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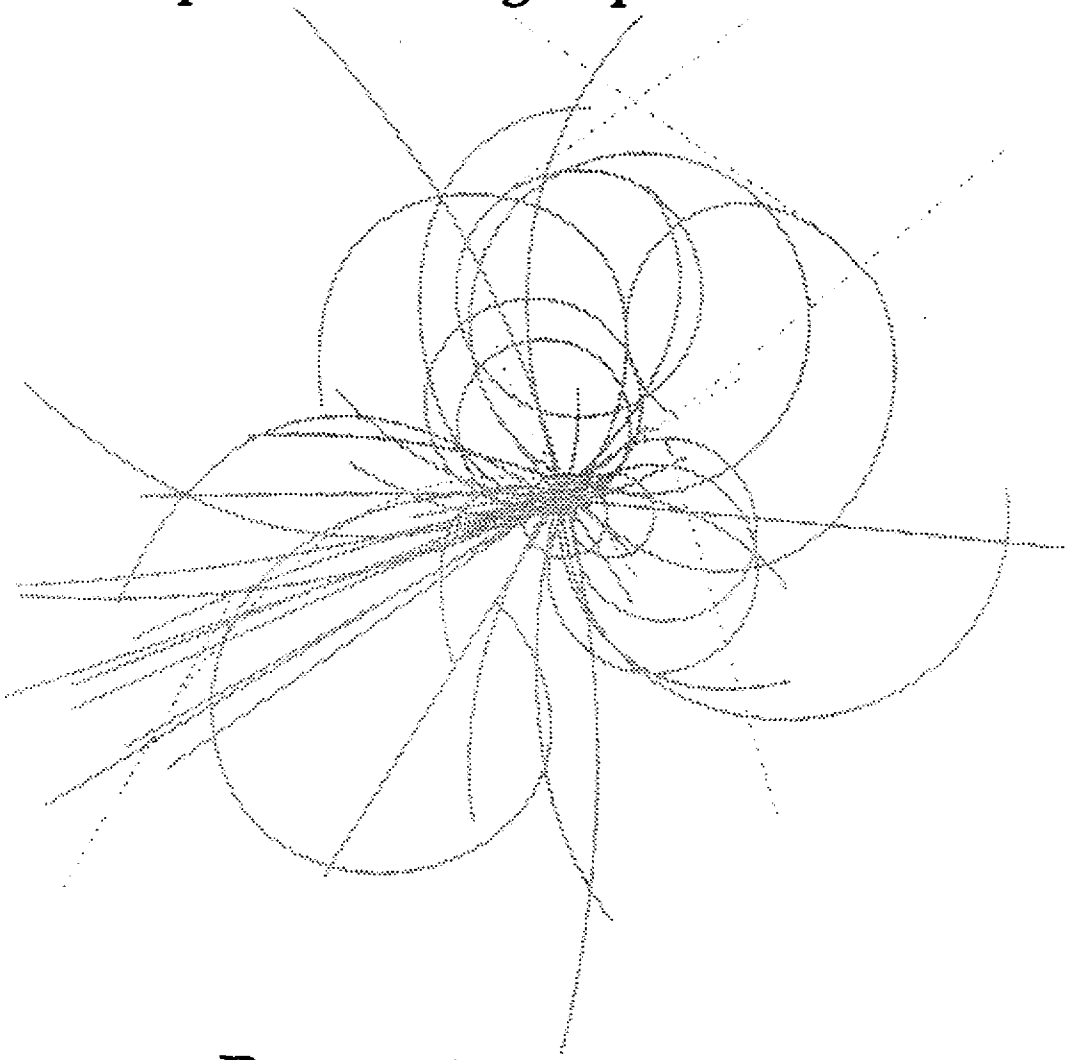
Superconducting Super Collider Laboratory



Research and Development for the Super Collider

M. Tigner

October 1985

RESEARCH AND DEVELOPMENT FOR THE SUPERCOLLIDER

M. Tigner

Universities Research Association

Testimony before

Subcommittee on Energy Development and Applications
Committee on Science and Technology
United States House of Representatives

October 29, 1985

Chairman Fuqua and members of the Subcommittee, I would like to thank you for this opportunity to describe the present status of the Supercollider research and development program. Over two years have now elapsed since the SSC was given the highest priority by the U.S. high energy community. Shortly after, in the fall of 1983, the Department of Energy formally initiated the R&D phase for this potential facility. The developments in the physics world during these past two years have strengthened the arguments for the SSC. Furthermore, the national effort devoted to the SSC R&D during that time has provided us with firm evidence that the SSC can be built with the existing technology and within the cost estimates originally calculated a year and a half ago. I would like to describe for you today some of the accomplishments of this R&D effort and tell you about our plans for the future. I would also like to touch briefly on the important subject of international collaboration.

The main objectives of the research and development effort are:

1) to develop and optimize the components necessary for construction of the SSC. Because the magnets are by far the single most expensive and most critical element of the SSC, the major effort during the past two years has been directed in this area.

2) to perform systems tests of the magnets and the associated cryogenic and control systems, and thus to optimize the systems aspects of the proposed machine;

3) to define the requirements that have to be satisfied by potential SSC sites;

4) to prepare a complete conceptual design of the SSC, including a detailed cost estimate, and the projected schedule for the construction, tests and start-up of the whole facility.

It was our initial belief that a three year period would be sufficient to accomplish all of these goals and provide firm data on the basis of which SSC construction could be approved with full confidence in its success. Even though the level of R&D funding has fallen short of our initial expectations we still believe that the initial target date can be met without undertaking any unacceptable risks. We have this confidence because we have been able to concentrate our limited resources on those problems that needed to be resolved before a final conceptual design can be generated.

Important milestones for FY 1985 were

- Develop site criteria for the SSC
- Select a Basic Magnet Type for complete development
- Verify power requirements for the SSC
- Continue development of superconducting materials and cable

All of these milestones have been met.

1) The site requirement document was submitted on schedule and, with DOE permission, made available to all interested parties. The requirements, as it turns out, are not very restrictive. There are many potential sites all over the U.S., regardless of which magnet technology is postulated.

2) A vigorous effort has been conducted to perform engineering and design studies of five basic magnet types. This has been a truly national effort with participation of several major U.S. national laboratories, universities

and industrial firms, and has resulted in a data base for an informed magnet choice.

3) Based on this work, a conductor-dominated, high-field magnet was chosen in September 1985 as the basis for the SSC conceptual design. (See attached File memorandum of 9/13/85.)

4) An extensive research effort into cryostat construction has resulted in a design that will significantly reduce the heat load on the refrigerator plant and thus result in significant operating power savings as projected in the Reference Designs Study.

5) A vigorous industry-university-national laboratory cooperative effort on improvement of the superconductor cable has resulted in a cable of current carrying capacity that has already exceeded the original expectations.

Two points need to be made here which summarize the results of this development effort. Firstly, the key assumptions that have been made in the May 1984 Reference Designs Study have been already confirmed or even surpassed. Secondly, our demonstrated ability to produce superconducting magnets of different types, which invariably have met the original design specifications, shows that the making of these magnets is a well understood engineering science rather than a delicate art that it was a decade ago. Thus one can have confidence that mass production of high quality superconducting magnets can be achieved for construction of the SSC. This belief is strongly reinforced by the operational experience of the Fermilab Tevatron, a synchrotron based on some 1,000 superconducting magnets, that has been now operating and producing physics results for over two years.

I would like to turn next to our plans for the future. Now that the basic magnet style has been selected we are proceeding with the optimization and testing of full length prototypes. We expect to have the first full length dipole magnet in its cryostat and ready for testing next April. Industry is already heavily involved in key areas of superconducting accelerator magnet technology. Now that the basic SSC magnet type has been determined it is desirable to involve industry as soon as possible in the remaining magnet R&D, from detailed design to assembly. A request for supplemental FY 1986 funding for this purpose has been submitted to DOE.

The magnet development effort to date has emphasized strongly the dipole (i.e., bending) magnets, since these are the most numerous and most critical components in the SSC. With the critical work in this area behind us, we are now ready to commence prototyping of other accelerator components, like the quadrupole (i.e., focusing) magnets and orbit correction system.

The results obtained from the ongoing research and development effort will be used to prepare a Conceptual Design Report of the SSC facility by the end of March 1986. This will be a non-site specific cost-optimized design of the technical and conventional systems. It will supply the technical and cost information needed for a DOE decision on whether to proceed with the SSC.

I should say a few words at this time about the systems test, sometimes called the string test, of the magnets. The prototype magnets, whose production is now beginning, will be fully tested individually after they are produced. In addition, we are planning to perform a systems test, designed to study their behavior as part of a complete system and at the same time test other large systems, like cryogenics and controls. During the FY86 period,

preparations will be made for this systems test, and the plans are to commence this test early in FY 1987 as soon as several prototype magnets are available.

If the needed budget support is forthcoming for FY 1987, industry-made prototype magnets will be available during 1987 and they will be tested at that time to ascertain that magnets mass produced by industry satisfy all the potential SSC requirements. In parallel with all the magnet development and construction, work will be performed on other accelerator systems like cryogenics, radio frequency cavities, injector components, and controls. The ultimate design of the accelerator complex must, of course, await decision on the siting. We hope that this decision will be made before the end of FY 1987 so that the construction could start in 1988.

