May 1988 SSC Monthly Report SSC-176

PROJECT SUMMARY	1	CENTRAL DESIGN GROUP (CDG)
	3	BROOKHAVEN NATIONAL LABORATORY (BNL)
	4	FERMI NATIONAL ACCELERATOR LABORATORY (FNAL)
	4	LAWRENCE BERKELEY LABORATORY (LBL)
CDG REPORT	5	MAGNET PROGRAM
	8	ACCELERATOR PHYSICS
	10	CONVENTIONAL SYSTEMS
BNL REPORT	12	MODEL MAGNETS
	13	TOOLING AND FACILITIES
	13	SUPERCONDUCTOR
	14	TESTS AND MEASUREMENTS
	14	CRYOGENICS
FNAL REPORT	16	DIPOLE CRYOSTAT
	16	MAGNETIC MEASUREMENTS
	17	LONG MAGNET FABRICATION
	18	COLD-MASS TOOLING
LBL REPORT	19	SUPERCONDUCTOR AND CABLE
	19	MAGNET MODELS
PROJECT COST DATA	21	INDEX

PROJECT SUMMARY

CENTRAL DESIGN GROUP (CDG)

Magnet Project

The MSI meeting was held at Fermilab May 5-6.

Work continued on documentation for Phase I of the Magnet Industrialization Program, and the plans were reviewed by legal counsel.

Continuing work on finite-element structural analysis for the NC-9 cross section concentrated on stress distributions at the coil midplane and pole. A report was released on the effect of copper-to-superconductor ratio on local temperature in the conductor of a dipole magnet.

Magnet DD0010 was recooled in mid-May; however, short circuits rendered it necessary to warm the magnet in preparation for disassembly. Analysis of data from the various transducers has verified the model of a collared coil interacting via friction with the yoke/shell assembly, as well as showing that the triggering event for a training quench is not cross-axial motion of the magnet end.

Testing of DD0012 began early in the month. The first quench occurred at 4.4 K at the short sample limit of 6500 A. No training was exhibited at this temperature. By the end of the first test sequence, on May 17, there were seven spontaneous quenches and one training quench at 3.4 K. Considerable strain gauge data confirmed that the goal of controlling axial motion was achieved.

The first test of the axial mechanics of a sliding collared coil assembly was completed; a report is being prepared.

Accelerator Physics

The Accelerator Physics Division's efforts for May included considerable preparation for the European Particle Accelerator Conference in Rome, several different projects related to accelerator lattice design, and a theoretical study on quench propagation in superconducting cables. The SUN workstation cluster was also upgraded.

Accelerator Systems

The Sybase database software was received and installed on the SUN. Work has started to try to use Sybase for the lattice parameters. Another early use might be organization of magnet performance data.

A small workshop is being organized for June 9–11 at the CDG for studying the use of self-describing data formats. This will be of wide-ranging use in the SSC control system, but the early emphasis is on magnet data from Fermilab MTF.

Air Products and Chemicals, Inc., has coded and made preliminary runs of three demonstration problems that are being used to test the dynamic simulator. It appears that some tapes and output will be ready in late June. The final installation meeting, it is hoped, will take place at CDG in mid-July, after the results are inspected by CDG staff. So far, this project has gone smoothly.

It is anticipated that the report on radiation levels in SSC detectors (SSC-SR-1033) will be completed by early June. New CDF results have led to the re-evaluation of conclusions concerning the height of the rapidity plateau and the mean value of $p_\perp$ in minimum bias events in SSC detectors. It was concluded that the values of 7.5 (rather than 6) and 0.6 GeV/c (rather than 0.45 GeV/c) for these quantities needs resolution. As a result, all doses and fluences are increased by about 50 percent. These values are based more on the extrapolation of experiment than on theoretical calculations.

In collaboration with R. Ruland of SLAC, a survey/alignment scenario was written for the meeting of the cryostat-tunnel interface group, scheduled for June 2.

SSC Note "Temperature Rise in the SSC Dipole Coils Under Synchrotron Radiation Heating" (SSC-N-514, May 27, 1988) contains an analysis of the heat transfer modes that determine the temperature rise of the SSC dipole coils under the nominal synchrotron radiation heat load of 0.142 W/m, namely: conduction across the dipole cross section, helium longitudinal convection in the annular passage between the beam tube and the coils, and helium transverse natural convection at lamination gaps. For the present design, the temperature rise is likely to exceed the desired value of 0.05 K. This is due mainly to the high thermal resistance of the insulation (Kapton layers), to the relatively small helium mass flow rate in the annular passage, and to the apparently small effect of transverse natural convection at lamination gaps. The actual value of the temperature rise is difficult to predict with the available information; measurements of Kapton thermal conductivity at low temperature under SSC-like conditions and of mass flow rate in the annular passage and temperature rise distributions under inner heat load on a full-scale dipole are needed. The most promising solution to this problem, suggested by C. Taylor, appears to be a "thermal shunt." Between the collars and the Kapton, an extra layer of high-conductivity

material would be inserted, extending into the helium annular passage. The path of low thermal resistance provided by this layer would enable the heat to bypass the coils and Kapton layers and flow through this layer to the collar. The temperature rise across the Kapton layers is accordingly eliminated. Detailed requirements for this layer are being studied.

