$

$$V_u = 1.8\ V_{max} \quad = \underline{0.0000056\ EI \text{ k}}$$

Design From consideration of Figures C-4 through C-6 check 7" thick segment

Moment $M_u = 0.00027$ EI from Table C-1
$M_u = 152$ in-k per foot of lining
$A_s = 0.52$ square inches/ft

Use ties spaced according to ACI (318-77) paragraph 7.10.5. with 5/8-in clear concrete cover

Shear $V_u = 0.0000056$ EI from Table C-1
$V_u = 3.2$ k per foot of lining

$\phi V_c = 8.2\text{k} > 3.2$ k

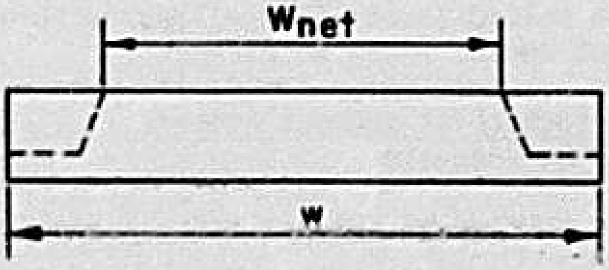
Note: Shear and moment capacities have not been reduced for blockout areas in the segments. It can be argued that since moment and shear are directly proportional to I, a blockout would reduce I and therefore reduce M_u and V_c proportionately

Thrust $P_u = 131$ k Table C-1

Reduce thrust capacity, ϕP_n, for blockouts:

Since thrust is independent of EI, blockout areas do not reduce thrust; therefore, the net capacity of the segment must be considered.

Assume bolt pockets are provided. The area of the segment which must be blocked out in order to place bolt pockets reduces the available compression area.



Since the compression block may be either on the inside or the outside of the segment reduce the thrust capacity by the ratio of width not blocked out to total width,

$$\frac{W_{net}}{W}$$

Net segment thrust capacity

Assume $W_{net} = 0.75\ W$

From Table C-1 at design moment ϕM_n = 152 in-k per ft
ϕP_n = 188 k

$$\frac{W_{net}}{W} = \phi P_n = 0.75(188)$$

$$= 141\ k > 131\ k$$

Reduce nominal thrust capacity, ϕP_n, for joint strength:

See Section 5.6 for test results regarding the reduction in joint capacity due to sealant material.

Assume a full face crushable compression seal. Test results indicate very little reduction in strength for plywood. Assume the crushable compression seal performs similarly. Assume a joint reduction factor = 0.9; in addition, reduce the segment capacity for blockouts at the joint. Again assume,

$$\frac{W_{net}}{W} = 0.75:$$

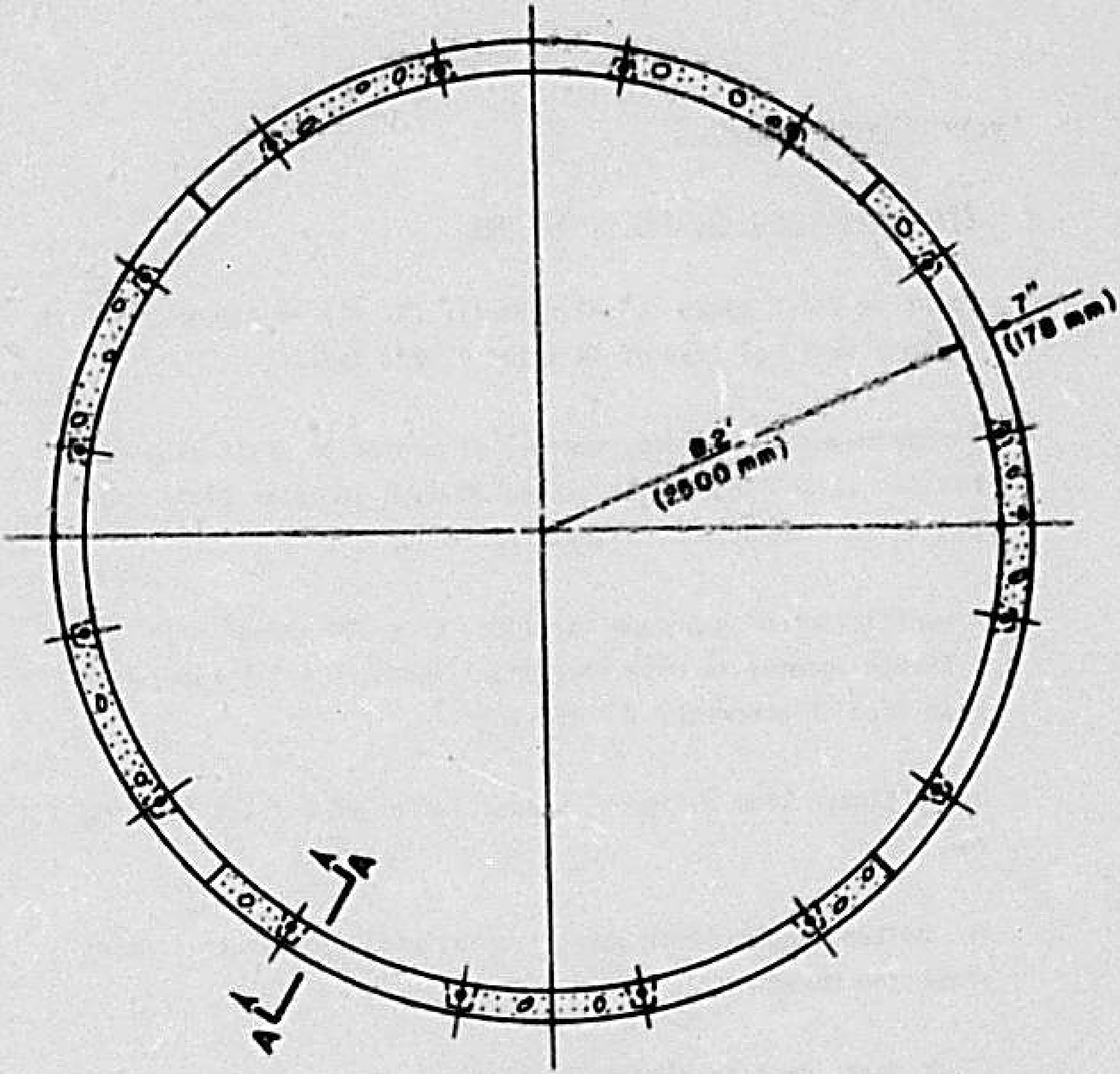
Therefore:

$$\phi Pn = (0.9)(0.75)(188)$$
$$= 127k \quad 131$$

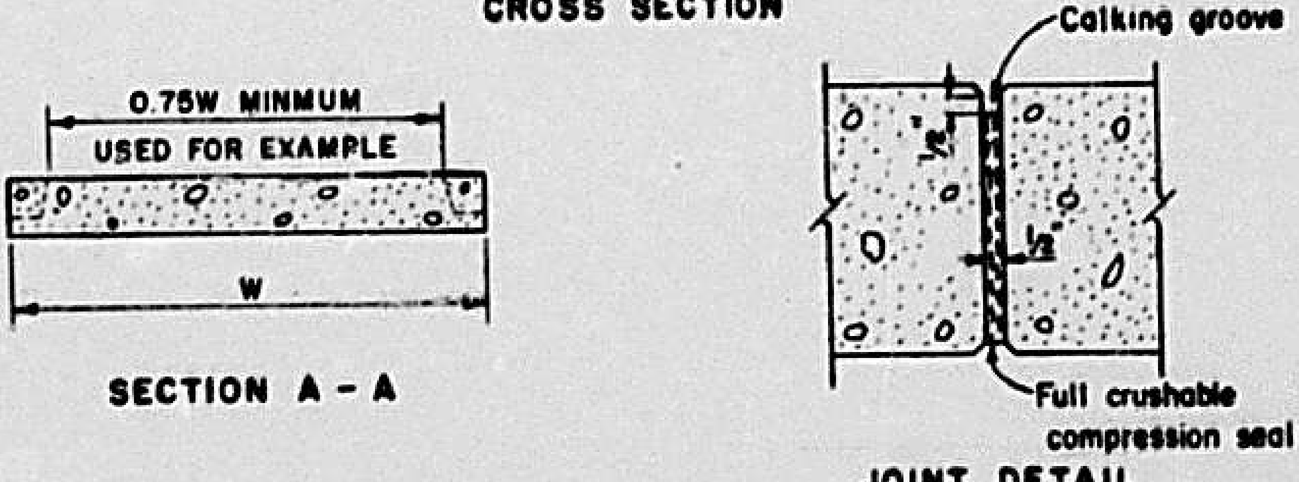
This is considered satisfactory since rotation is probable at the bolted joints (The allowable thrust in the segment without moment would be 232k).

CONCLUSION: <u>7-inch-thick segment appears to be adequate</u>

Figure C-7 is a summary of the preliminary segment sizing.



CROSS SECTION



SECTION A - A

JOINT DETAIL

FIGURE C-7. PRELIMINARY SEGMENT THICKNESS

Design Example - part 2

Assumptions and loading conditions

Cover is 2-1/2 times tunnel diameter (44 ft) at 120 lb/ft^3 with uniform vertical load of 44 x 120 = 5280 lb/ft^2.

A continuum (surrounding medium) of medium to stiff clay with bearing value (load in lb/in^2 on 30 inch circular plate that causes settlement of 0.1 inch) of 20 lb/in^2.

A coefficient of subgrade reaction, Ks = 200 lb/in^2 [1]*
A 15-ton locomotive with four wheel loads, P = 7.5 kips/wheel
Dead load of concrete, γ= 150 lb/ft^3.