I would like to conclude my remarks by discussing briefly the extent of international involvement in the SSC. Because of its reliance on large and, hence, expensive research facilities, particle physics has always had a strong international flavor, with physicists from one country frequently using accelerators in other parts of the world. Furthermore, there are several instances (e.g., CERN) of international cooperation on construction of accelerators, although this kind of collaboration has been limited to date to countries within one region. Because of its size and large initial cost, SSC is an ideal candidate for possible <u>interregional</u> collaboration in the construction phase. The high energy community in this country views with favor such a possible development, but because of the inherent complexity of such arrangements, the lead here must be taken by the governmental officials. In the meanwhile, however, we have been making efforts to collaborate on SSC planning with our European and Japanese high energy colleagues.

In assessing the extent of what is possible in this area one must take cognizance of the level of commitments of our foreign colleagues to their own domestic programs. At the present time, there are two large accelerator-construction projects underway in Europe, the large e^+e^- collider LEP at CERN, and the ep collider HERA being built at DESY in Hamburg, Germany. These two programs will absorb most of the European human and financial resources, at least until the end of this decade. In Japan, construction and commissioning of the e^+e^- collider TRISTAN will occupy the high energy community there for probably another two years. For now, our colleagues abroad are clearly preoccupied with their own vigorous accelerator construction programs. As these programs mature, possibilities for collaboration may well develop.

There has been significant interest expressed in the SSC by foreign physicists. We have received substantial help from both our Japanese and European colleagues by virtue of their participation in a number of SSC advisory panels, task forces, workshops and other planning activities. As a single example, the Magnet Selection Advisory Panel, which made the recommendation to me on the magnet style we should choose, included three foreign members and consultants.

The Canadian high energy community, at the annual meeting of its Institute for Particle Physics, has adopted a resolution strongly supporting the SSC and expressing its interest in collaboration. Cooperative efforts have been going on with the Japanese on understanding the effect of synchrotron radiation emitted by the 20 TeV protons on the quality of the vacuum in the beam tube. That collaboration has been formalized within the framework of a U.S.-Japan

agreement on collaborative efforts in high energy physics. Recently, a joint U.S.-Japan subcommittee has been formed to explore and review past joint efforts and make recommendations about their possible extension.

To conclude, we can all celebrate the progress that has been made in the research and development effort on the SSC. There has been a broad national involvement in this work, with significant foreign participation. Technically, the SSC today rests on a much firmer footing than it did at the time of the Reference Design. In the intervening period the physics research need for the SSC has been examined continuously and strongly reaffirmed. In early 1986 a conceptual design and detailed cost estimate will be delivered to the DOE for its consideration.

10/25/85

MT:SGW:dm

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One Cyclotron Road, Mail Stop 90-4040
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To: File, September 13, 1985

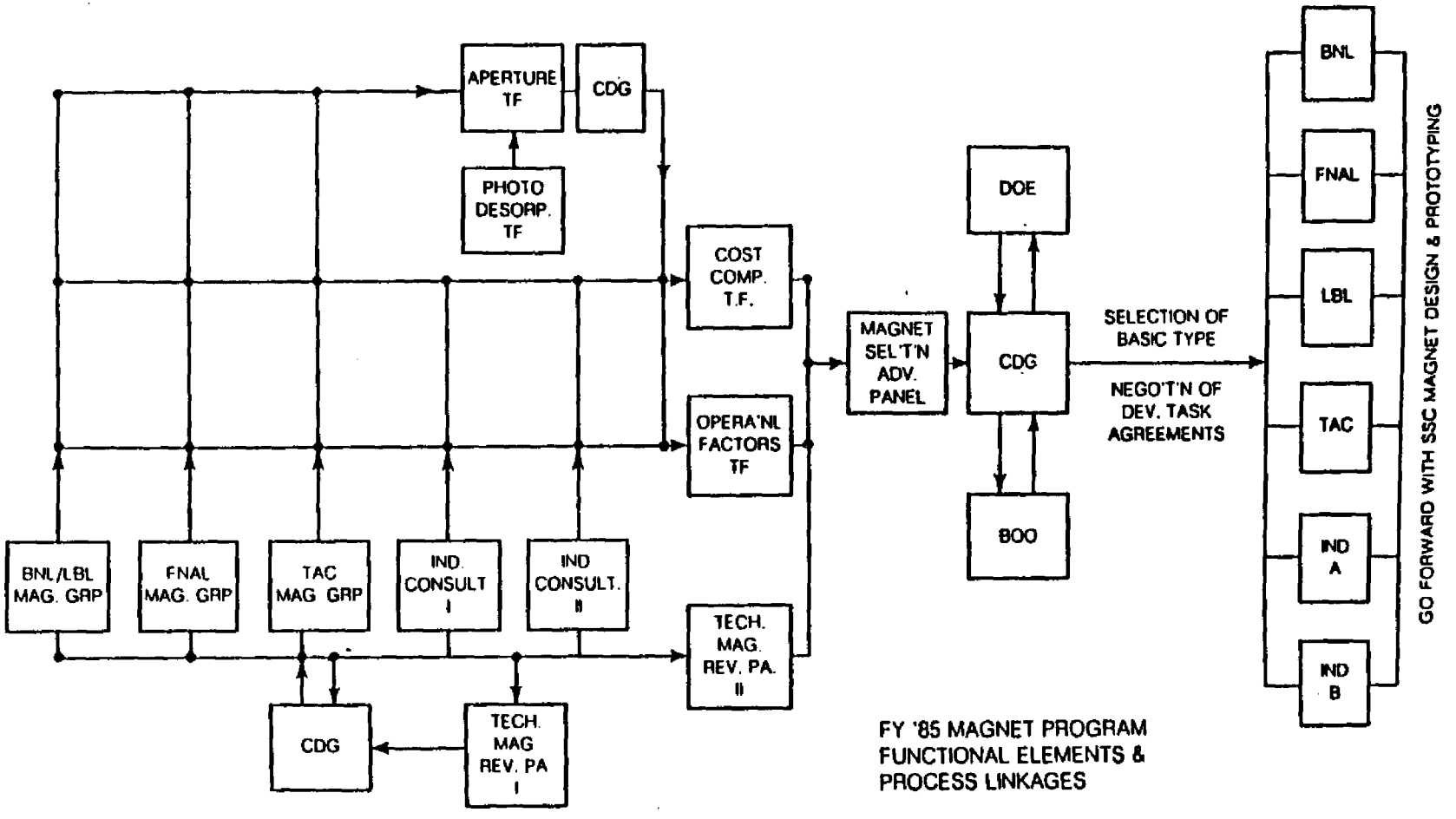
From: M. Tigner

Re: SSC Magnet Selection Process and Decision

The purpose of this memorandum is to convey the details of the selection process and the decision resulting from it.

The selection process was developed in consultation with the concerned community and made public in November 1984. It is diagramed in the attached figure. Early in FY 1985 a Technical Magnet Review Panel (TMRP) was convened to review the status of the SSC magnet R/D program and to recommend modifications to the ongoing program which would assure that the technical information needed would be available for a selection decision by the end of FY 1985. The TMRP, composed of senior representatives from the participating institutions, as well as disinterested parties with relevant technical expertise, delivered an interim report in December. Their recommendations were incorporated into subsequent agreements and contracts negotiated with the participating R/D institutions and industrial firms. Principal R/D institutions involved are Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Lawrence Berkeley Laboratory and Texas Accelerator Center. Eleven industrial firms were involved in a major way in the R/D program both in the development of superconductor and in engineering studies and modeling of superconducting magnets and magnet sub-assemblies. In superconductor development the University of Wisconsin has played a central role.

In addition to the results of model tests and engineering and manufacturing process studies, selection of a suitable magnet must take the needed magnetic aperture into account. Accordingly an Aperture Task Force, directed by the Central Design Group (CDG) and participated in by the world-wide community of experts in this matter was formed. Single particle dynamics, collective effects and vacuum considerations were taken into account. All of the information provided by the above mentioned activities were supplied to two task forces formed by the CDG with broad community participation. The responsibility of the Cost Comparison Task Force was to complete detailed cost estimates of all magnet-dependent SSC systems considering, in turn, all of the candidate magnet types. The responsibility of the Operations and Commissioning Task Force was to examine the operational implications of each of the candidate magnet types. In carrying out its responsibility the CDG Cost Comparison Task Force made independent analyses but received detailed input from proponents of the various candidate magnet types as well as magnet cost estimates and manufacturing plans produced by industrial firms under contract to



FY '85 MAGNET PROGRAM
FUNCTIONAL ELEMENTS &
PROCESS LINKAGES

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the CDG. The Operations and Commissioning Task Force received input from both European and U.S. experts in accelerator and storage ring operation. The TMRP, reconstituted with essentially its original membership supplemented by addition of a Japanese expert on superconducting magnets for accelerators, met during July 1985 for the purpose of reviewing and codifying the results of the SSC magnet R/D program. The TMRP final report was published August 5, 1985.

The reports of these task forces, as well as the background information supplied to them, were forwarded to a Magnet Selection Advisory Panel, along with the final report of the Technical Magnet Review Panel. The charge to the Magnet Selection Advisory Panel, including the criteria they were to use in making their recommendations and the composition of the Panel, were published in May, 1985 and reviewed by the Department of Energy in its annual review of the CDG in June 1985. The proponents of the various magnet types were given an opportunity to comment on the draft charge and proposed composition of the panel before formal announcement. The Panel members were chosen for their experience in large technical systems, superconductivity technology, accelerator design and operation, use of accelerators for particle physics, underground construction or experience with complex science and technical policy matters. They were: Professor Frank Sciulli, Columbia University (Chairman); Dr. Eberhard Keil, CERN; Dr. Neal Lane, University of Colorado; Dr. Michael McAshan, Stanford University; Dr. John Rees, SLAC; Mr. E. Parke Rohrer, Rohrer Associates; Dr. Alvin Tollestrup, FNAL and Chairman of TMRP; Professor Bjorn Wiik, DESY and University of Hamburg. In addition, three industrial consultants were appointed to advise the Panel. Each of the consultants and the firms with which they are associated have extensive experience in the technology of superconductivity and magnets utilizing it. They were Dr. Ray Beuligmann, General Dynamics Convair Division; Dr. Cord-Henrich Dustmann, Brown, Boveri et Cie; Dr. John Hulm, Westinghouse Electric Corporation.

