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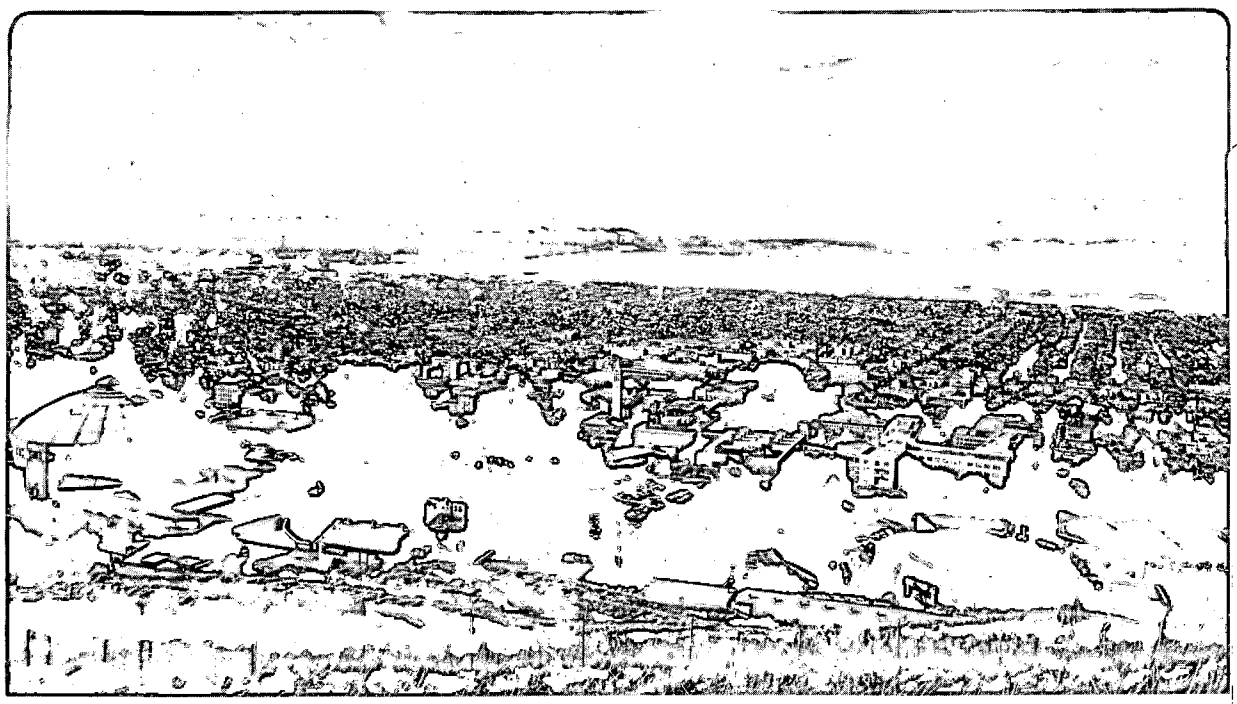
Underground Facility for Geoenvironmental and Geotechnical Research at the SSC Site in Texas

H.F. Wang and L.R. Myer

October 1994



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Technical Report to
U.S. Department of Energy
Office of Energy Research

UNDERGROUND FACILITY FOR GEOENVIRONMENTAL AND GEOTECHNICAL RESEARCH AT THE SSC SITE IN TEXAS

A Project Definition Study
of Future Uses of the
Superconducting Super Collider Assets

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October 31, 1994

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1 Executive Summary

The subsurface environment is an important national resource that is utilized for construction, waste disposal and groundwater supply. Conflicting and unwise use has led to problems of groundwater contamination. Cleanup is often difficult and expensive, and perhaps not even possible in many cases. Construction projects often encounter unanticipated difficulties that increase expenses. Many of the difficulties of predicting mechanical behavior and fluid flow and transport behavior stem from problems in characterizing what cannot be seen. An underground research laboratory, such as can be developed in the nearly 14 miles of tunnel at the Superconducting Super Collider (SSC) site, will provide a unique opportunity to advance scientific investigations of fluid flow, chemical transport, and mechanical behavior *in situ* in weak and fractured, porous rock on a scale relevant to civil and environmental engineering applications involving the subsurface down to a depth of 100 m.

The unique element provided by underground studies at the SSC site is three-dimensional access to a range of fracture conditions in two rock types, chalk and shale. Detailed experimentation can be carried out in small sections of the SSC tunnel where different types of fractures and faults occur and where different rock types or contacts are exposed. The entire length of the tunnel can serve as an observatory for large scale mechanical and fluid flow testing. The shallow depth of the tunnel and access shafts of 18 feet and more in diameter simplify logistics and reduce expense. The rock is completely free of weathering. The most exciting opportunity is to mine back a volume of rock to conduct a post-experiment audit following injection of a number of reactive and conservative tracers. Flow paths and tracer distributions can be examined directly. The scientific goal is to test conceptual models and numerical predictions. In addition, mechanical and hydrological data may be of significant value in developing safe and effective methods for closing the tunnel itself. Finally, the proximity of the SSC site to a major metropolitan area means that the research facility can serve as a resource for educating the public about utilizing and protecting the subsurface environment.

The project addresses the following national needs:

- **Improve the technology for environmental remediation of contaminated groundwater.**
- **Improve the technology for underground construction.**
- **Assure environmentally safe closure of the SSC tunnel.**

- **Educate the public about groundwater and underground construction issues.**

The estimated cost of the project is between $2 and $14 million to recommission the tunnel. The estimated annual cost of an experimental program is between $2 and $4 million per year for ten years. The total project cost is between $22 and $54 million dollars.

2 Project Goals and Rationale

Billions of dollars are spent for environmental remediation and for large-scale underground construction. The Department of Energy, Department of Defense and Environmental Protection Agency face, or are responsible for, thousands of contaminated sites. Large scale civil construction in the underground includes major projects such as deep storm sewer tunnels in Chicago and Milwaukee, subway tunnels in Washington, D. C., San Francisco, Los Angeles, and hydroelectric power generation sites. It is estimated that 5 to 100% of the initial contract value is spent on litigation and additional construction expense due to unanticipated difficulties. For example, a federal jury ordered the Milwaukee Metropolitan Sewerage District to pay the construction company $1.57 million in cost overruns due to excessive groundwater in an $8.85 million project for a 270-foot access shaft (Milwaukee Sentinel, July 26, 1994, p. 5A). At the SSC site the most up-to-date contracting methods were utilized and the tunneling was generally considered to be a success. Yet, there were internal questions, such as "How much would the shale floor heave over thirty years?" and "How much additional roof support might be needed near shaft N-35 where significant spalling had occurred in the roof due to a shale seam?" Uncertainties due to the current state of knowledge could have had long-term cost impact for the collider project had it gone to completion. Less hypothetical is whether or not the existing condition of the host rock and hydrologic regime for the SSC are understood well enough to anticipate any problems or concerns that can develop for the Texas National Research Laboratory Commission (TNRLC) during and after shutdown. What remediation efforts, or continued evaluation are appropriate?

Additional expense or risk of failure often inhibit private industry and government agencies from improving the basic understanding of the subsurface rock and water behavior and from trying innovative and new technologies. Basic research on these new methods is usually limited to studying the problems on scaled-down systems in the

laboratory or field. Because the SSC tunnel was a major $100 million construction project, it presents the opportunity for large-scale experimentation in the underground for investigating fluid flow and mechanical behavior with full three-dimensional access. Its own long-term fate also needs to be studied to assure the state of Texas that no unanticipated difficulties will result from the hurry-up, limited budget closure process. For example, how frequently should barriers be placed in the tunnel to prevent migration of a contaminant that might find its way into the tunnel? What long-term monitoring program should be instituted?

- **Therefore, the following national needs can be identified:**
- **Improve the technology for environmental remediation of contaminated groundwater.**
- **Improve the technology for underground construction.**

A subsidiary need is to:

- **Assure environmentally safe closure of the SSC tunnel.**

The inaccessibility of the underground environment decreases general public awareness and knowledge of issues related to groundwater use and protection and to underground construction practices. The facility can serve as an educational resource to the Dallas-Ft. Worth area, the state of Texas, and to university programs nationally in geotechnical engineering and hydrogeology.

- **Educate the public about groundwater and underground construction issues.**

The important geoenvironmental and geotechnical studies to meet these needs can be addressed most appropriately in an underground opening where large-scale experiments can be carried out. The scientific objectives are to: (1) Identify new and improved methods for investigating subsurface fluid flow and transport processes, (2) Characterize physical properties of weak and fractured rock through geophysics, (3) Predict long term strength and load-carrying behavior through geomechanical testing, and (4) Test model predictions through large-scale experiments in the underground.

3 Underground Facilities Background

Large scale underground facilities for studying rock mechanics and fluid flow have been developed for addressing issues in high-level radioactive waste disposal. The Bureau of Mines has also performed underground experiments, with emphasis on mechanical and fluid flow behavior related to mining operations and safety. Active underground research facilities have existed for a number of years in Canada (Pinawa), Switzerland (Grimsel) and Sweden (Stripa) in crystalline rock. A key question is how flow and transport occur through a fractured rock mass subjected to heating. Experiments conducted at the Stripa mine in Sweden show the occurrence of preferential flow paths. A major unresolved question was that tracer experiments could be explained either by sorption on fracture surfaces or by matrix diffusion.

Recently, the United States started a tunneling program, the Exploratory Studies Facility, at Yucca Mountain in unsaturated tuff. Other than the new Yucca Mountain project, the U.S. has no large-scale, underground facility. In 1981 Lawrence Berkeley Laboratory performed a survey of existing underground openings, such as mines and dam sites, for the purpose of identifying sites in crystalline rock for an *in situ* experimental facility to develop geomechanical and hydrological techniques for evaluating sites for radioactive waste isolation (Wollenberg et al., 1981). They also published plans for an underground research facility and research program dedicated to the radioactive waste isolation problem at an estimated cost of $28 million (1981 dollars) over eight years (Korbin et al., 1981), if an existing underground opening were used. A study committee was established in 1982 within the Geosciences Program of DOE's Office of Basic Energy Sciences to determine the advisability and feasibility of an underground facility for rock mechanics and hydrogeology research. A preliminary draft plan in 1985 to developed a facility and research program in an existing mine was about $39 million (now in 1985 dollars). Over the remainder of the 1980's, the committee's outlook on the need for an underground facility broadened considerably beyond the radioactive waste disposal problem. Its considerations included sites to investigate contaminant transport in fractured rock, hydrocarbon recovery in heterogeneous formations, and energy recovery from geothermal systems.

LBL submitted in 1990 a formal proposal to OBES for construction only (no operating costs) of a facility at a cost of $7 million (1990 dollars) over 3 years. Paul Witherspoon and Harold Wollenberg of LBL circulated a draft proposal in 1991 entitled "Use of Underground Research Facility to Investigate Effects of Heterogeneities on Rock

Mass Behavior." Response was generally favorable. For example, David Pollard, Professor of Geology at Stanford, wrote:

> The URF is an exciting concept and one that promises to admit important research projects. I would like to encourage you to continue investigating the feasibility of the URF. ...I share your concerns about how the shaft/drift/holes would perturb all of the physical fields one might want to monitor, but this would have to be evaluated through careful model studies and on-site measurements as drilling progressed. . . .It should be clearly proposed that this is a facility to provide answers to *fundamental* scientific problems of wide applicability, not site-specific engineering techniques.

The most recent outgrowth of this previous work was a meeting of the current steering committee, which includes many members of the previous study committee, in December, 1993 to discuss the opportunity in converting the SSC tunnel to research aimed at improving technology in underground construction and environmental remediation. This group submitted an expression of interest to DOE to utilize the 14 miles of SSC tunnel and conducted a workshop held at Lawrence Berkeley Laboratory on September 1-2, 1994. Most of the ideas presented in this project definition study were developed at the workshop and summarized in a report to the geophysics community (Wang et al., 1994). The workshop was attended by approximately 30 persons from national laboratories, federal agencies, academia and industry (Appendix A is the invitation letter, agenda and participants list.) The steering committee's focus has been on national needs in environmental remediation and protection, construction and transportation infrastructure, and aquifer and hydrocarbon reservoir behavior. The tunnel will serve as a national facility for geotechnical experimentation to understand the basic science and engineering of subsurface physical and chemical processes and to serve as a test bed for new and innovative technologies.

4 SSC Tunnel Facility Description

The SSC site near Dallas, Texas contains about 14.5 miles of tunnel, a number of shafts and associated test wells (Figure 1). This report focuses on the northern arc, from N15 to N45 in the figure. A small 800 foot long section was also completed in the southern arc in the area of the S40 magnet delivery shaft. This section is not extensive enough to be of

interest to this study. The geology and currently available underground workings are described in the following subsections.

4.1 Stratigraphy

The SSC tunnels lie completely within the Taylor, Austin, and Eagle Ford Groups of the Upper-Cretaceous Gulf Series. The traditional names for the Groups are Taylor Marl (TM), Austin Chalk (AC) and Eagle Ford Shale (EFS), reflecting the principal rock type in each group. These units are locally overlain by Quaternary terrace deposits and recent alluvium in streams.

The rock units dip gently to the southeast at the site. Figure 2 shows that portions of the planned tunnel were to be constructed in each of the three rock types. The figure is a generalized cross section taken along centerline of the tunnel and may not be accurate in detail. The approximate locations of shafts N15 and N35 are given on the figure as a reference to indicate the location of the excavated tunnels available for use as an underground research laboratory. It is noted that the Taylor Marl is missing in the region in which the laboratory would be located.

The lithology of the site is well described by a reference stratigraphic column (The Earth Technology Corporation, 1990) Figure 3. The reference column was based on core, lithologic logs, resitivity, and natural gamma logs obtained from holes located along the footprint of the tunnel. The Austin Chalk was divided into three units, the top 150 feet, middle 195 feet, and bottom 65 feet. The general characteristics of Austin Chalk and Eagle Ford Shale units in the north are defined as follows:

Austin Chalk

Top 150 feet:

- Thick light to medium gray limestone (microgranular calcite), beds generally greater than 1 food thickness but ranging from 0.1 to 8 feet thick
- Moderately argillaceous to shaly interbeds usually less than 1 foot thick but ranging from 0.1 to 15 feet thick
- Infrequent thin bentonite shale interbeds
- Top 10 to 15 feet generally weathered to soft limestone
- Contact with underlying unit indistinct

Middle 195 feet:

- Light to medium gray limestone (microgranular calcite)
- More frequent argillaceous to shaly limestone interbeds

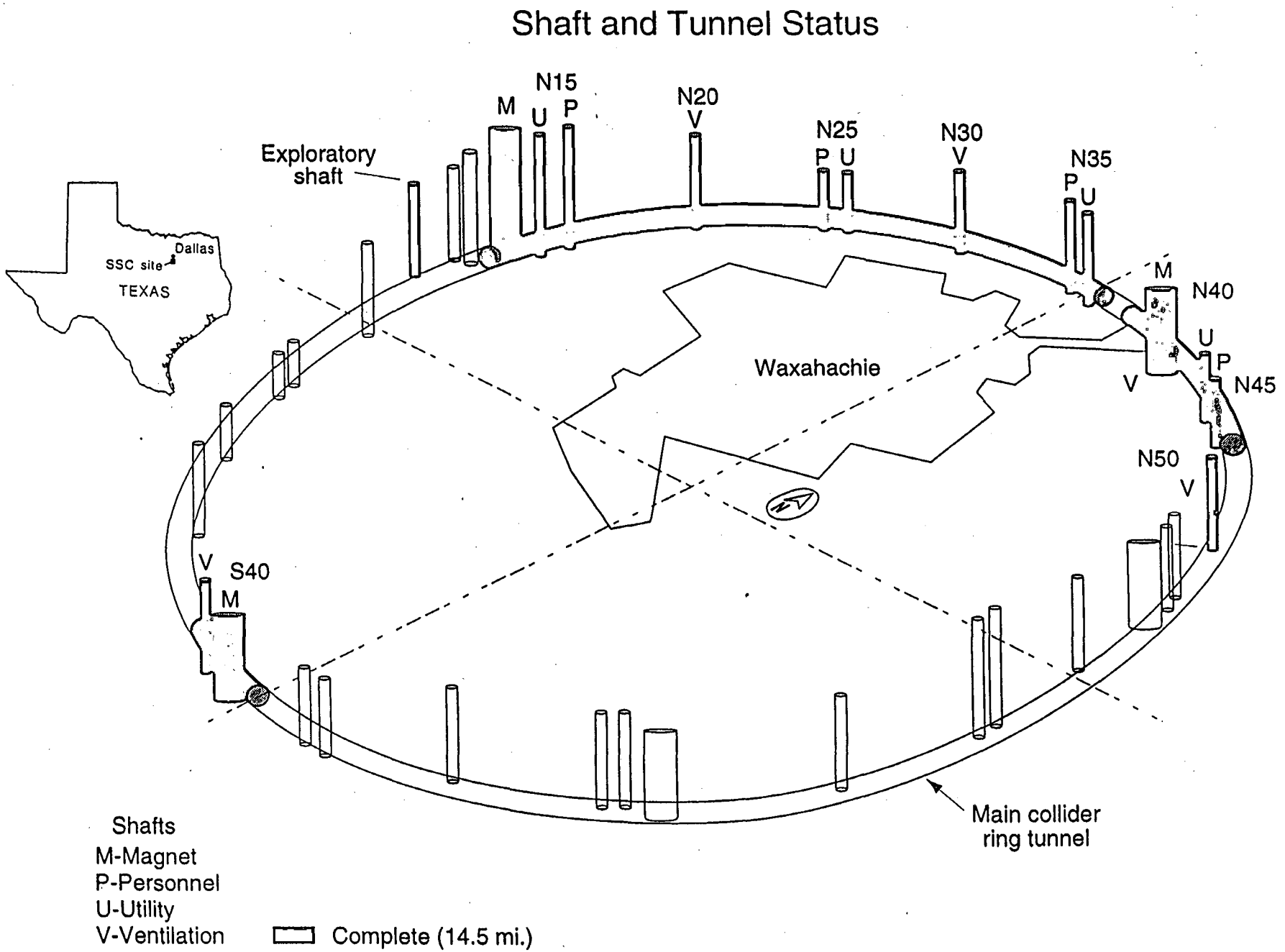


Figure 1. Location of the SSC underground facilities showing completed portions, modified after Risse 1994.

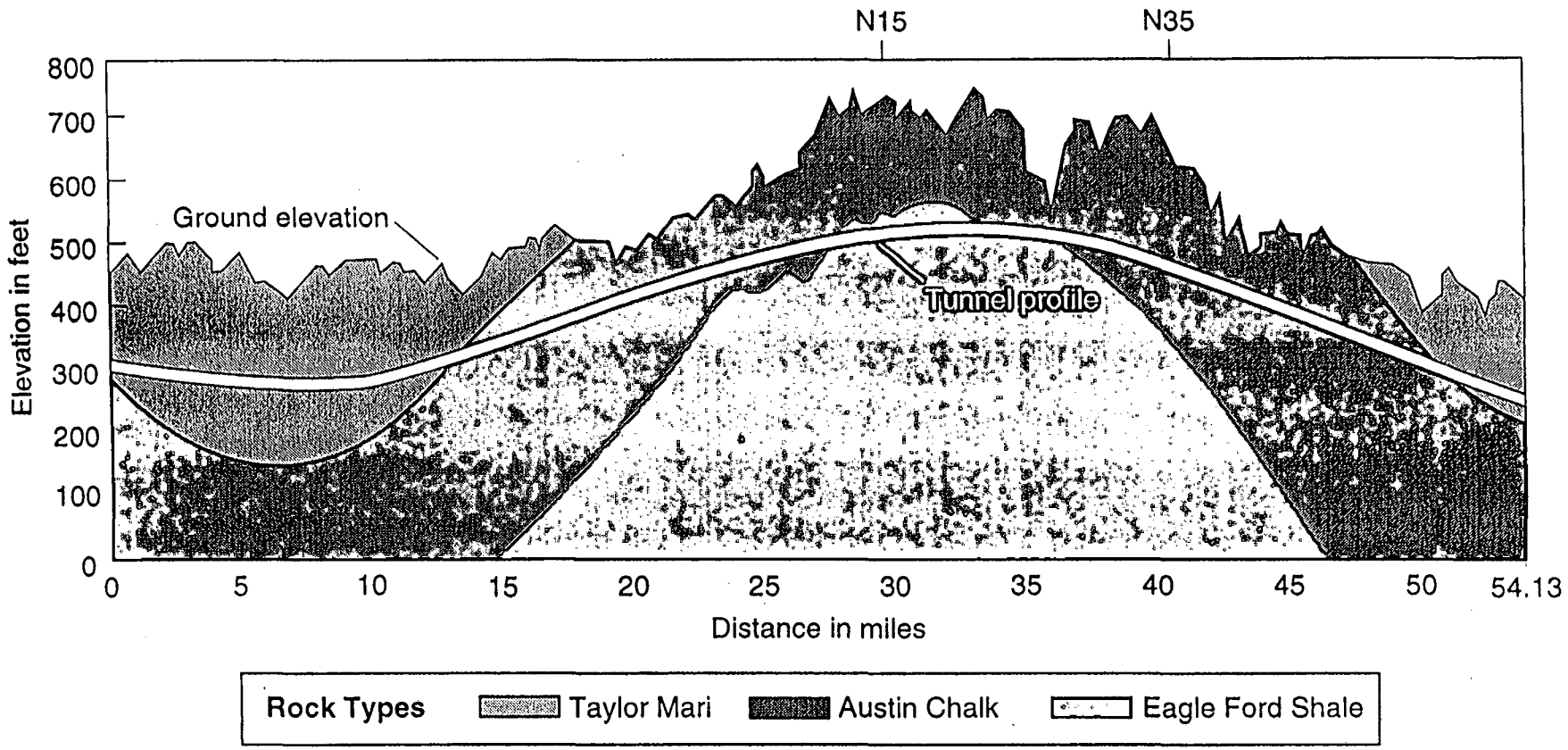


Figure 2. Generalized stratigraphic cross section along SSC tunnel centerline. Risse 1994.

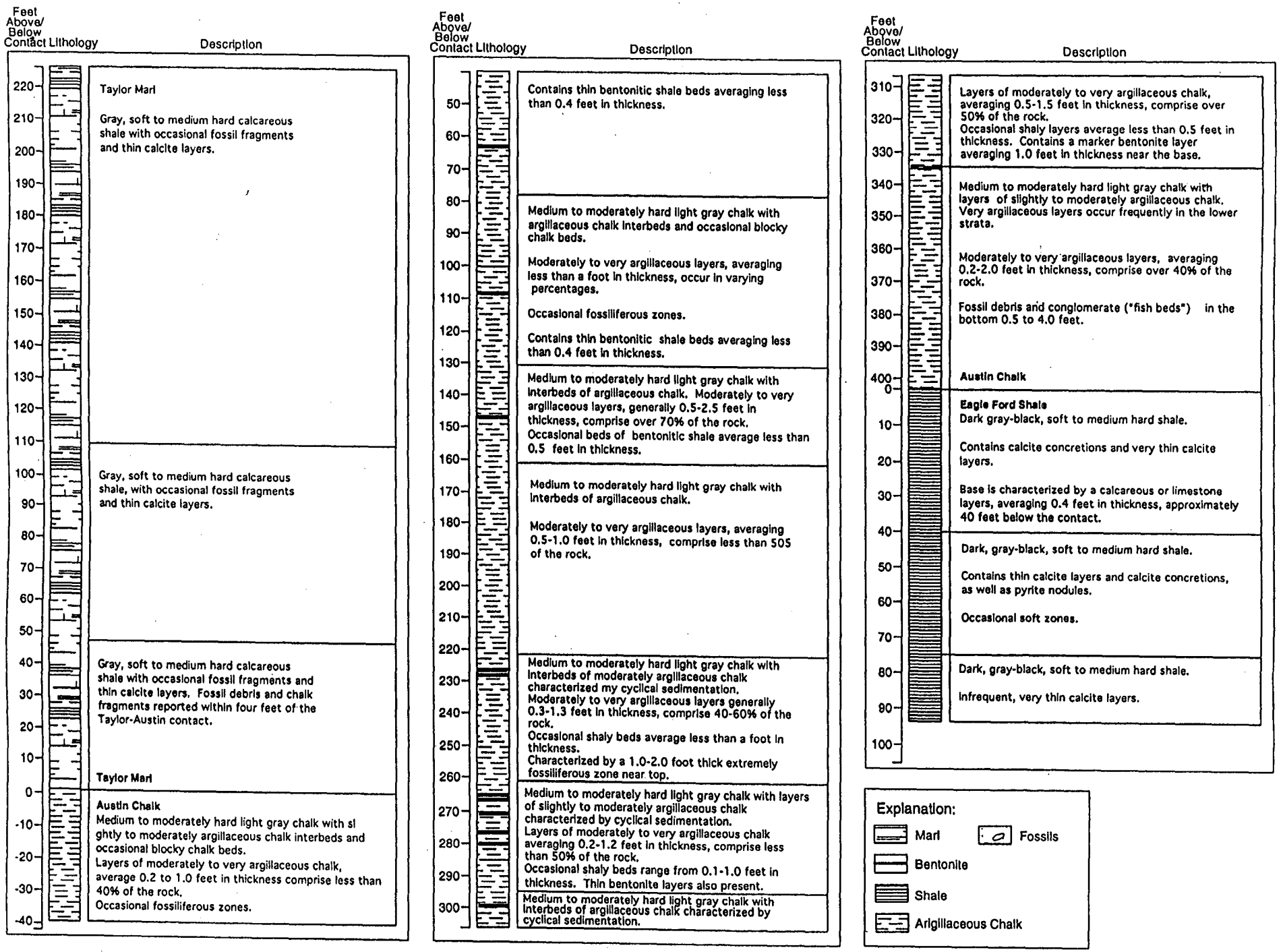


Figure 3. Reference stratigraphic column for SSC site, modified after the Earth Technology Corportion (1990).