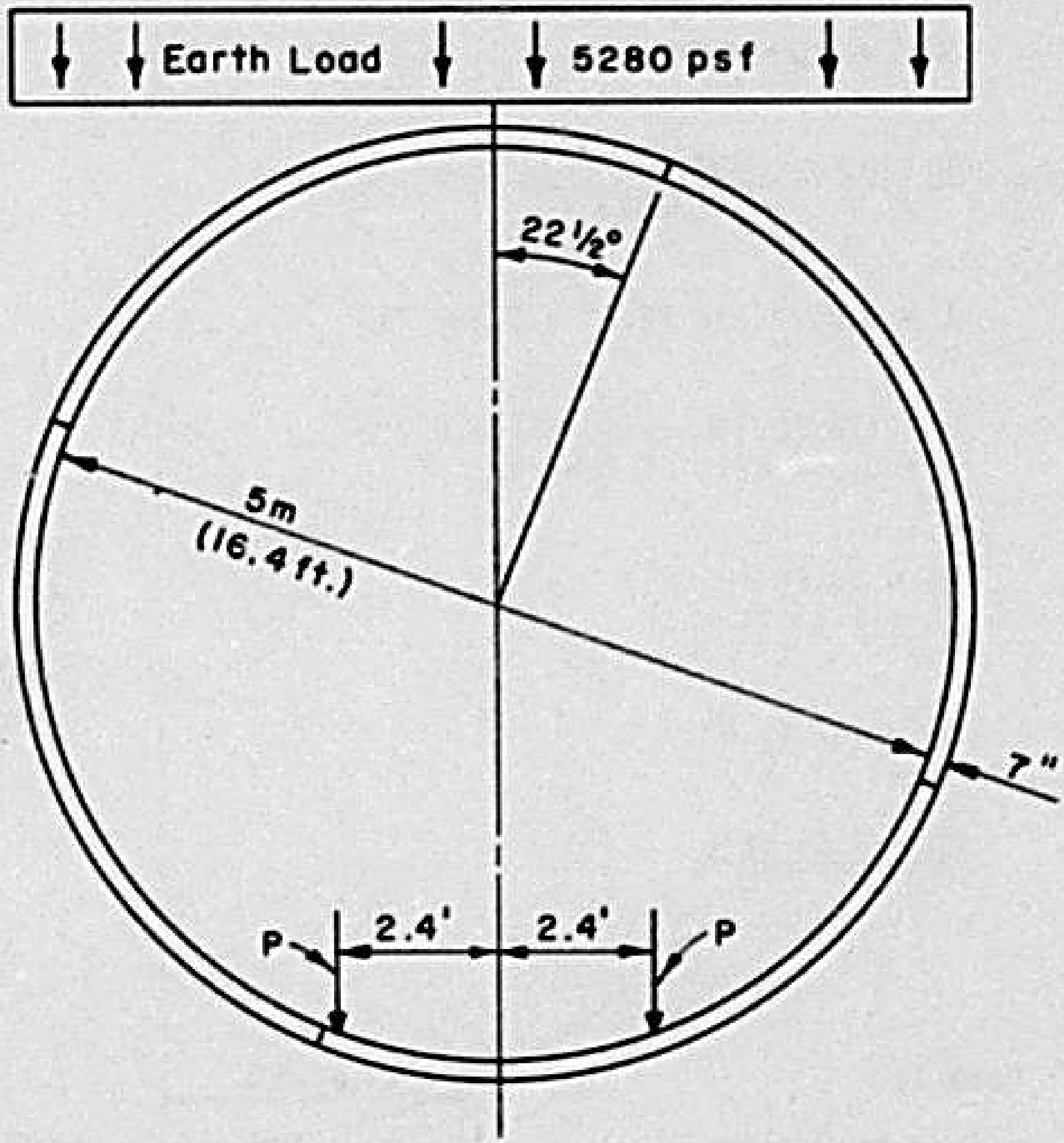
Use ultimate load design with load factor of 1.7 for L.L. and 1.4 for D.L.

The bolted longitudinal joints act as rigid joints that carry shear and moment

Clear cover over reinforcement steel to be 1 inch on each face.

---

* Numbers in brackets are references listed at the end of this appendix.



Geometrical Design:

A four segment bolted ring with crown segment joint to be 22-1/2° from vertical. Alternate rings to have joints rotated 45°. Each segment ring is to be 4 feet in width and 7 inches in thickness.

Concrete f'_c = 5,000 lb/in^2
Reinforcement steel f_y = 60,000 lb/in^2

Handling Loading

Case I:

SEGMENT STORED UPRIGHT

ARC = 2 γ radians

$$\text{Deg} = \frac{R \sin\gamma}{\gamma} = \frac{8494 \sin 0.393}{0.393} = 0.8277$$

$L = 0.8277 \sin 22.5° = 3.168$ ft

$W = 1/8\ (0.150)\ \pi(8.785^2 - 8.202^2)$
$= 0.584$ k/ft of length

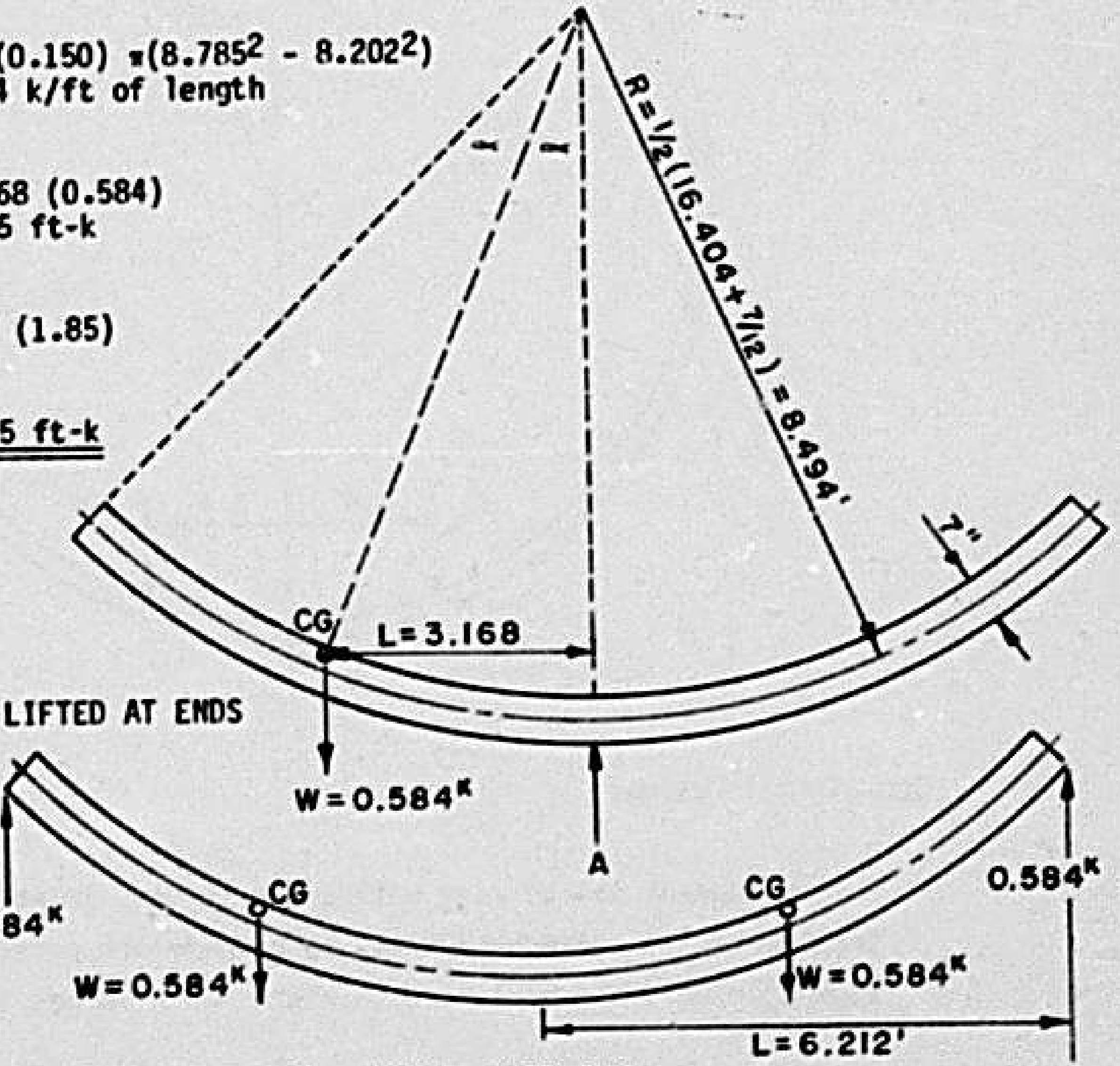
$M_A = 3.168\ (0.584)$
$= 1.85$ ft-k

$M_u = 1.7\ (1.85)$

$\underline{M_u = 3.15 \text{ ft-k}}$

Case II:

SEGMENT LIFTED AT ENDS



$M_a = 0.584\ (8.785 \sin 45°) - 1.85 = 1.78$ ft-k
$M_u = 3.03$ ft-k

Check moment capacity in simple bending (handling stress)

$d = 5.75$ $A_s = .30$ $f'_c = 5{,}000$ $f_y = 60{,}000$

$$F = \frac{12 \times 5.75^2}{12{,}000} = 0.03306$$

$$q = \frac{A_s}{bd}\frac{f_y}{f_c} = \frac{.30}{12\ (5.75)} \times \frac{60{,}000}{5{,}000} = 0.05217$$

$$K_u = \emptyset\ f'_c q\ (1.59q) = .9(5{,}000)\ 0.05217\ (1-.59(0.05217))$$

$$K_u = 227.56$$

$$M_u \text{ (allowable)} = FK_u = .03306 \times 227.56 = 7.52 \text{ ft-k}$$

$7.52 > 3.5$

Check bearing capacity at joints (service loads)

Net area available space per ft = (7-1-0.75) 12 = 63 in^2

Allowable bearing load = 0.85 $\emptyset f'_c$ = 0.85 (0.7)(5)(63) = 187 kips

Ultimate bearing load = 100 kips

See text for a reduction in bearing capacity at the joints due to the sealant system chosen.

Design of reinforcement for moment and thrust caused by service loads.