The Panel and its Consultants met at Berkeley August 25-28, to hear presentations, deliberate and produce a first draft of their report. Two and one-half days were devoted to open meetings where presentations from the R/D participants and proponents of the various magnet types were heard as were reports on the several CDG analyses. In attendance, in addition to the Panel and Consultants, were five representatives of each of the four R/D centers, as well as representatives of URA and DOE. During the meetings ample opportunity was provided for airing of all views with relevant discussions.

The report of the Magnet Selection Panel, dated September 9, includes a statement signed jointly by the industrial consultants. The Magnet Selection Advisory Panel and its consultants were unanimous in their recommendation that a high field cosine θ, cold iron, single channel magnet be used as the basis for the SSC design.

We note that the Panel addressed the question of high field and cosine θ design separately, both in the context of the presently conceived SSC. The cosine theta type was favored by the Panel for its well understood behavior and its predictable cost. High field was favored by the Panel for operational

and cost reasons. They observed that the larger transverse impedance concommitant to the larger ring implies need for larger momentum aperture and substantially more powerful rf system for the larger ring by comparison with the smaller ring. The Panel pointed out that the larger energy stored in the beam of the larger ring will increase the cost of an SSC with the larger ring and that one should expect higher operating costs in the larger ring.

The charge to the MSAP did not explicitly include future options in the criteria for recommendation. Some have urged, however, that possibilities for future expansion be given weight and that a low field be used so that a next generation collider with, say 10 T magnets, could be put in the same tunnel. I find this argument to be unpersuasive for several reasons. We do not know what beam energy the physics will demand fifteen years hence, nor do we know what technology for colliders will be developed by that time. We do know that simple extension of our currently understood circular collider technology to energies substantially larger than 20 TeV is likely to be economically infeasible and some marked change in technology will be needed. Our extensive cost studies show that the SSC as currently conceived will be somewhat more expensive if built with a low field and large tunnel than with high field and smaller tunnel. Given the uncertainties of the future and the need to minimize the cost of the presently proposed SSC it would be irresponsible to choose the operating field on anything other than operational and cost effectiveness for the collider we need now.

With this in mind and after due consultation with senior colleagues, I have decided to accept the recommendation of the panel. What has been selected is a style, not a finished design. Production of an optimized and industrially producible design is the next order of business.

MT:dm
Attachment

MAURY TIGNER

Curriculum Vitae

Born April 22, 1937, Middletown, New York

Married 1960, children 2

Advanced education:

Attended Webb Institute of Naval Architecture

B.S., 1958, Rensselaer Polytechnic Institute, in Physics

Ph.D., 1963, Cornell University, in Experimental Physics and Electrical Engineering

Present position:

Director, SSC Central Design Group, Universities Research Association, June 1984 -.

Previous positions:

Research Associate, Cornell University, 1963-68

Senior Research Associate, Cornell University, 1968-77

Professor of Physics and Staff Member of the Laboratory of Atomic and Solid State Physics, Cornell University, 1977-present

Memberships in professional societies:

Member, American Physical Society

Member, American Vacuum Society

TESTIMONY BY E. PARKE ROHRER
A MEMBER OF THE
MAGNET SELECTION ADVISORY PANEL
FOR THE
SUPERCONDUCTING SUPER COLLIDER

E. Parke Rohrer, P.E.
Consultant

Subcommittee on Energy Development and Applications
Committee on Science and Technology
United States House of Representatives

October 29, 1985

Mr. Chairman: You have asked me to address the magnet dependent conventional construction costs for the SSC (Superconducting Super Collider) as developed by the Central Design Group. Although there are many magnet dependent conventional construction items such as utilities, etc., I will concentrate on the major magnet dependent item which is the collider tunnel or enclosure. In order to furnish the DOE with a realistic accurate cost estimate of a collider/tunnel which was not site specific, the Central Design Group and its architect-engineer came up with the median site concept. A median site was created by utilizing main ring sectors taken from four differing geological regions. (See Fig. 1.)

This method allowed for the development of representative cost estimates for tunneling in the absence of a specific site, and served to illustrate tunneling techniques customarily employed for each of the various types of conditions. It was envisioned that segments of the tunnels were cut through hard rock (igneous, limestone, or hard sandstone), through soft clayey silt with sand and gravel, and through areas where the land had first been excavated, the tunnel constructed and then covered with soil. Precast concrete pipe, cast-in-place concrete liners, or segmented precast concrete liners were used, as appropriate. Figure 2 illustrates the variation in surface elevation of the various geological sectors of the median site. The median site was developed for the 6.5T magnet design. The method of extending the median site to other sizes is described in Section 2.

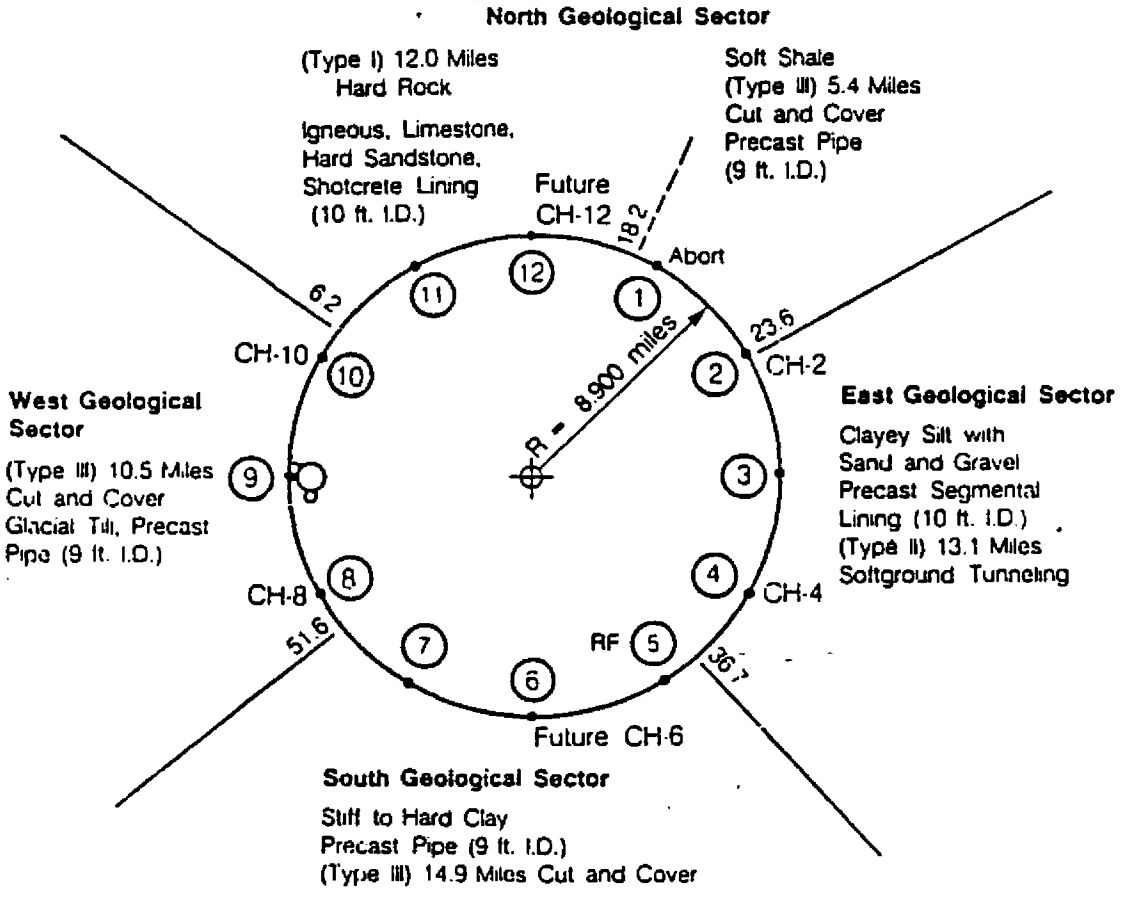


Fig. 1. The SSC main ring tunnel types in relation to the four hypothetical geological sectors and their composition. Mileage around the perimeter, clock position and the position of each collision hall are also indicated for a ring of 56 miles circumference.