- Frequent bentonite layers, generally 1 to 2 inches thick
- Common pyrite modules, 1 to 3 inches diameter
- Contact with underlying unit is a marker bentonite bed 0.75 to 1.0 foot thick

Bottom 65 feet:

- Thick light to medium gray limestone (microgranular calcite) becoming more argillaceous near base
- Moderate to very argillaceous limestone and shaly limestone interbeds
- Small pyrite modules
- Base is defined by a fossiliferous argillaceous and arenaceous zone known as the Fish Beds

Eagle Ford Shale

- Dark, gray to black, soft montmorillonitic shale with high shrink-swell potential
- Bentonite seams in upper part
- Very thin (3 to 9 inches) limestone laminae, more common toward base
- Slight to moderate carbonate content (1 to 54 percent) averaging 8.6 percent

4.2 Structural Geology

The SSC site is located in a tectonically stable region at the northern end of the Balcones fault system, the result of extensional faulting beginning in the mid-tertiary. Fault and joint strikes are predominately northeastward, parallel to the strike of the Balcones system, though subsidiary northwest striking faults are also found. Figure 4 is a geologic cross section along the tunnel in the northern sector from I15 to N50, showing the location and offset of the major faults in that area.

About 305 faults were mapped by the Texas Bureau of Economic Geology (Nance et al., 1994) in the tunnel from N15 to N45. Of 250 faults for which offset was measured 50% had offsets of 2 ft or less and only two faults had offsets in excess of 20 ft. Faults are predominately steeply dipping (45°-85°). Nance et al., 1994 found that joints rarely occurred together with faults. In one 12,000 ft segment between N25 and N35 no joints were found and few were found in 19,000 ft from N40 to N45. Nance et al conclude that both faults and joints occur in widely spaced swarms. Further discussion of fracturing is found in Appendix F.

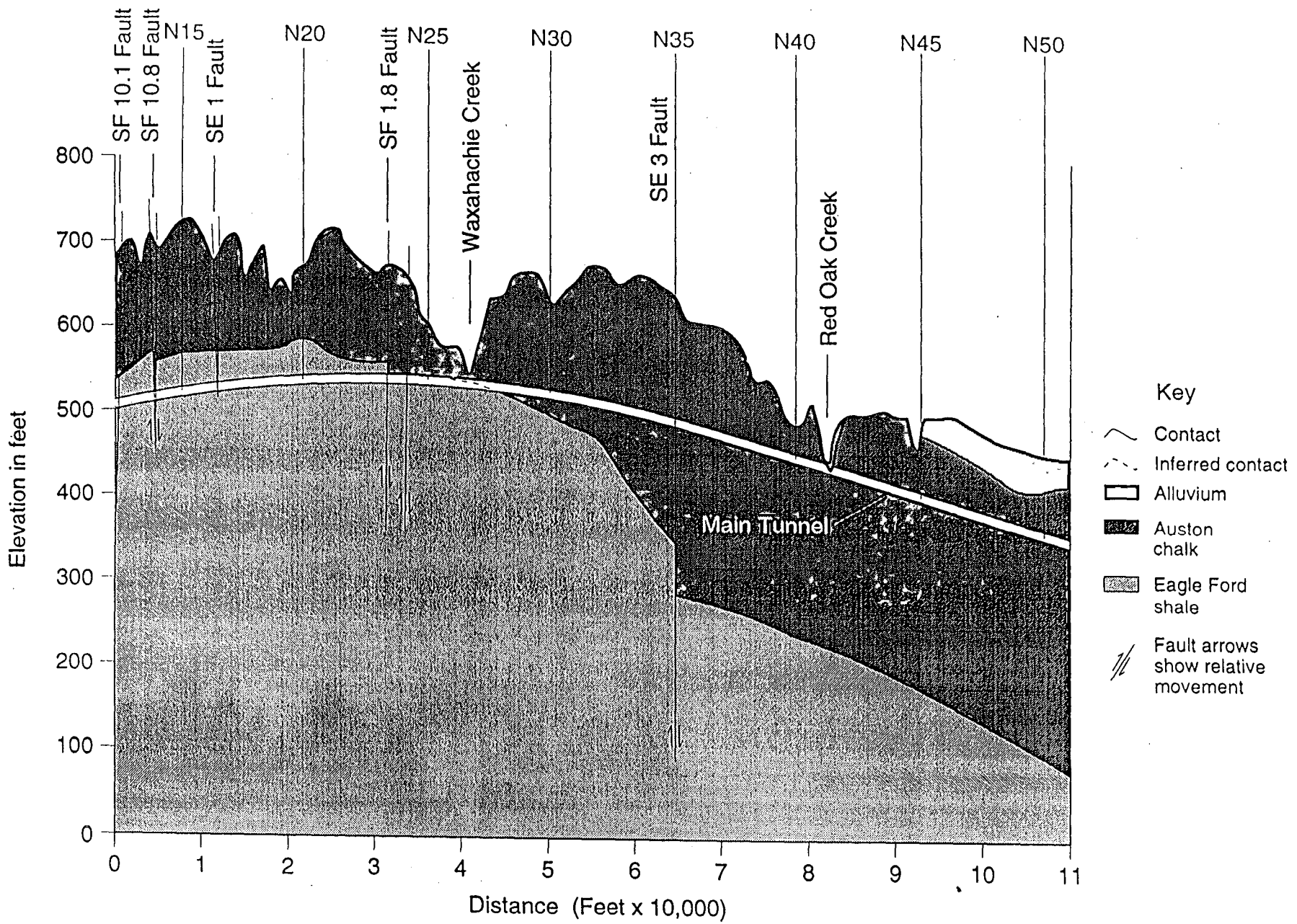


Figure 4. Geologic cross section of north arc of SSC site taken along tunnel centerline, modified after the Earth Technology Corporation (1990).

4.3 Description of Underground Workings

The SSC tunnel was excavated by tunnel boring machine (TBM) with an advance rate of up to 450 ft/day. In the EFS the tunnel was mined to a diameter of about 15.5 ft and then concrete liner segments installed so that the finished diameter was 14 ft. Grout was pumped into any space between the liner segments and the rock. The same procedure was used when mixed face conditions were encountered at the EFS/AC contact. The lined portion of the tunnel extends for about 8 km from N15. the shale-chalk contact is present in about 1 km of the tunnel.

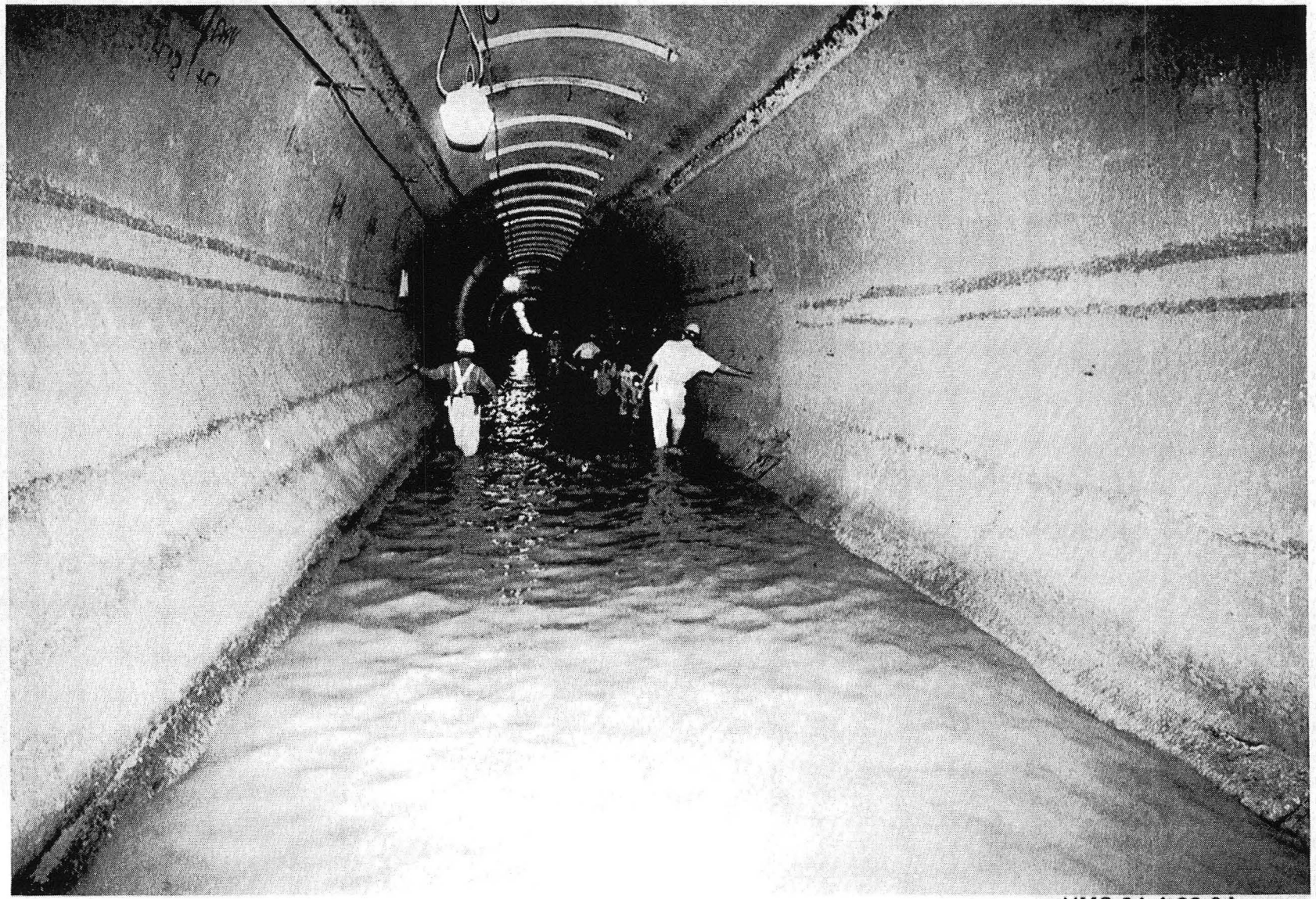
In the chalk the tunnel was mined to a diameter of 14 ft and left unlined. As shown in Figure 5 the tunnel is unsupported except for some tie bars in the crown. Bolts and mesh were used as required when minor stability problems were encountered. The dark lines seen in the figure running horizontally along the tunnel walls are argillaceous interbeds. The presence of these interbeds led to breakouts in several sections of the tunnel. Structural rehabilitation work would be required in these areas if they were to be used as part of an underground research laboratory.

A number of photos documenting the condition of the tunnels from N15 to N45 are included as Appendix B. As shown in Figure 1 a number of shafts also were constructed. Utility, personnel and ventilation shafts range in diameter from 19 ft to 31 ft. Two magnet delivery shafts are elliptical in shape. Two muck shafts and the exploratory shaft (see Section 5) were also excavated. Most of the shafts were placed off the centerline of the tunnel and connected to the tunnel by adits. Photos of some of these shaft intersections are also included in Appendix B in addition to a list of shaft dimensions.

At the time of writing access to the underground had been removed, along with ventilation. Roofs were constructed over the shafts as temporary barriers to shaft access. Tunnels were filling with water though it is understood that pumps had been left in place and may be turned on.

5 Previous SSC Investigations

The extensive geotechnical and hydrogeologic data base collected for the SSC tunnel construction is described in two documents --- Nelson et al. (1994) and Dutton et al.(1994), respectively. Both senior authors were participants at the DOE-sponsored workshop at LBL and were co-authors of the workshop report (Wang et al., 1994). An earlier overview of the geology, hydrogeology, and geotechnical characteristics of the



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N-30 to N-35 Tunnel

Figure 5. Typical view of tunnel conditions in Austin Chalk, taken from segment between N30 and N35; dark bands on walls are argillaceous interbeds; above and to the right of person on right is a fault offsetting the interbeds.

SSC site was given by Reaser et al. (1990). Also, fracture characteristics of the Austin Chalk (Nance et al., 1994; Hovorka, 1994) have been collected by the Texas Bureau of Economic Geology (BEG). These baseline studies constitute one of the attributes of the SSC site as a geotechnical test facility. Comprehensive understanding of site conditions is a necessary prerequisite to development of research plans in any proposed test facility. At the SSC site this baseline understanding, to a large extent, already exists.

5.1 Geotechnical Data

A significant amount of geotechnical data is available and will provide valuable information for the proposed research facility (see Appendix E, which is the summary of the geotechnical assets by Nelson et al.). Thirty-eight test borings were made as part of the site selection process and an additional 116 borings were made prior to 1990. Three further exploration programs included another 130 borings, which included sample and core logging, laboratory testing, and field packer testing in some cases. Other contracts were for long term strength tests on Eagle Ford shale and Taylor Marl, pressure meter testing in the Eagle Ford shale, hydraulic fracture testing in Austin Chalk and Eagle Ford shale, and instrumentation in the exploratory shaft, magnet delivery shaft and several other openings.

The Eagle Ford shale is very weak (unconfined strength between 150 and 300 psi) and contains highly expansive clays. The Austin Chalk is a moderately well-bedded limestone with unconfined strengths between 700 and 2,000 psi. It contains shaley layers up to 0.5 ft thick that are spaced in some areas about 5 ft apart. Appendix D presents a summary of engineering properties of Austin Chalk and Eagle Ford Shale compiled by Elioff, 1992.

5.1.1 Exploratory Shaft

A 17 ft diameter exploratory shaft near the linear accelerator (Figure 6 and Appendix E) was driven to a depth of 270 ft. A 10-meter long adit was excavated along the shale-chalk contact at a depth of 215 ft. The instrumentation emplaced included 28 piezometers in fourteen boreholes, 14 multiple borehole extensometers at three different levels, and 36 vibrating wire strain gages on a steel ring grouted in place. Valuable baseline data have been collected in the adit on the deformation and fluid flow behavior of carbonates and shales under natural conditions.

Design: ELECTRICAL & MECHANICAL DESIGN

- 16-inch-diameter duct fan will be installed for ventilation
- oxygen-deficiency sensors will be installed on portable personnel cage
- lighting will be provided in shaft and adit to accommodate instrument readings
- a small pump will be located at bottom of shaft to remove seeping groundwater by pumping to a small detention pond at the surface
- temporary power and water connections will be provided by Hill County Electric Cooperative, Inc. and Buena Vista Bethel Water Supply Corporation

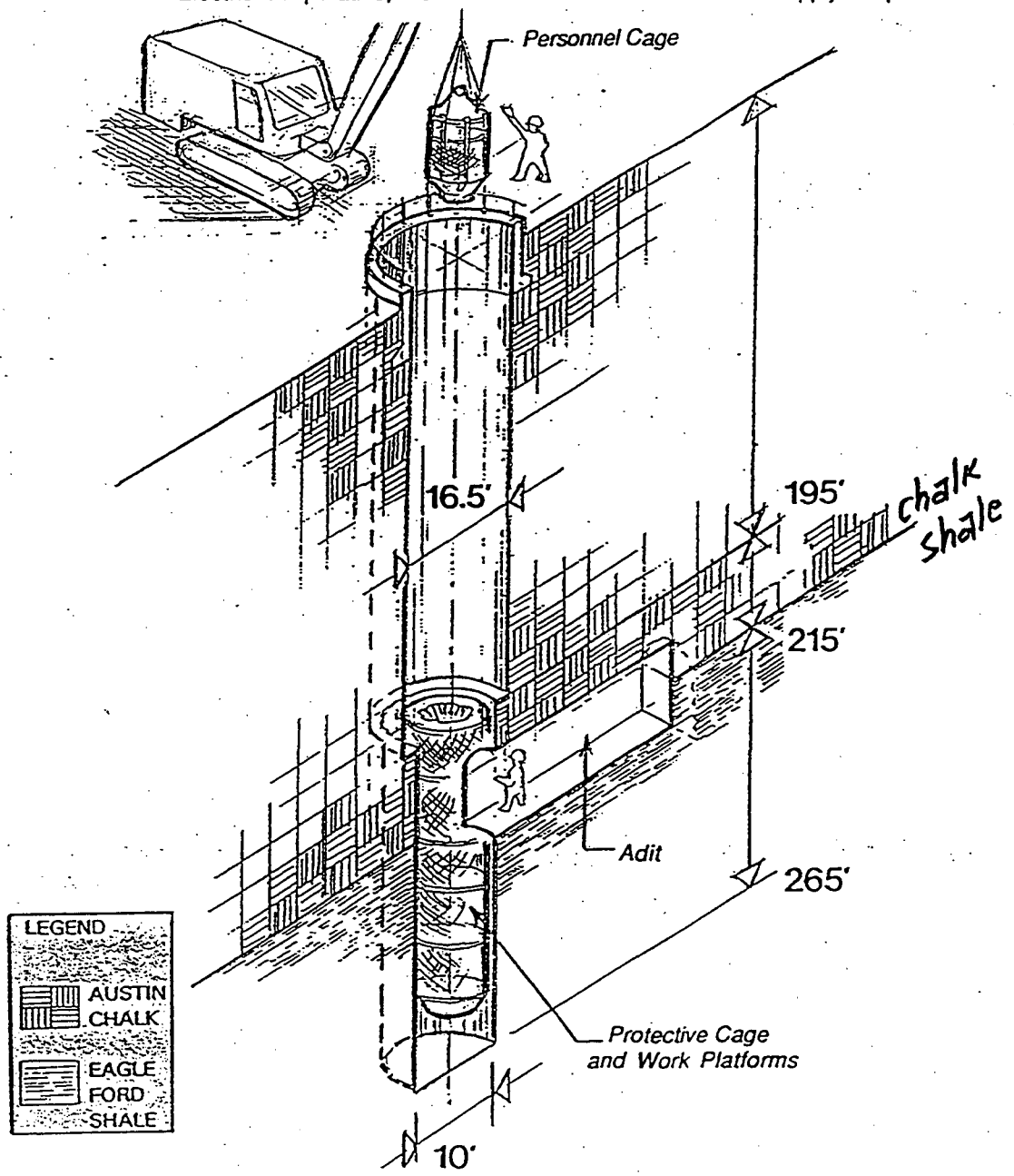

Figure 6. Exploratory shaft schematic. The 10-meter long adit runs along the chalk-shale contact.

5.2 Hydrogeological Data

The Texas Bureau of Economic Geology began its investigations to provide support on groundwater issues, such as inflow rates and long term environmental impacts, for the construction and maintenance of the Super Collider tunnel (see Appendix F for the complete summary of the BEG's hydrogeologic report). These studies were made to supplement existing regional data. The results were synthesized into three numerical models of groundwater flow. The primary hydrogeologic unit in which the tunnel was constructed was a regional confining system of unweathered Austin Chalk, Taylor Marl and Eagle Ford shale.

Fractures play an important role in the groundwater flow in this system. The Austin chalk contains varying degrees of jointing and faulting as shown in Figure 7. Field and laboratory measurements of hydraulic conductivity in the unweathered Austin chalk range from $10^{-11.5}$ to $10^{-5.5}$ m/s. A hypothesis was developed that the fracture distribution in the Austin Chalk was related to the microdistribution of clay in the various subunits.

6 Underground Utilization Research Objectives

The major research objective is to predict physical and chemical behavior in underground rock masses, because this underpins technological applications such as remediation and protection of aquifers and construction of underground facilities. The scientific challenge is to characterize the subsurface rock mass and the ongoing processes within it by integrating results from hydrogeology, geomechanics, geochemistry and geophysics (Figure 8). *A basic issue facing every method involved with subsurface geoscience is testing models against actual behavior at distance and time scales relevant to the desired engineering application.* This impediment can be overcome through studies conducted in an underground laboratory on the scale of the SSC tunnel.

Experimental groundwater remediation and underground construction technologies can be tested at the SSC site. Although the results obtained will be site specific to some degree, they should have transfer value to other urban areas in the central U.S. that are underlain by similar sedimentary strata. Significant advances in our understanding of subsurface processes are likely to result from a data base of geotechnical information on a spatial scale of miles and a temporal scale of years.

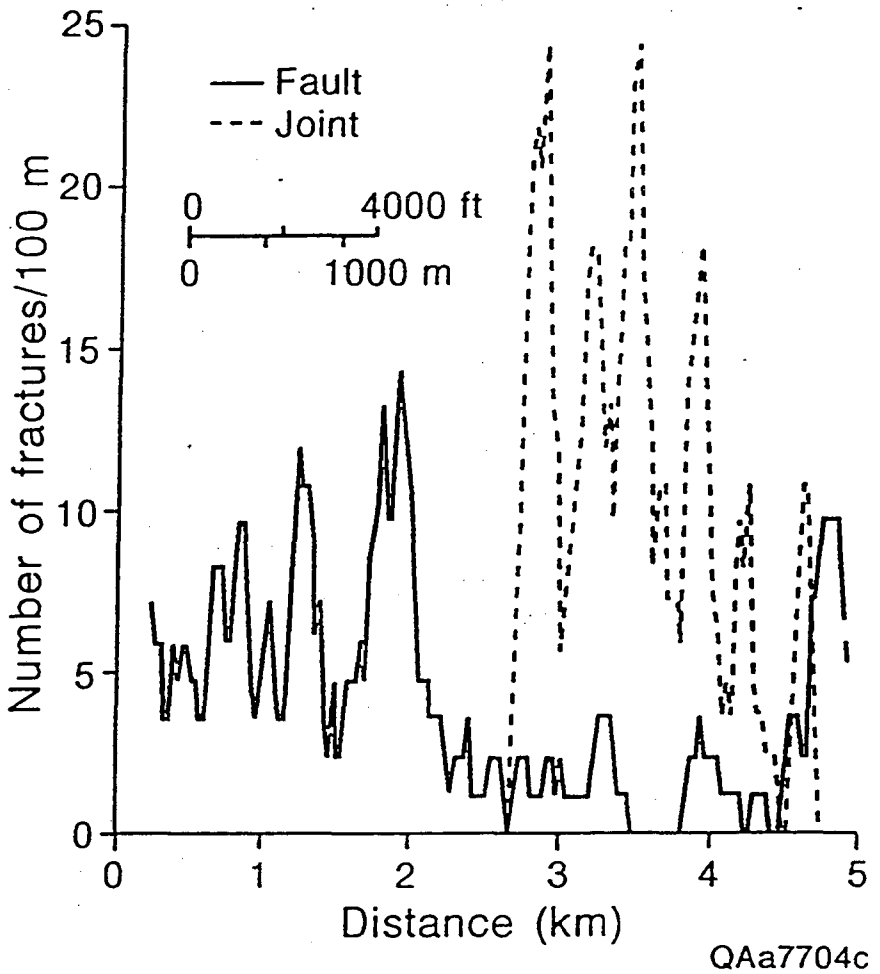

Figure 7. Fault (solid line) and joint (dashed line) frequency on the basis of 100-m running averages along tunnel segment N30 to N35. The horizontal axis is distance along the tunnel. Modified from Nance et al. (1994).

