SSCL-341

THE ADOPTION OF MECHANIZED EXCAVATION TECHNIQUES FOR THE SUPERCONDUCTING SUPER COLLIDER*

C. Laughton, P. Nelson and T. Lundin

Superconducting Super Collider Laboratory†
Conventional Construction Division
2550 Beckleymeade Ave.
Dallas, TX 75237

January 1991

---

*To be presented at the International High Level Waste Management Conference, Reno, Nevada, April, 1991.

†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

THE ADOPTION OF MECHANIZED EXCAVATION TECHNIQUES FOR THE SUPERCONDUCTING SUPER COLLIDER

Christopher Laughton, Priscilla P. Nelson, and Tracy K. Lundin
Conventional Construction Division
Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave
Dallas, TX 75237
(214) 708-4000

ABSTRACT

The Superconducting Super Collider (SSC) is the latest and largest in a line of high-energy physics accelerator projects. The five increasingly energetic accelerators which make up the physics laboratory complex are to be housed almost entirely in subsurface structures, which will include over 100 km of small-diameter tunnel.

Among other reasons, the Texas SSC site was chosen from a set of state proposals because of the suitability of the host rock materials for the performance of rapid and efficient excavation work. The site bedrock units are relatively soft and homogeneous and should allow for a maximum use of mechanical excavation plant for the various underground openings.

This paper will review the site conditions and describe the developed understanding of geologic material behavior. With completion of planned large-scale in-situ studies of the ground behavior to provide acquisition of early site-specific excavation data, final design and construction detail of critical structures can be undertaken with the necessary degree of confidence to satisfy the stringent performance requirements.

INTRODUCTION TO THE PROJECT

The SSC Laboratory complex may well prove to be the last machine of its kind to be constructed. With over one hundred kilometers of driven tunnel and large underground structures, having floor spaces larger than that of a football field, the space will be over three times larger than its nearest counterpart, the Large Electron Positron (LEP) machine run by the European Particle Physics Laboratory, at Geneva, Switzerland.

The machine follows a very similar design and layout to that of its smaller predecessors. It consists of a series of