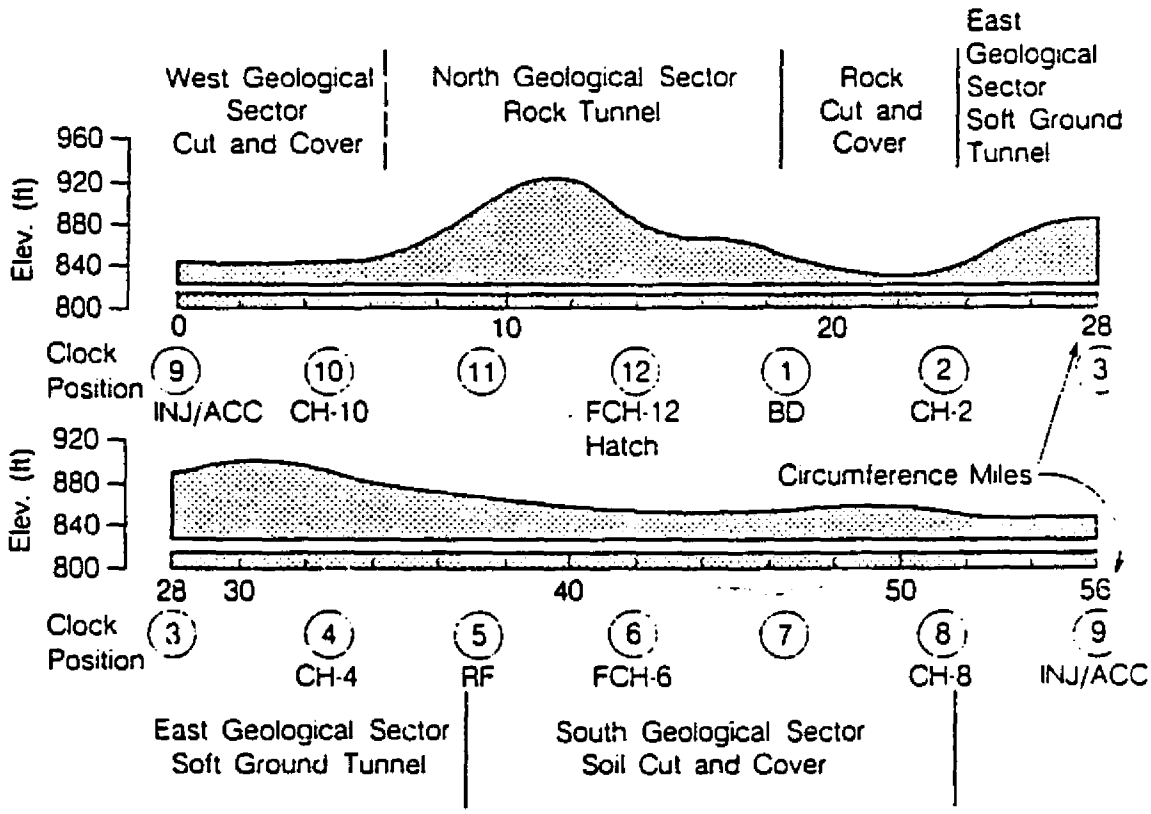


Fig. 2. Profile of assumed surface topography around the circumference of the main ring tunnel indicating the relationship between circumferential distance in miles and clock position and their joint relationship to main geological features and tunnel construction methods. Positions of the collision halls, rf acceleration section, injection to the SSC main ring, and beam dump are given to illustrate the nature of the overlying strata at these points (and thus assumed elevations). These features impact on construction costs and methods.

1. "Median Site" in the Reference Designs Study (RDS)

The north geological sector in the 56 mile ring in the RDS extends for 17 miles and varies from an elevation of 922 ft at mile 11.6 to 831 ft at mile 22. The beam dump is at mile 18.6, at depth of 30 ft, and collision hall 2 is at the eastern end of this sector at a depth of 17 ft. Surface deposits in this sector are sandy, silty clay to a depth of 10 ft, with some boulders up to 1.5 ft diameter. Layers of soft and hard rock can be found in this sector. Rock tunneling (Type I) is needed for the first 12 miles. This is bored with a machine and lined with shotcrete reinforced with welded wire fabric. Cut-and-cover tunneling in soft shale is needed in the last 5 miles of this sector and precast concrete pipe is used for this portion of tunnel.

The east sector extends for 13 miles and consists of sand and clayey silt near the surface, with sand and gravel increasing with depth. Surface elevation varies from 900 to 832 ft and, at collision hall 4, the surface elevation is 880 ft. Soft ground tunneling (type II) is assumed for this area, and the tunnel is formed from a precast segmented concrete lining.

The southern and western sectors extend 25 miles through hard clay and glacial till to a depth of 50 ft; the trenches in soil are stable, with near-vertical cut slopes, at depths up to 60 ft. Cut-and-cover tunneling (type III) is used for these sectors and precast concrete pipe is used for the tunnel.

The ring is interrupted at six locations by interaction regions (where the beams collide for physics experiments) and by three utility straight sections.

Two of the former areas are left undeveloped to allow for future expansion of experimental opportunities, while the other four are sites of the experimental halls and associated facilities. The complex of buildings at each interaction region is designed to allow the transport and assembly of experimental equipment, and to provide for the undertaking of long-term experiments. The utility straight sections contain the rf accelerating cavities, the injection system for the incoming beam, and the beam abort apparatus. Appropriate buildings are associated with each of these functions, and equipment access to the tunnel is provided.

2. Extension of the "Median Site"

The Median Site concept was developed to provide a technical baseline for conventional systems in the RDS. The A/E firm, Parsons Brinckerhoff, prepared this model so that civil, structural, electrical and mechanical engineers could do a design study under "almost realistic" conditions. As described earlier, the model was done for a 56 mile ring, employing 6.5T magnets, and extended to larger circumferences as required by the utilization of lower field magnets.

In order to illustrate how the median site can be extended, another illustration has been created. Assuming that the same proportions of geological conditions prevail, Figure 3 shows how the varying segments might appear. The length of such segments are shown as in Table I.

CONDITIONS:

GEOLOGICAL SECTOR		MATERIAL	METHOD
North	Type I	Hard Rock Igneous, Limestone Hard Sandstone	Shotcrete Lining (10 ft. I.D.)
North	Type III	Soft Shale	Cut & Cover Precast Pipe (9 ft. I.D.)
East	Type II	Clayey Silt with Sand & Gravel	Precast Segmental Lining, Softground Tunneling (10 ft. I.D.)
South	Type III	Stiff to Hard Clay	Cut & Cover Precast Pipe (9 ft. I.D.)
West	Type III	Glacial Till	Cut & Cover Precast Pipe (9 ft. I.D.)

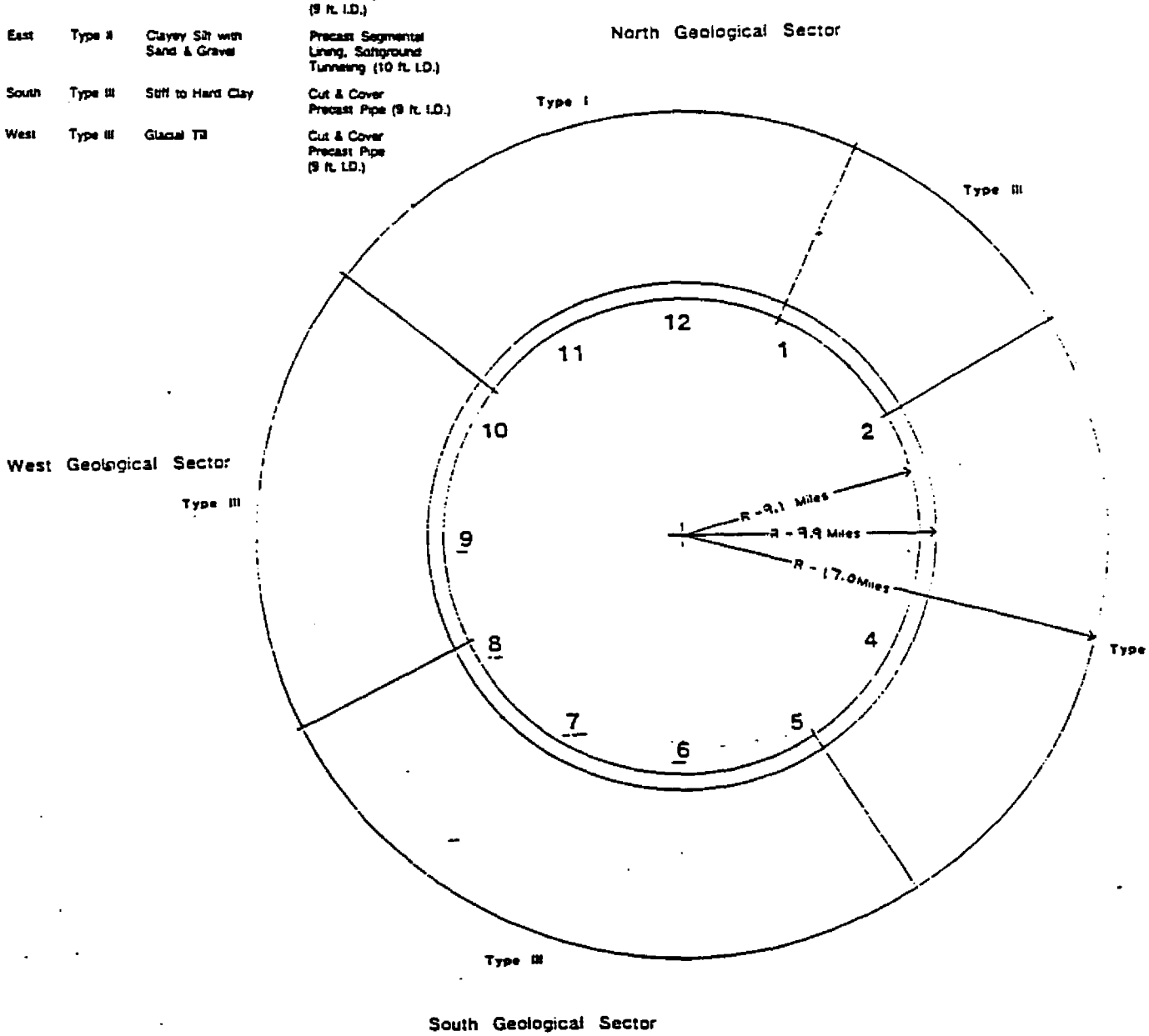


Fig. 3. Extension of Median Site Concept to Three Ring Sizes.