Minimum reinforcement of flexural section (Ref [4], chapter 10).

$P_{min} = \frac{200}{f_y} = \frac{200}{60{,}000} = 0.00333 \quad A_g = 7 \times 12 = 84 \text{ inch}^2$

$As_{min} = .00333 \times 84 = -.28 \text{ in}^2$

Six No. 4 bars, each face equals $0.20\ (6)/4 = 0.30 \text{ in}^2/\text{ft}$

Try: $A_s = .30 \text{ in}^2/\text{ft}$, and $A_s' = .30 \text{ in}^2/\text{ft}$

or, in other words, $0.30 \text{ in}^2/\text{ft}$ each face.

With this amount of steel as a starting point, a nuetral axis for a cracked section is assumed. From these basics the moment of inertia of the section cross section is calculated and the modulus of elasticity is found. These calculations are shown on the sheets that follow.

Once these values are found they are used as part of the input for the program TUNNEL [3]. Other input data for the coordinates of the node points, loads, foundation reaction coefficient, and joint and boundary conditions.

A computer run of "TUNNEL" is made to find thrusts and moments. A calculation is made of eccentricity for the moment and thrust found. The neutral axis of the cross section is then calculated A new moment of inertia (I) is calculated and moment and thrust capacity is checked to see that capacity is sufficient.

The iteration process is repeated until the moment of inertia calculated matches that assumed and the thrust and moment capacity provided are sufficient. Reinforcement could have been increased if necessary.

$P_{min} = \frac{200}{f_y} = \frac{200}{60,000} = 0.003333$

$As_{min} = 0.00333\ (84 in^2) = 0.28\ in^2$

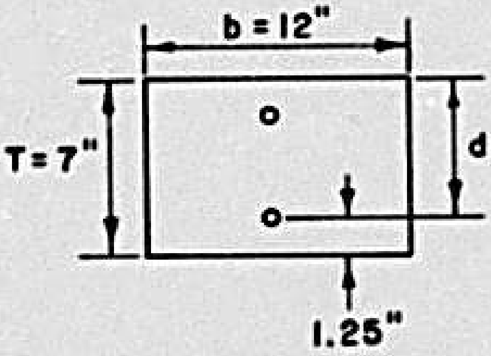
Six No. 4/segment = $\frac{6 \times 0.20}{4} = 0.30\ in^2/ft$

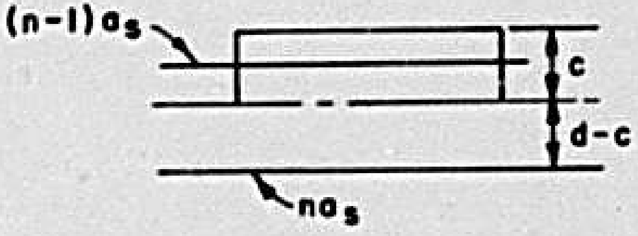
<u>First Iteration</u>

Try: $A_s = 0.30\ in^2$ or $0.025\ in^2/in$ each face

Try: Neutral Axis c = 2.1 inch

$I_t = 1/3\ bc^3 + n\ A_s\ (d - c)^2 + (n-1)\ A_s\ (c - 1.25)^2$





Transformed cross section

$E_s = 29,000 \qquad E_c = 4287\ k/in^2$

$n = \frac{29,000}{4,287} = 6.76$

$I_t = 1/3(12)(2.1)^3 + 6.76\ (0.3)(5.75 - 2.1)^2 + 5.76\ (0.3)(2.1 - 1.25)^2$

$I_t = 37.04 + 27.02 + 1.25 = 65.31\ in^4$ or $5.443\ in^4/in$

$I_t = 0.003150\ ft^4$

$P = \frac{0.30}{12(7)} = 0.0036$

R_R = 21.7×10^6 from diagram 19 ACI Publication SP-3 [5]

$A_s/in = 0.30/12 = 0.025$

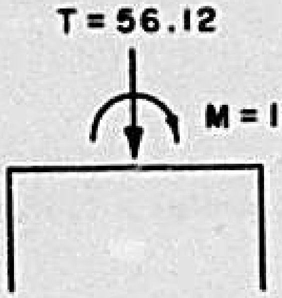
$EI = A_s d^2 R_R = 0.025(5.75)^2(21.7 \times 10^6) = 17.94 \times 10^6$

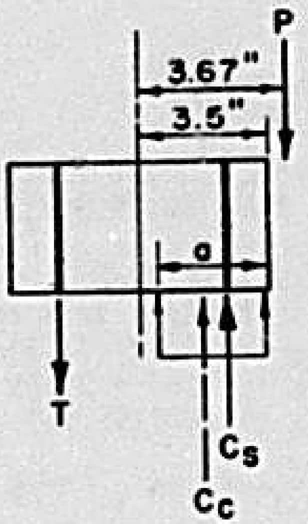
$E = 17.94 \times 10^6 / 5.443 = 3.296 \times 10^6$ lb/in^2 = 3296 k/in^2

$= 474{,}565$ k/ft^2

Run tunnel program to find M and P (T = P)

$M_{max} = 17.16$ $T = 56.12$





$M = P_t e \qquad e = \frac{M}{P_t} = \frac{17.16}{56.12} \times 12 = 3.67$ in

$T = A_s f_x = 0.30(60) = 18.00$ k

$C_c = 0.85\ f'_c ba = 0.85(5 \times 12)a = 51a$

$C_s = (fs - 0.85\ f'_c)\ A'_c = [29{,}000(\frac{c - 1.25}{c})\ 0.003 - 0.85(5)]\ 0.3$

$$= [87(\frac{\frac{a}{0.8} - 1.25}{\frac{a}{0.8}}) - 4.25]\ 0.3 = 26.1(\frac{a-1}{a}) - 1.27 = 24.83 - \frac{26.10}{a}$$

$\Sigma M_{pt} = 0$

$$51a(a/2 + 0.17) + (24.83 - \frac{26.1}{a}\ 1.25 + 0.17) = 18(5.75 + 0.17)$$

$$25.5a^2 + 8.67a + 35.26 - \frac{37.06}{a} - 106.56 = 0$$

$$25.5a^3 + 8.67a^2 - 71.30a - 37.06 = 0$$

$a = 1.743$ in $\qquad c = \frac{a}{0.8} = 2.18$ in (4 % off try another iteration)

$C_c = 51(1.743) = 88.89$
$C_s = 24.83 - \frac{26.10}{1.743} = 9.86$

$\Sigma F_y = 0$

$P_u = 88.89 + 9.86 - 18 = 80.75\text{k}$ P_u (allowable) $= 0.7(80.75) = 56.52\text{k}$
$M_u = 80.75(367)/12 = 24.70$ ft-k M_u (allowable) $= 0.9(24.70) = 22.231$ ft-k

Try $A_s = 0.30$
Try Neutral axis $c=2.17$
$I_t = 1/3(12)(2.17)^3 + 6.76(0.3)(5.75 - 2.17)^2 + 5.76(0.3)(2.17 - 1.25)^2$
$I_t = 40.87 + 25.99 + 1.46 = 68.33 \text{ in}^4$ or $5.694 \text{ in}^4/\text{in}$
$I_t = 0.003295 \text{ ft}^4$

$E = 17.94 \times 10^6/5.694 = 3.151 \times 10^6 \text{ lb/in}^2 = 3151 \text{ k/in}^2 = 453702 \text{ k/ft}^2$

TUNNEL program executed $M_{max} = 17.25$ $T_{calc} = 56.26$

$M = P_t e \qquad e = \frac{M}{P_t} = \frac{17.20}{56.09} \times 12 = 3.68$ inches

$T = 18\text{k} \qquad C_c = 51a \qquad C_s = 24.83 - \frac{26.10}{a}$

$\Sigma M_{pt} = 0$

$$51a(a/2 + 0.18) + (24.83 - \frac{26.1}{a})(1.25 + 0.18) = 18(5.75 + 0.18)$$

$$25.5a^2 + 9.18a + 35.51 - \frac{37.32}{a} - 106.74 = 0$$

$$25.5a^3 + 9.18a^2 - 71.23a - 37.72 = 0$$

$a = 1.738 \qquad c = 2.17$ <u>good</u>

$C_c = 51(1.738) = 88.64\text{k}$

$C_s = 24.83 - \frac{26.10}{1.738} = 9.81\text{k}$

$\Sigma F_y = 0$

$P_u = 88.64 + 9.81 - 18 = 80.45\text{k}$ $Pu_{allow} = 0.7(80.45) = 56.32\text{k}$

$M_u = 80.45(3.68)/12 = 24.67$ ft-k $Mu_{allow} = 0.9(24.67) = 22.20$ ft-k

Pu_{allow} 56.32 k > T_{calc} 56.26 Mu_{allow} 22.20 > M_{max} 17.25

SOLUTION GOOD

Figure C-8 shows the computed moments and thrusts for earth load, dead load, and track loads.

Conclusions, Part 2:

For the design assumptions and loading condition shown for part 2, a 7-inch-thick bolted precast segment appears to be adequate.