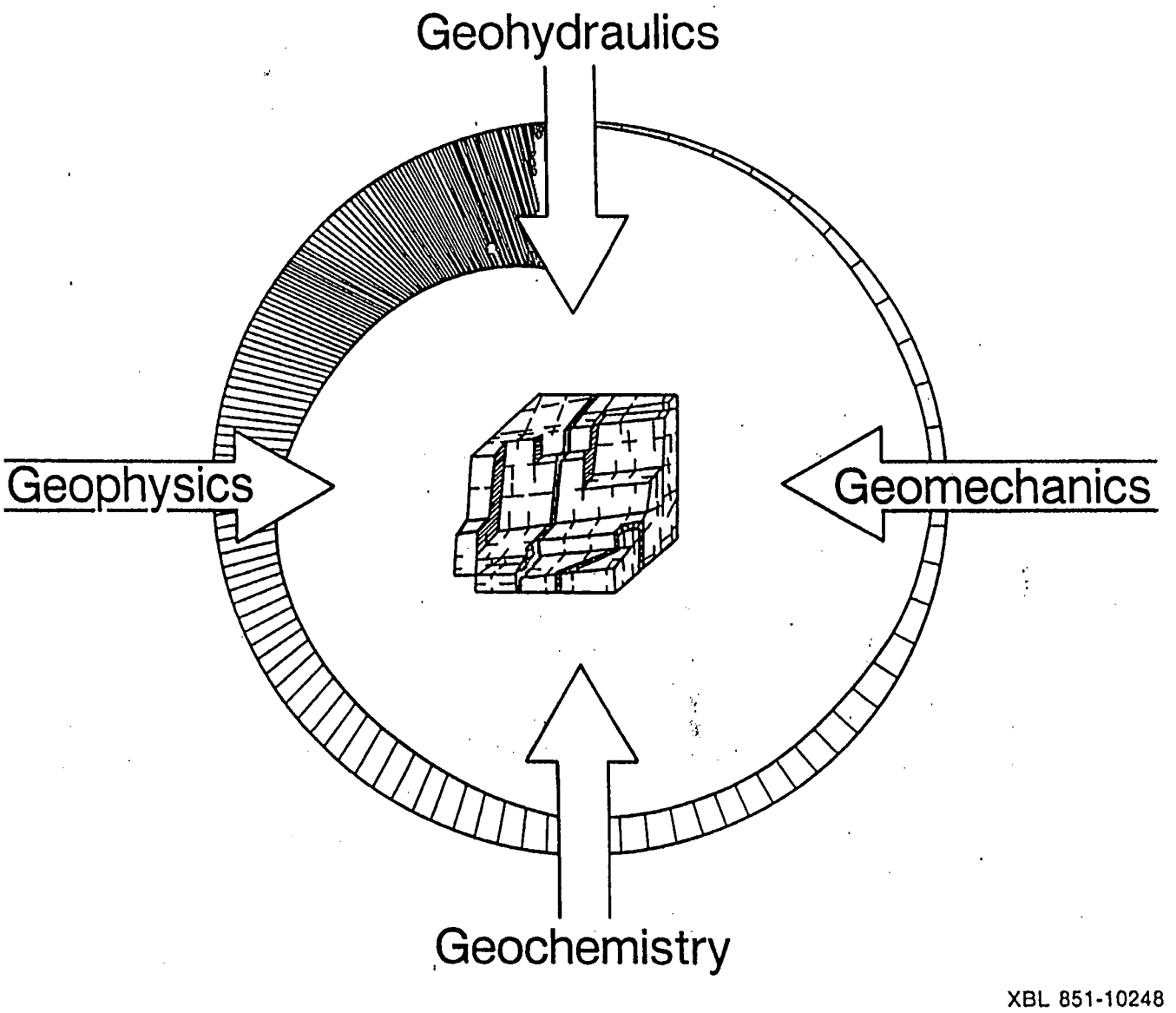

Figure 8. The interdisciplinary approach required to characterize a fractured rock mass. Diagram courtesy of P. A. Witherspoon.

The workshop divided into two groups for the purpose of identifying specific research questions in hydrogeology and geomechanics. The results from these two groups are summarized separately, although certain themes, such as scale dependence and coupled fluid-mechanical effects, emerged from both sides.

6.1 Hydrogeology Questions

Contaminated, fractured rock sites are the most difficult to remediate under present technology (MacDonald and Kavanaugh, 1994). The National Research Council's Committee on Ground Water Cleanup Alternatives concluded that the major barrier to using innovative technologies is the risk of failure. The SSC site would be a scientific test ground where profits are not at stake. A recent Chapman Conference on "Aqueous Phase and Multiphase Transport in Fractured Rock," convened by Kent Novakowski (Environment Canada), Leslie Smith (U. of British Columbia) and Paul Hsieh (U.S. Geological Survey), was devoted to many of the hydrogeological questions which can be addressed in the SSC tunnel.

Because research questions revolve around the role of fractures in rock behavior and fluid flow, a concern that arises is that seepage measurements from tunnel walls may be strongly influenced by the disturbance caused by excavation. At Stripa in Sweden, an experiment was undertaken to capture water seepage from 750 m^2 of tunnel wall, at a depth of 360 meters, by covering the wall with 2 m^2 sheets of plastic (Neretnieks, 1993). The majority of the flow was captured on only a few sheets; 70% of the sheets received no flow. Preferential flow paths have also been observed in a 625-m deep, 6,250 m-long tunnel in the Santa Ynez Mountains of Santa Barbara (Loaiciga, personal communication, 1994). In performing similar experiments, it is important to know that such results are representative of the natural, *in situ* distribution of flow and not the result of changes in stress around the tunnel due to the excavation. We believe the question of the effects of disturbance in the SSC tunnel, which is at considerably shallower depth and in much weaker rock, can be addressed through successive over-coring tests envisioned by the geomechanical group.

Another possible mechanical-fluid coupling phenomenon lies in the observation that water levels dropped dramatically in nearby wells as the tunnel boring machine (TBM) advanced in the underground operations at SSC (Figure 9). Simulations of the TBM effects can be made with standard excavation equipment to test whether fluid-mechanical coupling or induced rapid drainage is responsible for the effects on hydraulic head.

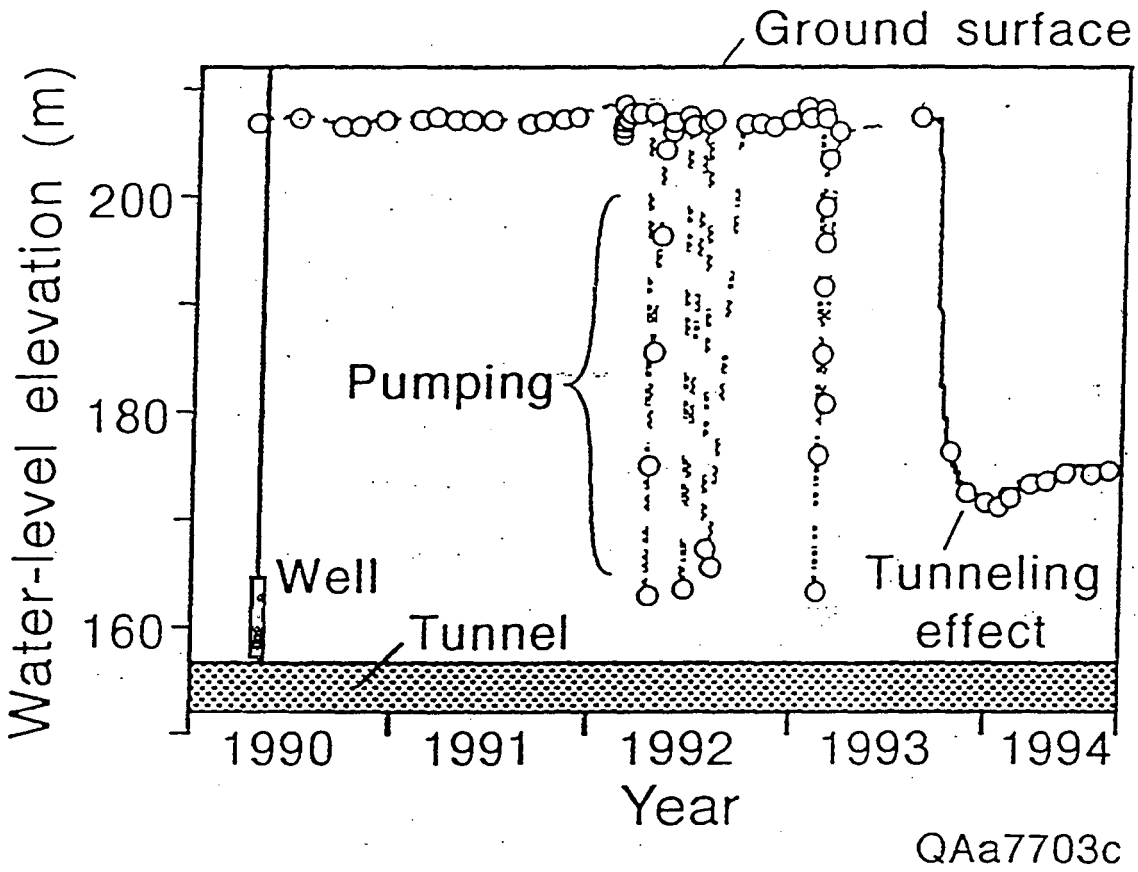

Figure 9. Hydrograph of water-level fluctuation at SSC Laboratory monitoring well BE3 measured by electrical sonde (circles) and pressure transducer (solid black line). Also marked are elevations of SSC tunnel and the BE3 well screen. BE3 lies approximately 10 m from the tunnel edge. Water level in BE3 abruptly fell when the tunnel was mined past the well.

Creating the tunnel opening can be viewed as a purposeful perturbation of the underground rock mass. All of the excavation effects, if properly identified, should serve to characterize the medium. Thus, one important objective is to predict the mechanical and hydraulic response to the excavation.

A comprehensive list of hydrogeological research questions was prepared by Dr. Alan Dutton of the Texas Bureau of Economic Geology and is presented in Appendix G. High priority basic needs are: (1) development of models to handle flow in fracture networks, (2) elucidation of factors affecting transport in fractures, (3) determining the nature of driving gradients for fluid flow through shale, (4) nature of scale dependence for transport of different chemical species, and (5) nature of colloidal particle migration in shale and chalk, and implications for bioremediation.

The following points are central to the opportunity the SSC tunnel presents:

- **The hydrogeological experiments are to be coordinated with geomechanics experiments.**
- **Model testing will be the common focus of experiments to maximize the technology transfer benefit.**
- **The tunnel provides a unique opportunity for analyzing scale effects up to those important for site remediation and large-scale civil construction.**
- **The experiments will be conducted in both chalk and shale.**
- **Previous fault and fracture mapping allow optimal planning for experiments.**

6.2 Geomechanics Questions

During or after construction, large-scale underground works often encounter unanticipated difficulties, such as higher than expected seepage or spalling, which lead to additional construction expense or litigation, typically 5 to 100% of the original contract cost. It is anticipated that major cost savings can be achieved by minimizing over-engineering and unanticipated difficulties through more accurate characterization of the upper 100 m of the subsurface.

A large fraction of the infrastructure of the United States is founded on fractured, sedimentary rock, much of which can be characterized as weak, high-clay content shales. These shales represent a continuing engineering challenge because their behavior is not

well described by established engineering principles in either of the disciplines of soil mechanics or rock mechanics. Though poorly defined as a class of materials, they are stronger than unconsolidated soil, weaker than intact rock, and exhibit time dependent properties and characteristics that are sensitive to moisture content and pore fluid chemistry. The Eagle Ford shale encountered in the SSC tunnels is a case in point. The rock formations are those that occur throughout the Dallas - Fort Worth metropolitan area. The most up-to-date contracting methods were utilized and the tunneling was generally considered to be a success. The difficulties encountered in predicting its behavior during construction typify the problems encountered in many other engineering projects in shales. In particular, the amount of time-dependent deformation, loads on supports and spalling of the Eagle Ford were very difficult to predict. The most problematical tunnel instability occurred due to interaction of the tunnel opening in chalk with a layer of weak rock. In addition, as described at the beginning of this report, unresolved questions remained about the thirty-year behavior the shale floor and the roof support near N-35. Uncertainties due to the current state of knowledge could have had long-term cost impacts for the collider project had it gone to completion. These examples point to the need for further research to define the constitutive behavior of weak rock and the effects of moisture and fluid chemistry on this behavior.

Given the present program of closure as mandated by Congress, relevant current questions are, "How long will it take for the tunnel to fill with groundwater?" and "Will the roof collapse eventually?" Therefore, a long-term study of the stress distribution, deformation and fluid flow within the tunnel will serve both as a post audit of SSC construction and as a predictive guide to SSC closure. A common theme at a ``Workshop on Prediction of Groundwater Flow into Deep Tunnels and Excavation" sponsored by the Army Corps of Engineers and held in Berkeley in February, 1987 was the question of how much flow to expect in deformable fractures. Instrumentation at the SSC tunnel to monitor the spatial variation of inflow rates over several years could improve significantly the predictive capability.

A number of the problems described above can only be addressed by an *in situ* test facility. The engineering properties of rock (e.g., compressibility, permeability, strength) are strongly influenced, even controlled, by conditions existing at a site that cannot be investigated by sampling, removing materials and testing them in a laboratory. Weak rock, particularly clay-rich rocks, are disturbed in the process of sampling and removal to a laboratory. The natural fractures in a rock mass, their connectivity, length and aperture, occur on a scale that cannot be sampled and tested in a meaningful way on a small scale. Improvements in methodology for site investigation and characterization will

lead directly to cost efficiencies through improved equipment selection and performance prediction.

A major question for the geomechanics research program is to determine how much disturbance of the initial condition was produced by the excavation itself (cf. quotation from David Pollard's letter and concerns about the Stripa flow experiments). A series of experiments, such as successive over-coring and hydraulic fracturing experiments at scales up to a tunnel diameter in both the chalk and shale in different segments of the tunnel can definitively answer this question.

A second major question is to validate surface and borehole geophysical techniques for characterization of a fractured rock mass. Geophysical methods, and in particular, seismic methods have been developed to a very high degree of sophistication for definition of large-scale deep structure relevant to petroleum reservoir development. The scale of interest in the near surface is smaller, requiring higher frequencies. Electrical methods are not likely to work at these depths in clay-rich, saturated rock. Different seismic sources and receivers must be used as well as modifications of source-receiver spacings and data acquisition design. Processing of high frequency data in fractured rock presents further difficulties. The SSC site offers the potential to carry out research aimed at resolving problems in all these areas.

An extensive and detailed list of topics and related experiments was prepared by Dr. Priscilla Nelson of the University of Texas-Austin and is presented in Appendix H. In broad terms the problems directly related to underground constructions problems are: (1) determining scale effects on shale rheology, (2) constitutive modeling of weak rocks, (3) determining stress history and joint formation through geologic time.

7 Management, Operations and Budget Plan

The enthusiasm of the research community within the national laboratories and universities associated with the development of this project definition study is high. Nevertheless, the enthusiasm is tempered considerably by the recognition that no source of funds has been clearly identified to carry through the facility construction and operation. Several federal agencies --- DOE, DOD, EPA and FHWA --- have programs and responsibilities that fit squarely within the objectives of the proposed facility and research program. Indeed, the development of a site or sites in which three-dimensional examination of mechanical and fluid flow and transport behavior can be observed directly is probably the single best way to create the knowledge base for solving the problems that

are currently recognized. Only the high-level nuclear waste disposal program is developing such a capability, because it is a large program focused on a single rock type. No such push has been made for environmental remediation and construction problems, because the individual efforts are scattered over many different problems and rock types. However, a collective need has been recognized, as documented by the decade-long study committee for an underground facility. The SSC tunnel presents itself as a target of opportunity. Its large scale and rock types will have wide applicability, and the construction has already been completed.

The management and operations plan, as well as the budget, described here is a "straw person" plan. It represents a reasonable consensus of the individuals on the steering committee, which represents half a dozen universities and national laboratories in total. Funding should be on a block grant or contract basis, with the specific experiments and investigators chosen and coordinated by the steering committee.

7.1 Steering Committee

The steering committee has worked together on this project definition plan for nearly a year. It represents a broad range of expertise in geotechnical engineering, geophysics and hydrogeology. It currently lacks expertise in geochemistry, although several of the institutions represented have very strong programs in geochemistry. This group of institutions would continue to provide the intellectual leadership for the overall facility. The steering committee would select and contract an organization or organizations to carry out the day-to-day construction and operations. A successful analogue in the earth sciences community is the Ocean Drilling Program (ODP) at Texas A\&M University. In addition, the steering committee will serve as an experiments panel for funding a base set of coordinated investigations.

7.2 Budget

At a minimum level, the facility would consist only of a mining crew responsible for keeping the portions of the tunnel operational and safe for personnel conducting experiments. Individual experimenters would be responsible for obtaining their own funding. The analogue in the physics community might be the synchrotron source at Brookhaven or the upcoming Advanced Photon Source at Argonne.

Maintenance and an operating crew for construction of individual experiments would be $2 million/year. However, the importance of integrating studies from

hydrogeology, geochemistry, geomechanics, and geophysics means that a core set of experiments is also essential to be part of the overall facility plan. These experiments would characterize the rock mass and study the high priority geomechanics and hydrogeology problems described in the narrative above. The level of effort will be on the order of 10 to 20 FTE's, based on experience developed at sites such as Stripa, which went into the budget plans of the study committee in the 1980's. These personnel and associated experimental costs would be about $4 million/year. The lifetime of experiments should be for a minimum of 10 years in order to obtain the benefit of characterizing the subsurface on a time scale that begins to represent the anticipated lifetime of civil construction.

Recommissioning costs depend on a large number of variables including how much of the tunnel and how many of the shafts will be recommissioned and the condition of the tunnels. Providing new access to the tunnels by elevator, ventilation, power, light, pumping and structural rehabilitation of all existing tunnels will cost about $14M. Included in this is about $7M for restabilization of portions of the tunnel where stability problems have occurred. There are many sections of the tunnels, however, which will not require such restabilization. These include tunnels in the Eagle Ford Shale (lined) as well as large sections of unlined tunnel in the Austin Chalk. It is also anticipated that 5,000 ft. of tunnel would be ample for many of the initial experiments which could be conducted. Both the selection of stable areas and the reduction in tunnel length would dramatically decrease recommissioning costs. On the other hand, it has also been assumed that shafts will remain open and the tunnels will remain drained. There is concern that allowing the tunnels to flood will increase structural deterioration. In addition, backfitting of shafts would lead to considerable additional expense associated with reusing,

Assuming present underground working conditions reflect those at the time of recommissioning, high and low facility cost estimates were computed as summarized in Table 1.

Option	Recommissioning	Operating/year	Total (10 years)
High	$14	$4	$54
Low	$2	$2	$22

Table 1: Ten-Year Budget (in millions of 1994 dollars) for Geotechnical Research Facility in the SSC Tunnel

8 Conclusion

An underground geotechnical facility can be established in most of the 14.5 miles of SSC tunnel to study the fundamental geomechanical and hydrogeologic processes within fractured sedimentary rock masses for applications to environmental remediation and protection of groundwater resources and to large scale civil works. It is hoped that a facility at the SSC will encourage other researchers interested in the problems described to consider utilizing it for their own specific experiments. The large diameter shafts permit easy access for most machinery and experimental equipment.

9 Acknowledgements

We thank Charles Daugherty of the PB/MK team, James Risse, director of conventional construction for DOE at the SSC site, George Kolstad, now retired from the Office of Basic Energy Sciences (OBES) at DOE, and Bill Luth, geosciences program manager in OBES at DOE. We thank all the participants of the workshop, whose ideas are in this report. The workshop and project definition study were supported by the Director, Office of Energy Research, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098 to Lawrence Berkeley Laboratory.

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Appendix A

Workshop on SSC Tunnel Facility

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ear Colleague:

We invite you to participate in a two-day workshop at LBL to define a research programn to utilize the 14 miles of tunnel, test borings, and exploratory shaft at the Superconducting Super Collider (SSC) site near Dallas, Texas. he workshop will begin on the morning of Thursday, September 1 and will conclude in the early afternoon of riday, September 2.

he proposed geotechnical facility is one of six project definition studies being pursued by the Department of nergy and one of four being pursed by the Texas National Research Laboratory Commission (see Science, May 13, p. 898 enclosed).

he background to the geotechnical project is provided in the enclosed narrative to DOE for the project definition study. he shallow depth (150 ft) of the tunnel and weak rock make it a target of opportunity for studying environmental problems associated with fracture hydrology, geophysical characterization, geochemical transport, and rock mechanics. e anticipate that the workshop schedule will include first a briefing on the tunnel characteristics followed by panel scussions on research objectives in the above four disciplinary areas that can be pursued because of the unique access to the shallow underground provided by the tunnel. Finally, we will meet in a plenary session to integrate the different anel conclusions into as coherent an interdisciplinary project as we can.

ravel funds are available for the workshop, although we do not anticipate that we can accommodate all requests. Please indicate your travel needs on the enclosed registration form.

lease complete the enclosed registration form and return it by fax as soon as possible, but no later than August 12. The nominal registration fee being collected pays for those items which are not allowable under DOE regulations. ou may pay the registration fee on site.

If you are unable to attend the workshop we would appreciate notification of this as well. Please complete the egistration form, check the appropriate box and fax to the conference coordinator before August 12. his information will be helpful in our planning.

A block of rooms has been reserved at the Berkeley Marina Marriott Hotel for this meeting. Individuals should make their wn reservations by phoning the hotel directly at (510) 548-7920 and asking for the GEOTECHNICAL FACILITY room block. ingle and double occupancy rooms are available at a special conference rate of $69.00 plus 12% sales tax. Reservations must be made before August 19 to ensure receiving the special workshop rate.

e look forward to seeing you at the workshop!

incerely,

Herb Wang and Larry Myer
on behalf of the Steering Committee

Workshop to Define a Geotechnical Facility for Environmental Research at the SSC Site

September 1-2, 1994

Lawrence Berkeley Laboratory, Building 70A, Room 3377

AGENDA

September 1

7:45 a.m.	Bus departs Berkeley Marina Marriott to LBL
8:30	Conference Welcome, (Larry Myer, LBL)
8:45	Underground Facilities Background, (Paul Witherspoon, LBL)
9:15	DOE/OBES/Geosciences Perspective, (Bill Luth, Dept. of Energy)
9:30	SSC Tunnel Construction, (James Risse, Dept. of Energy/SSC)
10:15	Exploratory Shaft, (Rickey Brouillete, Univ. Texas-Austin)
10:30	BREAK
10:45	SSC Site Hydrology, (Alan Dutton, Texas Bureau of Economic Geology)
11:30	Workshop Charge, (Herb Wang, Univ. Wisconsin)
12:00	LUNCH
1:00 p.m.	Opening Discussion
1:30 p.m.	Informal Presentation of Potential Experiments in shallow geophysical characterization, hydrogeology, geochemical transport, and rock mechanics.

Meeting participants are urged to come prepared to provide one or two tentative ideas for experiments during this phase of the workshop. Examples might include fracture flow, stress testing, scaling effects on dispersion, geochemical transport, etc.