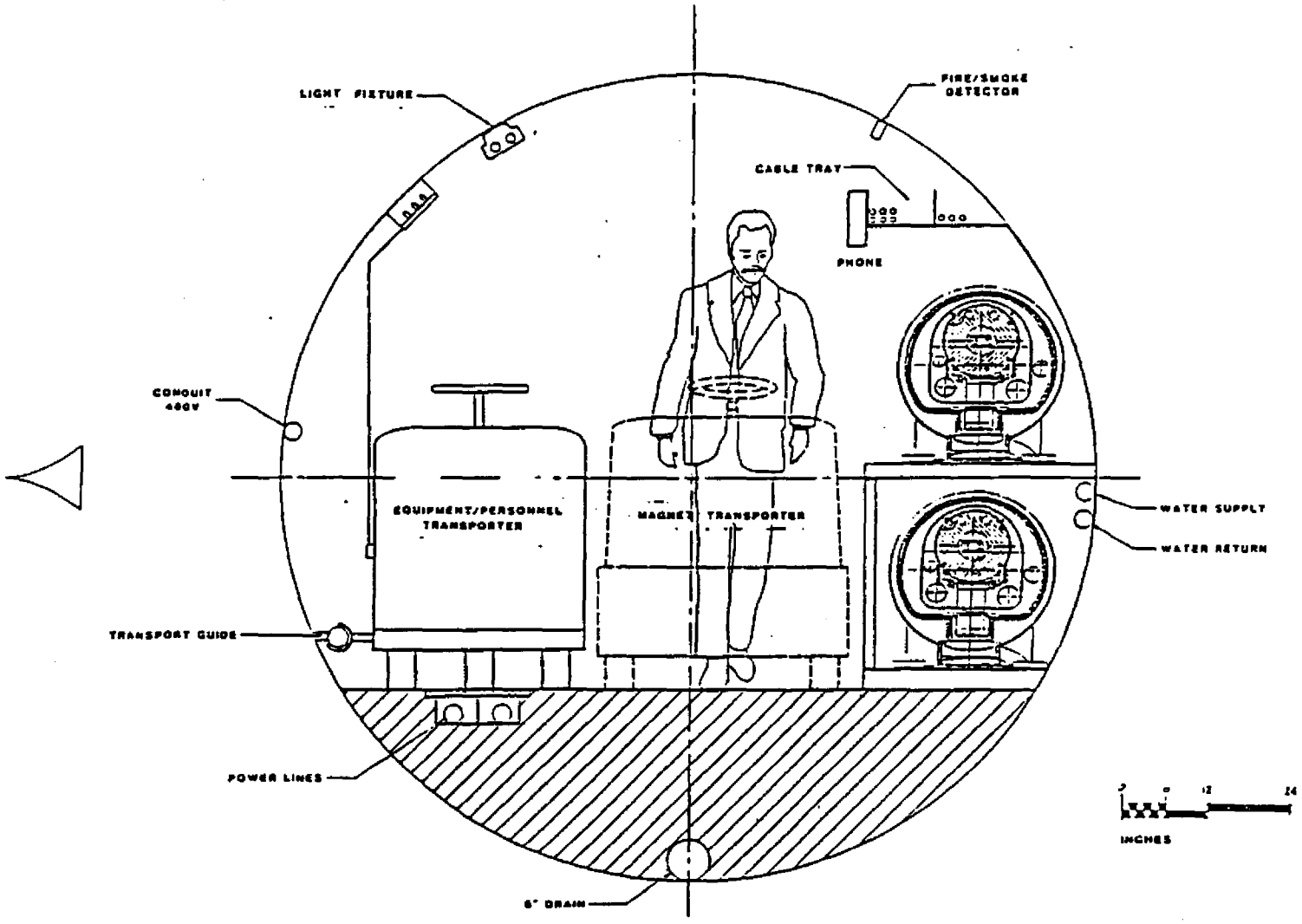
Table I
Length of Typical Tunnel Segments

Design Style	A, D	B	C, C*
Type I	64,806	70,442	121,160
Type II	70,722	76,872	132,220
Type III	166,317	180,779	310,940
Circumference (feet)	301,845	328,093	564,320
Circumference (miles)	57.2	62.1	106.9

3. Technical Considerations

In the RDS, a 9 or 10 ft internal diameter tunnel is assumed to lie in a horizontal plane at an average depth of 40 ft below the surface. The superconducting magnets and other beam handling devices are positioned and aligned in the tunnel. Vacuum pipes, cryogenic systems, power supplies, and instrumentation services must be provided. Space in the tunnel must also be allowed for suitable personnel and equipment transporters. In addition, adequate aisle space must be provided for the people who will work on technical components in the tunnel.

Recent work at the CDG has examined two tunnel cross sections. The arrangement of equipment, piping, magnets, transporters and working space can be seen in Figs. 4 and 5. The tunnel shell in the example is shotcrete lined, with welded wire fabric reinforcement, typical of hard-rock tunneling construction. A poured concrete floor results in a level, 8.3 ft wide working surface within a 9-10 foot circular cross section. Floor drainage is installed. Lighting fixtures and a cable tray are anchored in the roof and



TUNNEL CROSS SECTION

Fig. 4. Tunnel Cross Section Magnet Design D

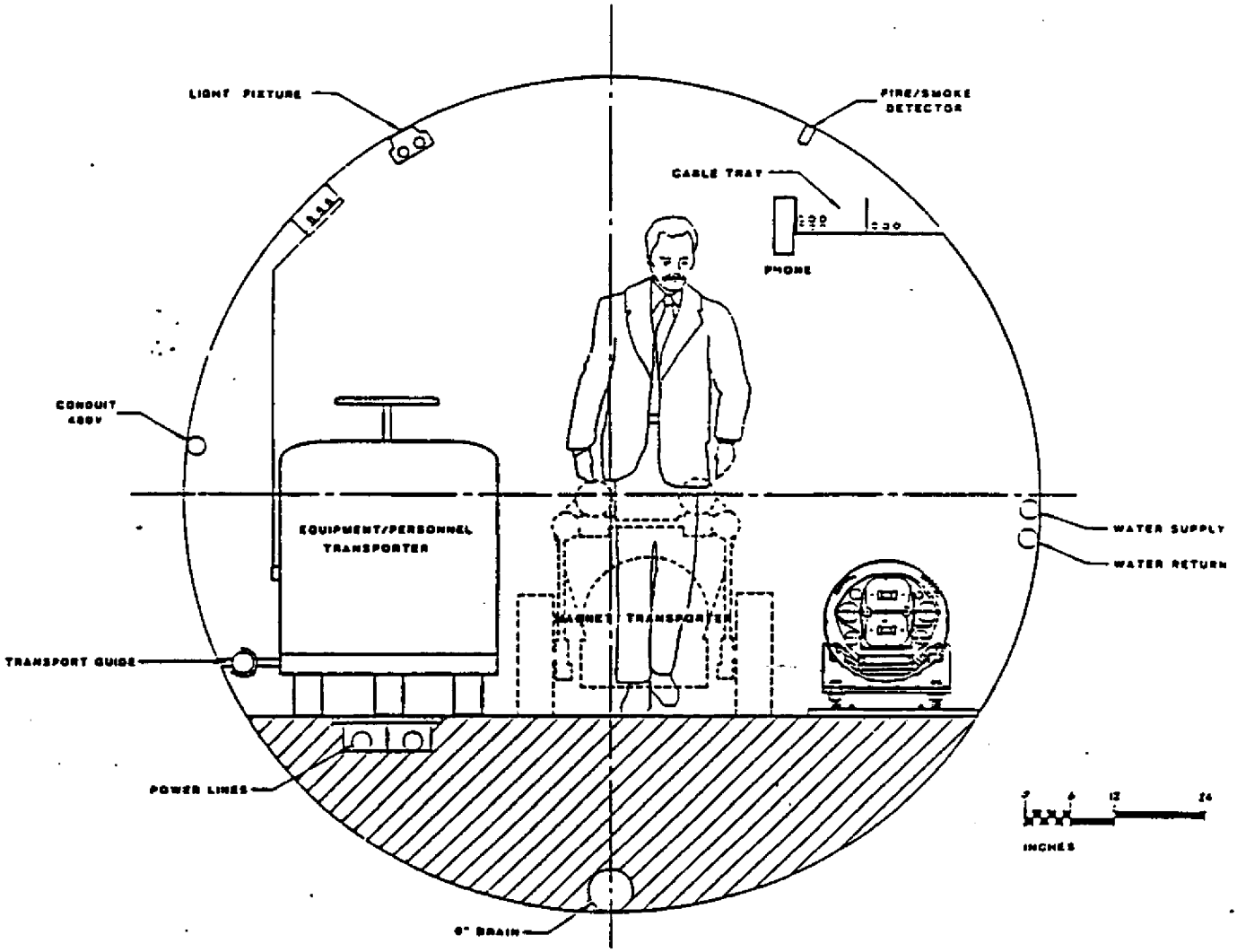


Fig. 5. Tunnel Cross Section Magnet Design C

conduit racks are fixed to the wall on the magnet side of the tunnel. These last items support lines for compressed gas, 480 V electrical cable, water supply and return lines, and a warm-helium gas return line. Periodically a signal area containing a telephone, signaling system, fire pull alarm, and space for monitoring instrumentation is located on the wall.

Normal and purging ventilation are provided, complete with the necessary fans, ducts, outlets and controls. Ventilation is an important feature in the tunnel due both to its length and because of the large numbers of people working at a variety of activities during the construction phase. An additional need for the ventilation is to replenish the atmosphere quickly if a large volume of helium were accidentally vented into a section of the tunnel during tests or operations. Matters of tunnel access for installation, and servicing coupled with safety consideration lead to using tunnel cross sections for this study similar to those used in the RDS.