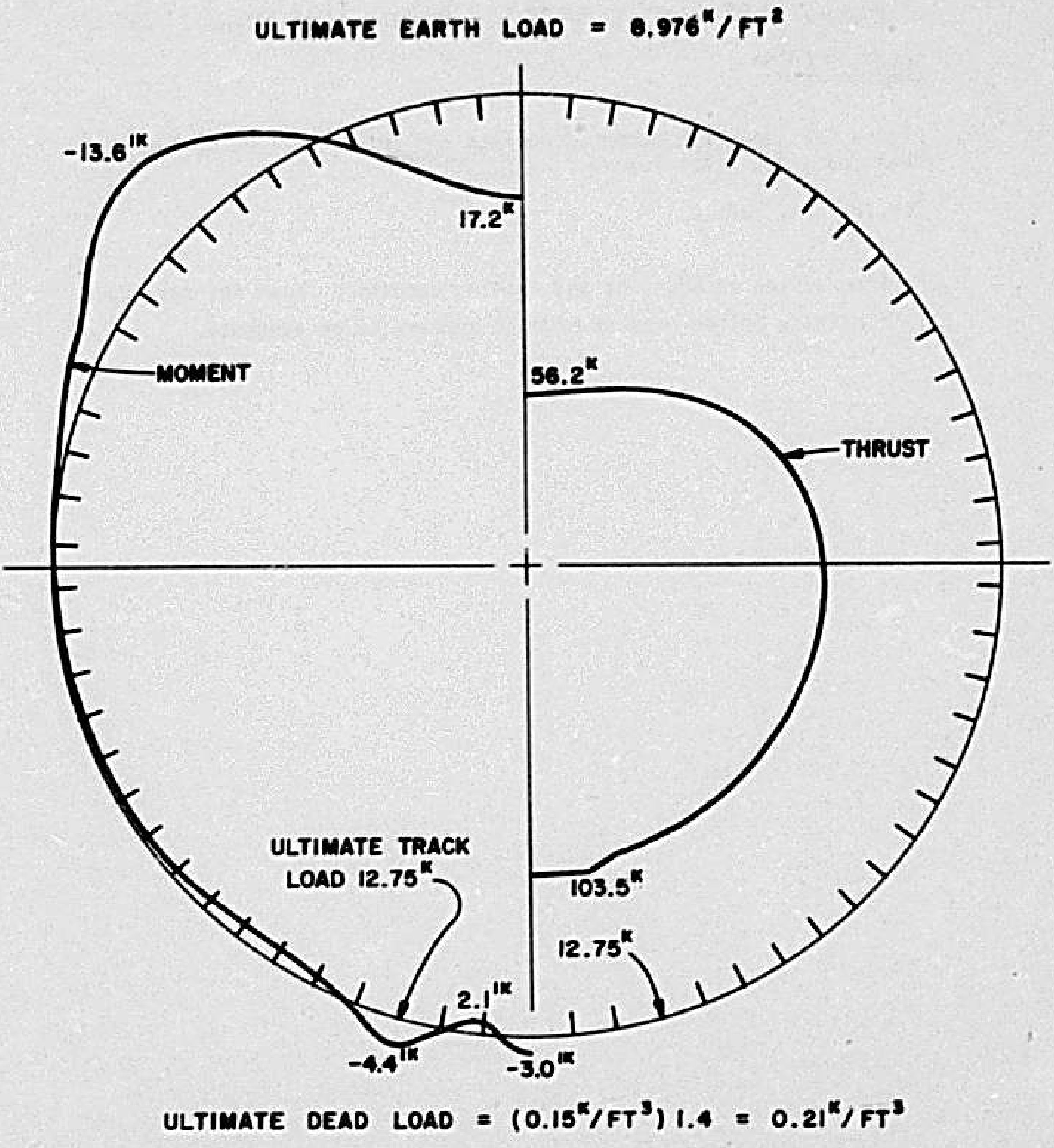


FIGURE C-8. MOMENT AND THRUST DIAGRAM FOR COMBINED ULTIMATE EARTH, DEAD AND TRACK LOAD

REFERENCES

[1] "Data Book for Civil Engineering Design," vol. 1, by Elwyn E. Seelye, published by Wiley, 1945, pp. 3-80

[2] "Reinforced Concrete Design," by Wang and Salman, second printing, 1967, published by International Textbook Company, pp. 259-281 and 369-372

[3] "Computer Study of Steel Tunnel Supports," by G. S. Orenstein, USAE Technical Report C-73-2, Vicksburg, Mississippi, August 1973

[4] Building Code Requirements for Reinforced Concrete (ACI 318-71), Detroit, Michigan

[5] "Reinforced Concrete Design Handbook, Working Stress Method," ACI Publication SP-3, third edition, Detroit, 1965

[6] "Formulas for Stress and Strain," Roark, R. J., W. C. Young, McGraw Hill Book Company, New York, 1975

[7] "Design of Tunnel Liners and Support Systems," Deere, D. V., R. B. Peck, J. E. Monsees, B. Schmidt, Department of Civil Engineering, University of Illinois, U.S. Department of Transportation, Washington, D.C., 1969, PB 183799, NTIS, Springfield, Virginia

[8] "Building Code Requirements for Reinforced Concrete (ACI 318-77)," American Concrete Institute, Detroit, Michigan, 1977

```
DOT/TSC   CRACKED SECTION (C=2.17 A =0.30)   K=200
34,    453744., 1
      0.0000,       -8.4938,      .000319
      -.8074,       -8.4553,      .000637
     -1.6075,       -8.3403,      .000637
     -2.3930,       -8.1497,      .000637
     -3.1568,       -7.8853,      .000637
     -3.8921,       -7.5495,      .000637
     -4.5921,       -7.1454,      .000637
     -5.2505,       -6.6765,      .000637
     -5.8614,       -6.1472,      .000637
     -6.4191,       -5.5622,      .000637
     -6.9188,       -4.9269,      .000637
     -7.3558,       -4.2469,      .000637
     -7.7262,       -3.5284,      .000637
     -8.0266,       -2.7780,      .000637
     -8.2543,       -2.0025,      .000637
     -8.4073,       -1.2088,      .000637
     -8.4841,        -.4041,      .000637
     -8.4841,         .4041,      .000637
     -8.4073,        1.2088,      .000637
     -8.2543,        2.0025,      .000637
     -8.0266,        2.7780,      .000637
     -7.7262,        3.5284,      .000637
     -7.3558,        4.2469,      .000637
     -6.9188,        4.9269,      .000637
     -6.4191,        5.5622,      .000637
     -5.8614,        6.1472,      .000637
     -5.2505,        6.6765,      .000637
     -4.5921,        7.1454,      .000637
     -3.8921,        7.5495,      .000637
     -3.1568,        7.8853,      .000637
     -2.3930,        8.1497,      .000637
     -1.6075,        8.3403,      .000637
      -.8074,        8.4553,      .000637
      -.0000,        8.4938,      .000319
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
        .003295,          .5833, 0
```

Modulus of Elasticity (ksf)

X-coordinates (ft)

Y-coordinates (ft)

Subgrade Modulus (ft³)

Moment of Inertia (ft⁴)

Area of horizontal x-sec.

joint fixity

0 - continuous

```
      .003295,        .5833, 0
  2,2
  3,1
 LC-1    V=    8.98 H=    0.00 H=    0.00,    0.00 R=    0.00 U=      .21 S=Y
  34
   1,     0.000,      0.000,       -.058
   2,     0.000,      0.000,       -.099
   3,     0.000,      0.000,       -.099
   4,     0.000,      0.000,     -12.849
   5,     0.000,      0.000,       -.099
   6,     0.000,      0.000,       -.099
   7,     0.000,      0.000,       -.099
   8,     0.000,      0.000,       -.099
   9,     0.000,      0.000,       -.099
  10,     0.000,      0.000,       -.099
  11,     0.000,      0.000,       -.099
  12,     0.000,      0.000,       -.099
  13,     0.000,      0.000,       -.099
  14,     0.000,      0.000,       -.099
  15,     0.000,      0.000,       -.099
  16,     0.000,      0.000,       -.099
  17,     0.000,      0.000,       -.099
  18,     0.000,      0.000,       -.456
  19,     0.000,      0.000,      -1.167
  20,     0.000,      0.000,      -1.868
  21,     0.000,      0.000,      -2.554
  22,     0.000,      0.000,      -3.217
  23,     0.000,      0.000,      -3.851
  24,     0.000,      0.000,      -4.452
  25,     0.000,      0.000,      -5.013
  26,     0.000,      0.000,      -5.530
  27,     0.000,      0.000,      -5.998
  28,     0.000,      0.000,      -6.412
  29,     0.000,      0.000,      -6.769
  30,     0.000,      0.000,      -7.065
  31,     0.000,      0.000,      -7.299
  32,     0.000,      0.000,      -7.468
  33,     0.000,      0.000,      -7.569
  34,     0.000,      0.000,      -3.802
```

Vertical load (ksf)

dead load (k/cuft)

special loading condition (rail load)

rail load + dead load

dead load

dead load + earth load

Force in X-direction (kips)

Moment (ft-kips)