3:00 p.m.	BREAK
3:15	Continue Discussion
5:00	Adjourn for day--Bus departs to Marriott
6:15	Bus departs from Marriott to Restaurant
6:30	Dinner

September 2

7:45 a.m.	Bus departs Berkeley Marina Marriott to LBL
8:30	Formulate workshop report in "bullet" format
12:00 noon	Adjourn
1:00	Steering Committee

Workshop to Define a Geotechnical Facility for Environmental Research at the SSC Site

September 1-2, 1994

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September 1-2, 1994

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Appendix B

Tunnel Conditions Prior to Shutdown, and Dimensions of Open Shafts

Shaft Dimensions

SHAFT NUMBER	INSIDE DIAMETER (ID)
N15 MDS	65'-2" X 34'-9"
N15 US	22'-6"*
N15 PS	25'-3"*
N20 VS	31'-5"+
N25 PS	27'-1"*
N25 US	22'-2"*
N30 V	20'-3"*
N30 Muck	7'-0"
N35 PS	25'-0"*
N35 US	22'-0"*
N40 MDS	66'-6" X 26'-8 1/2"
M40 VS	18'-8 1/2"*
N45 US	21'-11"*
N45 PS	24'-11"*
N30 VS	19'-2"*
N30 Muck	7'-0"

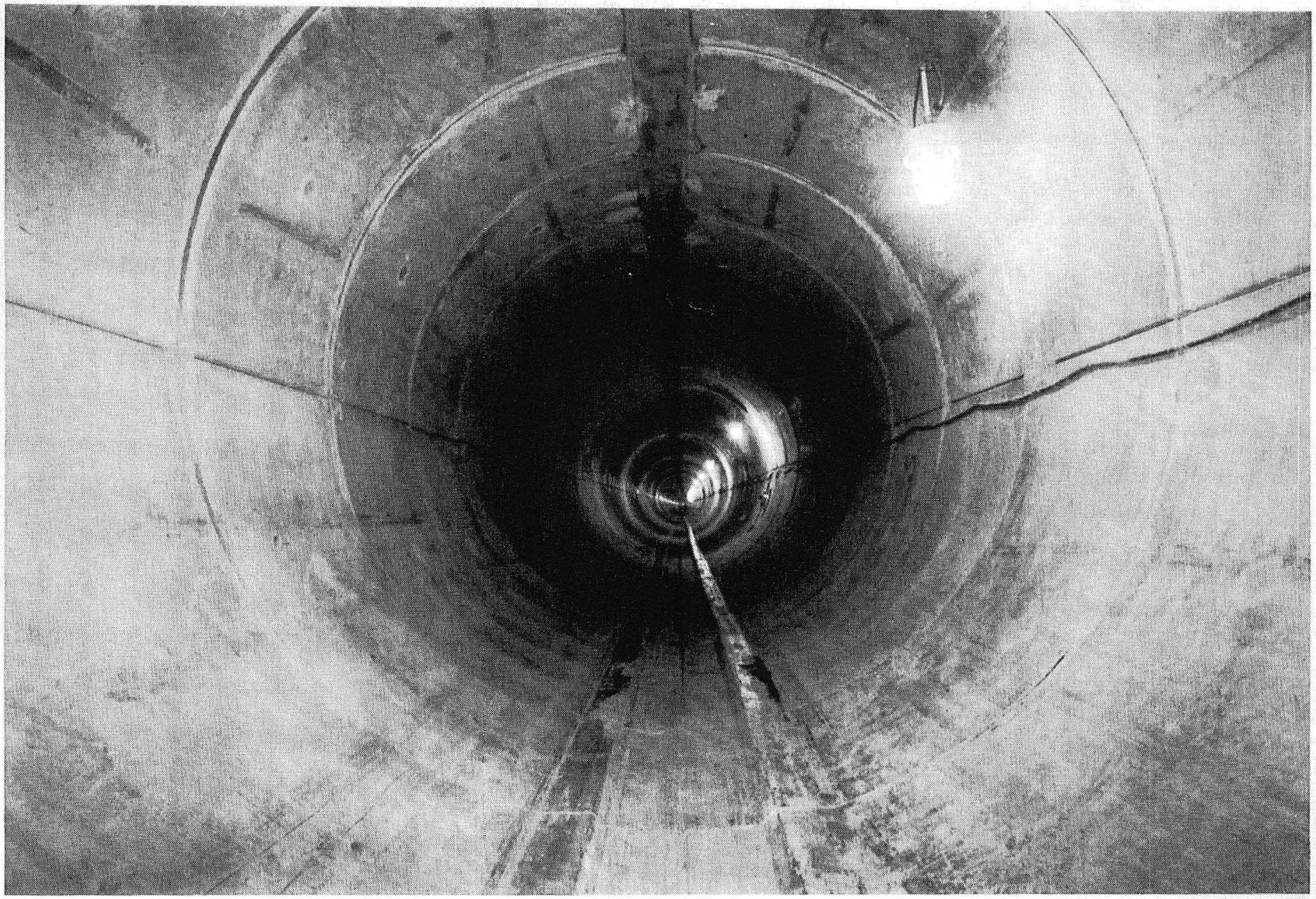
MDS = Magnet Delivery Shaft
US = Utility Shaft
PS = Personnel Shaft
VS = Ventilation Shaft

NOTES:

* SECANT PILE COLLARS: INSIDE DIAMETER [ID] = ID (Centerline PIER - Centerline PIER) - PIER DIAMETER = 30" (2'-6").

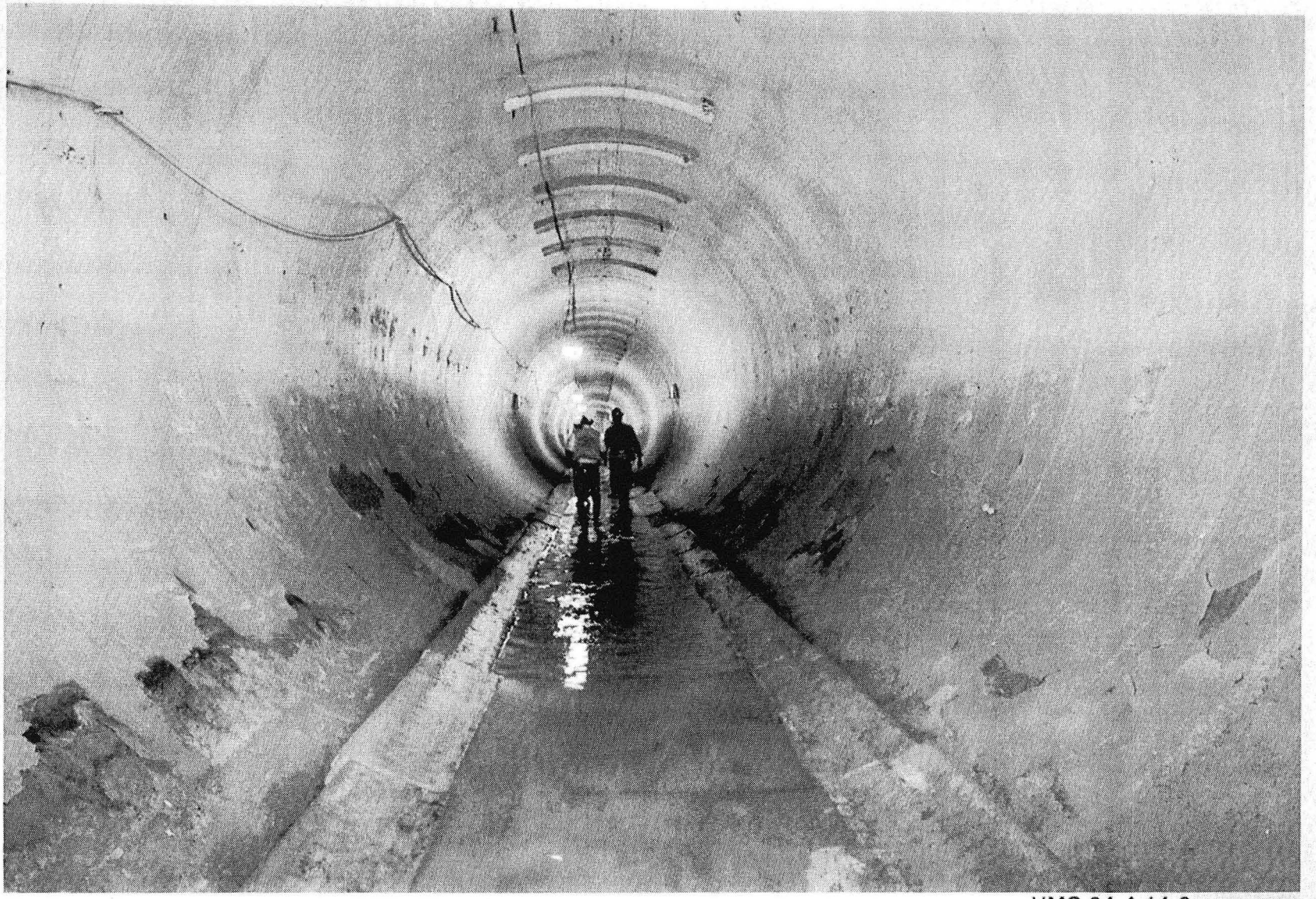
\+ LINER PLATE COLLARS: ID = ID EXCAVATION - 2 X I-BEAM.

Tunnel near shaft N35 in Austin Chalk. Individual is standing by horst block. Bounding fault at left is part of fault zone with approximately 20 m of throw. Calcite veins (c) fill part of fracture apertures. Roof supports retain individual fracture-bounded blocks in fault zone. Photo by David Stevens.



VMS 94-4-17-10
4-6-94
N-15 to N-20 Tunnel

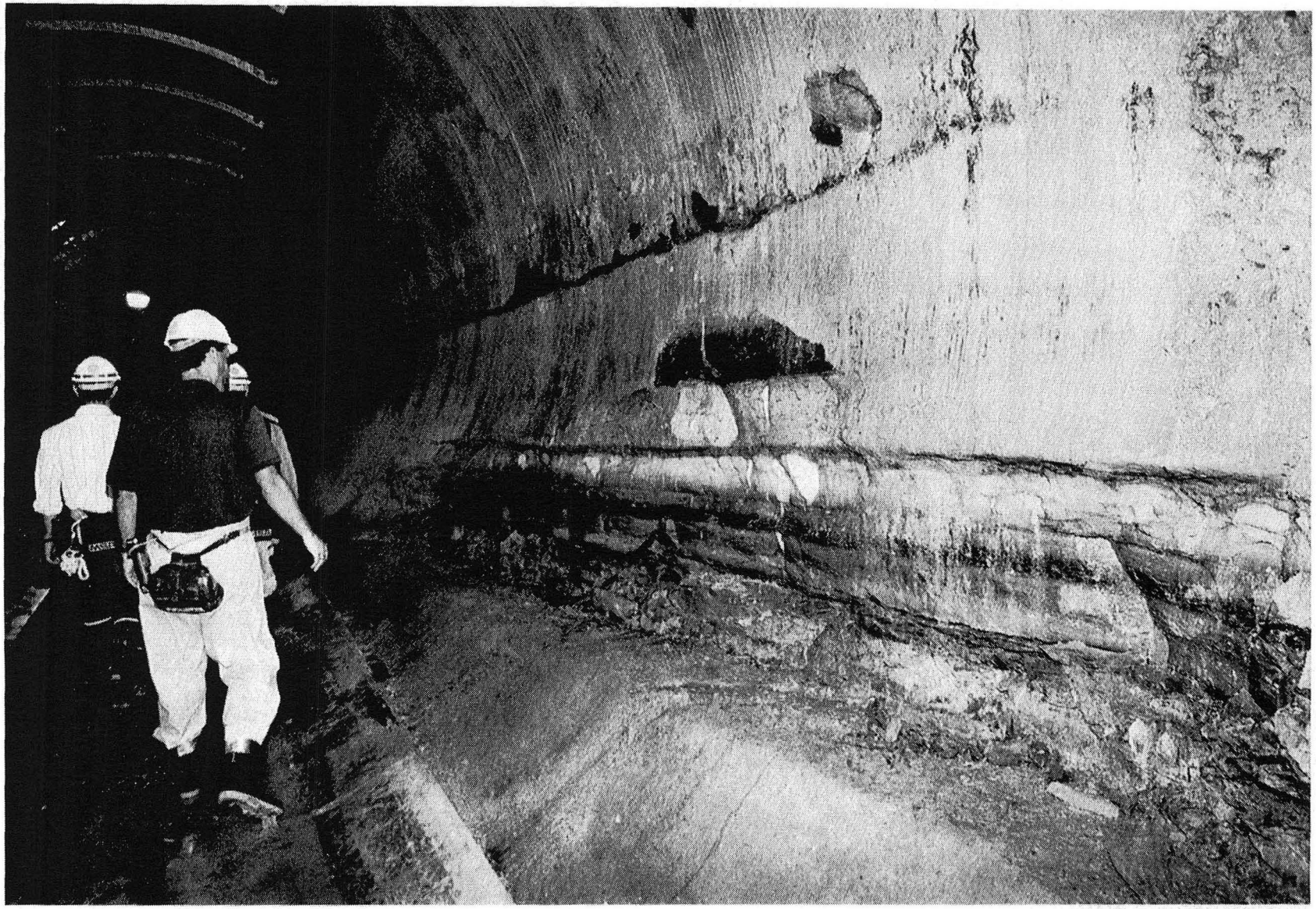
VMS 94-4-25-13
4-19-94
N-20 to N-25 Tunnel



VMS 94-4-14-8
4-5-94
N-25 to N-30 Tunnel

VMS 94-4-14-22
4-5-94
N-25 to N-30 Tunnel

VMS 94-4-39-1
5-24-94
N-30 to N-35 Tunnel



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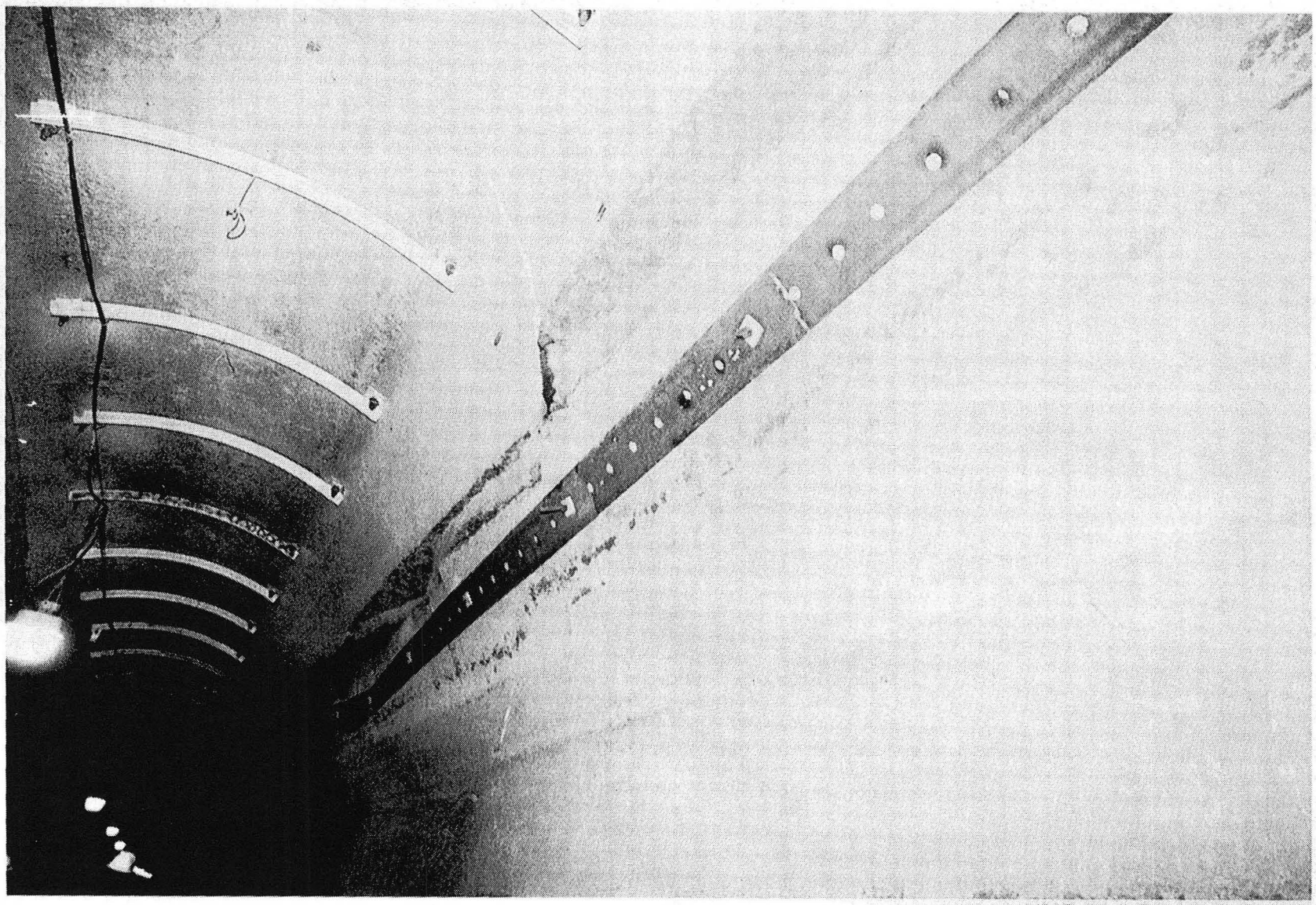

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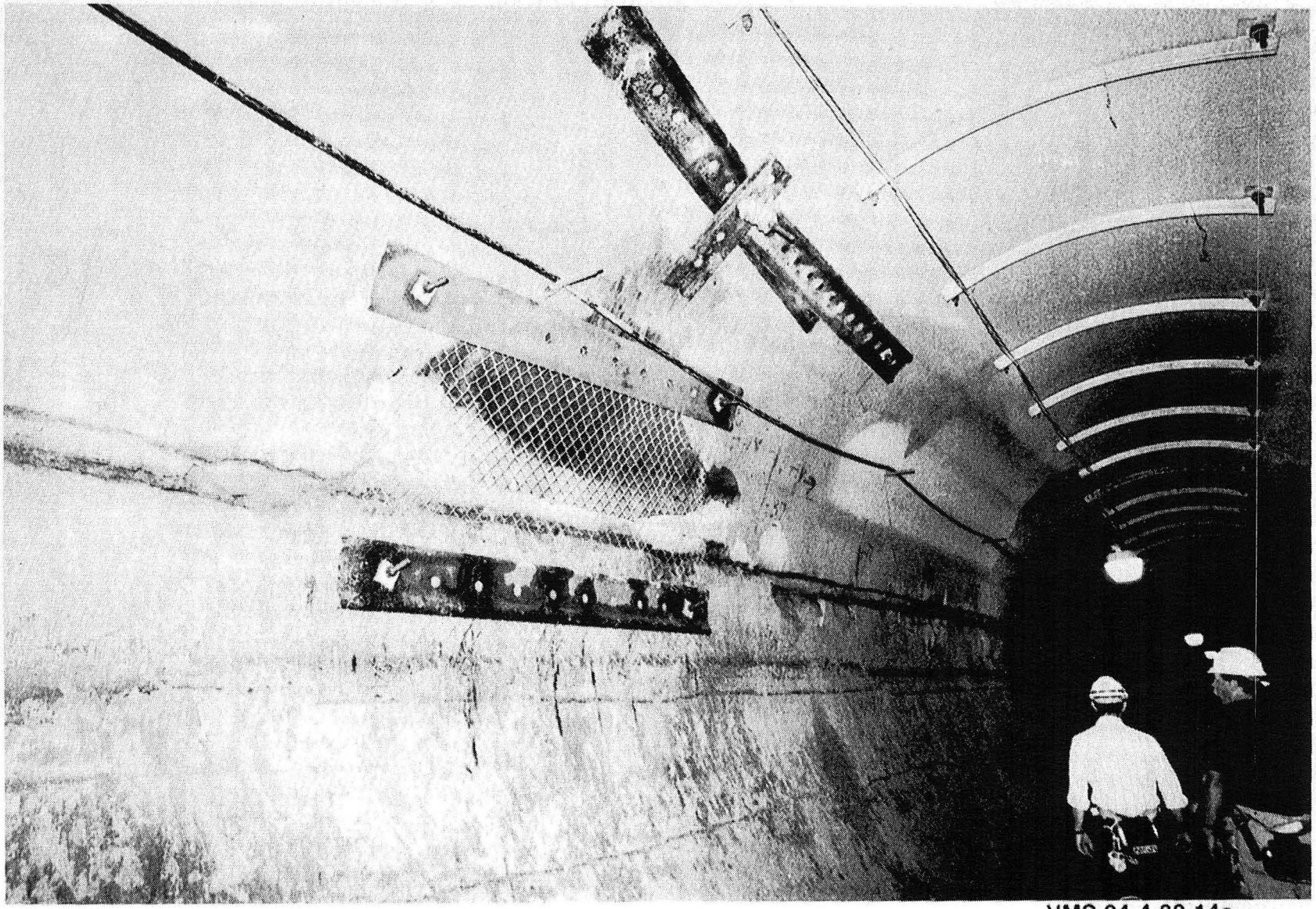

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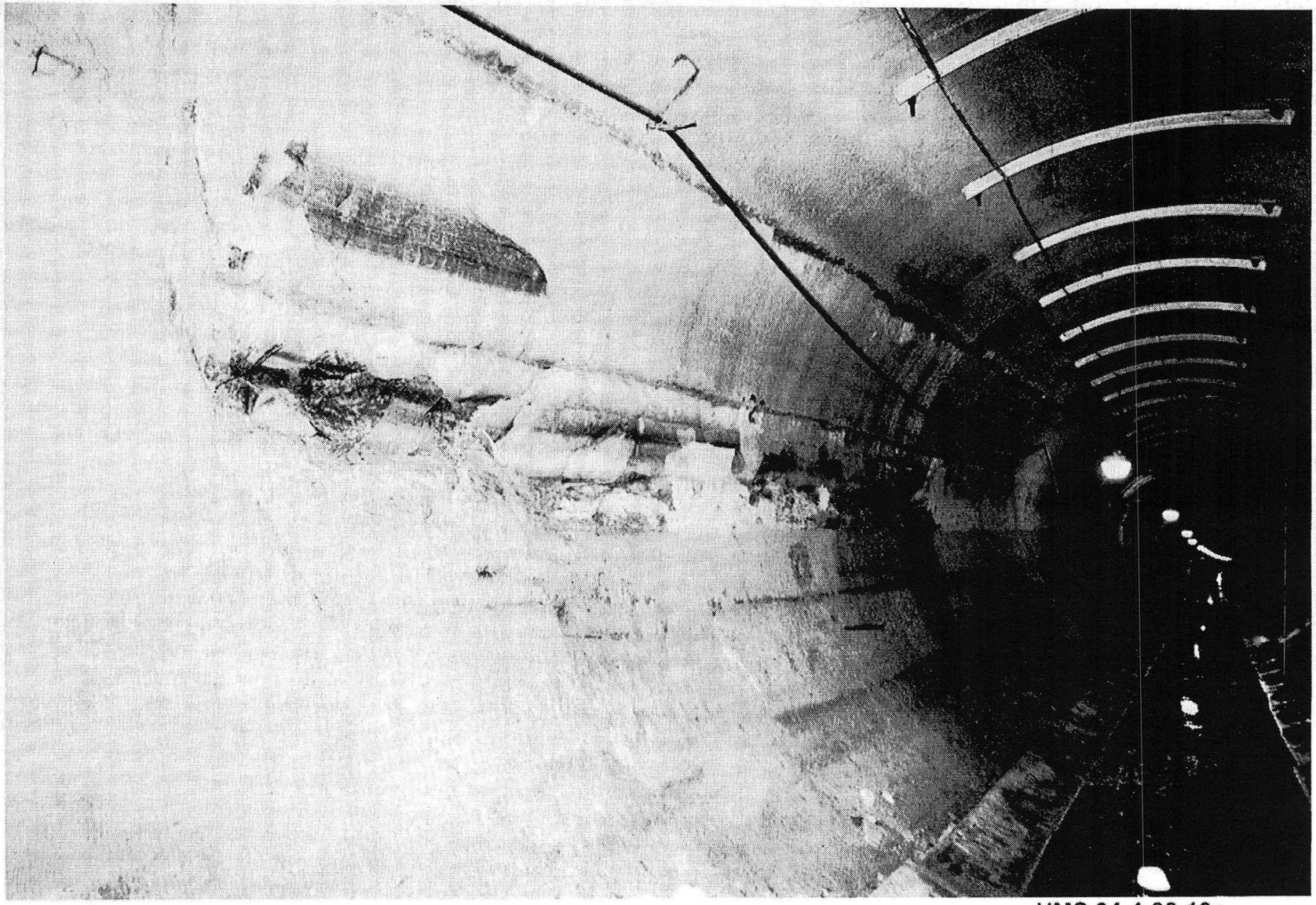