4. Unit Costs

A) Tunnel

The A/E firm developed unit costs for the three different tunnel types by a careful evaluation of the appropriate method of construction in each case. By assembling information on materials and labor requirements, rate of advance, etc., Parsons Brinckerhoff provided a basis for a cost estimate of the tunnels. This information was combined with the costs for access shafts, exits, auxiliary buildings, etc., to form an overall cost for the collider ring.

Recently, another A/E firm, RTK (Raymond Kaiser Engineers, Tudor Engineering, Keller & Gannon-Knight), has been engaged. One of their first

tasks was to consider the cost of tunnels such as those used in the RDS. RTK chose to examine the data from a variety of completed tunnels. For the analysis, case histories and data on 84 tunnels used by the U.S. National Committee on Tunneling Technology (USNCTT) were used. The raw USNCTT data were originally analyzed for the USNCTT by Don Rose, a member of the RTK team. The USNCTT data are drawn nationwide and represent a recent study published in June, 1985. The USNCTT cost data have been normalized and are the final as-built cost including all paid claims and change orders.

a. Hard Rock Tunnels (Type I). The USNCTT weighted average cost for hard rock tunnels excavated by tunnel boring machines (TBM's) is $323/CY. The USNCTT costs are all normalized to July, 1982, costs and have been increased by 3.7% to compare to 1984 costs used in the RDS. This USNCTT cost is given in $/CY and must be converted to $/LF for comparison with the RDS. For an 11-foot outside diameter hard rock TMB tunnel, the USNCTT weighted average cost, updated to the first quarter of 1984, is $1180/LF.

b. Soft Ground Tunnels (Type II) The USNCTT weighted average cost for soft ground tunnels is $300/CY. The USNCTT costs are all normalized to July, 1982, costs and have been increased by 3.7% to compare to the RDS. This USNCTT cost is given in $/CY and must be converted to $/LF for comparison with the RDS. For an 11-foot outside diameter soft ground tunnel, the USNCTT weighted average cost updated to the first quarter of 1984, is $1,095/LF.

c. Cut and Cover Costs (Type III) The scheme considered an open cut about 45 feet deep with steep side slopes open for a relatively short time. These slopes are assumed stable in all weather conditions the

year around, provided no groundwater problems exist. An unusually wide bottom width is provided to allow special vehicles to carry precast pipe alongside the finished work. The precast pipe would be carried from the plant to a point near to the excavation, a distance of up to several tens of miles. The excavation work lends itself to mass production work using innovative excavators, or conventional scrapers and tractors. Different bidders will no doubt select different methods and equipment. For this report, the cut/cover scheme shown in the RDS has been evaluated by an RTK study with reference to federal, state and private agencies for costs comparable of work done using conventional equipment. RTK believes the cut/cover tunnel will cost $873/LF (first quarter 1984 prices) for the example studied. The average cost for all cut and cover costs (Type III) described is estimated as $780/LF.

d. Summary The recent evaluation by RTK can be conveniently compared to the earlier work by looking at Table II. There is excellent agreement between these independent estimates by experienced A/E firms.

B) Ramps/Slots

There are several differences that arise from the choice of magnetic field and corresponding style of magnet. The different circumferences have been addressed earlier, although there are additional items that must be considered. First of all, the allowance for site infrastructure (such as roads, utilities) must scale with the circumference. In addition, the number of exits will be increased in proportion to the increased tunnel length, thereby keeping fixed the distance between exits within the tunnel.

Table II
Unit Cost Estimates for Tunnel Types
($ Per Linear Foot)

	RDS	RTK	CDG Value
Main Ring Tunnel - Type I	1,150	1,167; 1,180	1,160
Main Ring Tunnel - Type II	1,100	1,095	1,100
Main Ring Tunnel - Type III, avg	755	780	770
Weighted Avg., Types I, II, III	920	-	930

The total Conventional Facility costs for the Collider Ring WBS 1.4.1 are shown for the five designs in Table III.

In contrast to the position taken during the RDS, the same number of refrigerator/compressors stations (12) will be used in all the configurations. This will change the distance between stations from 5 miles in Design A to almost 9 miles in Design C.

Because it is envisioned that the very long superferric magnets will be assembled at four places adjacent to the collider ring, a number of adjustments must be made to the plan for a campus works area, and to the approach used for getting the 380 ft magnets into the ring. One might expect to need more works building space due to the assembly areas being dispersed.

The predominant effect of the long magnets is to require access ramps or slots at four locations to move assembled magnets down into the tunnel. RTK has done a study of this approach using a depth appropriate for soft ground tunnels. In FY84 dollars they have established a cost of $5.7M each for a ramp scheme and $3.4M each for a vertical slot scheme.

Table III
Conventional Facility Cost Comparison Summary
(FY 84K$)

	MAGNET STYLE:	A	B	D	C	C*
	PARAMETER VALUES:					
	FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
	CIRCUMFERENCE, MI	57.17	62.14	57.17	106.88	106.88
	(CIRCUMFERENCE, KM)	92.00	100.00	92.00	172.00	172.00
(WBS) 1.4.1	CONVENTIONAL FACIL. SYSTEMS,					
.1	LAND IMPROVEMENTS	15,300	16,631	15,300	28,605	28,605
.2.1	TUNNEL TYPE I	88,038	95,693	88,038	164,592	164,592
.2.2	TUNNEL TYPE II	90,249	98,097	90,249	168,726	168,726
.2.3	TUNNEL TYPE III	154,292	167,709	154,292	288,459	288,459
.2.4	TUNNEL (OTHER ELEMENTS) (CRYO, BM DUMP, RF, ETC)	13,927	13,927	13,927	13,927	13,927
.3	CRYOGENIC FACILITIES	7,998	7,998	7,998	7,998	7,998
.4	SUPPORT BUILDINGS	1,750	1,902	1,750	3,272	3,272
.5	UTILITIES	38,822	42,198	38,822	72,581	72,581
.6	ACCESS SHAFTS	0	0	0	13,540	13,540
	TOTAL CONVEN. FACILITIES	410,376	444,154	410,376	761,700	761,700

The SSC Central Design Group in its presentation to the magnet selection advisory panel used the median site weighted average of $930 per linear foot of tunnel as the basis for deriving the total tunnel costs applicable to the various magnet designs.

Dr. John Rees, a panel member for SLAC, and myself were assigned to the Conventional Facilities aspect of the SSC Magnet Advisory Panel. We both believe the figure of $930 per linear foot for determining the total tunnel cost for a representative site on which the SSC could possibly be constructed is both prudent and realistic.

E. Parke Rohrer

EPR:lcm

Rohrer Associates Inc.
Management, Engineering, Construction Consultants
E. Parke Rohrer P.E. President

E. PARKE ROHRER, P.E.

BIRTH: June 22, 1924 Lancaster County, PA

EDUCATION: B.S.M.E. New York University, NY

PROFESSIONAL LICENSE: Pennsylvania & California (Both by examination)

PROFESSIONAL EXPERIENCE: Most recent first

1984-date PROJECT MANAGER Construction of multi-purpose Complex
JAARS Center, Waxhaw, NC

1977-1983 BROOKHAVEN NATIONAL LABORATORY, Long Island, NY

1981-83 DEPUTY DIRECTOR Colliding Beam Accelerator Project

1977-81 DIRECTOR DESIGN & CONSTRUCTION of Conventional Facilities for Intersecting Storage Accelerator

1961-1976 DANIEL, MANN, JOHNSON and MENDENHALL (DMJM)
International consulting architectural engineering firm

1974-76 V.P. DIRECTOR OF REGIONAL OFFICES
10 Branch Offices from Honolulu to Washington, DC

1968-74 V.P.DMJM - GENERAL MANAGER JOINT VENTURE of Four Firms responsible for Design & Construction (AEM) of Fermi National Accelerator Laboratory Conventional Facilities

1966-68 CHIEF ENGINEER - HOME OFFICE
Daniel, Mann, Johnson and Mendenhall, Los Angeles, C

1961-66 FAR EAST MANAGER DMJM Tokyo, Japan
Master Planned, designed, and managed construction for all Military Facilities in Japan, Korea, Taiwan and Okinawa for all Branches of Services

1957-1961 GENERAL SUPERVISOR - ROHR CORPORATION, Riverside, Cal.
Responsible for Conventional and Manufacturing Facilities Design and Construction in manufacture of metal-bonded honeycomb structures

1952-1957 PROJECT ENGINEER - Armstrong Cork Company, Lancaster, PA
Central Engineering Department

1946-1952 Formal Education

1943-1946 U.S.Army Air Corps

Magnet Selection for the Supercollider

Frank Sciulli, Columbia University

Testimony before the Subcommittee on Energy Development and Applications, Committee on Science and Technology, U.S. House of Representatives

October 29, 1985

A brief biographical sketch is enclosed with my written submission. Of relevance to my appearance here is my familiarity, through my own research, with large experimental systems in the field of Elementary Particles and my experience with advisory tasks of a similar nature. Over the past several years, I have been asked to advise each of the various laboratories and the funding agencies on the approval and review of large technical projects.

My purpose today is to review for this Subcommittee the process of magnet selection for the Superconducting Super Collider. I was asked by the director of the Central Design Group (CDG) to serve as the chairman of a Magnet Selection Advisory Panel to advise him on the selection of the most appropriate magnet element for the SSC. This formal selection process is unusual, reflecting the importance attached by the U.S. High Energy Physics community to securing the best and most cost effective possible technology for the SSC design.