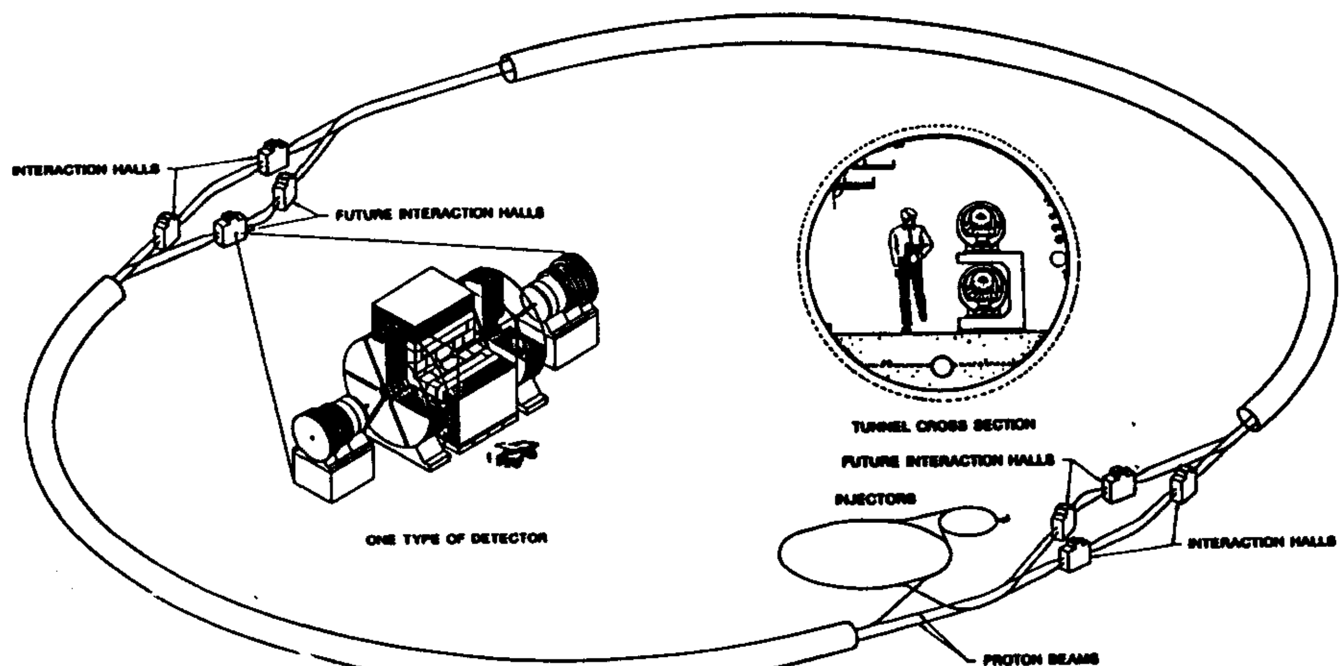


FIGURE 1 SCHEMATIC LAYOUT OF THE SUPERCONDUCTING SUPER COLLIDER UNDERGROUND FACILITIES

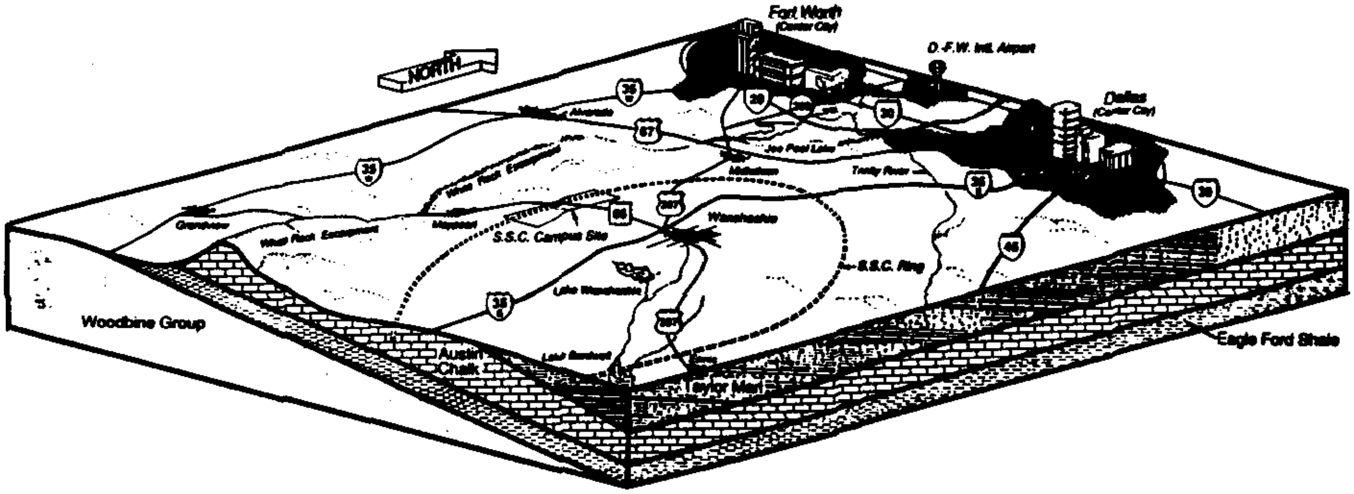


FIGURE 2 THE SUBSURFACE SETTING OF THE COLLIDER FACILITIES

particle accelerators, as shown in Fig. 1, which allow protons to be accelerated to higher and higher energies until they are injected into the collider ring. These proton streams are narrowly focused in two (east and west) straight tunnel sections, and are brought to collision at the Interaction Halls. At these Interaction Points, the particles produced by collision will be tracked and studied by a set of detectors which will be capable of picking-up and identifying even the most exotic particles. Results of such experiments have been responsible for recent physics discoveries and it is hoped that SSC, which can generate higher collision energy levels than have previously been attainable, will lead to the discovery of particles as yet undetected by experiment.

To attain these unrivalled energy levels, the relatively heavy protons are to be contained and accelerated within a strong magnetic field. The radius of curvature of the two collider arcs, at the northern and southern ends of the collision straights, is large to minimize the particle energy loss which increases dramatically with tighter bending. To create the magnetic fields in which the electrically charged particles can be deflected, strings of dipolar electromagnets are used. The high magnetic field levels needed (6.6 Tesla) call for the use of superconduction, which has already been successfully used at other laboratories. Superconducting temperatures are obtained by means of a Helium cooling system which is incorporated into the magnet coil design. Provision is made for closed-circuit Helium circulation through 8 km long loops between service shafts along the main ring.