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N-30 to N-35 Tunnel

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5-24-94
N-30 to N-35 Tunnel

VMS 94-4-38-23a
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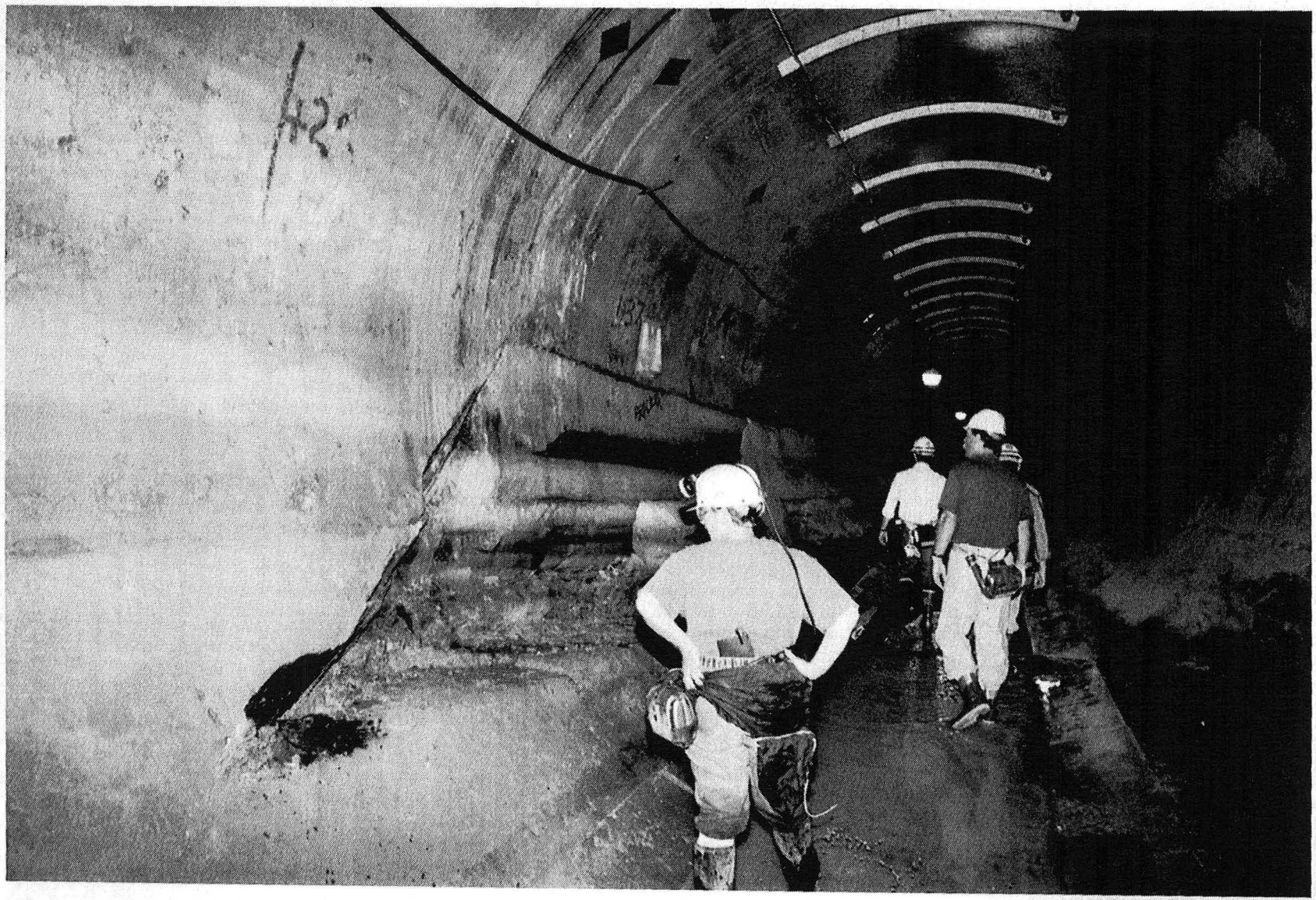
N-30 to N-35 Tunnel



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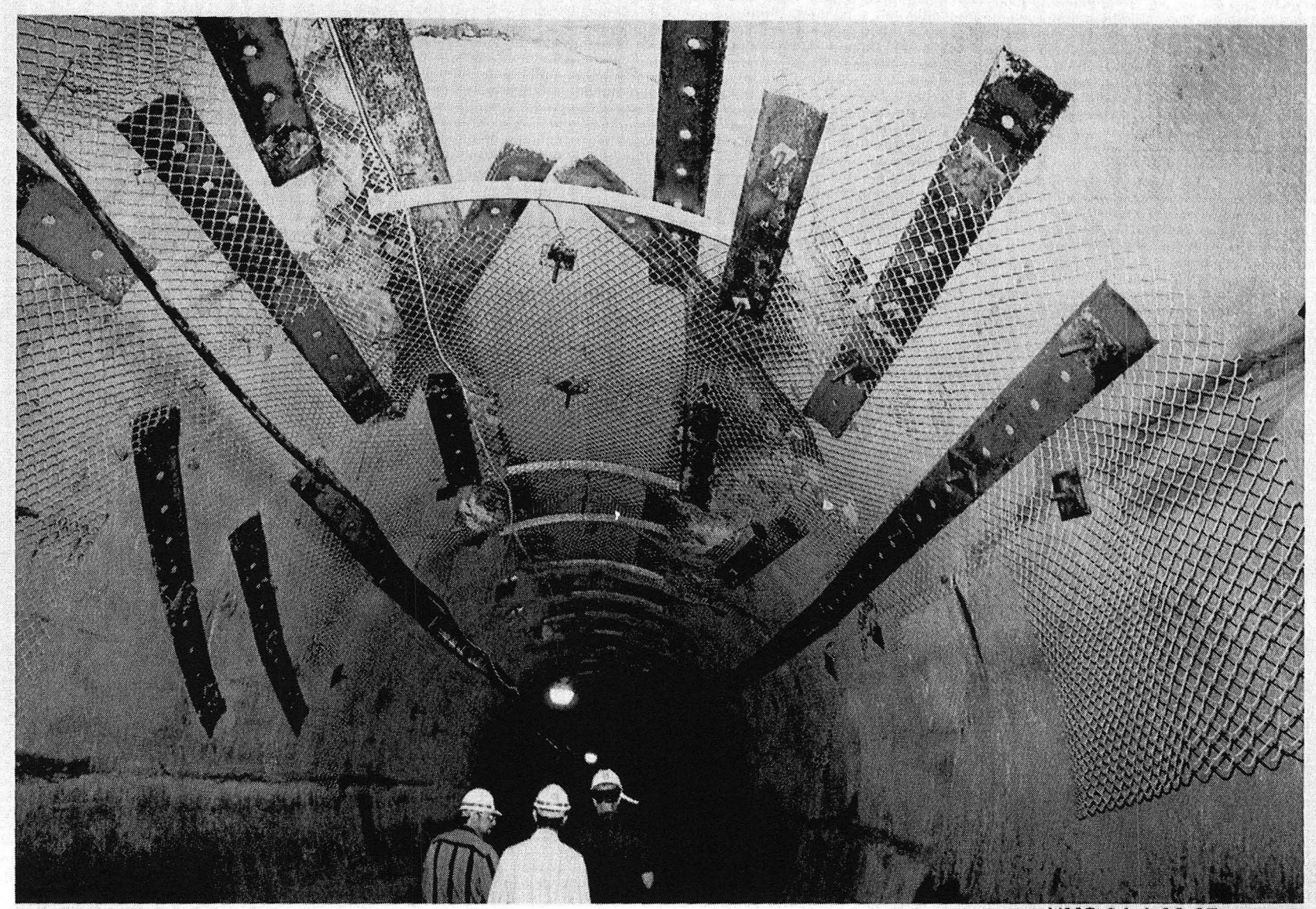
N-30 to N-35 Tunnel



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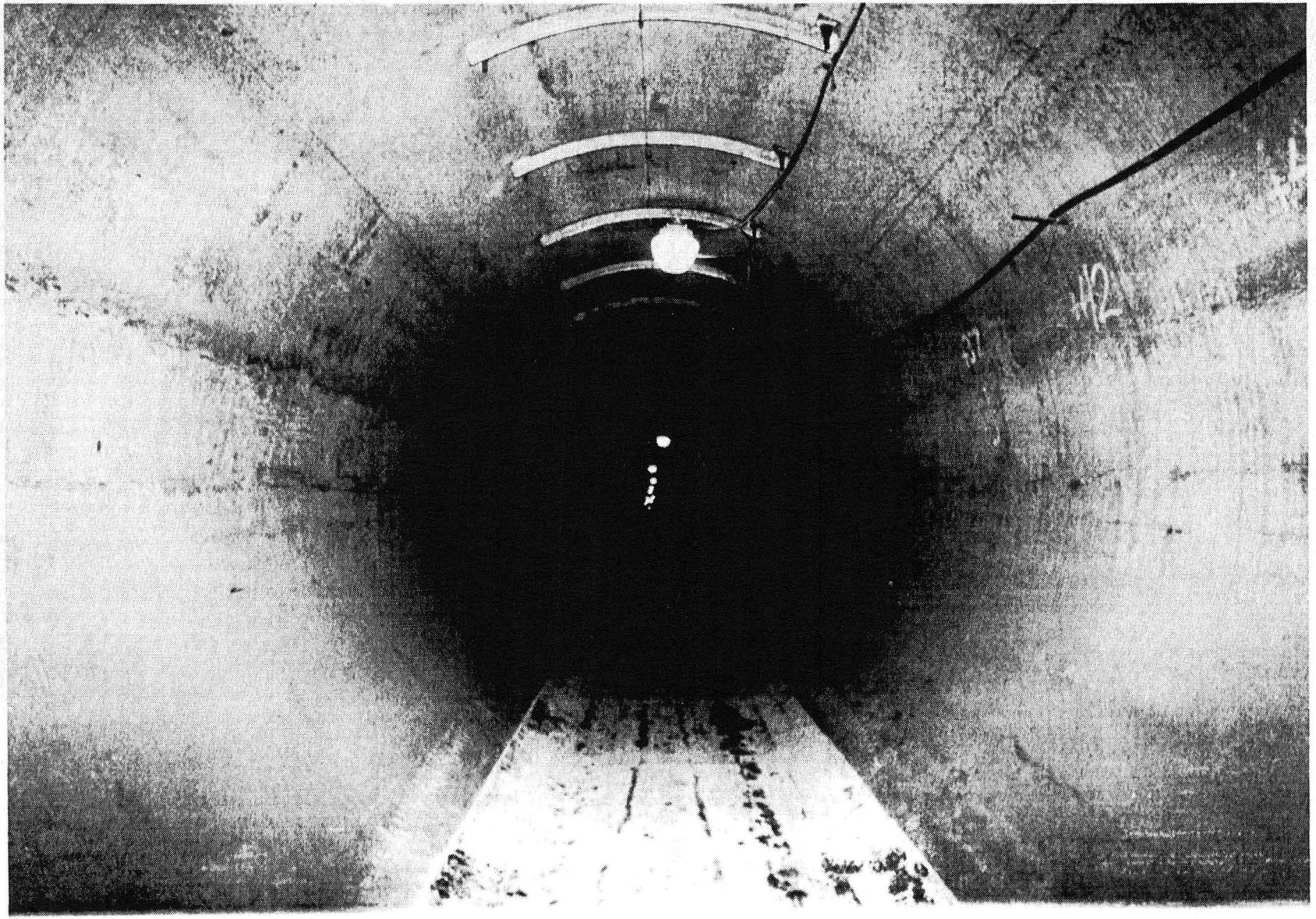
N-30 to N-35 Tunnel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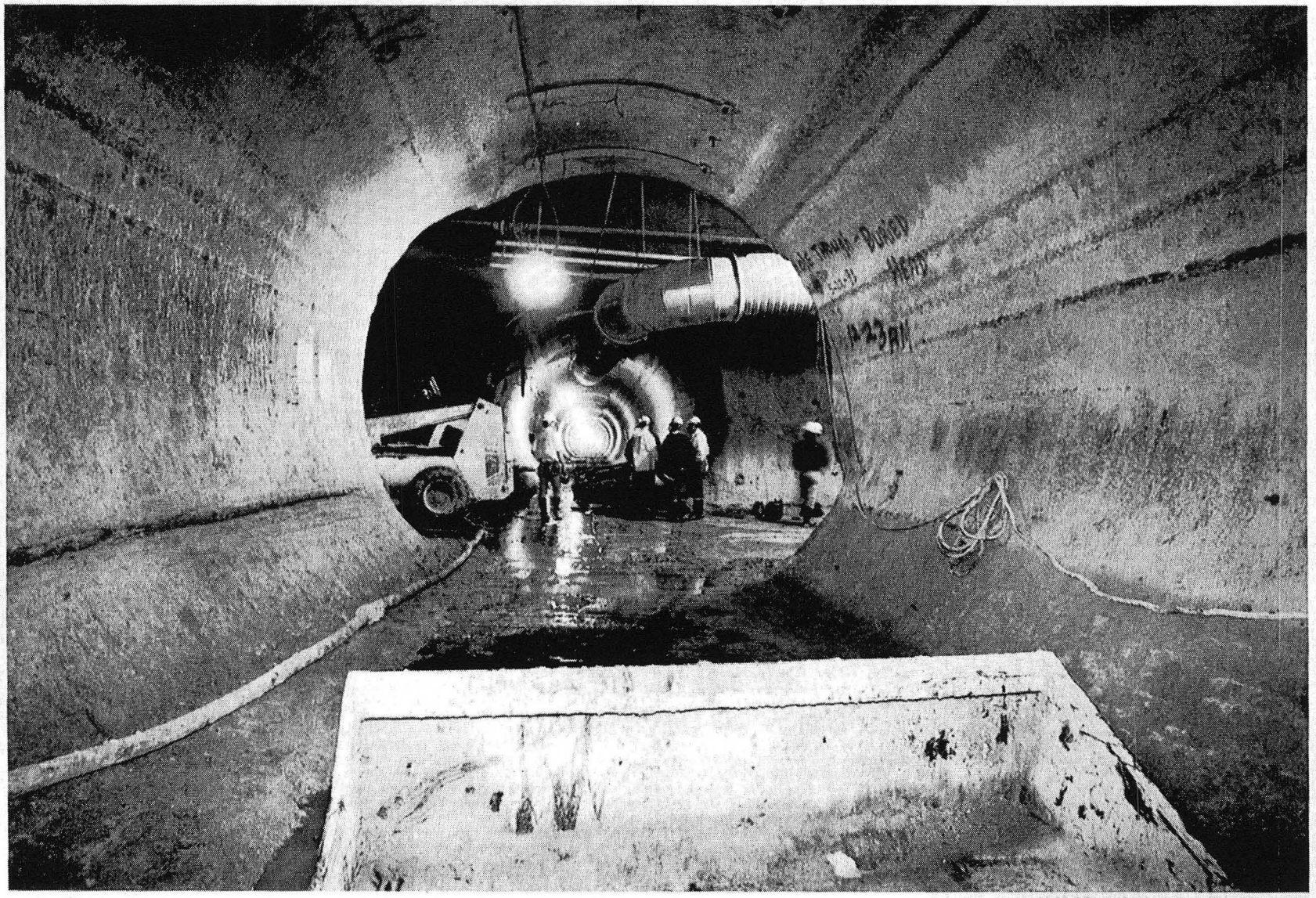
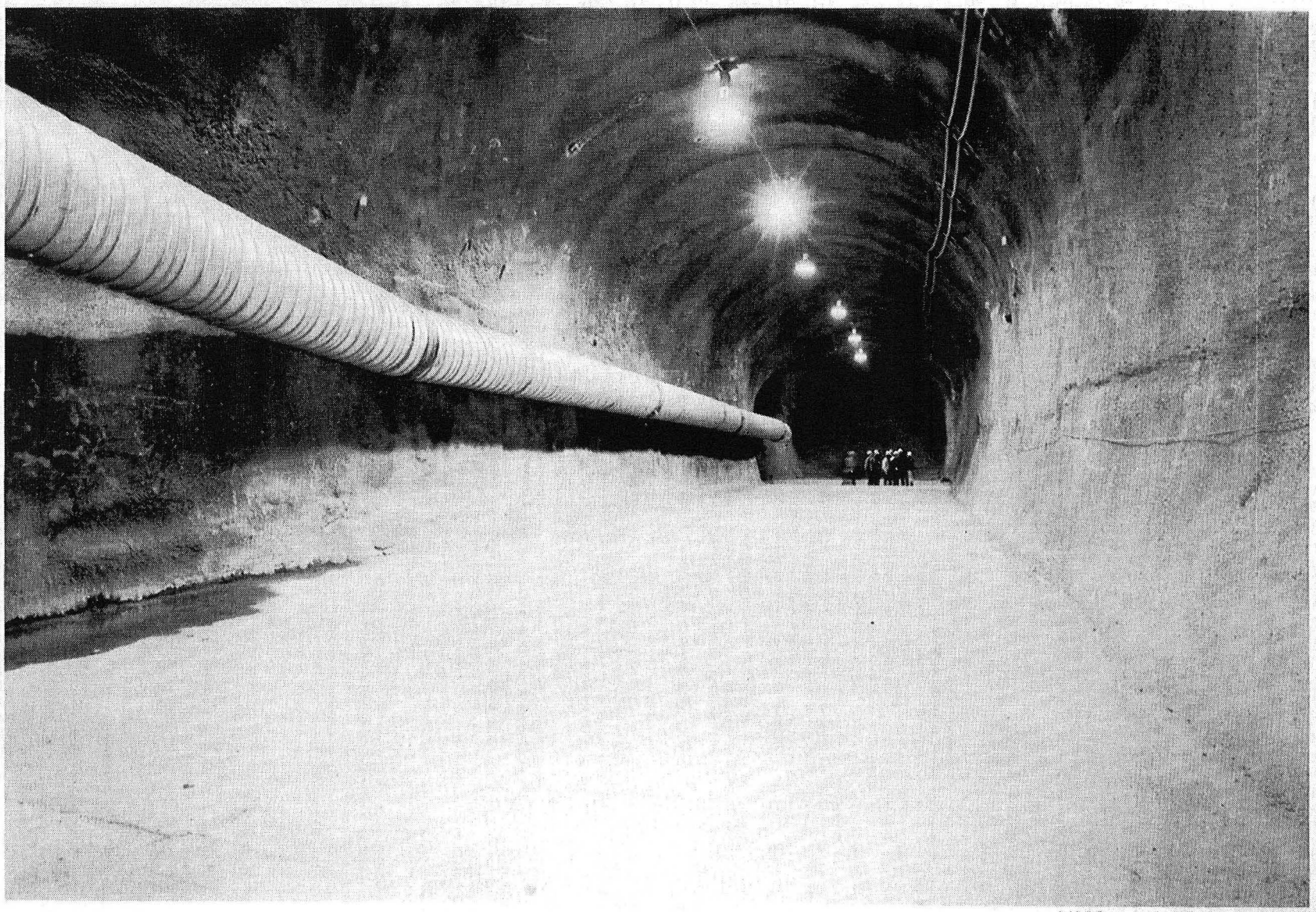
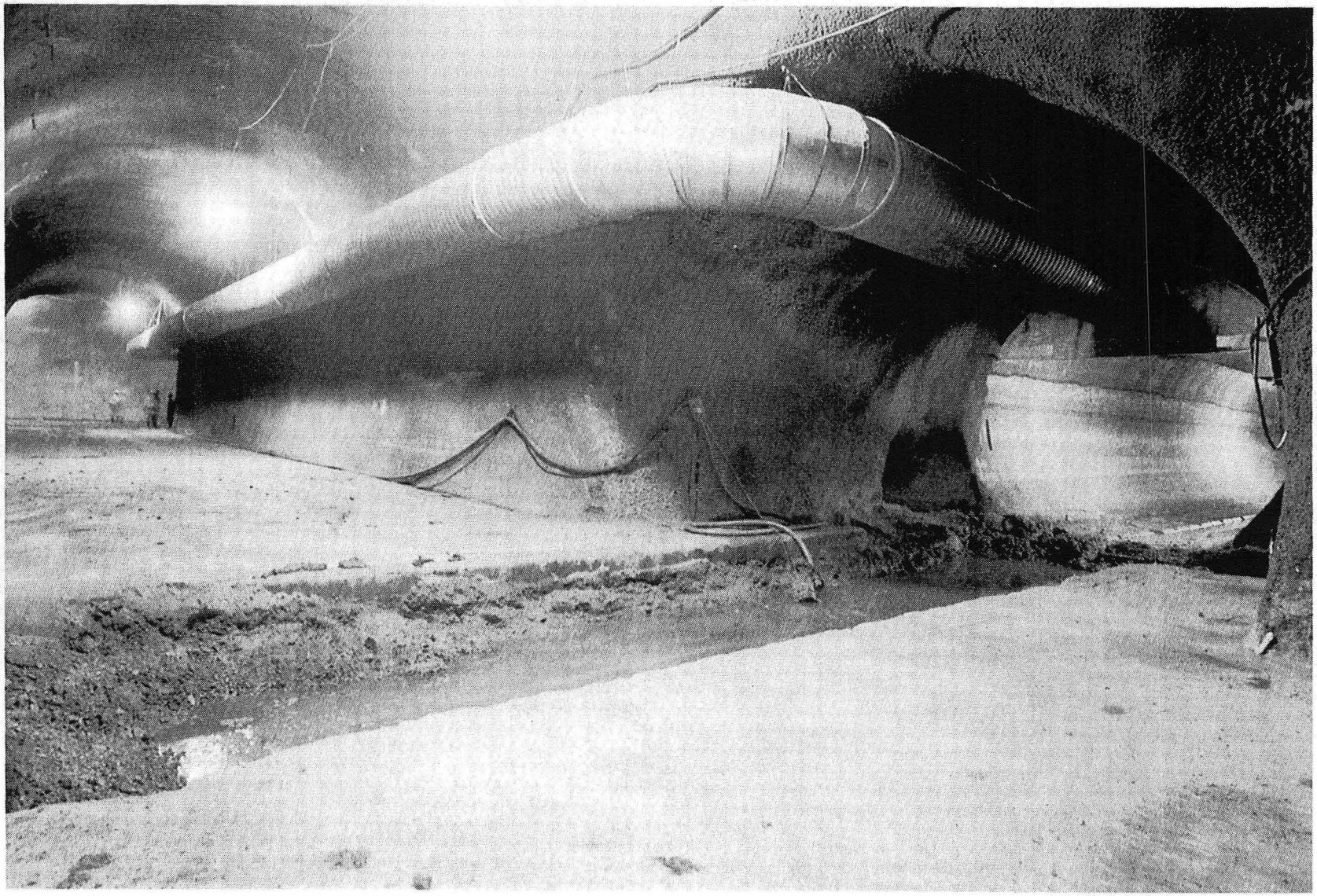


VMS 94-4-15-18
4-5-94
N-25 to N-30 Tunnel



VMS 94-4-17-4
4-6-94
N-15 to N-20 Tunnel



VMS 94-4-14-5
4-5-94
N-25 to N-30 Tunnel

Appendix C

Geotechnical Assets
(Nelson et al, 1994)

CHAPTER THREE

GEOTECHNICAL ASSETS

3.1 EXPLORATION AND INSTRUMENTATION PROGRAM DATA

The data collected from the exploration programs during the Earth Technology Corporation's tenure prior to 1991 are contained in a series of reports, most of which are listed in Appendix 3. These reports include boring logs, early hydrologic studies, fracture studies, insitu stress studies, insitu dynamic modulus studies, geomechanical testing from commercial laboratories, geomechanical characterization from university studies (mostly on EFS and TM), and numerous other studies. Raw data from many of these studies were turned over to the PB/MK team and these are listed as part of the system 038 listed in appendix 2 (item #87, system member # 0000070).

Geotechnical data collected during the PB/MK team's tenure included several deep and shallow boring programs, with reports generated by each professional subcontractor. These reports included recommendations for design (for shallow boring programs), boring logs, results of packer tests, and results of laboratory testing. In addition, a synthesis of this information was normally included in contract documents in the form of GDSR's and GDR's. Results of special studies such as drained and undrained triaxial testing on EFS and TM by UT, pressuremeter testing, hydraulic fracturing, tieback pullout tests in TM, and instrumentation of the Exploratory and the N15 Magnet Delivery Shafts were also subcontracted by the PB/MK team. Copies of most of these reports have been collected and are listed in appendix 3. Many, if not all, also probably reside in the SSC laboratories document control warehouse and may be parts of documents listed in Appendix 5.

The PB/MK team personnel were also responsible for the continuation of data collection at the Exploratory Shaft and N15 Magnet Delivery Shaft. In addition, PB/MK personnel

installed and monitored instrumentation in the Cryogenic Chamber area, the N20 adit, the N30 to N35 tunnel, and execution of field resistivity studies. Instrumentation installed at other locations (N55 Magnet Delivery Shaft, S30 Shaft, and the S40 Magnet Delivery Shaft) were installed by tunneling contractor's geotechnical instrumentation specialist. The information collected by contractor's instrumentation specialists was submitted to PB/MK. The data from these studies were not a part of any formal report; thus, they probably reside only in PB/MK's files listed in appendix 4 (the exception being the Exploratory Shaft which is included in this report).

3.2 FIELD INSTRUMENTATION PROGRAMS

This section describes the underground facilities monitored with geotechnical instrumentation. The instrumentation layout and specifications were designed by PB/MK and their in-house instrumentation specialist (J. Dunnicliff). In general, the instrumentation included some of the following: piezometers, multiple point borehole extensometers (MPBX's), inclinometers, heave gage casing, and tape convergence points.

Instrumentation was installed prior to or during (at convenient pre-planned stages) the excavation of the underground opening. Monitoring was usually scheduled to coincide with the excavation sequence advances so that construction related movements could be detected.