There were two basic, and rather different, design concepts advocated. The $\cos\theta$ magnet, which obtains the magnetic field solely through use of current-carrying superconductor, is exemplified by the "D" design; the superferric magnet, which obtains the magnetic field partly through the use of superconductor and partly through the placement of iron, is exemplified by the "C" design. Since the D design achieves a magnetic field about twice as large as that of the C design, a given accelerator need only be half the circumference utilizing the D design. More detailed descriptions of these and other candidate magnets, as well as recommendation of the panel, can be found in the Panel's report, "SSC Magnet Selection Advisory Panel Report to the Director of the Central Design Group, September 9, 1985".

The charge to the Panel and the membership of the Panel were chosen several months in advance of its meeting. These were specified by the director of the Central Design Group in consultation with myself and with each of the four proponent R & D centers: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley Laboratory (LBL), and the Texas Accelerator Center (TAC). The proponents had direct impact on both the Panel charge and its membership.

The complete charge to the Panel is included in the Panel's report as Appendix B. I quote here from this charge the criteria for selection to be used in the selection process.

... "The Criteria to be used in making an overall recommendation are:

1. Relative capital cost of an SSC facility employing a particular Basic Magnet Design.
2. Workability of the Basic Designs presented.
3. Complexity of the overall magnet system inherent to the particular Basic Design.
4. Operational complexity of an SSC employing the particular Basic Design.
5. Relative flexibility of an SSC design employing the particular Basic Design.
6. Likely impact of the Basic Magnet Design on the SSC construction schedule.
7. R & D time and effort needed to develop the Basic Design.
8. Accelerator Physics considerations.
9. Other considerations deemed appropriate by the Advisory Panel."

The approximate relative weight applied in making the recommendation is in the order indicated in the charge, with particular emphasis on the first four items. I emphasize that this was largely a technical decision based on technical information.

Clearly, to make such a recommendation requires individuals encompassing broad technical expertise in magnets, magnet systems, and construction of physical plant to house the accelerator. I believe that the membership of the Panel reflected both breadth and depth in this regard. The individuals constituting the Panel are listed:

Frank Sciulli, chairman - Columbia University.

Eberhard Keil - CERN
Well-known accelerator physicist with experience in the design and operation of large accelerator systems, including the CERN ISR and LEP.

Neil F. Lane - Univ. of Colorado
Theoretical physicist highly knowledgeable in science policy. Chairman, Physics Dept., Rice Univ.; Assoc. Director for Physics at NSF; Chancellor at Univ. of Colorado.

Michael S. McAshan - Stanford Univ.
Low temperature physicist at HEPL Lab highly experienced in design and construction of large cryogenic systems.

John Rees - Stanford Univ.
Responsible for construction, commissioning, and operation of the SLAC PEP facility. Associate Director of SLAC, responsible for construction of the SLC facility.

Parke Rohrer - Rohrer Associates
Expert on conventional construction. Head of DUSAF construction at Fermilab; responsible for conventional construction for the CBA facility at Brookhaven.

Alvin Tollestrup - Fermi National Accelerator Laboratory
Experimental physicist renowned as a problem solver for technical problems affecting accelerators; instrumental in resolving the technical difficulties of the early SAVER/TEVATRON magnet design.

Bjorn Wiik - Univ. of Hamburg; DESY
Experimental physicist with long experience at DESY accelerators. Presently, as Associate Director at DESY, has primary responsibility for the proton beam magnet systems of HERA facility.

Consultants to the Panel:

Ray F. Beuligmann - Vice President for Research and Engineering, General Dynamics Convair Division.

Cord-Henrich Dustmann - Group Leader for Marketing and Development of Superconducting Magnets, Brown, Boveri, and Cie.

John K. Hulm - Director of Corporate Research, Westinghouse R & D Center.

In order to be well informed on the technical issues, the Panel obtained a large quantity of detailed information prior to the meeting, which is listed below and included as Appendix C of the Panel Report.

(mailed August 16, 1985)

1. Report of Cost Comparisons for SSC Magnet-Dependent Systems, SSC-SR-1012, (August 15, 1985).
2. SSC Aperture Estimate for Cost Comparisons, SSC-SR-1013, (August 9, 1985).
3. Recent Magnet Test Data and Information from BNL (August 2, 1985).
4. Recent Magnet Test Data and Information from FNAL (August 5, 1985).
5. Recent Magnet Test Data and Information from TAC (August 15, 1985).

(mailed August 5, 1985)

6. Report of Technical Magnet Review Panel, SSC-SR-1010 (July 25, 1985) (and cover letter of Chairman TMRP).
7. SSC Interim Report, SSC-SR-1011 (June 1985).
8. Vol. 1 Reference Designs Study Report (May 8, 1984).
9. Agenda for August 25 meeting.

(mailed July 8, 1985)

10. Report of Task Force on SSC Commissioning and Operations, SSC-SR-1005, (July 1, 1985).

These include detailed information on the technical magnet designs by the proponents, the report of a special task force on commissioning and operating, as well as the cost comparisons compiled by the Central Design Group. Furthermore, considerable additional technical material was available to the Panel members prior to and during the meeting.

The Panel, including Consultants, formally met on the days beginning Sunday, August 25 until Thursday, August 29. The detailed agenda of the meeting is included as Appendix D of the report. Briefly, the first day was primarily concerned with technical issues having to do with the magnet designs, status of the R & D on those designs by the principle advocates, and technical questions posed by the Panel to the proponents to be answered later. The morning of the second day was devoted to issues involving the commissioning and operation of an accelerator built using each of the candidate magnets and the cost of magnets and related costs (including tunneling) as summarized by the Central Design Group. Most of the afternoon of this day was spent in open discussion by participants and Panel of all relevant issues. The principal issue contested was the cost summary of the Central Design Group, as argued by the proponents from the Texas Accelerator Center. Ample opportunity was provided for relevant issues to be aired; a summary of the points of contention was provided by the TAC and was included as Appendix H of the report. The morning of the third day was spent in hearing responses by the proponents to technical questions posed by the Panel. In my opinion, these two and one-half days of testimony provided adequate time to explore all relevant issues. There were no requests to prolong testimony on any relevant issue beyond that time by any participant.

The remaining two and one-half days were spent in deliberations by the Panel in executive session and drafting of the report. I emphasize that the thrust of these deliberations was in response to the criteria described above. That is, these were technical issues discussed by a group of technical experts.

An outline of the principle judgments and recommendations made by the Panel follows:

(1) There is at present adequate information on which to base a technical decision about the magnet type.

(2) The high-field, cosθ, one beam per cryostat (design D) is recommended unanimously.

(3) A cosθ version with two beams per cryostat (deign B) is rejected due to commissioning and operating complication.

(4) The promise of two years ago that the superferric design would provide a simpler, cheaper SSC has not come true. The complexity of the superferric magnet (design C) has increased with time.

(5) The total magnet-related costs for the cosθ and superferric designs, as presently conceived, are comparable. The Central Design Group costs comparisons indicate that the superferric system would be more expensive.

(6) The Panel questioned the contingency costs used by the Central Design Group for the superferric design (C). These presumed that the magnet as presently designed would be constructed. In the Panel's view, there is a real possibility that further R & D will indicate even higher total project costs than provided by the CDG for the superferric design, exclusive of R & D costs.

(7) The long R & D history and production experience on the cosθ style was deemed adequate to provide a reliably predictable cost estimate for the D design.

(8) The Commissioning and Operations considerations indicate higher operating costs for a larger ring, or lower field magnet.

(9) The Industrial Consultants stated that both styles were buildable by industry, but that there is a higher degree of cost and schedule uncertainty with the superferric style magnet. They agreed with the Panel that the cost contingency factor for the superferric style should be greater than stated.

It is perhaps worth noting several issues which affected these recommendations, and which were considered in depth by the committee.

(a) The TAC group argued at the meeting that the appropriate maximum magnetic field should be presumed 6 1/2% higher than previously assumed. Based on their own technical evaluation, the Panel did not agree with this argument.

(b) Since these magnets are presumed to be constructed by industry, there were issues related to the readiness of each design for production and the reliability of the magnet cost estimates for production. Drs. R. Beuligmann, J. Hulm, and C.-H. Dustmann are present today. Dr. Beuligmann's testimony will relate to these issues.

(c) The TAC group argued at the meeting that the tunneling costs used by the Central Design Group were too high. The Panel did not agree. Mr. E. Parke Rohrer and Mr. Keith Bull are present today, and there will be testimony on this issue. This is relevant because the fraction of total magnet-related cost for tunneling is higher for the superferric C design than for the cosθ D design. However, I should mention that, so long as we discuss the range of values discussed to date on the tunneling costs, this is <u>not</u> the crucial issue on which the decision turns. Even with the lower tunnel costs advocated by the TAC group, the CDG estimates show the superferric total costs to be higher. Furthermore, this is without any added contingency for producing the C-magnet, judged necessary by the Panel.

Biographical Sketch

Frank Sciulli

Birthdate: August 22, 1938

Education

A.B.	University of Pennsylvania	1960
M.S.	" "	1961
Ph.D.	" "	1965

Positions

Research Fellow, Univ. of Pennsylvania	1965-66
Research Fellow, Caltech	1966-68
Assistant Professor, Caltech	1969-71
Associate Professor, Caltech	1971-77
Professor, Caltech	1977-80
Professor, Columbia University	1981-

Recent Service

High Energy Physics Advisory Panel (DOE), 1977-81
Physics Advisory Committee (Fermilab), 1981-84
HEPAP Woods Hole Subpanel, 1982
DOE Advisory Panel for Non-Accelerator Experiments, 1981-83
URA Visiting Committee at Fermilab, 1982; Chairman 83,84
Tevatron Association of Fixed Target Spokesmen,
  Executive Committee, 1984-85
NSF Advisory Committee for Physics, 1984-
Associate Editor, Zeitschrift fur Physik, 1985-
Magnet Selection Advisory Panel for SSC, Chairman 1985

Research Activities

Primarily in experiments on the Weak Interactions of Elementary Particles.