The high technology environment and the physical challenges of constructing not just one but five accelerator machines and detector equipment make the project a daunting logistical challenge which will stretch the machine and engineering design expertise of the various disciplines involved.

LABORATORY FACILITIES LAYOUT AND STRUCTURES

The technical facilities sited underground can be divided into three categories; injector, collider ring and experimental facilities, as numbered and described below.

1) The injector, which encompasses the near surface and tunnel structures, within which the proton particles are generated, accelerated and from which they are injected into the collider ring. It includes a linear accelerator, a set of circular energy boosters (low, medium and high energy) and associated interconnecting transfer lines which link-up the near-surface linear accelerator with the deepest tunnel element (the collider). Table 1 gives the approximate dimensions of the main structures,
2) The collider, an 87 km long tunnel with a "racetrack-type" layout, in which the two beams of particles are accelerated to their final collision energies.
3) The experimental facilities, aligned on one leg of the beam bypass, along the western straight of the racetrack, in which the particle detectors are assembled and aligned to observe the particles produced by the high energy particle collisions.

Physical Descriptions of SSC Tunnel Components

Component	Tunnel Area	Length (m)*	Cross Section Size(m)	Shape
Injector/Test	Linac	244	3.66	square
	Linac/HEB	111	2.44	square
	LEB	540	3.66	circle
	LEB/MEB	219	1.83	square
	MEB	3,959	3.05	circle
	MEB/HEB	3,125	3.05	circle
	HEB	18,887	3.66	circle
	HEB/Main	1,258	3.05	circle
	Test Beams	4,218	1.8/3.0	circle
	Subtotal-Injector/Test	24,561		
Main Collider	N and S Arcs	70,542	3.66	circle
	E and W Cluster	16,556	3.66	circle
	Abort and Dump	951	3.66	circle
	Subtotal-Main Ring	88,049		
TOTAL		112,610		

Source: SSC Site-Specific Conceptual Design, SSC Laboratory, 1990

TABLE 1 PHYSICAL DESCRIPTION OF SSC TUNNEL COMPONENTS

Vertical shafts are the preferred means of access to all the subsurface components of the laboratory housings.

Shaft depths vary from 20 to 75 m for the collider and experimental facilities, but are shallower for the injector structures, which are some 9 to 55 m below ground level.

The accelerator and detector structures present several difficult challenges to the underground design engineer. Strict floor stability is essential in all the areas where the elements of the proton beamlines are founded. The circulating particles need to be aligned to very small tolerances for particle collision to have any chance of occurring. Sub-millimetric tolerances are normally specified for all elements of accelerator and detector work. Foundation displacements, on the order of tenths of millimeters, either absolute or relative, from one part of the machine to another during experimental runs will severely disrupt machine operations. The second design need that is beyond that normally expected in a tunnelled environment is that of "relative" dryness; water seepage can be tolerated but its channeling and control should be adequate to ensure that the delicate electrical and electronic equipment is maintained within a controlled humidity and temperature environment.

It should be pointed out that the more strict design requirements, outlined above, only apply to the detector and accelerator housings; elsewhere, in the access tunnels and shafts, the design requirements can be somewhat relaxed.

SITE GEOLOGICAL SETTING

The SSC subsurface structures, sited some 40 km south of downtown Dallas, Texas, are to be housed below gently rolling countryside. The ground elevation over the site varies from between 120 to 230 m above sea level and the main ring, the lowest of the five interconnected accelerators, varies from 15 to 75 m below ground level.

The underground complex will be housed in a set of sub-horizontally bedded sedimentary rock formations covered by relatively shallow residual soil and weathered materials, as shown schematically in Fig. 2. The accelerator structures will be sited within three rock strata; from youngest to oldest, Taylor Marl, Austin Chalk, and the upper member of the Eagle Ford Shale.

Terrace and stream deposits overlie parts of the site and these overburden materials vary considerably from clays through to sands and gravels. Free water tables are present in some of these deposits. Underlying the site at depth is the Woodbine Group of rock strata which serves as one of the main confined groundwater reservoirs for the regional water supply.