The redesign of the sample holder for the photodesorption versus temperature experiment was completed, and part drawings were started. It is hoped that fabrication will be complete by the end of June.

Talks with W. Worthington and K. Franck indicated sufficient manpower and space are available for correction magnet prototypes to be designed and built at Building 25.

Studies were started on vacuum considerations for an SSC beam tube with a ~20 K bore liner.

Conventional Systems

Presentations of evolving design concepts for the SSC tunnels and access shafts were made to the Institute of Shaft Drilling Technology and to the U.S. National Committee on Tunneling Technology (USNC/TT). Discussions were held with USNC/TT in preparation for a DOE-funded study of contracting practices used in underground construction.

Budget and schedule scenarios were developed for early construction of a production magnet cooldown facility and the first tunnel segment.

BROOKHAVEN NATIONAL LABORATORY (BNL)

Recollaring of DD0015 commenced with alternatively stacked collar packs.

Short magnet DSS12 was essentially assembled.

Dipole DSS11 was tested with satisfactory results: a plateau of ~6.7 kA at 4.35 K was reached after a single training quench, and a maximum current in the range 7.6–7.7 kA at 3.3 K was reached after modest additional training.

New layout drawings were prepared for planning a new MAGCOOL arrangement to allow single tests of long magnets as well as the Accelerated Life Test.

FERMI NATIONAL ACCELERATOR LABORATORY (FNAL)

Magnet DD0012 was warmed up for a thermal cycle and recooled. Testing is expected to begin shortly. Magnet DD0014 was mounted on the test stand and is ready for cryogenic connections.

Assembly of magnet DD0011 was nearly completed. DD0011 will replace DD0012 on the MTF test stand.

Short model F2, which contains three strain gauge styles, has been delayed by a short at one end. An improved end geometry is being developed for the first Fermilab-wound coil, F4.

LAWRENCE BERKELEY LABORATORY (LBL)

Evaluation of the 23- and 30-strand cables made at NEEW during April was completed. The results were satisfactory, so the wire vendors were instructed to proceed with production runs to produce the cable required for long magnets DD0017 and DD0018.

Cable for the outer layer of LBL 1-m dipole D15-A6 was completed, using strand from billet 355-2 (copper-manganese matrix) for both inner and outer coils. This magnet is now ready for collaring.

Magnet D15A-5 was disassembled after testing and then reassembled. The sole modification was replacement of the ground-plane insulation. Testing will continue into June.

A mid-plane wedge was introduced into the design of the flared end to make winding easier; numerical geometry information for the first prototype parts was electronically transferred to the main shops.

The constant-perimeter end spacers for the next test coil are being prepared in the main N.C. machine shop.

Preliminary testing of newly-built features started on the new MTS 55,000-pound test machine

Additional 20-stack samples of insulated cable, cured under pressure, were prepared for the CDG-LLNL mechanical properties tests.

CDG REPORT

MAGNET PROGRAM

MSI Meeting

The MSI Meeting was held at Fermilab May 5–6. The highlight of the meeting was undoubtedly a report of the superb performance of magnet DD0012, whose testing under power began in the early hours of May 6. Test results are reported below.

The meeting proper began with a comprehensive summary of test results for DD0010, the initial testing of which was completed during the second week of April. The main results included a quench performance characterized as attaining only 90 percent of its short sample limit, considerable instability of its quench current plateau, mechanical behavior essentially like that observed in DD000Z, and the successful deployment of a large inventory of instrumentation. The performance review covered strain gauge results, voltage tap data, and analysis of quench locations by several methods. The analysis confirmed that in DD0010 the quenches originated near the pole in the body of the magnet and were not confined to the ends, as observed in earlier long magnets.

The status of other long magnets in advanced stages of assembly was reported to be as follows: DD0011 and DD0014 both undergoing assembly into their respective cryostats at Fermilab; DD0013 awaiting shipment from BNL (timed to coordinate with the return of the DD0010 cold mass for reworking); DD0015 awaiting recollaring with "twist-compensated" collar packs.