Force in Y-direction (kips)

```
DOT/TSC   CRACKED SECTION (C=2.17 A =0.30)    K=200

LC-1   V=   8.98 H=   0.00 H=   0.00,   0.00 R=   0.00 D=      .21 S=Y

JOINT DISPLACEMENTS (GLOBAL COORDINATES)

JOINT          X           ROTATION          Y              RADIAL
             (ft.)                         (ft)
   1       0.00000        0.00000         -.04081         -.04081
   2        .00029         .00139         -.04141         -.04120
   3        .00039         .00193         -.04287         -.04202
   4        .00042         .00068         -.04412         -.04221
   5        .00075        -.00067         -.04409         -.04065
   6        .00125        -.00047         -.04373         -.03830
   7        .00152         .00048         -.04385         -.03607
   8        .00127         .00165         -.04473         -.03438
   9        .00033         .00276         -.04629         -.03327
  10       -.00136         .00369         -.04832         -.03267
  11       -.00376         .00443         -.05059         -.03241
  12       -.00682         .00502         -.05291         -.03235
  13       -.01047         .00551         -.05514         -.03243
  14       -.01466         .00595         -.05714         -.03254
  15       -.01935         .00636         -.05883         -.03267
  16       -.02450         .00676         -.06013         -.03281
  17       -.03006         .00711         -.06095         -.03292
  18       -.03592         .00738         -.06125         -.03297
  19       -.04195         .00750         -.06093         -.03284
  20       -.04792         .00734         -.06014         -.03239
  21       -.05348         .00669         -.05881         -.03131
  22       -.05811         .00519         -.05727         -.02907
  23       -.06107         .00244         -.05605         -.02485
  24       -.06148        -.00193         -.05610         -.01754
  25       -.05858        -.00795         -.05871         -.00583
  26       -.05209        -.01487         -.06524          .01127
  27       -.04264        -.02130         -.07651          .03378
  28       -.03165        -.02596         -.09232          .06055
  29       -.02082        -.02804         -.11150          .08956
  30       -.01165        -.02717         -.13205          .11827
  31       -.00508        -.02341         -.15162          .14404
  32       -.00135        -.01714         -.16773          .16444
  33       -.00000        -.00905         -.17833          .17752
  34       0.00000        0.00000         -.18202          .18202
```

```
MEMBER FORCES          (LOCAL COORDINATES)

MEMBER       SHEAR            MOMENT          THRUST
          (Kips/ft²)        (ft-Kips)        (Kips)
   1          -.95249          2.14757        102.98033
   2         -2.96421          -.20347        103.15739
   3         -5.17028         -4.49758        103.52640
   4          4.65038          -.62882         99.92645
   5          2.47587          1.37255         99.55036
   6           .95198          2.14201         99.34172
   7           .06716          2.19530         99.23954


   8          -.35989          1.93539         99.19221
   9          -.45467          1.53791         99.16265
  10          -.41470          1.20271         99.12909
  11          -.28415           .97303         99.08169
  12          -.16236           .84179         99.01714
  13          -.07405           .78194         98.93823
  14          -.03638           .75254         98.84981
  15          -.05847           .70528         98.75803
  16          -.12535           .60395         98.66870
  17          -.25526           .39765         98.58778
  18          -.44886           .03481         98.16535
  19          -.81109          -.62080         97.06897
  20         -1.46185         -1.80233         95.35978
  21         -2.37927         -3.72548         93.12648
  22         -3.38317         -6.46028         90.47137
  23         -4.02592         -9.71529         87.48550
  24         -3.49884        -12.54331         84.21386
  25          -.63396        -13.05571         80.61752
  26          2.86316        -10.74140         76.69062
  27          5.24681         -6.50037         72.59277
  28          6.57781         -1.18374         68.55833
  29          6.90436          4.39739         64.81131
  30          6.35308          9.53238         61.55083
  31          5.08230         13.64037         58.94700
  32          3.27594         16.26838         57.13352
  33          1.12631         17.19880         56.20372
```

```
BLOCKING POINT THRUSTS

 JOINT       THRUST
     1        5.85634
     2       11.80827
     3       12.04758
     4        -.12822
     5       11.65812
     6       10.98105
     7       10.34304
     8        9.85836
     9        9.54576
    10        9.37752
    11        9.31092
    12        9.30465
    13        9.33121
    14        9.37268
    15        9.42055
    16        9.46876
    17        9.51081
    18        9.55048

    19        9.65937
    20        9.80219
    21        9.88413
    22        9.73900
    23        9.11090
    24        7.65104
    25        4.96667
    26        4.00216
    27        4.71473
    28        5.39411

    29        6.01660
    30        6.55978
    31        7.00323
    32        7.33304
    33        7.53473


    34        3.80200


 END JOINT REACTIONS

 JOINT      X-FORCE              MOMENT              Y-FORCE

 FIRST    -102.81864            -2.95748              .05000
 LAST      -56.08664            17.19880             3.80200
```

APPENDIX D

TENTATIVE SPECIFICATIONS FOR EDGE SEALANT FOR PRECAST CONCRETE TUNNEL LINER SEGMENTS

UNITED STATES
DEPARTMENT OF THE INTERIOR
Water and Power Resources Service

Revised Dec. 5, 1979

Tentative Specifications for Edge Sealant for Precast Concrete Tunnel Liner Segments

1. Scope

These specifications cover elastomeric material for sealing the seams between precast concrete tunnel liner segments.

2. Classification

The sealant shall be of the following classes:

a. Type I. - Multicomponent, thermosetting viscous liquid.

b. Type II. - Preformed, precured tape.

3. Material Requirements

a. General requirements. - The sealant is intended for application to all mating surfaces of precast concrete tunnel liner segments. Since it is expected to provide protection for the segment edges during storage, shipping, handling, and installation, application of the sealant is to be made at the segment fabricating plant.

The sealant shall be furnished either as a thermosetting, viscous liquid or as a preformed, precured tape. The thickness of the cured coating or tape material shall be as required by the construction specification; the thickness shall be uniform and the surface shall be free of irregularities, pits or protrusions. For test purposes the thickness of the type II samples submitted shall be 1/8 ± 1/64 inch.

The sealant shall be supplied as, or shall rapidly cure to, an adhesive, resilient coating of such properties that it will bond effectively to concrete surfaces at least 7 days old.

The type I sealant shall have such properties that the pressure induced during installation of the segments shall cause a fusion or bond of the sealant on mating segment edges to occur, thereby providing a continuous seal for the seams between segments. The type II material shall fuse in the same manner or be furnished with a sealant manufacturer's recommended adhesive that will produce satisfactory bond or sealant to sealant between segments. The installation pressure shall cause the material to deform so as to accommodate irregularities or roughnesses in the mating surfaces of the segments. The sealant shall not be extruded from the seams by the installation pressures.

The sealant shall be sufficiently resilient and adhesive to maintain a waterproof seal for the seams between segments during repeated cycles of expansion and contraction of the segments; of alternate and continuous water immersion; and under varying hydrostatic pressures.

The exposed edges of the sealant may be covered with a strippable protective film, at the manufacturer's option. Any such film must be easily and completely removable and shall leave no residue which will interfere with subsequent bonding or fusing of the edge sealant on mating surfaces.

b. Detail requirements. - The sealant shall conform with the detail requirements listed in Table D-1 when tested as herein specified.

TABLE D-1. TEST METHOD AND REQUIREMENTS

Property	Test Method	Required	
		Minimum	Maximum
Cold flow, inches	Sub. 4b	-	0.1
Flow at 160°F, inches	Sub. 4c	-	0.0
Hydrostatic pressure resistance, 26 psi	Sub. 4d	No leakage	-
Irregular surface accommodation	Sub. 4e	Continuous seal	
Pressure stability	Sub. 4f	-	1/8-inch extrusion
Resistance of protective film to 30-day accelerated weathering exposure	Sub. 4g	Film easily strippable	
Weight loss, percent	Sub. 4h	-	15
Water-immersed bond	Sub. 4i	Pass 3 cycles	-
Resistance to hydrolysis	Sub. 4j	Retain 50% tensile strength	-

4. Test Methods

a. The sealant shall be tested in accordance with the following procedures:

All tests on Type I material shall be performed on specimens prepared with material preconditioned and mixed at standard conditions (73°F±2°F and 50 percent ± 5 percent relative humidity). The preconditioning period shall be 24 hours minimum.

(1) Type I material shall be mixed using method 1 or 2 as follows: A sufficient quantity of the base material together with the appropriate amount of accelerator to comprise a 5/8-quart sample shall be preconditioned. Following preconditioning, the components shall be intermixed for 5 minutes at 550 rpm 50 rpm in a standard 1-quart paint can, with friction lip removed, using a Jiffy Mixing Company Model No. 5 mixing blade fitted to an electric motor. The position of the mixing blade within the sample shall be continuously changed within the sample to obtain thorough mixing. Filling of the test specimens shall commence immediately following the mixing period.

(2) Mix preconditioned sample using calibrated automatic proportioning equipment and "Static Mixer" manufactured by Kenics Corporation, 166 Elm Street, N. Andover, MA 01845.

b. Cold flow (Type I materials only). - A metal channel with inside dimensions 3/4-inch wide by 1/2-inch deep by 6 inches long, with the bottom surface extended 2 inches at one end, as shown in Figure D-1 is filled with Type I sealant as in Paragraph 4a. The filled channel shall be immediately suspended with the open end downward for 24 hours at standard conditions. The sag or flow of the sealant below the end of the channel section shall be measured and recorded as the cold flow.

c. Flow at 160°F (Type I materials only). - A metal channel with inside dimension 3/4-inch wide by 1/2-inch deep by 6 inches long, with the bottom surface extended 2 inches at one end, as shown in Figure D-1 is filled with Type I sealant as in Paragraph 4a. The channel, after conditioning 24 hours at standard conditions shall be placed in a forced draft oven at $158^{o}F \pm 2^{o}F$ for 5 hours at a 60^{o} angle. The sag or flow of the sealant beyond the end of the channel is measured and recorded as the flow. Flow at $160^{o}F$ (Type II materials). A section of the preformed tape 1-inch wide by 3 inches long is affixed to a clean tinned steel panel. The test specimen is immediately placed in a forced draft oven at $158^{o}F \pm 2^{o}F$ for 5 hours at a 60^{o} angle. The flow or sag of the sealant below the original lower end is measured and recorded as the flow.

d. Hydrostatic pressure resistance shall be determined using test specimens shown in Figure D-2. For Type I sealants a ring of the sealant shall be molded on each of the opposing concrete slabs as shown in Figure D-3. For Type II sealants a square shall be formed as shown in Figure D-4, making sure there are no gaps at the end of the pieces of tape. After 24 hours curing at standard conditions, in the case of Type I sealants, or immediately in the case of Type II sealants, the opposing faces of the concrete blocks shall be pressed together using a preload pressure of 10 lb/in^2. After 10 minutes the gap between the blocks shall be measured to establish the "original gap dimensions." The concrete blocks shall then be pressed together to two-thirds of the "original gap dimension" to fuse or bond the opposing sealant faces. A bond promoting agent or an adhesive shall be used when recommended by the sealant manufacturer for obtaining satisfactory bond strength.