Only the upper member of the Taylor Group of rock strata is present within the limits of the ring site. This unit, the Taylor Marl, is characterized as a bedded claystone with significant calcium carbonate content in its structure (between 15 and 40 percent by dry weight is noted). Below the Taylor Marl lies the Austin Chalk Group, which largely consists of sets of grey chalk layers with occasional weaker clay-rich or bentonite beds. At the base of the SSC strata lies the upper part of the Eagle Ford Shale. As for the Taylor Marl, some calcium carbonate content is found within the matrix (5 to 9 percent by dry weight) and the overall rock structure has significant amounts of swelling clays. Within all the rock masses some variation in strength characteristics occurs from bed to bed, largely due to variation in the calcium carbonate and clay content, which yield changes in both strength and slaking resistance. Average geotechnical properties for the three rock formations are given in Table 2.

Property	Recommended or Average Property Value		
	Taylor Marl	Austin Chalk	Eagle Ford Shale
Dry Density (kN/m^3)	18.1	19.5	18.4
Water Content (%)	17	13	17
Specific Gravity	2.71	2.67	2.72
Slake Durability (%)	52	95	21
Hydraulic Conductivity (cm/sec)	5×10^{-8}	3×10^{-7}	2×10^{-7}
Uniaxial Compressive Strength (MPa)	4.8	18.0	3.4
Young's Modulus (MPa)	1250	3450	900
Poisson's Ratio (Static)	0.32	0.19	0.29
Liquid Limit	81		81
Plasticity Index	51		52
Carbonate Content (%)	24	65	8

TABLE 2 GEOTECHNICAL PROPERTIES FOR UNWEATHERED ROCK AT THE SSC SITE

The Ellis County site is in a tectonically stable region, ranked as a zone of lowest activity under the Unified Building Code. This implied stability is an important factor for the overall operation of the accelerator, given the sensitivity of the machine to minimal displacements and vibration during particle circulation. Cretaceous-age Balcones fault activity resulted in numerous extensional faults in the area. There is no evidence for fault rectivation since Miocene time.

An example of these faults is shown in Fig. 3, where two mapped faults account for a total of about 25 m of displacement (Kau = Austin Chalk, Ksb = Eagle Ford Shale) Graben structures are also often present. In the Austin

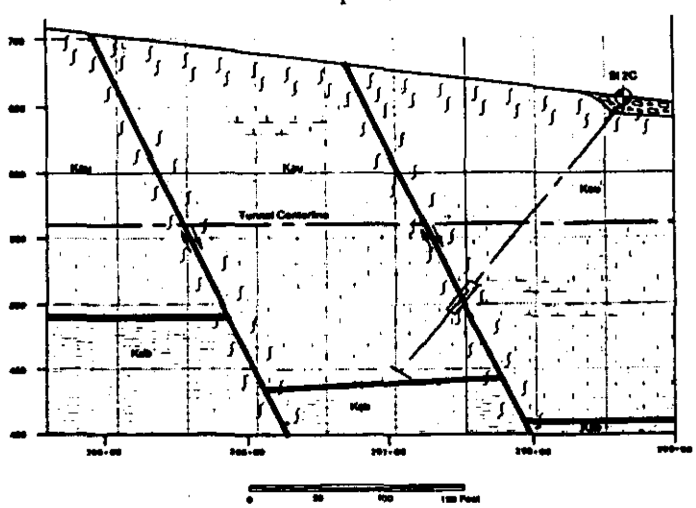


FIGURE 3 CROSS-SECTION THROUGH A TYPICAL FAULT STRUCTURE IN THE SSC SITE VICINITY

Chalk, faulting is clearly identified by reference to cores, and to borehole geophysical logging and surface reflection surveys. Shallow exposures of major faults may have measurable apertures, sometimes open and some with infillings of residual clays. However, most faults have been rehealed by materials such as calcite. Fault offsets in the Chalk are sometimes up to 20 to 30 m, but most faults thus far identified have offsets on the order of 3 to 6 m.