The methods of construction of the shafts varied from bored with a modified oil well rig, blasting, or road header methods. Adits and startup tunnels were mined with road headers, blasted, hand mined with spaders and splitters, and mechanically removed with pneumatic picks on mining equipment. The support methods included liner plate and tangent pile shaft collars; rock bolts, wire mesh, and shotcrete lining in shafts; rock bolts, spiling, lattice girders and shotcrete in adits (in EFS), or in some cases only rock bolts (in AC).

These underground facilities represent a fairly wide variety of shaft and adit shapes and sizes, residing in rocks with strengths ranging over one order of magnitude. At the depths encountered at the SSC project, undrained yielding of the EFS was expected. In the vicinity of a

circular opening, the EFS might be expected yield, resulting in a decrease in the mean total stress under short term conditions. As a result, the EFS adjacent to the shaft wall would experience long term swelling, being a function of its consolidation properties after yielding, and may induce a long term buildup of the rock pressures acting on the lining system. The TM (30% stronger than the EFS) was encountered at shallower depths than the EFS and was not expected to yield under short term (undrained) conditions.

The AC contains thin argillaceous beds, some with strengths as low as that of the EFS and TM, and could be expected to yield locally in those zones. In general, the AC was not expected to yield under short term conditions (excluding the bentonite seams or in the vicinity of pre-existing fracture or fault zones). The water table is within 10 ft of the ground surface and, as a result, the rocks are essentially saturated. Major inflows of water were not expected, or encountered, except in locations intersecting major open fault or fracture zones (decreasing from 100 gpm initially to negligible rates after grouting).

The instrumented locations afford a unique oportunity to observe construction related and long term responses of a variety of underground openings. Unfortunately, these sites have not been monitored for over one year and no plan currently exists to do so. Continuation of the monitoring program would require (1) some familiarity with the existing equipement, previously collected data, locations of instrumentation, and (2) a significant source of funding. Reinitiating the monitoring program would require using the the same readout units used to initially monitor the sites; otherwise, new initial readings would have to be established.

3.2.1 Exploratory Shaft

Table 3.1 Shaft Information

Excavation Description	Excavation Depth	Excavation Size
Circular Shaft	270 ft	16.5 ft dia. to 195 ft depth 10 ft dia. to 270 ft depth

Table 3.2 Geology at the Site

Depth Range, ft	Material
0 to 215	Austin Chalk (AC)
> 215 ft	Eagle Ford Shale (EFS)

Table 3.3 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Vibrating Wire (VW) Piezometers	Yes	VW Readout Box and Automatic Data Acquisition System (ADAS)	Tips lie at various depths within the EFS and AC
Pneumatic Piezometers	Yes	Pneumatic Readout Unit Only	Tips lie at various depths within the EFS and AC
Convergence Anchors	No	Tape Extensometer	Within the Shaft and Adit (at the EFS/AC interface) in both AC and EFS
Multiple Point Borehole Extensometer (MPBX)	Yes	Linear Potentiometer Readout Box and Automatic Data Acquisition System (ADAS)	Within the Shaft and Adit in both AC and EFS. One Vertical MPBX from the surface in both AC and EFS.
Inclinometer Casings	No	Inclinometer Probe Only.	To a depth of 305 ft, mostly within the EFS
Heave Gage Casing	No	Heave Gage Probe Only.	To a depth of 305 ft, mostly within the EFS
Vibrating Wire Strain Gages on Instrumented Steel Ring	Yes	VW Readout Box and ADAS	Circumferentially located on 10 ft high steel ring grouted in EFS
Extensometer Rods	Yes	Linear Potentiometer Readout Box and ADAS	At the Base of the Shaft

3.2.2 N15 Magnet Delivery Shaft

Table 3.4 Shaft Information

Excavation Description	Excavation Depth	Excavation Size
Oval Shaft with two starter tunnel adits	240 ft	60-75 ft long axis 30-45 ft short axis

Table 3.5 Geology at the Site

Depth Range, ft	Material
0 to 199 ft	Austin Chalk
> 199 ft	Eagle Ford Shale

Table 3.6 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Vibrating Wire (VW) Piezometers	Yes (some are not)	VW Readout Box Only	Tips lie at various depths within the EFS and AC
Pneumatic Piezometers	Yes (some are not)	Pneumatic Readout Unit Only	Tips lie at various depths within the EFS and AC
Convergence Anchors	No	Tape Extensometer	Within the Shaft in both AC and EFS and Adit (completely in EFS)
Multiple Point Borehole Extensometer (MPBX)	Yes	Linear Potentiometer Readout Box Only	Within the Shaft in both AC and EFS.
Inclinometer Casings	Yes	Inclinometer Probe Only.	To a depth of 355 ft, within the AC and EFS
Heave Gage Casing	No (at base of shaft, but casing was sheared off)	Heave Gage Probe Only.	From 240 ft to 355 ft, within the EFS

3.2.3 N15 Cryogenic Chamber

Table 3.7 Chamber Information

Excavation Description	Excavation Depth	Excavation Size
Main Adit with smaller tunnels forming a central pillar of EFS	240 ft apprx. (All within EFS)	35 ft wide by 25 ft high main chamber. 17 ft diameter tunnel. 45 ft square central pillar.

Table 3.8 Geology at the Site

Depth Range, ft	Material
0 to 199 ft	Austin Chalk
> 199 ft	Eagle Ford Shale

Table 3.9 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Convergence Anchors	No	Tape Extensometer	Within the Chamber in EFS
Multiple Point Borehole Extensometer (MPBX)	No	Linear Potentiometer Readout Box Only	Within the Chamber in EFS.

3.2.4 N20 Adit

Table 3.10 Adit Information

Excavation Description	Excavation Depth	Excavation Size
Main Adit at the base of the shaft, leading to the TBM startup adit/tunnel	175 ft apprx. (All within EFS)	Main adit is appr. 30 ft wide and 160 ft long. Start up adits for the tunnel are appr. 22 ft and 30 wide, respectively.

Table 3.11 Geology at the Site

Depth Range, ft	Material
>175 ft	EFS

Table 3.12 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Convergence Anchors	No	Tape Extensometer	Within the Chamber in EFS

3.2.5 N30 to N35 Tunnel

Table 3.13 Geology at the Site

Depth Range, ft	Material
varies	AC

Table 3.14 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Convergence Anchors	No	Tape Extensometer	Within the Tunnel in AC

3.2.6 N55 Magnet Delivery Shaft

Table 3.15 Shaft Information

Excavation Description	Excavation Depth	Excavation Size
Oval Shaft with two starter tunnel adits	195 ft proposed 66 ft completed	70 ft long axis 40 ft short axis

Table 3.16 Geology at the Site

Depth Range, ft	Material
0-61	Clay and Weathered Taylor Marl
61-156	Fresh Taylor Marl
> 156	Austin Chalk

Table 3.17 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Convergence Anchors	No	Tape Extensometer	Within the Shaft in TM
Multiple Point Borehole Extensometer (MPBX)	Possibly	Linear Potentiometer Readout Box Only	Within the Shaft in TM.
Inclinometer Casings	Yes	Inclinometer Probe Only.	To a depth of 205 ft

Note: Only one level of convergence anchors and one MPBX were installed before termination of construction, when the shaft had reached a depth of 66 ft.

3.2.7 S30 Shaft

Table 3.18

Excavation Description	Excavation Depth	Excavation Size
Circular Shaft	209 ft	18 ft diameter

Table 3.19 Geology at the Site

Depth Range, ft	Material
0-7	Clay
7-56	Weathered Taylor Marl
56-209	Taylor Marl

Table 3.20 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Vibrating Wire (VW) Piezometers	Yes	VW Readout Box Only	Tips lie at various depths within the TM
Convergence Anchors	No	Tape Extensometer	Within the Shaft in TM
Inclinometer Casings	Yes	Inclinometer Probe Only.	To a depth of 260 ft
Heave Gage Casing	Yes	Heave Gage Probe Only.	To a depth of 260 ft

3.2.8 S40 Magnet Delivery Shaft

Table 3.21 Shaft Information

Excavation Description	Excavation Depth	Excavation Size
Oval Shaft with two starter tunnel adits	145 ft	70 ft long axis 40 ft short axis

Table 3.22 Geology at the Site

Depth Range, ft	Material
0-10	Clay
10-43	Weathered Taylor Marl
43-115	Taylor Marl
> 115	Austin Chalk

Table 3.23 Details of the Instrumentation at the Site

Device	Readable from Surface	Readout Unit	Description
Convergence Anchors	No	Tape Extensometer	Within the Shaft in TM
Multiple Point Borehole Extensometer (MPBX)	Possibly	Linear Potentiometer Readout Box Only	Within the Shaft in TM.
Inclinometer Casings	Yes	Inclinometer Probe Only.	To a depth of 155 ft

3.3 GEOTECHNICAL ASSETS - EQUIPMENT, INSTRUMENTATION, AND DATA REDUCTION / DATA INTERPRETATION SOFTWARE AND HARDWARE

The geotechnical instrumentation used to monitor the underground construction activities were procured by either the PB/MK team or by the contractor, meeting specifications written by PB/MK & their consultant. The instrumentation was permanently installed according to the specifications. The readout equipment is now being held in the SSC Central Facilities warehouse in a area assigned to the System # 038. This equipment included, but is not limited to, the following instrumentation readout units: (1) inclinometer readouts, probes & cables, (2) heave gage readouts, probes, rods & cables, & calibration casings, (3) vibrating wire strain gage readouts, (4) linear potentiometer readouts, (5) pneumatic piezometer readouts, (6) tape extensometer units and calibration frames, (7) hand micrometers, and (8) a portable clinometer and portable extensometer.

A variety of other miscellaneous hardware and left over components are also held within the system from the instrumentation program and these include: (1) wax pots or stoves, (2) MPBX assemblies, (3) inclinometer casing, (4) terminal boxes, electrical panels and a data acquisition system, (5) a field packer assembly, (6) miscellaneous tools, (7) gas generators, (8) a water pump, (9) cameras and tripods, and (10) load cells and LVDT's for laboratory rock testing.

Data reduction and analysis software and hardware are also included in the archived system 038. Namely, Mac or IBM compatible computers and a lazer printer with software for word processing, spreadsheets, statistical analysis, drawing, and data reduction programs. An IBM RS 6000 is also stored in the system and is useful for running advanced geotechnical analysis software such as ABAQUS (ABAQUS's software license is renewed on an annual basis and was not purchased). Other specialty software archived includes gINT (boring and geotechnical investigation software), Flac (finite difference mechanical analysis), and UTEXAS 3 (slope stability software). This software was purchased for the project; however, the licensing was originally issued to the PB/MK team and the SSC laboratory was investigating the ramifications of transferring the software. The items listed in bold are those that would be most useful for continuation of monitoring and interpretation of the Exploratory and N15 Magnet Delivery Shafts. Monitoring of some of the other sites would require use of other readout units not labelled in bold.

Appendix D

Representative Engineering Properties of Austin Chalk and Eagle Ford Shale (Elioff 1992)

Representative Engineering Properties

Parameter	Units	Fresh Austin Chalk Range (Mean, Std. Dev.)	Marker Bed (Bentonite) Range (Mean, Std. Dev.)	Eagle Ford Shale Range (Mean, Std. Dev.)
Unconfined Compressive Strength, qu	psi	300-4000 (2070,760)	170 (one test)	9-840 (280,140)
Undrained Tangent Young's modulus, E_{50}	psi x 10^3	13-2300 (420,250)	3 (two tests)	3-295 (80,40)
Drained Secant Young's Modulus, E_{50}	psi x 10^3	n/a	n/a	7-32
Drained Tangent Young's Modulus, E	psi x 10^3	n/a	n/a	17-130
Dry Density	pcf	97-144 (127,7)	70-110 (87,9)	101-139 (117,4)
Specific Gravity	-	2.62-2.71 (2.67,0.02)	2.32-2.74 (2.51, 0.02)	2.57-2.79 (2.72, 0.03)
Water Content	%	7 - 25 (13.3)	17-47 (34,7)	6-23 (16,2)
Degree of Saturation	%	100	100 (one test)	100
Brazil Tensile Strength	psi	50-450 (240,70)	n/a	30-340 (120,95)
RQD(1)	%	50-100 (95,n/a)	n/a	25-100 (95,n/a)
Slake Durability (second cycle)	%	88-98 (96,3)	n/a	0-52 (21-11)
Carbonate Content	%	32-100 (85, n/a)	2-33 (10,7)	1-54 (8,58)
Swell Pressure (2)	psi	n/a	5-58 (18, n/a)	8-115 (36,16)
Free Swell (3)	%	n/a	n/a	1.0-2.6
Liquid Limit	%	n/a	62-211 (116,28)	40-120 (84, 18)

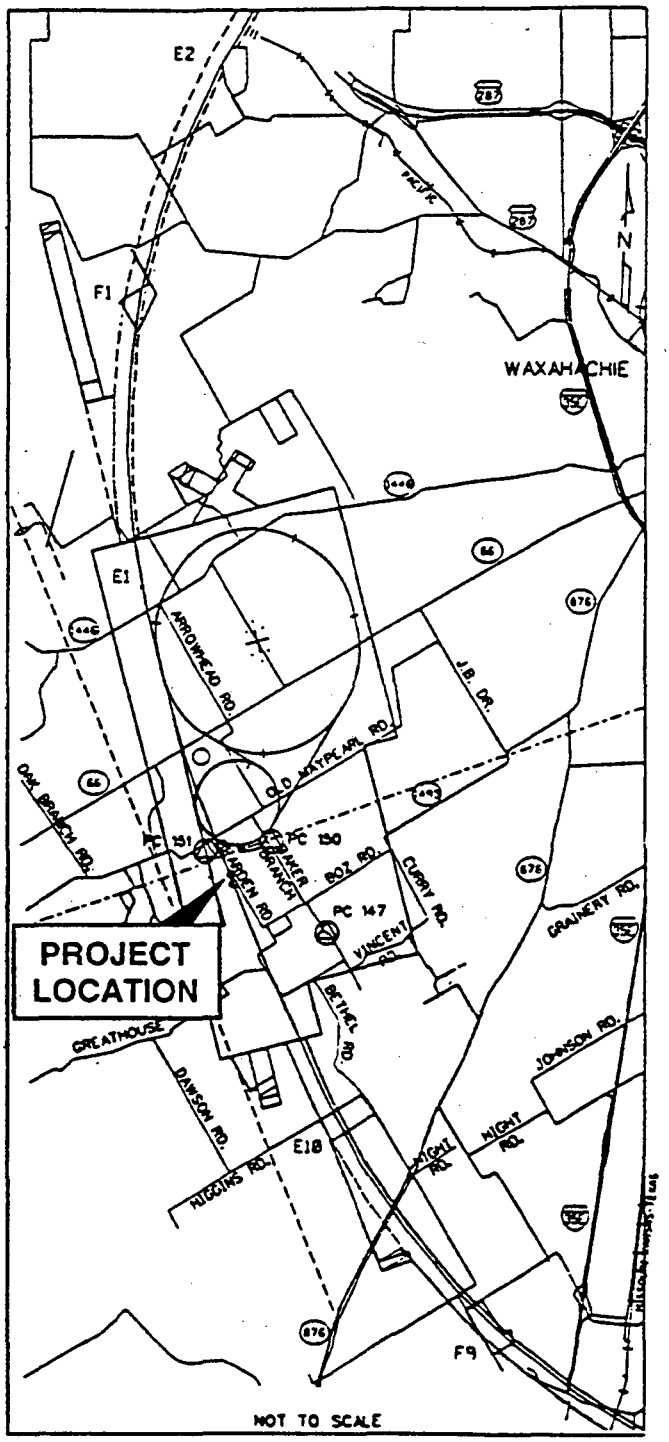
Representative Engineering Properties (Continued)

Parameter	Units	Fresh Austin Chalk Range (Mean, Std. Dev.)	Marker Bed (Bentonite) Range (Mean, Std. Dev.)	Eagle Ford Shale Range (Mean, Std Dev.)
Plasticity Index	%	n/a	35-136 (72,23)	21-82 (54,14)
P Wave Velocity	pfs	5700-9600 (8800, 960)	n/a	5000-7000 (6100,570)
S Wave Velocity	pfs	2200-5100 (3500,700)	n/a	1400-1970 (1670, 190)
Dynamic Young's Modulus	psi x 10^3	420-1900 (1070, 390)	n/a	170-330 (240, 50)
Dynamic Shear Modulus	psi x 10^3	140-760 (390, 160)	n/a	60-110 (80, 20)
Dynamic Poisson's Ratio	-	0.25-0.46 (0.39, 0.07)	n/a	0.44-0.48 (0.46, 0.01)
Recompression Index	-	n/a	0.007-0.29 (n/a, N/a)	0.003-0.05 (n/a, n/a)
Coefficient of Consolidation	ft^2/day	n/a	0.0007-0.06 (n/a, n/a)	0.0001-0.20 (n/a, n/a)
Hydraulic Conductivity (from field tests) [includes' tests at AC/EFS interface]	cm/sec	$3x10^{-8}$ to $3x10^{-5}$ ($5x10^{-7}$, n/a)	-	$1.2x10^{-8}$ to $1.5 x 10^{-5}$ ($2x10^{-7}$, n/a)
Hydraulic Conductivity (from lab tests)	cm/sec	n/a	7.0^{-10} to $1.5 x 10^{-9}$ (one specimen)	$1x10^{-11}$ to $1 x 10^{-9}$ (n/a, n/a)
Estimated Peak Effective Angle of Friction	degrees	38 (limited data)	31 (very limited data)	25 (limited data)
Peak Effective Cohesion (c)	psi	0 (limited data)	5 (limited data)	25 (limited data)
Discontinuity Effective Residual Angle of Friction (phi)	degrees	22-28 (limited data)	33 (very limited data)	5-10 (limited data)

Notes/Key: n/a = not available or not applicable
(1) = Low RQD values in range possibly due to mechanical breakage or poor coring techniques
(2) = Semi-log plot of initial void-ratio versus log of vertical effective stress (swell pressure at virtually no volume change)
(3) = Range at an approximate swell pressure of 1.4 psi

Appendix E

Exploratory Shaft Detail



NOTE

Map taken from Plans prepared by the PB/MK Team for the SSC Exploratory Shaft, dated June 1991.

SSC - Exploratory Shaft
Waxahachie, Texas

GENERAL LOCATION MAP

December 1992 W-5929-01

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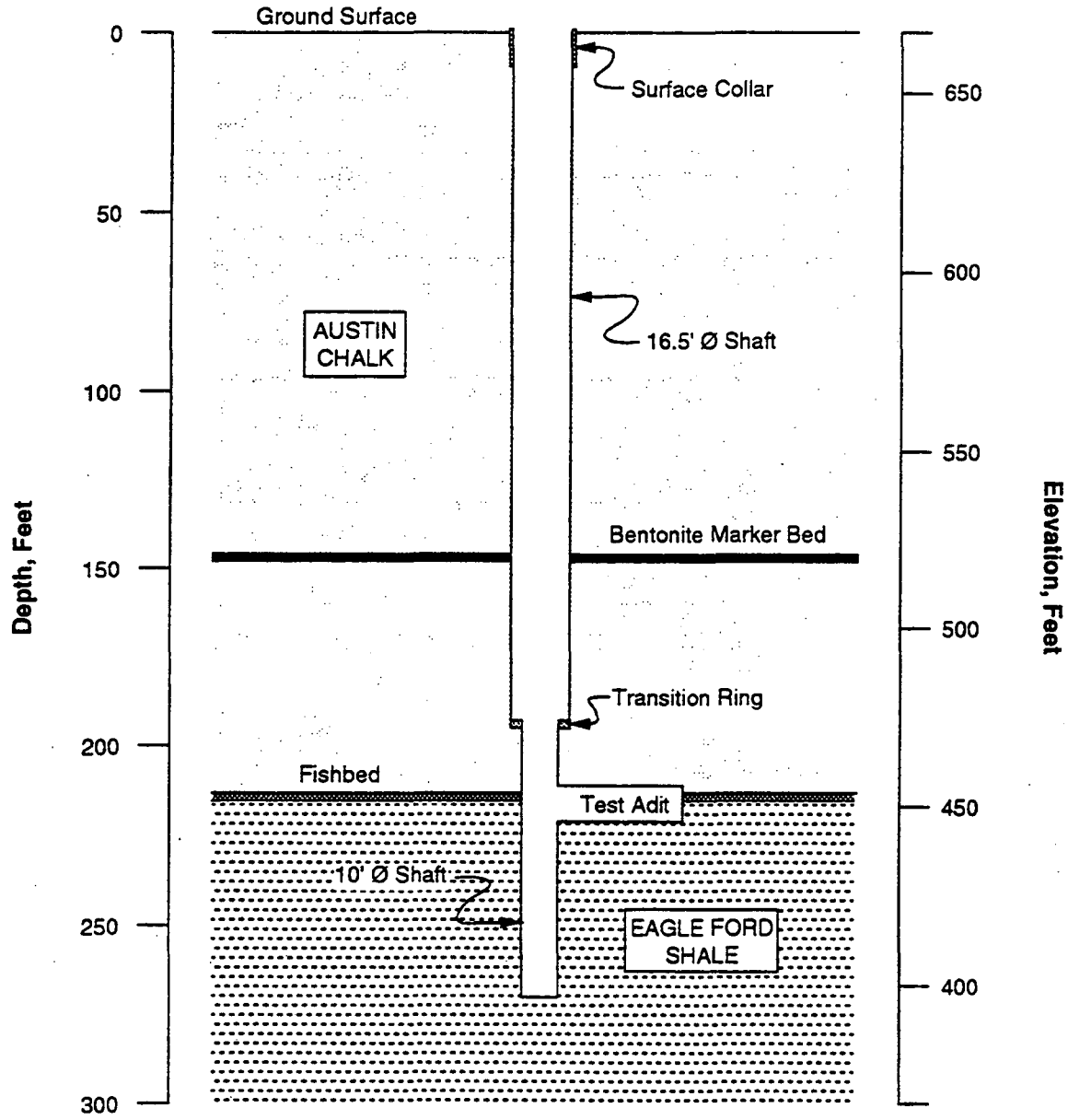
FIG. 1



SSC - Exploratory Shaft
Waxahachie, Texas

SITE GEOLOGY AND SHAFT CONFIGURATION

December 1992 W-5929-01

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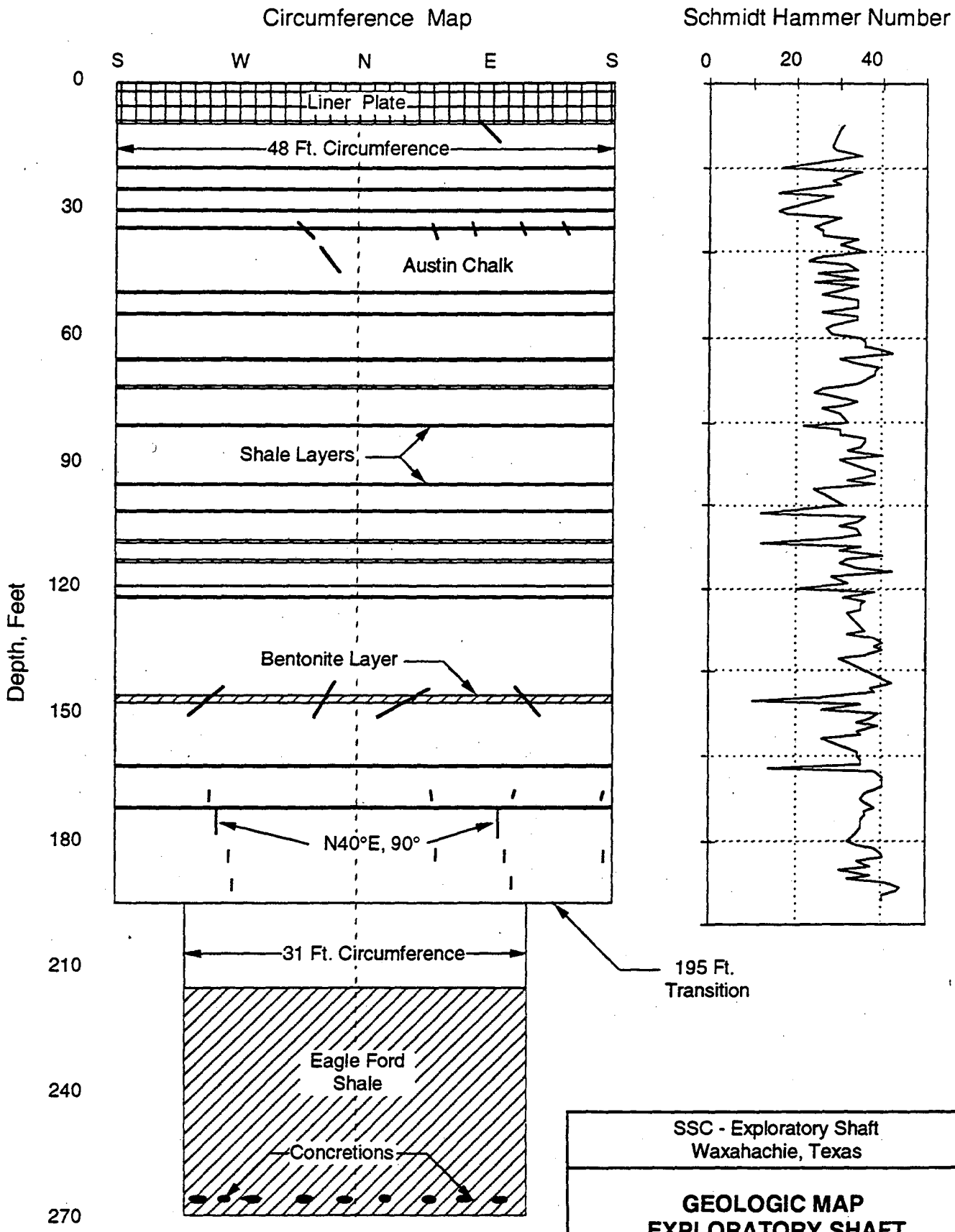
FIG. 2