After maintaining two-thirds of the original gap dimension for 2 hours, continue to maintain that gap dimension, and introduce 26 lb/in^2 water pressure. After maintaining the compressed joint gap and 26 lb/in^2 water pressure for 72 hours, the joint gap will be increased to 75 percent of the original gap dimensions and held at that extension for 24 hours while maintaining 26 lb/in^2 water pressure. Failure is indicated by any water leakage between the originally opposing faces, through the sealant, or at the bond line between sealant and concrete.

e. Irregular surface accommodation is determined by a preparing of three test specimens as shown in Figure D-5A, using one flat-faced block and one wherein the center portion for a distance of 1-1/2 inches is curved at an 8-inch radius. Coat the entire 1-inch by 2-inch face on each concrete block with either Type I or Type II sealant to a thickness of 1/8 $\pm$ 1/64 inch. After 24 hours curing in the case of the Type I sealant at standard conditions, or immediately, in the case of Type II sealants, the opposing faces of the concrete blocks shall be pressed together using a preload pressure of 10 lb/in^2. After 10 minutes, the gap between the blocks shall be measured to establish the original gap dimensions. The concrete blocks shall then be pressed together to two-thirds of the specimen's original gap dimension to fuse or bond the opposing faces. A bond promoting agent shall be used when recommended by the manufacturer. Pressure is to be maintained for 2 hours or until the bond promoting agent has cured as recommended by the manufacturer after which time the sealant in the test specimen will be extended to 110 percent of the original gap dimensions and held at that extension for 24 hours. Failure is indicated by any separation between the originally opposing sealant faces.

f. Pressure stability is determined from the same test specimens prepared in Subparagraph 4e. If at the end of the 24-hour extension period, extrusion of the sealant beyond the edges of the test face exceeds 1/8-inch, the sealant is considered to have failed pressure stability.

g. Resistance of protective film to accelerated weathering exposure. - Three test specimens will be prepared as in Subparagraph 4e., except that any protective film recommended or supplied by the manufacturer will be applied to the exposed sealant face. Three specimens, with protective film applied, will be subjected to accelerated weathering as described in Paragraph 4 of ASTM Designation D750-68 for 30 days. At the conclusion of this period, the protective film shall be easily stripped away intact.

h. Weight loss. - This determination is made on sections of the sealant having a surface area of approximately 6 square inches. In the case of liquid applied material, two preweighed tinned steel containers approximately 2-3/4 inches in diameter by 1/4-inch deep are overfilled with the mixed material and the overfill immediately struck off. In the case of preformed tape, two sections of 6 square inches surface area are affixed to preweighed 3-inch by 6-inch tinned steel panels. After 24 hours at standard conditions test specimens shall be placed in a forced draft oven at $158^{o} \pm 2^{o}F$ for 7 days. After 7 days, remove the specimens from the oven and condition for 4 hours at standard conditions, then weigh to the nearest 0.01 g. Calculate the weight loss as follows:

$$\text{Weight loss, percent} = \frac{(A-C)\ (100)}{A-B}$$

A = Initial weight of specimen and container

B = Weight of container

C - Final weight of specimen and container

i. Water-immersed bond. - Three flat surface test specimens prepared as in Subparagraph 4e, having been conditioned for 24 hours at standard conditions, shall be placed in a forced draft oven maintained at 158°F ± for 7 days. After 7 days at $158^{o}F \pm 2^{o}F$, the three specimens shall then be conditioned for 7 days in 500 ml of distilled water at $73^{o}F \pm 2^{o}F$. After conditioning 7 days in water, specimens shall be removed from the water, blotted dry with an absorbent tissue, and immediately placed in an atmosphere of $+20^{o}F$. After conditioning 4 hours at $+20^{o}F$, the specimens shall be extended 10 percent at the rate of 1/8-inch per hour at $+20^{o}F$.

Test specimens shall be removed from the extension apparatus and allowed to return to their original dimensions at room temperature. Three cycles of extension and recovery shall be completed within 5 days after the start of the first cycle, and shall constitute one complete test for water-immersed bond.

j. Resistance of hydrolysis. - Ten tensile specimens shall be prepared in accordance with ASTM Designation D-412, "Standard Method of Tension Testing of Vulcanized Rubber." Five specimens shall be exposed in a chamber controlled at 80 ± 2°C and 95 ± 5 percent relative humidity for 14 days. The other five specimens shall be stored at 23 ± 1°C and 50 percent relative humidity for the 14 day period. At the end of this exposure, all specimens shall be stored at standard conditions (23 ± 1 °C and 50 percent relative humidity) for 3 hours. The tensile strength test shall then be conducted as specified in ASTM D-412. Tensile strength shall be reported as the average of five tests for humid aged and five tests for standard conditions. Resistance to hydrolysis shall be the aged strength as a percent of the stored strength.

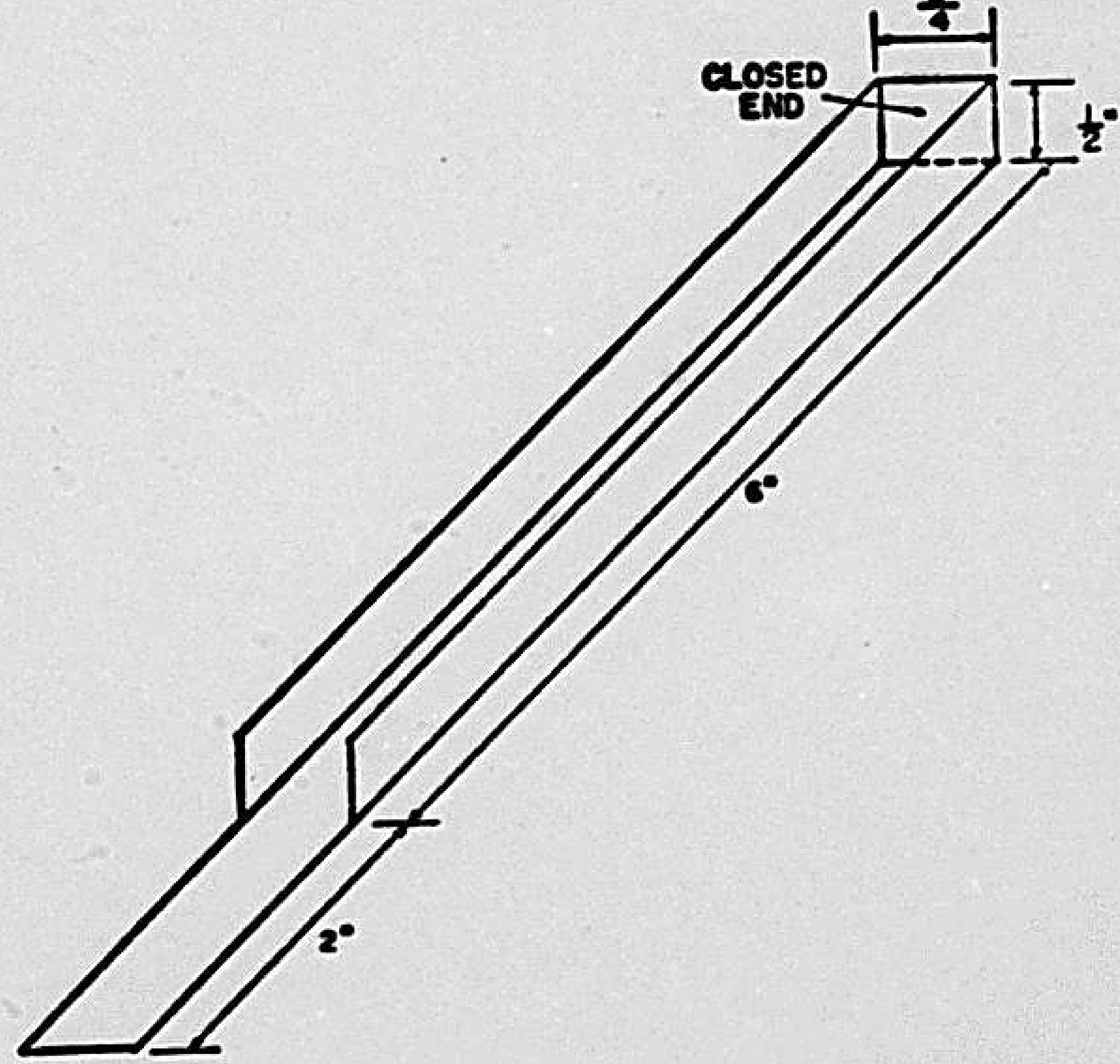
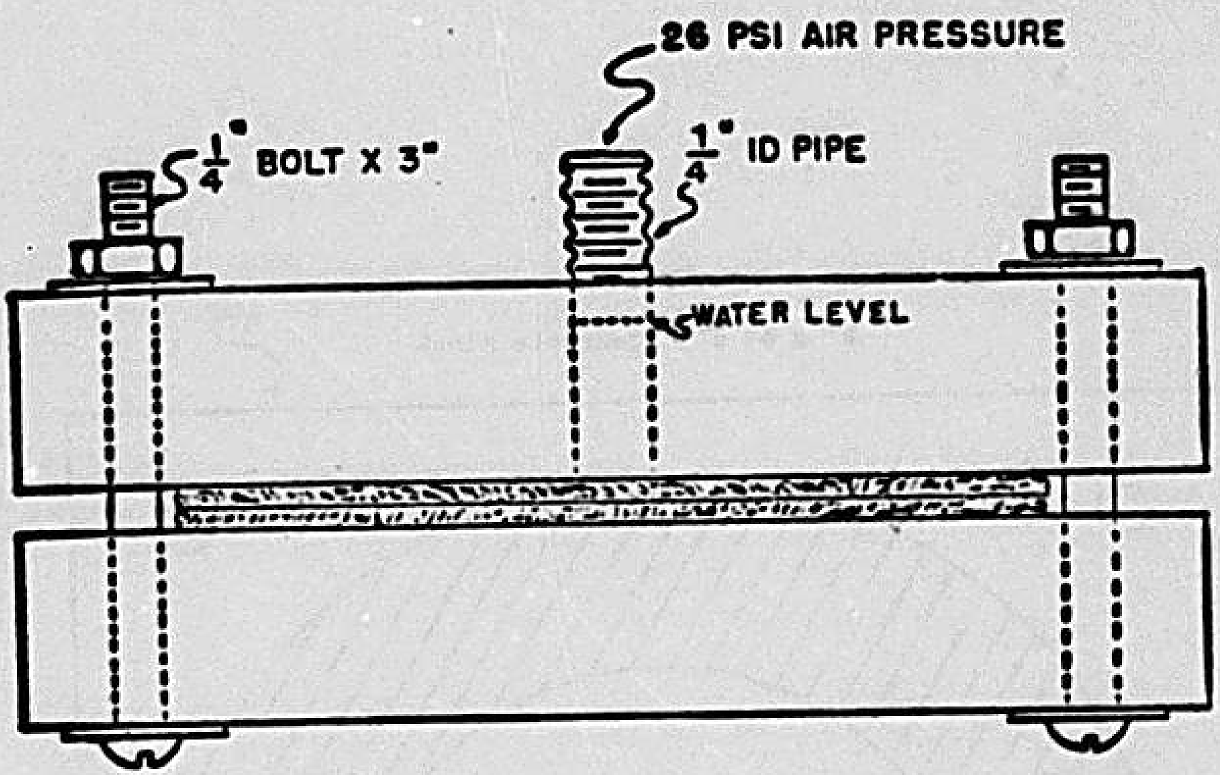
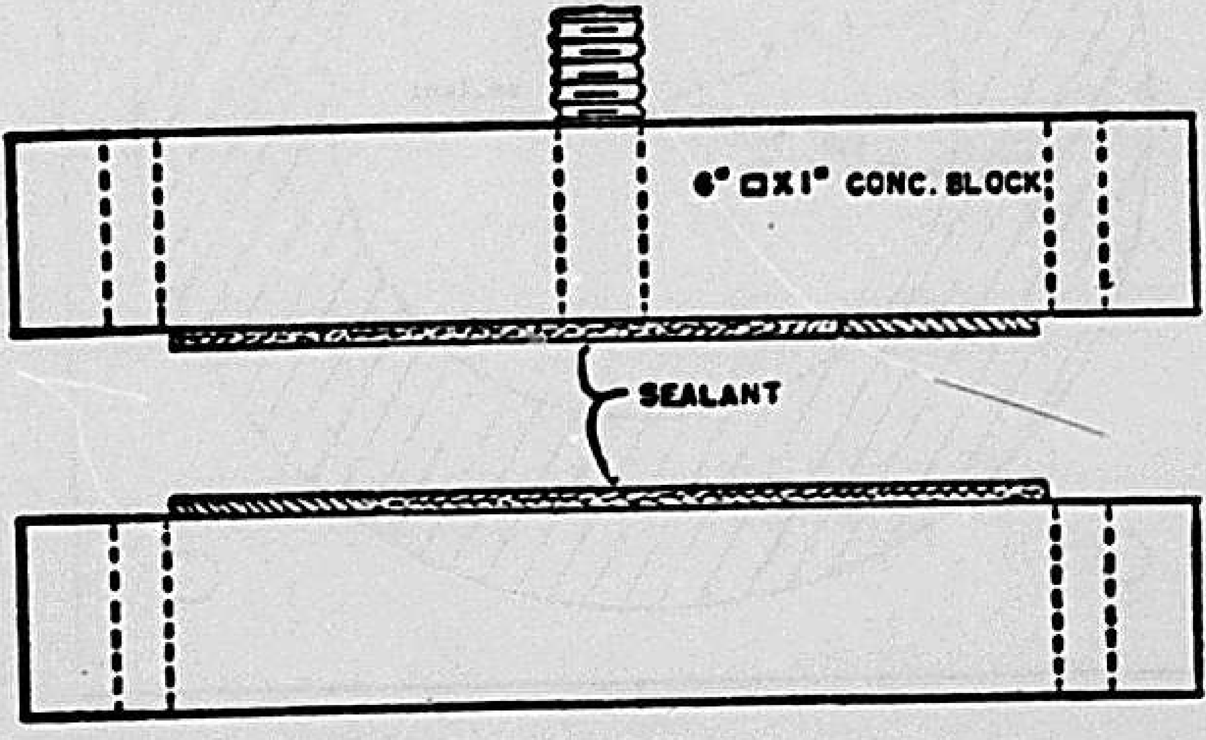