For the past fifteen years, I have carried out a program of experiments dealing with the interactions of neutrinos with matter. Presently, I am beginning involvement with an experiment (ZEUS) to investigate electron-proton interactions with colliding beam energies at HERA.

24 October 1985

The Honorable Don Fuqua
Chairman
U. S. House of Representatives
Committee on Science & Technology
Suite 2321 Rayburn House Office Building
Washington, D. C. 20515

Dear Mr. Fuqua:

We, Dr. Raymond F. Beuligmann, Dr. Cord-Henrich Dustman, and Dr. John K. Hulm were invited to serve as industrial consultants to the Magnet Selection Advisory Panel (MSAP) to assist in the selection of the SSC magnet type from a set of five proposed basic magnet styles. The panel met for four days, August 25-28, 1985 and we were present and heard all of the testimony from proponents of the various styles and from members of the SSC Central Design Group. We participated in the executive sessions of the panel. We were able at all times to ask questions of the proponents and of the panel members. We were consulted by the panel throughout these executive sessions. The panel charged us, the industrial consultants, to comment on those factors relating to all aspects of industrial production of the SSC magnets, with specific reference to design C and D. We addressed our comments to:

(1) Defining the elements of an R&D phase and the respective status of maturity of designs C and D in successfully completing this R&D phase.

(2) Determining the viability of transitioning either design C and D successfully into industry for full-rate production.

(3) Recommending steps for involvement by industry with the SSC magnet development groups so that an orderly transition of technology sufficient to permit competitive bidding on production magnets could be achieved.

(4) Comparing the costs to develop and the costs to produce magnet designs C and D.

The industrial consultants report was sumitted to the panel and became Appendix G of the MSAP report. Appendix G is attached herein.

Sincerely,

Dr. R. F. Beuligmann Dr. C. H. Dustmann Dr. J. K. Hulm

APPENDIX G. STATEMENT OF THE INDUSTRIAL CONSULTANTS

As industrial consultants to the Magnet Selection Advisory Panel, we have been asked to comment on those factors relating to all aspects of industrial production of the SSC magnets, with specific reference to designs C and D. We perceive the following major factors to be relevant to support the MSAP deliberations.

R&D Phase

In our definition, the Research and Development phase is finished when the following are completed: material specifications, component detail design and testing, analyses, tool design, manufacturing processes, and prototype testing. We are in unanimous agreement that on this definition, the cos θ style magnet is at a more advanced state of development than the superferric style magnet, for the following reasons.

The cos θ style has an extensive base of R&D, testing, production and operating knowledge. More than 1000 units have been incorporated in a large machine which is in successful operation. Extensive R&D has continued to refine the cos θ style design in the past several years. We believe that the cos θ design is a mature technology.

A very limited data base exists for the superferric style magnet. The first long superferric magnet will be tested in the first quarter of FY 1986. It is our conclusion that the superferric style magnet technology is not mature. There are more unknowns in the superferric style design. This should be interpreted as higher risk and longer R&D schedule needed for the superferric style.

It is our judgment that the superferric style will need at least two years more R&D development time than the cos θ style design.

Production Phase

We conclude that either style magnet design in its present state of development, can be produced in industry and achieve the production rates specified in the CDG plan. Manufacturing studies have already been performed by General Dynamics, Westinghouse and Brown Boveri. General Dynamics has assembled one 1 m magnet and one 28 m magnet of the superferric style. Brown Boveri has already built eight magnets of the cos θ style, four for the Brookhaven RHIC and four for HERA at DESY. Thus, we conclude that from the point of view of producibility there is no reason to chose one style over the other.

It is our view that the production rate required by the CDG plan can be successfully met, provided that the following involvement with industry is achieved:

1. The current level of industrial involvement should be increased in order to meet the present CDG construction schedules. Industry should have the experience of doing the production plan and assisting the magnet-development laboratories in the detail design, fabrication, and testing of prototype magnets prior to the preproduction phase.

2. Industry must have the experience of doing the tool design, tool fabrication, and magnet fabrication of the preproduction magnets in their own shops prior to production contract awards. The deliveries of production magnets per the CDG plan can start 12 months after production contract award.

Costs and Schedules

We believe that the CDG cost estimates are sufficiently accurate to support the decision of selecting the magnet style for the SSC at this time. There is a higher degree of cost and schedule uncertainty with the superferric style magnet. The contingency factors applied for the two magnet styles by the CDG are relatively close. We feel that the cost contingency factor for

the superferric style should be greater than stated, due to the higher degree of uncertainty both in cost and development schedule.

As an example of the higher uncertainty of production costs for style C, we note that the cos θ style coil can be warm tested for field quality prior to insertion into the yoke. The superferric style cannot be warm tested in a similar manner due to the non-linear field dependency for the iron. Therefore, the quality of superferric windings can only be verified in a final cryogenic test. This type of in-process test cited as possible for the cos θ magnet is very important in reducing costs in production. We draw attention to this difference as support for the argument of having a higher cost contingency factor for the superferric style design.

C.H. Dustmann, Brown Boveri

R.F. Beuligmann, General Dynamics

J.K. Hulm, Westinghouse

RAYMOND F. BEULIGMANN, Ph.D.
Vice President, Research and Enginering
General Dynamics Convair Division

Biographical Summary

Education: University of Illinois, B.S.E.E., 1957
University of Illinois, M.S.E.E., 1958
University of Illinois, Ph.D.E.E., 1961

Dr. Beuligmann joined the General Dynamics Pomona Division in 1961. In his 15 years with this division he has a wide range of engineering experience from technology development to full-scale engineering design and transition to production for guidance and control systems, fire control systems and tactical missiles. He was director of design engineering for the Pomona Division in 1976 when he transferred to the Convair Division in San Diego.

Dr. Beuligmann was Vice President of Research & Engineering for Convair during 1976-1978 and for the period of March 1985 to present. In this responsibility, he directs the efforts of 1600 professional, technical and support personnel involved in the development of cruise missiles and aircraft systems.

For six years beginning October 1978 he directed the acquisition and management of large superconducting magnet programs. Six development and fabrication programs ranging from $5 million to $40 million were accomplished. General Dynamics became the most experienced U.S. supplier of large superconducting magnets for Fusion, Isotope Separation, and Magnetohydrodynamics (MHD) having won and successfully delivered 70% of the U.S. business in this area. Beginning in 1982 he directed the efforts of the Convair superconducting magnet team on contracted and company funded tasks on the Superconducting Super Collider dipole magnet developments beginning in 1982.

Dr. Beuligmann served on the Magnetic Fusion Advisory Committee of Department of Energy in 1982-1983. From September 1984 he has been a member of the Board of Directors Applied Superconductivity Conference. From 1984 he has been a member of the Board of Directors of Fusion Power Associates.

DR. CORD-HENRICH DUSTMANN
Marketing & Development Super-Conducting Magnets
Power Generation Division
Brown, Boveri & CIE AG

Biographical Summary

Dr. Dustmann studied physics at the Free University of Berlin and the Technical University of Karlsruhe. From 1970-74 he worked on the development of collective ION Accelerator at the Instiute for Experimental Physics. The thesis was written on the development and testing of the high current pulsed electron gun needed for the electron ring accelerator.

1974-79 He was at the Institute of Technical Physics of the Nuclear Research Centre at Karlsruhe. After having developed and tested the flying capacitor system for energy transfer between superconducting coils he was in charge of TEHE TESPE experiments which is a small superconduction Torus dedicated to the development of superconducting coils for fusion.

1979 - Today he is in charge of all activities on superconducting magnets at Brown Boveri and CIE AG in Mannheim. In this time BBC fabricated the first industry developed accelerator magnets for the HERA-project. Other magnets have been produced for a superconducting sector cyclotron, an electron resonance ION source and RHIC. Design and manufacturing studies have been worked out for SSC, Synchrotron High Source Magnetsystems, ore separation magnet sytems and fusion magnet systems.

DR. JOHN K. HULM
Director of Corporate Research and R&D Planning
Westinghouse Research & Development Center

Biographical Summary

Dr. Hulm is responsible for planning and developing the R&D Center technical and scientific program, coordinating the technical activities of the Center with the goals of the Westinghouse groups, and obtaining corporate and other funding for the projects being conducted by the R&D Center Staff. He is responsible for R&D contract marketing and administration.

Dr. Hulm attended Cambridge University, England, where he received his B.S. and M.A. in mathematics and physics and his Ph.D. in physics (1949). He is also a graduate of the Advanced Management Program, Harvard Business School (1970). Dr. Hulm served as the Scientific Attache, U. S. Embassy London from 1974-1976. Dr. Hulm was a research fellow and professor at the University of Chicago from 1949 to 1954. He joined Westinghouse in 1954 and has held several management positions at the R&D Center, including director of cryogenics, director of solid state research, director of systems research, and manager of the Chemistry Research Division. In 1980, he received the Westinghouse order of merit for his pioneering efforts in the application of superconductivity to electric power technology. Dr. Hulm has published over 100 technical papers relating to superconductivity ferroelectrics, magnetic materials, and semiconductors. He received the John Price Wetherill medal of the Franklin Institute (1964), the IBM international prize for materials research (American Physical Society 1980), and was elected to the U. S. National Academy of Enginering in 1980. He has served on many U.S. Government advisory panels. He is currently on the Advisory Boards of Brookhaven National Laboratory, the National Magnet Laboratory (MIT), the National Bureau of Standards, the Los Alamos Scientific Laboratories, and the Board of Overseers, Universities Research Association.