A status report was presented of MTF refrigeration improvements at Fermilab. The compressor cooling water system upgrade is scheduled to be completed in August. Various longer-term improvement options were noted, including duplication of stand 5. Brookhaven National Laboratory gave a status report of Mole C, one unit of which is to be utilized at Fermilab; a principal component, its warm bore tube, is to be designed and developed at Fermilab in coordination with ongoing test stand preparations.

Each of the three laboratories gave a report highlighting cable insulation progress. BNL has entered an informal arrangement with DuPont, which will furnish Kapton samples with glass or other fillers to be tested at BNL. Although this program should yield results within a few months, a longer range program exploring alternative insulation systems is also under way at LBL. At Fermilab, the focus has been on bringing a new cable insulation fixture on line. Preliminary results of Hipot testing various combinations of Kapton and fiberglass as a function of applied pressure were presented. The ensuing discussion took note of the advisability of reviewing the present insulation composition at an appropriate time in light of new material developments.

Brief laboratory presentations were also made of measurements relating the use of warm measurements of field multipoles to forecast the multipoles when the magnet is cold. The first test results from the latest 1-m LBL model (D-15A-5) were reported, as well as the gist of a disassembly and inspection report on BNL's DSS10.

Two further laboratory presentations were made, one on coil end improvements and one on finite element analysis. In the first area, BNL is concentrating its efforts on improving the present end construction in various ways. Fermilab is working on new methods for deriving constant perimeter coil end configurations, while LBL is pursuing a fully empirical route with the same goal. At the same time, LBL continues its parallel program to develop flared ends with internal supports. In the finite element area, BNL is concentrating on evaluating the structural adequacy of the present slotted ramp collars. The CDG reported progress in its two parallel programs involving finite element modeling of the NC-9 and C358A magnet cross sections using ANSYS and NIKE 2D, respectively.

The meeting ended with a discussion of plans for further testing of DD0012 and DD0010. The precise test sequence will depend in part on the logistics necessary for returning the latter cold mass to BNL for reworking, as noted earlier.

Industrialization

Work continued on the development of documentation for Phase I of the Magnet Industrialization Program, and the plans were reviewed by legal counsel. The labs were reminded of the importance of obtaining patent and copyright protection for any material that may be included in the technology orientation phase of the program.

Mathematical Analysis

Work continued on finite-element models of the collared coil. For the NC-9 cross section, computations were performed to investigate the effect of material properties on boundary conditions, for a combination of energization and assembly loading. Hand calculations were performed, as appropriate, to verify various features revealed by these studies. At this time, effort has been concentrated upon the stress distributions at the coil midplane and coil pole, as these are quantities amenable to hand calculation and to experimental verification. In summary, the average stress levels agree with simple calculations, but the predicted stress distributions are not yet understood. In addition, the computed change in average stress at the pole upon energization is considerably less than that observed experimentally. A detailed report is being prepared on these studies.

Report SSC-N-513 was published on the effect of copper-to-superconductor ratio on local temperature rise in the conductor of a dipole magnet, as calculated from minimum propagating zone theory with a number of simplifying assumptions. For currents well below the critical current—the region of interest for training quenches—there is a modest effect. At 6000 A, for

instance, a typical conductor with copper-to-superconductor ratio of 1.25 can tolerate 50% more energy release than a conductor with a copper-to-superconductor ratio of 1.6.

Magnetic Measurements

Hardware design studies began on a new version of a Hall-probe based field inclinometer, and laboratory tests are proceeding on several candidate commercial Hall devices. The devices are also being evaluated for use in a room temperature, harmonic measurement array.

Test and Analysis of Magnet DD0010

Instrumentation problems were corrected and the magnet was recooled in mid-May. Before the magnet could be energized, however, short circuits were discovered between the outer coil and one strip heater and between that strip heater and ground, so the magnet was warmed and prepared for disassembly. Data from the various electrical and mechanical transducers on the magnet were transformed into graphical form. Plots were prepared showing time history during cooldown and magnet energization, as well as detailed behavior during single or multipole excitations. These plots have been distributed to all participating laboratory personnel. The wealth of redundant data supplied by the mechanical transducers has verified the model of a collared coil interacting via friction with the yoke/shell assembly. In addition, data were obtained on magnet end motion during a quench, showing that there is no correlation between the phenomena. That is, the triggering event for a training quench is not gross axial motion of the magnet end.

Test and Analysis of Magnet DD0012

The magnet was first powered on May 3, and testing continued through May 17. By then there had been seven spontaneous quenches at 4.4 K, one spontaneous quench at 3.4 K, plus a number of strain gauge cycles and spot heater quenches. Although the data have not been analyzed in detail as yet, it is clear that the goal of controlling axial motion and eliminating ratcheting was achieved. Furthermore, there was no apparent training at 4.4 K; the first quench reached the short sample limit of 6500 A, and all subsequent temperature-corrected quench currents had essentially identical values. Quenches 1, 3, 4, 5, and 7 all occurred at the same current, but involved the ramp splice between the lower inner and lower outer coils. The one quench at 3.4 K was at 6816 A, well below the short sample limit, and occurred in the return end. The apparent structural weaknesses of both the ramp splice and the end have been previously noted, and corrections have already been incorporated in future magnets. Testing was suspended due to a buildup of contamination in the refrigerator caused by low-temperature operation. Additional low-temperature testing is planned for June.