FIGURE D-1. FLOW TEST ASSEMBLY

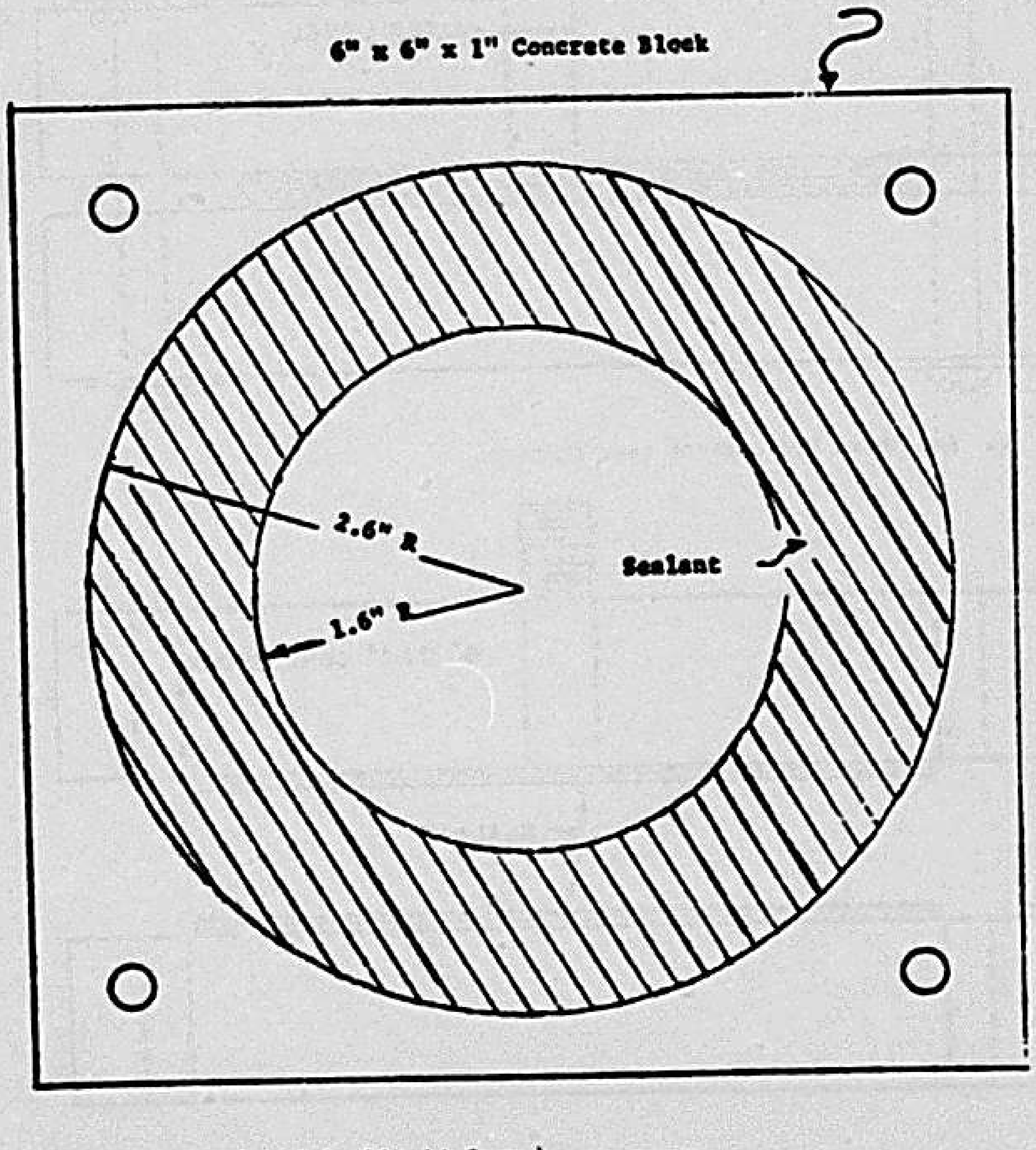


A. Assembled hydrostatic test fixture.



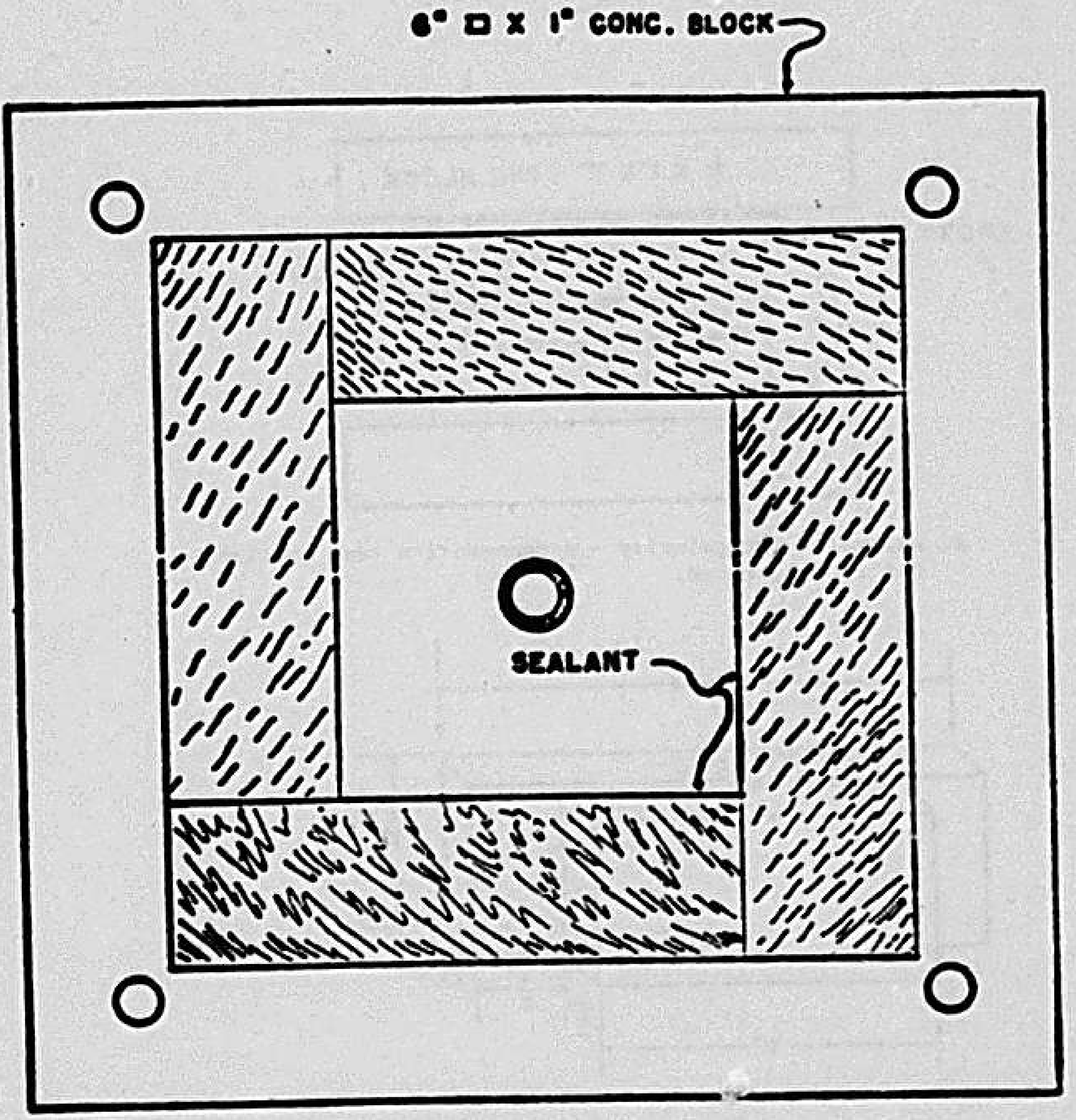
B. Two pieces comprising the hydrostatic test specimen.