Evidence of faulting in the shales and marl materials has not been clearly identified by the use of either direct or indirect means (offsets between boreholes or seismic reflection). Oblique and subvertical fracturing has been encountered within the rock mass but no large scale discontinuity patterns have emerged. At the contacts between the rock strata the local variation in structure is significant; erosional debris and fish bed layers are present in these uncomformable transition zones.

Information on fracture zone extent and depth of weathering, as determined from exploratory core, is summarized in Table 3. The most frequent fractures were noted for the upper Eagle Ford Shale, where shear zones are relatively common. Regardless of the rock unit, however, fractured zones are relatively thin. Weathered zone thicknesses are also small. Since cover over the tunnel is always greater than about 14 m, there is little likelihood of encountering weathered ground during tunnel excavation.

Criteria		Geologic Material		
		Taylor Marl	Austin Chalk	Eagle Ford Shale
Distance Cored (m)		1,302	3,484	585
Percent of Core Classed as Fractured		0.7	0.9	4.3
Width of Fractured Zone[a] (m)	Maximum	1.7	4.5	1.8
	Mean	0.5	0.6	0.3
Depth of Weathered Zone (m)	Maximum	13.4	9.9	
	Mean	4.0	2.7	

[a] Fracture zone is defined as a depth range containing six or more fractures per meter, not including bedding planes.

TABLE 3 FRACTURED AND WEATHERED ZONE CHARACTERISTICS FOR SSC SITE ROCK UNITS

The marl, chalk and shale are understood to be saturated but relatively impermeable. The main potential for water inflow during the various tunnelling activities is associated with open faulting connecting the tunnelled structure with overlying water sources, particularly from the alluvium. The intact rocks are expected to act as aquitards, and water seepage into the tunnelled structures should be minimal outside shallow fractured zones. Open faults and joints are only encountered at shallow depths. While not of extreme importance to construction, these discontinuities do participate in groundwater circulation for the surficial aquifer which is accessed at the site primarily for stock water. Care will be taken during construction to minimize construction impact, particularly at shaft locations.

DEVELOPMENT OF THE CONCEPTUAL DESIGN CRITERIA FOR THE UNDERGROUND FACILITIES

The Austin Chalk and Taylor Marl rock masses form a highly favorable setting for the laboratory facilities. Previous tunneling work in these materials indicated that straightforward excavation approaches and conventional support mechanisms, such as precast linings, rockbolts and shotcrete, perform well.

One recently completed tunnel project in Austin, TX, was the Govalle Project, involving almost 13 km of tunnel excavated in Austin Chalk and Taylor Marl. Chalk excavation was accomplished mainly by a full-face rock TBM (The Robbins Co.) and the Marl was mostly excavated by a fully shielded TBM with a rotary cutterhead (Lovat Tunnel Equipment, Inc.). Information concerning this project is summarized in Table 4. Support installed in the Chalk was minimal at most locations, and Robbins TBM utilization (the percentage of shifted time the TBM was actually operated) was relatively low at about 29%. This low utilization was primarily associated with mucking system backup delays, in turn related to the use of light and reused track and to the small tunnel diameter which precluded a double track. Lovat operation in the Taylor Marl was similarly plagued.

Item	Excavated Material	
	Austin Chalk	Taylor Marl
Excavated diameter (m)	3.2	3.5
Equipment description		
Original TBM manufacturer	Robbins	Lovat
Tools	Discs	Teeth
Tunnel length[a] (m)	4,600	6,760
Advance rate (m) per shift hour	1.9	2.2
Penetration rate (m) per TBM operating hour	6.5	10.9
Average thrust per disc (kN)	20 to 40	
Average torque force per disc(kN)	6 to 8	
Utilization (%)	29	20
Support installed (as % of tunnel length)		
Bolts only as needed	83	-
Bolts and strapping	17	
Ribs and lagging		100

[a] Length reported includes only Robbins in Chalk and Lovat in Marl, and excludes slow startup caused by poorly reconditioned equipment

TABLE 4 INFORMATION SUMMARY FOR A 1986/88 TUNNEL PROJECT IN AUSTIN, TX

The excavation and support characteristics of the underlying Eagle Ford Shale, on the other hand, have always been subject to uncertainty. The upper part of the shale has rarely been worked in an underground environment, but its mineralogy and mechanical properties indicate that the shale may present the designer with markedly less favorable construction conditions than the other two rock materials. Apart from being generally softer than the overlying strata, in terms of compressive strength and stiffness, the rock matrix contains a considerable potential for swelling and creep, both of which could impact the stability of the machine. During the past two years, site investigation was heavily orientated towards delineation of the chalk/shale contact, in an effort to precisely identify and avoid the shale. However, in compromise with other factors, optimization of geologic conditions was not possible. Therefore, the SSC will be constructed with the foundations of the western halls and some 11 km of tunnel in the Eagle Ford Shale.