SSC - Exploratory Shaft
Waxahachie, Texas

GEOLOGIC MAP
EXPLORATORY SHAFT

December 1992 W-5929-01

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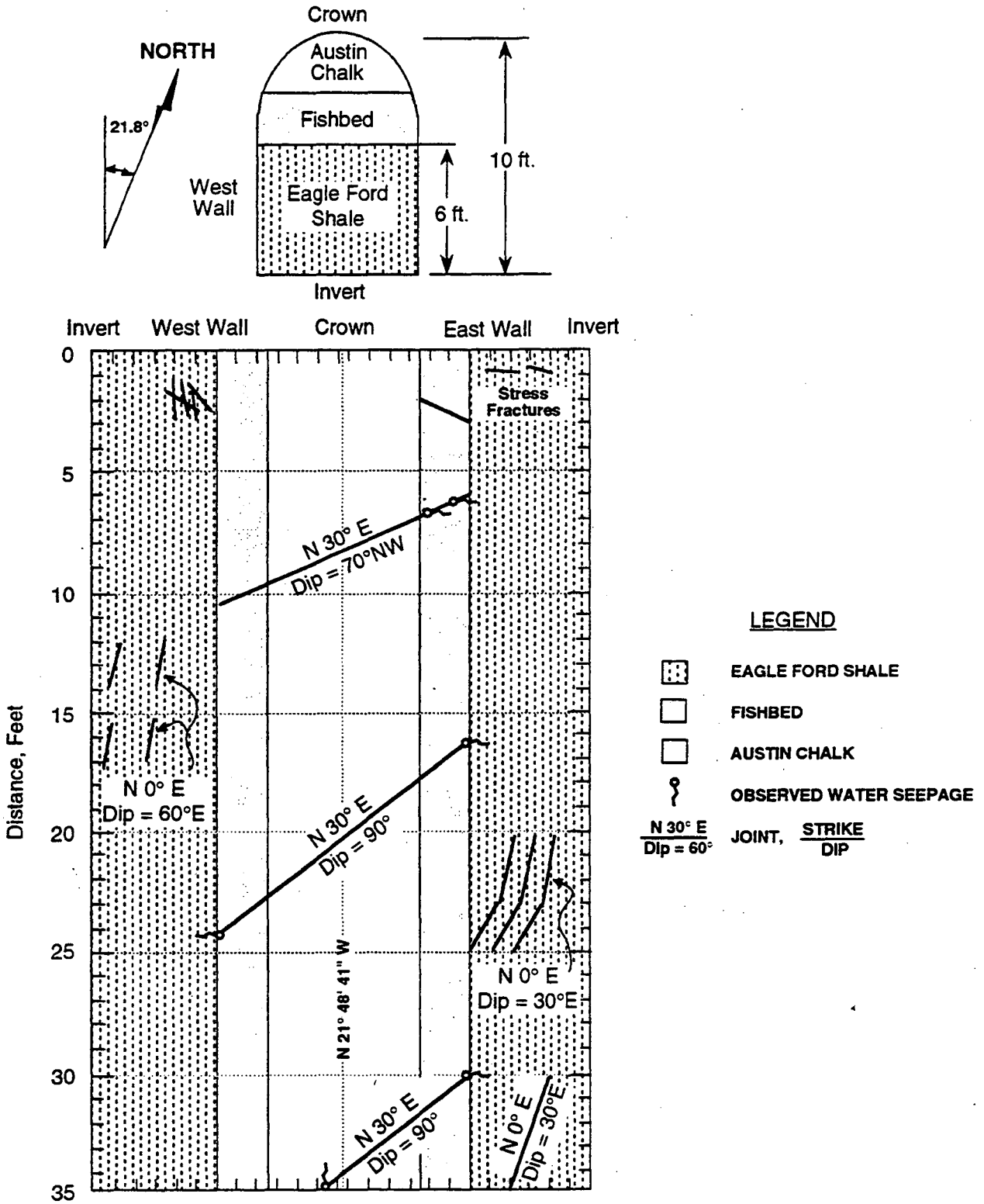
FIG. 3



SSC - Exploratory Shaft
Waxahachie, Texas

GEOLOGIC MAP
EXPLORATORY TEST ADIT

December 1992 W-5929-01

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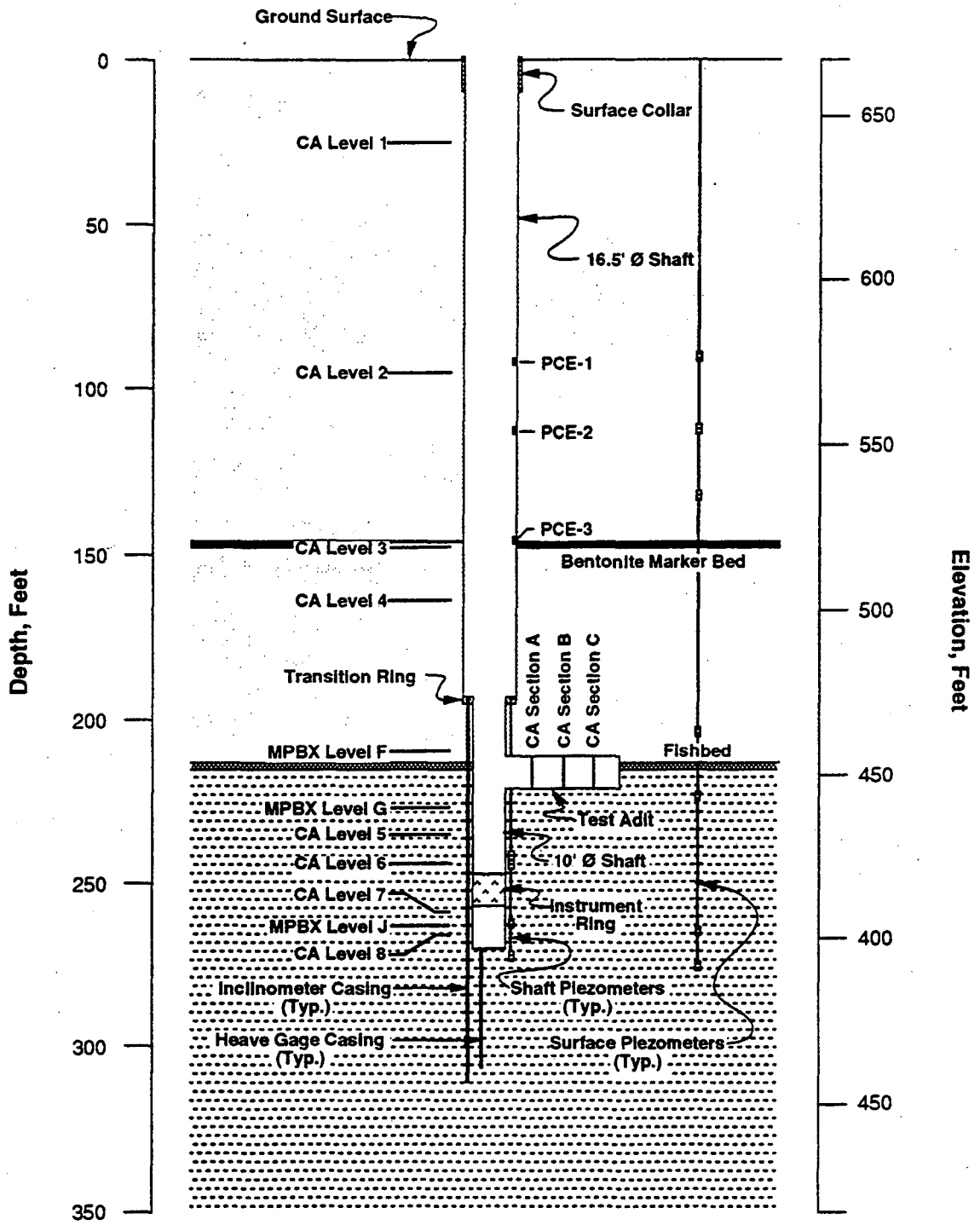
FIG. 4



LEGEND

	Austin Chalk
	Eagle Ford Shale
CA	Convergence Anchor
PCE	Portable Clinometer/Extensometer
MPBX	Multiple-Position Borehole Extensometer

SSC - Exploratory Shaft
Waxahachie, Texas

GENERAL INSTRUMENTATION SECTION

December 1992 W-5929-01

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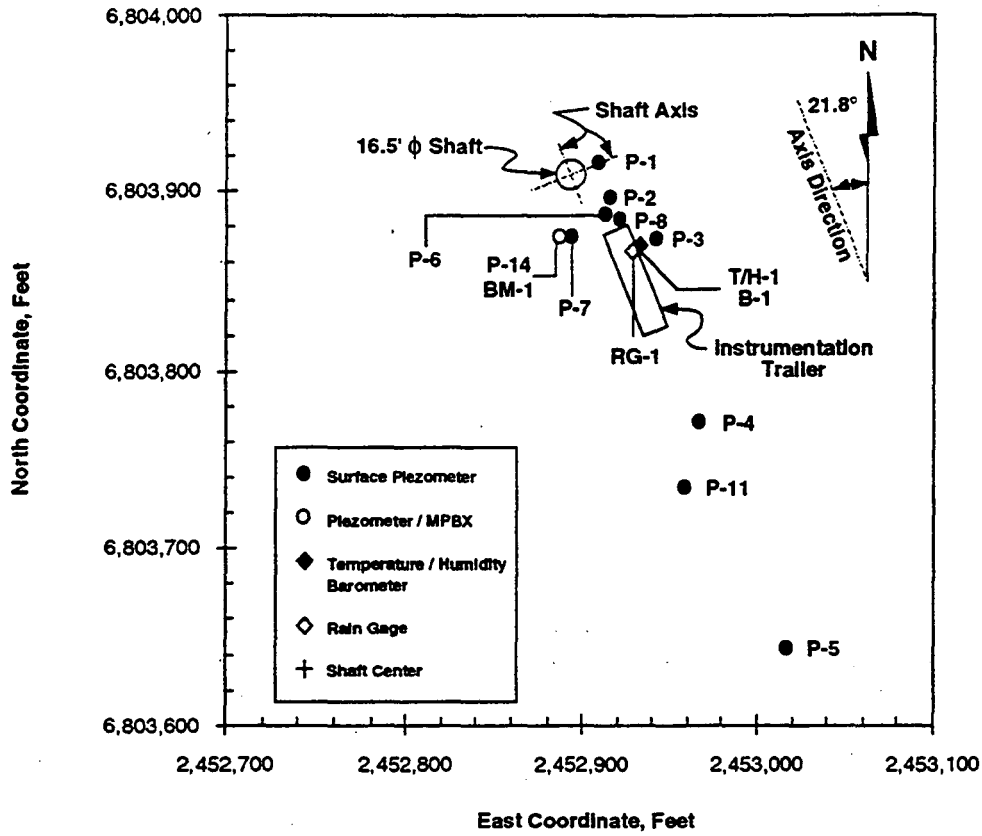
FIG. 17



Instrument No.	Coordinates North (feet)	Coordinates East (feet)	Dist. From Shaft Center (feet)	Angle From North (°)	Top Elevation (feet)	Bottom Elevation (feet)	Top Depth (feet)	Bottom Depth (feet)
Shaft Center	6,803,910	2,452,893	-	-	-	-	-	-
P-1	6,803,916	2,452,909	17.00	68	665.73	532.30	0	134.43
P-2	6,803,895	2,452,917	27.57	121	666.63	552.20	0	114.43
P-3	6,803,873	2,452,942	61.24	127	665.89	574.00	0	91.89
P-4	6,803,770	2,452,967	157.88	152	666.55	574.70	0	91.85
P-5	6,803,643	2,453,017	294.31	155	665.52	572.60	0	92.92
P-6	6,803,886	2,452,913	30.96	139	666.89	461.50	0	205.39
P-7	6,803,874	2,452,894	35.87	178	667.09	401.00	0	266.09
P-8	6,803,883	2,452,922	38.97	133	666.26	440.60	0	225.66
P-11	6,803,733	2,452,959	188.10	160	666.53	389.10	0	277.43
P-14/BM-1	6,803,874	2,452,888	35.93	188	667.06	291.60	0	375.46
T/H-1 / B-1	6,803,869	2,452,933	56.68	136	670.89	670.89	-	-
RG-1	6,803,868	2,452,928	54.95	140	677.89	677.89	-	-

SSC - Exploratory Shaft
Waxahachie, Texas

INSTRUMENTATION PLAN SURFACE

December 1992 W-5929-01

SHANNON & WILSON, INC.
Geotechnical and Environmental Consultants

FIG. 18

Appendix F

Hydrogeology Summary (Dutton et al., 1994)

Hydrogeology at the SSC

Introduction

The focus of this report is on ground water in weathered and unweathered Austin Chalk and Ozan and Eagle Ford Formations in the vicinity of the Superconducting Super Collider (SSC) site in Ellis County, Texas. Major topics discussed include the structural, stratigraphic, and mineralogic controls on fracture intensity and fracture characteristics; influence of fractures on hydrogeologic properties and ground-water flow; the role of springs and seeps in the local hydrological cycle; regional hydrologic controls on artesian conditions; paleohydrologic and mineralogic controls on chemical composition of ground water; sources of ground water and ground-water residence time; inventory of in-use and abandoned water wells; effects of SSCL construction on ground-water flow; and methods used to conduct the geologic and hydrologic studies. The studies were conducted between December 1990 and March 1993. Studies included

- **the inventory of 1,130 wells, including 419 wells on footprint parcels and 40 wells within 150 feet of accelerator beam line;**
- **monitoring of water levels at more than 120 public, private, and Superconducting Super Collider Laboratory (SSCL) project wells and description of the three-dimensional distribution of hydraulic head and flow potential;**
- **hydrologic testing at 29 of the SSCL project wells and at 43 private wells;**
- **sampling of ground water at the 37 SSCL project wells and at 38 private wells and analyses of chemical and isotopic composition;**
- **petrographic study of the stratigraphic controls on fracture intensity;**
- **definition of the mineralogic and paleohydrologic controls on water chemical composition and interpretation of ground-water ages;**
- **modeling of ground-water flow in Austin Chalk, Eagle Ford and Ozan Formations to evaluate hydrologic interpretations and to estimate difficult-to-measure hydrologic properties; and**
- **delineation of the ground-water capture zone around SSCL particle-interaction halls.**

Petrology of the Austin Chalk in the Ellis County Area

The Austin Chalk at the SSC site is a 400- to 500-ft-thick (121.1- to 151.4-m) sequence of chalk beds alternating with thinner marl beds. Matrix porosity and permeability are low, but the unit is fractured both in fault zones and in more widely spaced regional fracture systems. This study focused on understanding the stratigraphic and mineralogic controls on the distribution of these fractures.

The Austin Chalk accumulated as a nannoplankton ooze in a deep- water shelf environment. The stable depositional environment accounts for the lithologic homogeneity of the Austin Chalk. Variability in chalk/marl cycle patterns, texture, fauna, and the amount and sources of clay affect the mechanical properties of the Austin Chalk, for example, fracture spacing and weathering characteristics. Cycles in the Austin Chalk are defined by repetitive alternation of carbonate-dominated chalks and marls. Marl beds have a consistently higher acid-insoluble content of 18 to 26 percent than do adjacent chalk beds, which have an average insoluble content of 8 to 15 percent. Clay minerals include smectite, kaolinite, and illite.

Clay origin as well as distribution influence the mechanical properties and log-response character of the chalk and marl. In the lower and upper Austin Chalk, detrital clay and sand are recognized in most chalk and marl beds, except in discrete beds of altered volcanic ash. The middle Austin Chalk, with its low-SP response, is traditionally interpreted as a high-clay unit. In Ellis County, however, the middle Austin Chalk does not have a markedly higher clay content than other units but the source and microdistribution of clay are different. Clay coats on nannoplankton grains are interpreted as devitrified volcanic ash that was codeposited with the chalk. The authigenic clay is associated with volcanic biotite, quartz, and feldspar. The middle Austin Chalk typically has lower porosity, greater ductility, lower fracture intensity, and lower average hydraulic conductivity compared to the upper and lower Austin Chalk. These properties are controlled by clay distribution around and between individual coccoliths rather than total clay content.

Thirteen subsurface units are delineated on the basis of gamma-ray patterns, core description, and fracture intensity. Units T, A, B, C, and D correlate approximately with the lower Austin Chalk. Units E through I are approximately equivalent to the low-SP middle Austin Chalk, and units J, K, and L correspond to the upper Austin Chalk. Subsurface units projected to ground surface form the basis of a geologic map, structural cross sections, and a three-dimensional stratigraphic model. The structural cross sections were used for hydrologic modeling. From structural cross sections, part of the upper

Austin Chalk is found to be missing from the previously defined stratigraphic section. Adding this interval to the cross section, however, has little impact on the interpretation of the structure or stratigraphy at collider tunnel depth, but slightly increases stratigraphic dips along the eastern part of the ring.

Fracture Systems of the Austin Chalk

Fractures probably are the primary conduit of ground-water flow in the Austin Chalk and Ozan and Eagle Ford Formations because unfractured bedrock typically has low hydraulic conductivity. This study focused on mapping and describing fractures in outcrop and core in the Austin Chalk in the Ellis County area. Fractured marl of the Ozan Formation and fractured shale of the Eagle Ford Formation were not studied in the same detail as the Austin Chalk because unweathered Ozan outcrops are sparse. The Ozan Formation is less brittle than the Austin Chalk and usually is less fractured.

The zone of weathered Austin Chalk is locally as much as 45 ft (14 m) thick in the Ellis County area. Joints are more abundant than in unweathered chalk and small cavities and vugs are locally common along fractures and bedding planes. Unloading might cause fractures and bedding planes near the surface to be more permeable than fractures at greater depths. Permeable bedding planes might aid in connecting vertical fractures.

Deeper, unweathered Austin Chalk units have variable fracture frequencies in areas away from large faults. In Ellis County, fracture intensity is highest in upper (units J, K, L) and lower (unit A) units of the chalk. The least fractured units are E through I in the middle zone, and units T and B, C, and D of the lower interval. Slant-core data and long outcrop traverses verify that fractures do not have uniform spacing within any given unit and that fracture swarms occur away from large faults or folds.

Areas of high fracture abundances and well-interconnected fractures occur near faults and folds. Fractured areas surrounding faults are relatively narrow, and the most highly interconnected parts are small faults that in many cases are at least partly coated with calcite. Halos or zones of fractured rocks surrounding large faults have well-interconnected fracture networks of considerable vertical and lateral extent. These networks extend vertically across bedding and might be in both hanging wall and footwall blocks. Bending of brittle chalk can create fractures, so folds adjacent to curved faults, fault-propagation folds near lateral fault terminations, and areas between overlapping fault tips are areas where abundant, well-interconnected fractures might occur. Hinges of folds have greater fracture frequency than fold limbs. In Ellis County,

exposed parts of large faults are nearly planar, but slight bends are loci of fracture zones. Small-scale examples show that these zones are common where faults steepen or flatten.

Fractures are commonly joints or veins, which tend to be confined to individual chalk beds. Fold-related fractures in areas or stratigraphic intervals with numerous marly or shale interbeds tend to be confined to individual chalk beds, and fluid communication along fractures is vertically partitioned.

Water Resources

A total of 1,130 wells have been located near the SSC in Ellis County, 419 of which are on parcels on the SSC footprint. The inventory of 108 wells on the West Campus corresponds to a well density of 9.1 wells/mi2 (3.5 wells/km2). If the well density on the West Campus is representative of Ellis County, there might be more than 4,300 wells in the 475 mi2 area. Most (72 to 75 percent) of the wells are shallow dug wells less than 50 ft (15.24 m) in depth and 10 to 15 percent are drilled water-supply wells in the regional confined aquifers at depths generally in excess of 420ft (128 m). Only 40 wells lie within 150 ft (45.72 m) of the beam line projected at land surface. Of these, 17 are being used as of this 1991 to 1992 survey. About 5 percent of the shallow wells on the SSC footprint are used for domestic water supplies and another 8 percent supply water for livestock or home gardens and yards. At least 87 percent of the shallow wells on the SSC footprint are unused or abandoned and as many as 2,700 shallow wells might be unused or abandoned in the entire study area within Ellis County. Most abandoned wells are in disrepair and have been used for disposal of trash. Because of the potential for rapid recharge and flow rate, the unconfined surficial aquifer in alluvium and in fractured, weathered bedrock is susceptible to contamination through these abandoned wells.

Deep wells in the regionally confined aquifer system typically are drilled into the Upper Cretaceous Woodbine or Lower Cretaceous Paluxy and Twin Mountains Formations. Reported depths of wells range from 230 to 3,285 ft (70.1 to 1001.3 m). Wells operated by the City of Avalon, City of Bardwell, Buena Vista Water Supply Corporation, City of Ennis, City of Palmer, and Rockett Water Supply Corporation serve communities near the SSC. At least 58 of the deep water wells in the study area have been abandoned.

Water-Table Elevation

The position of the water table or potentiometric surface fluctuates seasonally, daily, and episodically as the balance changes between rate of recharge from precipitation and rates of discharge by evapotranspiration, flow to springs and seeps, and pumping of wells. At any given time, water levels closely mimic topography, with high elevations along upland surface-water divides and low elevations in valley floors beneath stream beds. Depth to water averaged 8.1 to 8.5 ft (2.47 to 2.59 m) below land surface during 1991 and 1992, respectively. Water levels in wells in the weathered Austin Chalk generally rise and fall quickly after precipitation events. The magnitude of water-level changes decreases with depth and generally is less in unweathered bedrock than in the surficial aquifer in alluvium and weathered bedrock. In most deep wells in the unweathered bedrock there were no detectable fluctuations in water level associated with precipitation events or seasons, indicating very low recharge rates. Water level in SSCL monitoring well BI3, however, responds rapidly to precipitation events, and there there are suggestions of a possible annual cycle at wells BE10, BI3, BI6, BIR31, and BF6, where water levels are as much as 8 to 10 ft (2.4 to 3 m) higher during January to April than during June to September. Additional data, however, are needed to confirm the periodicity of fluctuations and to quantify how such fluctuations relate to recharge and discharge rates.

The dynamic pressure increment (p), calculated from water levels measured in SSCL monitoring wells, is used to evaluate potential for vertical flow of ground water. Artesian wells such as BE6 and BF3 have large positive p values and indicate local and regional potentials for upward-directed flow. Among wells with very negative p values, BE2 shows a normal rate of water-level recovery but plots alongside wells B1697 and BE1A, which have extremely slow rates of water-level recovery. These data suggest that low hydraulic heads occur naturally beneath upland recharge areas.

Hydrologic Properties

Hydraulic conductivity of the weathered Austin Chalk averages 0.61 ft/d (105.66 m/s) and decreases with depth. Hydrologic tests conducted at low initial water levels affect only the deeper, less permeable section of the weathered zone, and tests conducted at high initial water levels yield a higher hydraulic conductivity weighted both by the hydraulic conductivities of different strata and by the effective hydraulic conductivity of

intersected fractures. The potential for transport of contaminants by ground water in the weathered chalk, therefore, varies seasonally with water-table elevation.