FIGURE D-2. HYDROSTATIC TEST SPECIMEN



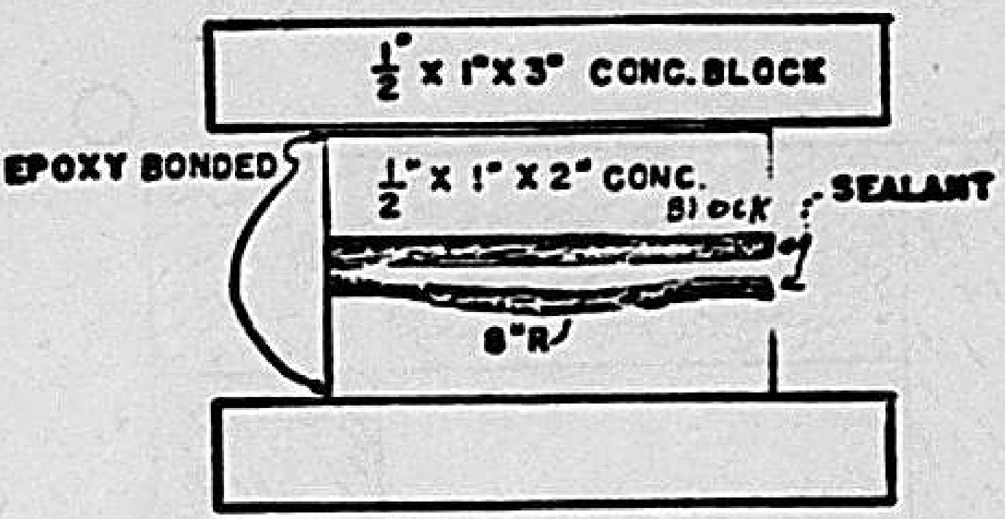
(Material furnished in liquid form.)

FIGURE D-3. ONE FACE OF A HYDROSTATIC TEST SPECIMEN

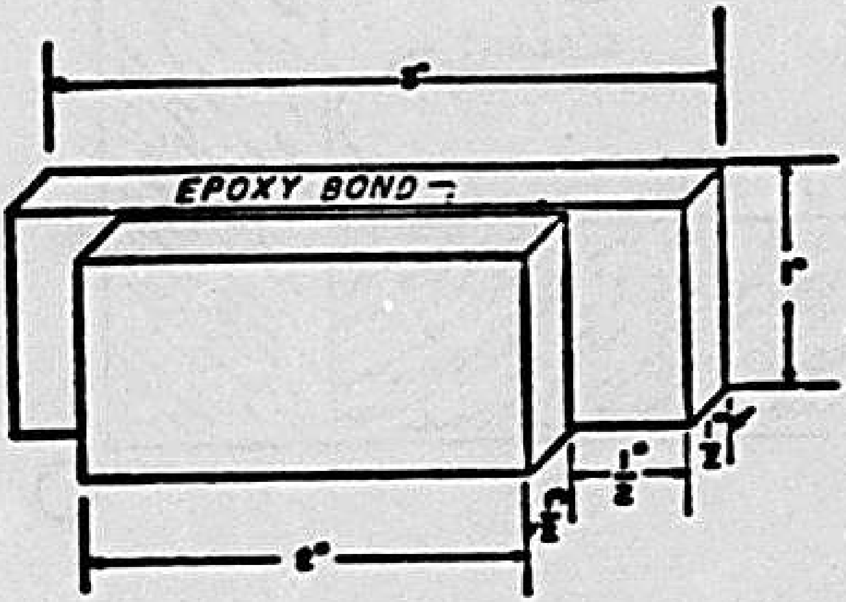


(Material furnished in tape form.)

FIGURE D-4. ONE FACE OF A HYDROSTATIC TEST SPECIMEN



A. Assembled irregularity - accommodation test specimen. Gap is exagerated.



B. Concrete blocks forming one side of bond specimens or the flat side of irregularity,

FIGURE D-5. IRREGULARITY-ACCOMMODATION TEST SPECIMEN

APPENDIX E

COST ESTIMATES

[illegible]
Bureau of Reclamation

ESTIMATE WORKSHEET

PROJECT DOT/TSC
DIVISION
UNIT
SHEET 1 OF 3

QUANTITIES BY: J S CKD. LLM
DATE: 1/8/80 APPROVED

UNIT PRICES BY: CKD. KB
DATE: APPROVED

PLANT ACCOUNT	PAY ITEM	DESCRIPTION	CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT
		2,000 foot long 16.4 foot diameter precast tunnel in SC soil using a shield with water table drawn down by surface well pumping. Four bolted segments 1 to 5 foot long ring.					
	1.	Excavation in tunnel		19,000	yd^3	135.	2,565,000
	2.	Furnishing precast concrete segment tunnel lining 7 inches thick		103,000	ft^2	11.	1,133,000
	3.	Installing precast concrete segment tunnel lining		2,000	lin. ft.	160.	320,000
	4.	Drilling weep holes		50	lin. ft.	30.	1,500
	5.	Dewatering and handling water including pumping and treatment facilities		lump sum			350,000
	6.	Furnishing and installing sealant systems		lump sum			115,000
				Unlisted items	.10		415,500
				Subtotal			4,900,000
				Contin-gencies	.20		1,000,000
		Supplemental data precast segments contain concrete - 2,370 cu. yd., cement - 668 tons, reinforcement - 500,000 lbs.		Field Cost			5,900,000

7-1040 (3-73)
Bureau of Reclamation

ESTIMATE WORKSHEET

PROJECT DOT/TSC
DIVISION
UNIT

SHEET 2 OF 3

QUANTITIES BY: JS CKD. LLM
DATE: 1/8/80 APPROVED

UNIT PRICES BY: CKD. KB
DATE: APPROVED

PLANT ACCOUNT	PAY ITEM	DESCRIPTION	CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT
		12,000 foot long 16.4 foot diameter precast tunnel in SC soil using a shield with water table drawn down by surface well pumping. Four bolted segments 1 to 5 foot long ring					
	1.	Excavation in tunnel		114,000	yd^3	140.	15,960,000
	2.	Furnishing precast concrete segment tunnel lining 7 inches thick		618,000	ft^2	11.	6,798,000
	3.	Installing precast concrete segment tunnel lining		12,000	lin. ft.	165.	1,980,000
	4.	Drilling weep holes		300	lin. ft.	30.	9,000
	5.	Dewatering and handling water including pumping and treatment facilities		lump sum			570,000
	6.	Furnishing and installing sealant systems		lump sum			680,000
				Unlisted items	.10		3,003,000
				Subtotal			29,000,000
				Contingencies	.20		5,000,000
		Supplemental data - Precast segments contain concrete - 14,200 cu. yd., cement - 4,000 tons, reinforcement - 3,000,000 lbs.		Field Cost			34,000,000

7-1040 (3-73)
Bureau of Reclamation

ESTIMATE WORKSHEET

PROJECT DOT/TSC
DIVISION
UNIT
SHEET 3 **OF** 3

QUANTITIES BY: JS **CKD.** LLM
DATE: 1/8/80 **APPROVED**
UNIT PRICES BY: **CKD.** KB
DATE: **APPROVED**

PLANT ACCOUNT	PAY ITEM	DESCRIPTION	CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT
		24,000 foot long 16.4 foot diameter precast tunnel in SC soil using a shield with water table drawn down by surface well pumping. Four bolted segments 1 to 5 foot long ring					
	1.	Excavation in tunnel		228,000	yd^3	155.	35,340,000
	2.	Furnishing precast concrete segment tunnel lining 7 inches thick		1,237,000	ft^2	11.	13,607,000
	3.	Installing precast concrete segment tunnel lining		24,000	lin. ft.	170.	4,020,000
	4.	Drilling weep holes		600	lin. ft.	30.	18,000
	5.	Dewatering and handling water including pumping and treatment facilities		lump sum			800,000
	6.	Furnishing and installing sealant systems		lump sum			1,350,000
				Unlisted items	.10		5,805,000
				Subtotal			61,000,000
				Contingencies	.20		12,000,000
		Supplemental data - Precast segments contain concrete - 28,400 cu. yd., cement - 8,000 tons, reinforcement - 6,000,000 lbs.		Field Cost			73,000,000

APPENDIX F

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APPENDIX G

REPORT OF NEW TECHNOLOGY