With the collider alignment fixed, it was essential to promote the gathering of more pertinent information upon the large-scale, in-situ ground characteristics of the shale. The use of full circular linings was anticipated in the normal cross-section of the collider tunnel for the claystone materials. For the majority of the relatively straightforward underground openings, geotechnical design data gathered from surface and borehole-based site investigation has served as an adequate basis for design.

In addition, several non-circular excavation profiles are to be sited along the western straight of the collider, at depth, in the shale, notably along sections of the injector transfer lines and at the base of both of the large detector halls. In the more sensitive shale areas, a greater level of site-specific large-scale detail of the ground behavior would be required to support design work. To provide this confident basis on which to move toward final design, planning has begun to include access for large-scale testing and in-situ monitoring in the early, non-beamline underground openings.

MECHANICALLY EXCAVATED UNDERGROUND SECTIONS

From the time the SSC was first envisaged as a tunnelled structure the attractions of mechanical excavation have been evident. The majority of SSC structures are long and linear in nature and lend themselves to the adoption of repetitive, systematic excavation and support techniques. The soft rock strata of the Texas site make the adoption of mechanical excavation even more attractive, as the individual materials are relatively consistent and few transitions, from one rock type to another, are encountered at the site. Long stretches of uncomplicated tunnel work can be envisaged along the accelerator paths. The use of mechanical excavation is also to be encouraged from the stand point of maintaining the structural integrity of the rock mass during the excavation process, this will ensure that the surrounding rock mass remains relatively undisturbed and its contribution to the overall stability of the reinforced opening maximized. The importance of obtaining an early convergence confinement equilibrium is of particular importance in the soft claystones, where at collider depths the material may well be overstressed with respect to the in-situ loading levels.

All pre-design space requirements have been developed on the assumption that mechanical techniques will be preferred by the contractor for the quasi-totality of the underground excavation works. Large-scale excavation by explosives appears inappropriate for such soft rocks but may be considered for certain special applications. For the longer collider tunnels Tunnel Boring Machine (TBM) excavation has been assumed. Elsewhere, for enlargements to the side of the principle accelerator housings and small stub or access tunnels, roadheader type excavation and compatible profiles have been selected.

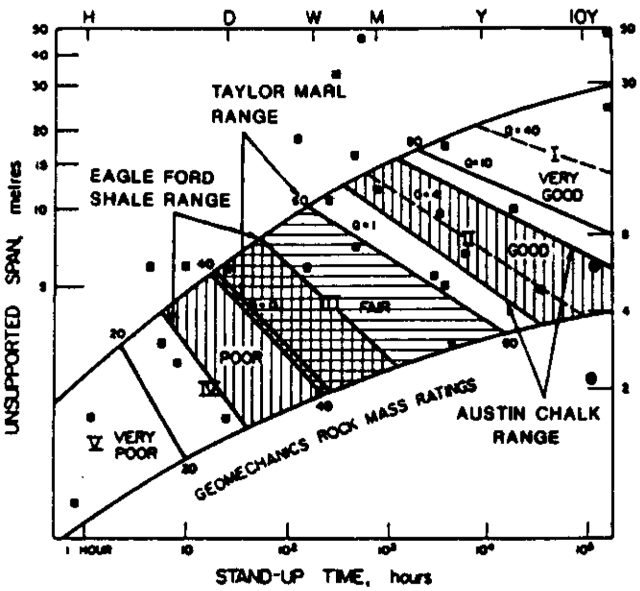
To complement the adoption of mechanized rock tunneling techniques, conceptual design has looked increasingly towards the incorporation of simple, systematic support techniques, which not only provide the necessary structural support to the rock mass but also optimize compatibility of the support and production work.