Average hydraulic conductivity of unweathered chalk, marl, and shale is almost 1,000 times lower than hydraulic conductivity of weathered bedrock, but hydraulic conductivity of unweathered, fractured chalk can be as great as the average hydraulic conductivity of weathered bedrock. Hydraulic conductivity measured in the unweathered Austin Chalk ranges over 6 orders of magnitude from 106.0 to 100.07 ft/d (1011.5 to 105.5 m/s). Factors that affect the range of hydraulic conductivity in Austin Chalk are (1) variations in fracture intensity and fracture aperture and (2) variations in chalk/marl ratio and microdistribution of clay. Analysis of variance shows that average hydraulic conductivity of fractured chalk statistically differs between the subdivided units of the Austin Chalk, a different conclusion than previously made. Hydraulic conductivity of fractured zones near faults tends to increase with greater fault throw for faults having throws of 5 to 40 ft (1.5 to 12 m). The increase reflects the interconnection of fractures adjacent to faults. Lower than expected hydraulic conductivity of fractured rock near the three largest fault zones results from partial occlusion of fracture porosity by calcite vein filling. Fracture apertures in the Austin Chalk calculated using a cubic-law relationship range from 0.00003 to 0.0043 inches (0.0009 to 0.108 mm) and average 0.0011 inches (0.029 mm).

Specific storage is calculated at 11 SSCL monitoring wells from the water-level response to atmospheric-pressure changes. Calculated barometric efficiencies are low, possibly indicating extreme confinement of ground water. Mean specific storage calculated for the Austin Chalk is 10 5.76 and mean specific storage for the Eagle Ford Formation is 106.29. Storativity has not been measured directly in test wells in unweathered bedrock at the SSC site so there is no independent comparison for the value calculated using water-level fluctuations. Whether estimation of specific storage from the response of water-level fluctuations to atmospheric-pressure change is representative of in-situ specific storage requires further study and analysis.

Geothermal Gradient

Bottom-hole temperature increases with depth. The intercept of the regression matches the 66F (18.9C) 19311965 average of air temperature in Waxahachie. The calculated slope estimates a geothermal gradient of 1.7F/100 ft (30.3C/km), which agrees with the regional trend in geothermal gradient.

Chemical Composition of Ground Water

Ground water in weathered bedrock of the Austin Chalk and Ozan Formation ranges from calcium-bicarbonate to mixed-cation-bicarbonate and mixed-cation-sulfate types. Water collected from springs issuing from fractures in the Austin Chalk also is a dilute calcium-bicarbonate type water resembling ground waters collected from wells in the weathered chalk. Ground water from unweathered bedrock tends to have the highest TDS and a large proportion of samples were sodium-chloride hydrochemical types. Na+ and Cl concentrations lie along or above the seawater dilution line. Similarly, the Br/Cl ratio of the ground waters generally is similar to that of seawater. Geochemical models are used to simulate reactions hypothesized to control chemical composition of ground water. Simulated reactions include (1) dilution by recharged rainwater of sodium, chloride, and other dissolved salts inherited from seawater trapped in pores in low-permeability rock, and (2) reactions of the diluted mixture with minerals such as calcite, pyrite, and clays (ion exchange) that make up the formations. The ratio of conservative ions such as Cl and Br between ground water and seawater, therefore, might be an estimate of how much recharged water has circulated through the rock, displacing and diluting ancient seawater, since the stratigraphic section has been in its present hydrological setting. Although most seawater has been displaced from pores in low-permeability rock, flushing is incomplete. The amount of flushing of marine salts presumably is related to the interconnectedness and hydraulic conductivity of fractures. In such situations, solute concentration might be controlled by diffusion from unfractured rock as well as by advective flow within fractures.

BI3 and BF9 are the two SSCL monitoring wells that have high enough yield to provide a ground-water sample for carbon-14 (14C) analysis. Carbon-14 content measured at BI3 is 97 0.7 percent of Modern atmospheric 14C activity (pmc). Carbon-14 content measured in ground water from BF9 is 2.1 0.2 pmc, but above detection limit. Tritium (3H) concentrations in water samples from alluvium and weathered bedrock are low but above background, ranging from 3.58 to 11.1 TU (11.45 to 35.5 pCi/L). Tritium concentrations of water samples from SSCL monitoring wells range from 0 to approximately 7 TU (0 to 22.4 pCi/L). The 14C and 3H data suggest that ground water in shallow or fractured bedrock, such as at BI3, was recharged within the last 40 to 50 years. High 3H content in ground water at depths of approximately 90 ft (27 m) or more in chalk is evidence of rapid vertical flow, which most likely occurs through fractures. The above-background 3H values suggest that fractures also might influence ground-water flow at wells BI4, B1597B, and B1697B. Inferences of rates of ground-water flow cannot

be made with confidence on the basis of samples without detectable 3H , but 3H activity of less than 0.4 TU (<1.3 pCi/L) in ten samples must represent sufficient time of travel, at least 40 to 50 years, for "bomb" tritium to decay in activity to below detection limits. Ground water in bedrock with less well interconnected fractures, such as at BF9, is older, possibly recharged within the past 15,000 to 20,000 yr on the basis of limited 14C data. Numerical model results suggest an average age of ground water in unweathered, unfractured bedrock of 1 million years.

All ground water is expected to show minute levels of radioactive constituents such as 40K, radium, and 232Th, which are derived from the rock and soil through which the water passes. Radioactive isotopes of beryllium, sodium, calcium, manganese, cobalt, and cesium were not detected in these natural waters but might be generated by SSCL accelerator operation.

Ground-Water Flow Paths

The physical and chemical hydrogeologic studies indicate that recharge from precipitation over the upland drainage divides percolates into the ground and moves downward through the soil zone and weathered bedrock to the water table. Beneath the water table in the weathered zone, ground water percolates along vertical fractures and horizontal bedding- plane joints and through the more permeable sedimentary layers. Vertical movement can be retarded by unfractured beds of low permeability. Because of the decrease in hydraulic conductivity with increasing depth below ground surface, only a small fraction of recharged ground water, estimated to be only 1 percent by numerical models, moves downward into unweathered bedrock. The important exception to this occurs in zones of interconnected fractures. Deep vertical circulation is more likely in fractured chalk than in marl because fractures in chalk remain open to greater depth.

Regional flow paths through the unweathered chalk are assumed to be mainly through interconnected fractures rather than through unfractured matrix. The strike of fractures, however, imparts a northeasterly anisotropy to regional values of hydraulic conductivity in the Austin Chalk that might influence direction of ground-water flow. Ground water flows generally southeastward but flow paths bend toward discharge points in the valley bottoms and stream banks. At the margins of incised stream valleys, ground water discharges in springs and seeps from bedding plane joints and vertical fractures. Perennial streams can be fed during droughts until the water table falls below the elevation of the springs and seeps, leading to testimony that such springs have "not gone dry in living memory." Notable examples of fracture-controlled springs in weathered

chalk include Brach Spring, which feeds part of Greathouse Branch, Mammouth Spring, which feeds Armstrong Creek, and Hawkins Spring, which feeds Waxahachie Creek in Midlothian, Texas.

Water temperatures at such springs ranged from 62.6F to 69.8F (17C to 21C). The coolest temperatures suggest that ground water circulated only to shallow depths of less than approximately 65 to 100 ft (20 to 30 m). The warmest temperatures suggest that ground water might have circulated to a depth of approximately 250 ft (77 m). This places the depth of circulation near Hawkins Spring into the Eagle Ford Shale. The chemical composition of the Hawkins Spring water, however, closely resembles the chemical composition of shallow Austin Chalk water and shows no evidence of contact with such a distinctly different mineralogy and lithology as the Eagle Ford Formation. Depth of circulation of ground water feeding Hawkins Spring remains an unresolved question.

Ground-water velocities in unfractured rock are very slow and should retard the transport of radionuclides. However, where bedrock is intensely fractured, rapid flow velocities and transit times of less than 50 years can be obtained. Therefore, it is important to identify fracture zones and to quantify their hydraulic properties in the vicinity of expected sources of radioactivated ground water.

Simulation of Ground-Water Flow

Numerical modeling is used as a tool to interpret and better understand the parameters that control regional ground-water flow paths and travel times and to evaluate the conceptual hydrologic model. A "West Campus" model investigates local flow rates and flow paths in weathered and unweathered Austin Chalk and in fractured zones. An "Ellis County" model evaluates regional flow paths within unweathered Ozan Formation, Austin Chalk, and Eagle Ford Formation and determines the hydrogeologic control of artesian pressure in Austin Chalk at the eastern side of the SSC site.

Hydraulic properties are initially assigned on the basis of data from hydrologic tests and adjusted by matching simulated hydraulic head with water-level data from SSCL monitoring wells and exploratory-borehole- shaft piezometers. Model calibration provides estimates of hydrologic properties that cannot be readily measured and indicates that (1) horizontal hydraulic conductivity is a little more than 100 times greater than vertical hydraulic conductivity, (2) average hydraulic conductivity of the Austin Chalk is 18 times greater than average hydraulic conductivity of the Ozan Formation, (3) hydraulic conductivities between 1.4 and 4.0 ft/d (105.31 and 104.85 m/s) in a fracture

zone on the West Campus yield flow velocities that are consistent with tritium data and simulated hydraulic heads that match measured values, and (4) vertical gradients in hydraulic head range from 0 to 0.1. In addition, model results suggest that (1) less than 3 percent of precipitation is recharged, (2) 99 percent of ground water flows through the weathered zone and less than 1 percent moves downward into unweathered bedrock, (3) ground-water residence time in the weathered zone is 5 to 10 years, (4) average ground-water residence time in unweathered rock is 1 million years, (5) ground-water circulation is deep and rapid in fracture zones, (6) ground water that is recharged at the Austin Chalk outcrop either discharges to creeks that cross the outcrop or flows downdip and eventually discharges upward through the Ozan Formation, (7) ground-water velocity ranges from 102 to 106 ft/d (107.45 to 1011.45 m/s) in weathered bedrock and from 10 6 to 108 ft/d (1011.45 to 1013.45 m/s) in unweathered bedrock.

These models can be modified for other purposes, for example, to locate optimum locations of ground-water monitoring wells and to predict travel time between specific SSCL facilities and a monitoring well.

Effect of SSCL Excavations on Ground-Water Flow

An "Interaction Hall" model estimates the size of the zone in which ground water will be captured, that is, drawn into the large excavations of interaction halls and adjacent tunnel segments owing to the local hydraulic-head gradient imposed by these openings. Construction of hall IR8, for example, is designed to be 113.8 ft wide, 344.5 ft long, and 160 ft deep beneath ground surface (34.7, 105, and 48.77 m, respectively). The interaction hall will be surrounded by near-horizontal boreholes to promote drainage of the rock adjacent to the interaction hall.

The amount of ground-water inflow and hydraulic-head decline after excavation depends on the hydraulic conductivity of rock, the number and size of the drainage boreholes installed in the walls, and the effect of wall treatments such as application of a geotextile-material cover and shotcrete. To simplify the problem, an analytical solution combining mutual effects of drainage boreholes and the tunnel is developed to determine effective conductivity of the zone influenced by drainage holes, calculate discharge, evaluate how discharge and capture zone are affected by design of drainage boreholes.

These calculations show that (1) total flow rate is larger from the long eastern and western walls than from the short southern and northern walls, especially early in the history of the excavation when the radius of influence is small, (2) the collider tunnel might yield a greater flow rate than other boreholes if the hydraulic conductivity of its

concrete lining is not much less than the hydraulic conductivity of the bedrock, (3) the uppermost and middle rows of drainage holes yield the second and highest and least flow rates, respectively, and (4) the number of drainage boreholes drilled into marl might be determined on the basis of required drainage rate as much as on the basis of capture-zone size.

Hydrologic properties initially are assigned in the numerical model on the basis of tests of SSCL monitoring well BIR81 and results of West Campus and Ellis County model simulations, but are varied to evaluate sensitivity of model results to the assumed values. The model is executed first as a steady-state model to establish a pre-excavation baseline, then is modified to include the change in hydraulic conductivity imposed by construction of the interaction hall. Model results show that the interaction-hall excavation acts as a hydrologic drain, lowering water level in the marl and chalk, and capturing ground water from at least 115 ft (35 m) away in the marl and 492 ft (150 m) in the chalk. Calculation of water levels near the interaction hall is sensitive to the vertical and horizontal hydraulic conductivity of the drainage zone.

Use of a geotextile cover or shotcrete on walls of the interaction hall and precast concrete lining on tunnel walls in marl limits exposure of bedrock to air. Painting chalk walls with a sealant also influences hydrologic conditions behind the wall. Tunnel walls might become dry, nonetheless, owing to the low hydraulic conductivity of chalk and marl and forced circulation of air. Drying of tunnel walls might limit movement of captured ground water into the excavations. It is possible that volatile isotopes such as 3H might move in water vapor while nonvolatile radioisotopes such as 22Na might be concentrated at the capillary fringe at some distance from the wall. Additional study is necessary to quantify the probable flux of volatile and nonvolatile radioactive isotopes.

Appendix G

Hydrogeology Research Questions

Hydrogeology Research Questions

Questions	Managed sequence of experiments to optimize tunnel resource
1. What does the geometry and texture of fracture interconnections control preferential flow paths, and how do can knowledge of these effects optimize remediation techniques?	• Fracture characterization by tomographic and other geophysical techniques in • lateral borings from tunnel and vertical borings from ground surface; • Flow and transport experiments with tracers, dyes, and benign "contaminants"; • Remediation simulation; • Autopsy of experiments by mining out experimental blocks mapping traces of dyes and "contaminants" on exposed surfaces, and synthesizing three-dimensional maps of preferential pathways through fracture networks; • Benchmark fracture network and fracture flow models; • Develop eostatistical techniques for handling scale-dependent geohydrologic properties of fractures.
2. How do fracture apertures fill with mineral cements, and how do texture and mineralization of fracture surfaces effect fluid and contaminant transport?	• Correlate geohydrologic properties with classification of fractures; • Distinguish effects of regional; local; and mining induced stresses on fracture distributions. • Measurement of "skin effect" of mineralized fracture surfaces on near-fracture dispersivity; • Flow and transport experiments with benign "contaminants" known to interact with in situ minerals.
3. How accurate are tomographic and other geophysical techniques for characterizing fracture distribution and interconnections?	• Fracture characterization by tomographic and other geophysical techniques in lateral borings from tunnel and vertical borins from ground surface; • Overcoring of tunnel boreholes and remeasurement; Autopsy of experiment by mining out experimental blocks mapping fractures on exposed surfaces, and synthesizing three-dimensional fracture distributions.
4. How well do surface geophysics identify fracture and fault swarms in the shallow subsurface?	• Conduct surface geophysical surveys, core boreholes, and conduct tomographic surveys from ground surface at locations of fault and fracture swarms mapped in the SSC tunnel.
5. How do fractures propagate at rock interface, and how can 'directed-hydraulic-fracture' techniques be improved?	• Build on existing tunnel maps of fractures contacting chalk and marl beds; • Mine back to expose fresh shale and map fractures in contact with chalk and shale. • Conduct hydraulic fracture tests from ground surface using conventional and improved technology, followed by mined out autopsy of induced fractures.
6. What is history of mineralization and how is it related to rock deformation and geohydrologic history?	• Sampling and geochemical analyses of vein cements, which are uncontaminated and unweathered; • Preparation of a three-dimensional view of fracture mineralization in conjunction with other mining-out experiments.

7. What is local variability of chemical composition of pore fluids, what does that indicate about geologic-time-scale displacement of connate water in low-permeability matrix by meteoric water transported in fractures, and can in situ solute variabilit ndicate patterns in dispersivity?	• Sampling and geochemical analyses of rock samples and of solute extracts; • Advantage of subsurface experiments free of near-surface contamination, weathering, and flushing; • Preparation of a three-dimensional view of ionic composition of solutes in conjunction with other mining-out experiments.
8. How can experiments take advantage of "problems" of the tunnel environment to maximize research yield?	• Unsaturated zone experiments and experiments at the air/water interface near tunnel walls that have dried with exposure; • Distinguish effects of regional; local; and mining induced stresses on fracture distributions; • Analysis of "tight" fractures which predominate;
9. How does subsurface environment in fractured porous sedimentary rock respond to tunnel opening, and what interconnection is there to near surface weathered zones and local aquifers?	• Instrument and monitor fluid pressures and rock stress before, durng, and after opening of adits and rooms off from SSC tunnel; • Conduct tracer tests from land surface to tunnel depth to measure flow velocity in fracture swarms; • Analysis of "tight" fractures which predominate;

Appendix H

Geomechanics Research Questions

Geomechanics Research Questions

Questions	Experiments	Clients/Applications
1. What are real loads which develop on underground support systems, and how do these loads change with time?	• Take advantage and develop experiments to be set up with installed instrumentation at locations including MDS, S30, S40, N55, Exploratory Shaft (most extensive). In tunnel, only convergence measurements possible for early base-lining. • Track rock/lining interaction and measure stresses in the linings. • Excavate different diameters and investigate scale effects on loads • Analytical model and constitutive model verification • Understand variability of rock loads and relate to variability in rock mass condition. • Evaluate the function of different support systems (active and passive, bolts, steel sets, shotcrete, grout) and developed improvements in rock mass strength and stiffness. • Evaluate the efficiency of backfill and grouting in terms of placed condition, variability of properties, and loads on the lining during installation. • Test to evaluate performance of new ground support technologies.	• designers, contractors, owners
2. What are the scale effects on rheology and rheologic models themselves.	• Excavate openings of different sizes to investigate shale rheology and size effects. • Investigate the effects of rock mass structure on time-dependent response. • Investigate the effects of disturbance on time-dependent response.	• designers and owners

3. Relationship between intact material petrology and material behavior.	• Develop tests which could be done to determine which shales will cause problems in surface and underground engineering projects. • Evaluate the nature of problem responses of the shales. • Identify lithologic differences which can be correlated with significant differences in response.	• owners of civil works surface and underground structures
4. In situ stress measurements and interpretations in weak rocks.	• Comparisons of interpreted results among various methods. • Evaluate the influence of scale on method of test performance and interpreted results. • Conduct tests involving imposed stress states (less than failure). • Conduct tests involving imposed stress stated which cause failure of the material (possible since shale, marl, and chalk strengths are low). • Conduct tests in boreholes (of different sizes) to investigate different modes of failure and borehole instability development.	• designers
5. Induce fractures in boreholes and study rock failure.	Conduct borehole induced fracture experiments. Study the results in "post mortem" to evaluate/verify theories on: • fracture propagation directions. • crack response on propagating through sharp or gradual material interfaces (e.g. bedding or fault fillings). • crack response on crossing joints.	• designers, environmental engineers, petroleum engineers
6. Sensitivity of material response to moisture content or exposure conditions.	• Conduct experiments to separate shrink/swell from stress-related effects. • Develop and perform tests to predict swell pressure development under controlled conditions of exposure. • Evaluate the relative success of various sealant programs designed to stop moisture content variations.	• designers, civil engineers, environmental engineers, petroleum engineers

7. Corrosion	• Conduct a test program to evaluate the relative and absolute corrosivity of the underground environment. • Perform experiments to evaluate the relative success of corrosion protection systems, and to develop and prove new protection systems.	• designers, contractors, civil works owners.
8. Develop and evaluate new instrumentation techniques.	Develop equipment to: • permit self-contained measurement and storage capacity/remote retrieval of data in situ. • create a "calibration chamber" resource to compare among various equipment or techniques used for mechanical property measurement. • develop/incorporate new technologies to produce inexpensive, reliable, and safe monitoring and testing for rock material properties.	• designers, civil works owners
9. Use the SSC tunnels as the best case history of engineering characterization as predicted versus that encountered.	• Use surface exposures and boreholes available to make predictions of subsurface conditions according to existing and new geologic models.	• civil works, environmental assessment and remediation, petroleum industry
10. What can be determined/guessed about the changing intact and rock mass material properties through geologic time.	• Construct geologic history and stress history, evaluate reconstructed condition of the rock material at the time of natural joint formation. • Perform fractographic analysis of joints to evaluate physical and hydrologic properties, and evolution through geologic time and via natural and man-induced damage.	• researchers

11. Observe joints/discontinuities present in surface and subsurface exposures.	• Evaluate the failure modes exhibited in natural joints. • Evaluate the modes of failure developed in the tunnel exposures (deteriorating rock conditions). • Evaluate how variable are the properties of the joints. • Evaluate how variable are the orientations and other geometric characteristics of the joints present at the surface and in the tunnel. • Evaluate the bias in mapping the joints in subsurface exposure. • Evaluate the differences between interpretations based on 2-D exposures and those based on 3-D exposures.	• civil works designers and owners, environmental design and remediation, petroleum engineering
12. Geophysics - develop equipment and methodology for civil works projects, and identify improvements needed (including high frequency sources and new processing routines).	Develop tests to evaluate the capability of geophysical methods to: • Make predictions from the surface and boreholes, and have the tunnel exposures as "truth". • Identify subtle differences in properties (contrasts in velocity, density, etc.) • Detect joints and faults, test and excavate - post mortem • Identify quantitative differences in exposures between the surface and the underground (idea of a "weathering" filter effect and perhaps extrapolation to a joint/fault distribution expected at depth.) • Use electrical potential measurements to identify ground water flow conditions. • Perform experiments to identify uses and limitations of 2-D and 3-D tomographic imaging techniques - sources, detectors, and interpretations. • Use methods to remote-sense the geometry and characteristic properties (identification) of waste through a confining cap at a landfill.	• designers, site investigators, owners of underground works, petroleum engineering

13. Use geophysics measurements in conjunction with other tests to monitor rock response.	• Verify volume of rock mass involved in response. • Monitor and identify progressive processes (as deterioration). • Conduct mine-by experiments (possible at low cost with light-weight excavation equipment appropriate for the low strength rock present).	• owners, designers, quality assurance
14. Detection of underground openings and dimensions.	• Conduct tests from ground surface. • Conduct tests from underground.	• military, site investigators, geotechnical engineers, owners
15. Tests in bulkheaded tunnel sections.	• Evaluate containment capability. • Conduct gas pressurization experiments. • Conduct fluid pressure experiments. • Evaluate potential for gas or fluid storage, and verify models used for design.	• owners of storage facilities, utilities, environmental system designers
16. Application of microtunneling technology to excavation in weak rock	• Evaluate how environmental containment barriers can be mined and formed in situ. • Evaluate what grout or backfill property development is required. • Identify what equipment development is necessary to install reliable barrier/cutoffs (horizontal or vertical). • Identify what equipment developments are needed to extend microtunneling operations into rock and with drives to greater lengths.	• contractors, equipment developers, owners
17. Excavate underground space as containment facility	• Evaluate how containment can be developed (sealing), and what new materials development and application procedures are required. • Evaluate how containment reliability can be established and verified.	• designers, owners, chemical, environmental, and petroleum industries

18. Use SSC excavations (and additional excavations) to evaluate and monitor performance of environmental facility designs and remedial actions.	• Evaluate how underground excavations function for long-term passive collection of migrating fluids. • Develop experiments to monitor performance for remedial actions including pump-and-treat operations or barriers.	• designers, owners, chemical, environmental, and petroleum industries
19. Investigate heat transfer and specific capacity properties of rock masses.	• Test in Eagle Ford Shale and Austin Chalk. • Test at different volumes and to investigate scale effects. • Test at different moisture conditions. • Test to evaluate property changes at high temperature.	• low and high level radioactive waste disposal designers, host states, and federal agencies
20. Seek opportunities for technological advancements in the state-of-the-practice for drilling and sampling	• Compare drilling and sampling technologies, important for this weak and water content-sensitive rock. • Develop alternative descriptors for core quality and rock mass condition prediction, and prove correlation with rock exposed in excavations.	• engineering geology and geotechnical site investigation firms, owners
21. Identify techniques which can be used to evaluate the extent of the damage/changed zone associated with excavation?	Conduct: • Geophysical tests. • Pseudostatic tests. • Hydrologic tests.	• designers, owners
22. Investigate information associated with "seismic signatures" of underground construction equipment.	• Conduct tests to define whether signatures can be used to identify operational efficiency of underground construction equipment. • Conduct tests to determine whether seismic waves can be used as a source for advance probing. • Evaluate other ways of advance probing.	• designers, contractors, equipment manufacturers

23. Evaluate characteristics of muck (mined rock).	• Test to evaluate changes during and rates of weathering. • Evaluate shrink/swell soil properties and response. • Develop tests to define muck transport characteristics (sticky muck has been the source of claims on several underground construction projects).	• designers, contractors, equipment manufacturers
24. Test to prove new excavation technologies. What construction-related issues can be addressed in the SSC excavations?	• Conduct research to develop improved bonding between rock and concrete, grout, and shotcrete. • Conduct research on composite (possibly laminated) lining systems designed to promote drainage and/or sealing, and a dry finished tunnel (water tightness is a continuing problem for many underground structures).	• designers, contractors, equipment manufacturers

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