Rock Unit	3 to 4 m Span		8 to 10 m Span	
	Support Required?	Stand-up Time	Comments	Stand-up Time
Taylor Marl Good Poor	 yes yes	 ~ 1 year 1-2 days	very poor chance to complete if wide shear zones present	hours to weeks
Austin Chalk	no	2 to 10 years	support required	1 month to 2 years
Eagle Ford Shale Good Poor	 yes yes	 ~1 month ~8 hours	very poor chance in even the best material	minutes to hours

TABLE 5 ROCK MASS RATING CLASSIFICATION OF SSC SITE ROCK UNITS

As an initial step in evaluating support requirements, some attention has been given towards application of rock mass rating indices to predict support requirements and stand-up time for the tunnel openings. Accordingly, the rock masses at the SSC site have been classified using the Bieniawski (1979) RMR classification. A summary of the RMR values is presented in Table 5. The poorest quality rock mass is anticipated to be the Eagle Ford Shale, in the poor condition of sheared zones.

A correlation between unsupported span, stand-up time, and the "Geomechanics" RMR index has been suggested by Bieniawski (1979). This relationship is presented in Fig. 4, and the correlation predicts that no support will be required in Austin Chalk tunnel. Other predictions are summarized in Table 6. In 3 to 4 m-span openings, both Taylor and Eagle Ford tunnels require support, with the stand-up time for poorer quality Eagle Ford sections reduced to on the order of hours. This implies that support should be installed quickly, and that the shielded length of tunneling machine should be kept to a minimum to avoid the impact of loosening and potential shield stall. A further potential complication for Eagle Ford Shale tunneling involves the potential for overstress conditions to develop, even in small-diameter tunnel excavations. With the compressive strength on the order of the vertical overburden stress, overstress complications might well develop.



NOTE: THIS RELATIONSHIP IS AFTER BIENIAWSKI, 1979.

FIGURE 4 RMR VS UNSUPPORTED SPAN AND STAND-UP TIME FOR SSC-SITE ROCK UNITS

Rock Unit	Rock Mass Rating[a]			Basic Rock Description
	Nelson, 1987	TETC,'90 Basic	TETC,'90 Adjusted[b]	
Taylor Marl		56	41	good
Good	70			good
Poor	37			poor
Austin Chalk	65 to 70	72	76	good
Eagle Ford Shale		46	29	fair
Good	61 to 66			good
Poor	35 to 43			poor/fair

[a] after Bieniawski, 1979

[b] modified for joint orientation with respect to tunnel stability and including slake adjustment modifier (Newman and Bieniawski, 1979)

TABLE 6 PREDICTED SUPPORT REQUIREMENTS AND STAND-UP TIME FOR SSC-SITE ROCK UNITS

For larger spans, up to 8 to 10 m in characteristic dimension, the potential for loosening ground loss and material failure is greatly enhanced in both Taylor Marl and Eagle Ford Shale excavations. In fact, it is conjectural if large-span excavations in Eagle Ford Shale can even be made without extensive pre-reinforcement ahead of excavation. These predictions will have to be verified by careful monitoring of the earliest excavated exposures.

To ensure that the data acquired by instrumentation of the initial underground excavations is relevant to the design and construction of the future works, care has been taken to ensure that excavation and support techniques used will simulate those to be used for the subsequent accelerator housings. It is hoped that only limited interpretation from observed behavior of monitored the rock mass will be necessary in order to formulate realistic design performance limits of the later, more critical underground structures. The early mechanically excavated structures will also be used to analyze a whole host of construction questions prior to launching the final design and contracting of the various beam line structures. Based upon the observed results rock parameters will be developed to understand the mechanisms at play inside the rock mass during and after the excavation and support period. Models produced will be used to generate accurate predictions of short and long-term ground response to be expected using various design and construction methodologies to ensure that stability of accelerator elements is adequate for the purposes of accelerator and experimental operation.

The most critical design area in the Eagle Ford Shale is likely to be in the base of the detector hall foundations, here the material will be unloaded over effective floor widths of between 20 to 30 m, prestressing of the material may well reduce the extent of heave but the removal of such overburden loads (60 m) and reload by the floor slab and detector assembly (up to 30,000 tons in weight) may lead to the creation of an evolving stress-strain regime within the altered rock mass, capable of subjecting the detector to either sizeable upward or downwards motions during the machine life time. The design engineers involved in the hall and detector construction need a precise definition of both the short and long term behavior so that loading and displacement rates and overall levels can be predicted and controlled by design measures, with an high degree of confidence, over the life of the project. Adjacent to these experimental facilities it is intended to sink an instrumented shaft within which passive and active testing of the rock mass will be undertaken.

In the initial accelerator excavation, instrumentation sections are also planned. For the beamline tunnel itself ground response measurements will be made to confirm the establishment of a convergence confinement equilibrium prior to the installation and final alignment of the magnet rings. Away from the accelerator foundations more scope for variation of the excavation and support techniques will be possible, as absolute stability of the finished opening is less critical to the machine operations. Here several excavation parameters can be studied in the shaft and non-circular roadheader cross-sections, including an assessment of phasing, profile shape and equipment suitability. Rock reinforcement and support mechanisms can be varied and applications staggered in time to give valid comparisons of their effectiveness in terms of strengthening the rock mass, inhibiting ground movement and providing protection of the rock from slaking deterioration and swelling.

CONCLUSIONS

The selection of mechanical excavation techniques for the main underground structures of the site has never really been in doubt since selection of the Texas site in late 1988. The use of mechanized equipment should allow higher rates of production than would be otherwise possible in the main tunnels and should reduce the disturbance of the surrounding rock mass considerably, when compared to other excavation techniques such as drill and blast. The presence of the Eagle Ford Shale in the floor of the experimental hall structures and in certain non-circular sections of the collider tunnel will require an in depth analysis of the rock mass. The value of feedback from observing the performance of the initial underground structures excavated within the shale should not be underestimated, within the context of such a large construction project, where stability requirements are so strict. Structures in the shale must rely heavily upon experience gained from the exploratory work and monitoring undertaken in the early excavation phases, only in this way can adequate confidence be expressed in the performance of the beamline structures to yield predictions of displacement limits, not just for the construction and installation period of the machine but, more significantly, for the operating life of the project. Early excavations should provide the designer with an ideal opportunity to assess the larger scale rock mass behavior before he is committed to final design work.

From a practical stand point care must be taken in the establishment of construction methodology, ensuring compatibility with the underground environment within which the construction will take place. Early excavations should lead to a better appreciation as to the practical limitations to which the excavation and support work is inevitably subject. Underground working conditions are far from ideal and a built-in margin needs to be incorporated into the design and construct methodologies to ensure that variations in excavation, reinforcement and rock qualities can all be accommodated and still provide for a stable finished structure. To this end it may well prove advantageous to define not just the completely supported structure but also the intermediate construction phases, so that a good compromise can be reached between production and a timely installation of the reinforcement.

At the time of writing, December 90, the SSCL is in the process of moving from the design to construction phase. The engineering consortium Parsons Brinckerhoff / Morrison Knudsen (PB/MK) has been selected to carry-out final design and construction of the Laboratory structures. Contract negotiations are nearing completion and PB/MK's initial tasks will include development of final designs for both the exploratory shaft and the early accelerator tunnel for which conceptual designs were produced by the engineering group of Kaiser, Tudor and Keller, Gannon-Knight . It is hoped to put both of these underground contracts out to bid within the next twelve months.

REFERENCES

Nelson, 1987, "Performance Comparisons for Tunneling Projects in Weak Rock," Proceedings, 28th U.S. Rock Mechanics Symposium, Tucson, AZ, pp 329-336.

SSC Laboratory, 1990, "SCDR"

Werner, M. et al., 1990, "Preliminary Geotechnical Parameters for the Superconducting Super Collider, 1990," Geotechnical Report GR-69, prepared by the Earth Technology Corporation.

Newman, D. A and Z. T. Bieniawski, 1985, "A Modified Version of the Geomechanics Classification for Entry Design in Underground Coal Mines," Fall Meeting of the Society of Mining Engineers/AIME, Albuquerque, Oct. 16-18.

Z. T. Bieniawski, 1979, "The Geomechanical Classification in Rock Engineering Applications," Proceedings, 4th International Conmference of ISRM, Montreaux, Vol. 2, pp. 41-48.

† The SSC Laboratory is operated by the Universities Research Association Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.