Test of Dipole Parameters

The first test of a dipole coil assembly sliding axially through a locked collar pack was completed, using the test fixture described in the March Report. The collared coil assembly from 1-m magnet D-14-B9 was used in the test, and the axial force required to produce sliding was determined at room temperature and at 77 K. This magnet used the NC-7 cross section, straight-key aluminum collars, and it had an average coil preload of 5500 psi. At room temperature, the axial force required to produce sliding between one collar pack pair and the coil assembly was 17,000 pounds, while at 77 K, this same assembly required a force of 40,000 pounds to initiate sliding. A report describing the test fixture and the test results is being prepared.

Insulation Tests

Fabrication was completed on a test chamber for testing turn-to-turn, mid-plane, layer-to-layer, and coil-to-ground insulation of collared coil end assemblies in one atmosphere of helium gas. Testing of the first new end design is scheduled for June. It is expected that three more end assemblies will be tested by the end of the fiscal year.

Cable Database

Test results for the cable received from Furukawa were added to the CDG cable database. The table of cable information can now be related to a strand map table, which in turn relates to a billet or strand table. A set of tables was generated that describes in detail the contents of each column in each table of the database. These data are now being combined with data from LBL and BNL.

ACCELERATOR PHYSICS

European Particle Accelerator Conference

Many papers on the SSC were prepared for the European Particle Accelerator Conference to be held in Rome in June. This conference will be the European equivalent of the U.S. Particle Accelerator Conference and will be the first of its kind. Two of the papers will be orally presented; the rest will be presented in poster sessions.

Lattice Design and Studies

A considerable amount of work concerning lattice design and the methods of designing lattices was accomplished. This work included:

- A short study on the feasibility of increasing the vertical beamline separation of the SSC was made, in collaboration with D. Groom (Accelerator Systems). Separation can be increased from the present 70 cm to 73 cm by adding more vertical dipoles in the existing spaces. If, in addition, the quadrupoles between the two vertical steps are shifted towards the IP, the separation can be increased to 80 cm. Neither method requires shifting any of the six quadrupoles on each side of the IP that match the beams from the IP to the arc cells, so the quadrupole excitations and beam optics are unchanged. Greater separations are possible, but changes, probably for the worse in the optics, would be required. An 80-cm beam separation would ease magnet installation, as well as allow for the extraction of a neutral beam from the normal beam interactions.

- Work on the SYNCH program continues with Fermilab collaboration. Conversion of the program into standard FORTRAN is essentially complete. Improvements in calculations of off-energy orbit behavior are under way. The fitting of transport lines for high-intensity beams was adapted to the present version and improved. A new feature was introduced that permits output of orbit functions in selected elements of a lattice.

SUN Cluster Upgrade

A new 700 Mbyte disk was installed. There are now approximately 1500 Mbytes of disk storage on the SUN cluster. Increased disk needs are anticipated, both for the operations simulation and for the accelerator database work. An order was placed for a SUN-4/260 with 32 Mbytes of memory, which should be delivered sometime in July. This machine will significantly increase the computing power available for the operations simulation, as its speed is approximately four times that of our SUN-3/160 with Floating Point Accelerator.

Minimum Propagating Zone in a Superconducting Cable

The minimum propagating zone (MPZ) of the superconducting cable in the SSC dipoles (the C385a Cross Section) has been computed by solving analytically the steady-state one-dimensional heat flow equation. Cooling is included as a heat transfer around the cable perimeter. A solution does not exist when the operating current is too high, because the critical temperature when generation sets in may fall below the bath temperature. Nor does a solution exist when the surface cooling is too large. Once a stable heated zone exists, however, there are in general infinitely many solutions. The one that can be established with the minimum amount of energy is called the MPZ.

The effect of cooling is negligible unless it is very large. For example, at a bath temperature of 4.2 K and an operating current of 6.5 kA, a cooling effect is not visible when the heat transfer coefficient H is less than $\approx 1000\ \mathrm{Wm^{-2}\,K^{-1}}$. Even with $H = 1 \times 10^4\ \mathrm{Wm^{-2}\,K^{-1}}$, the increase in minimum energy required to trigger a quench is still rather small. For comparison,

$H \approx 5 \times 10^4$ Wm^{-2} K^{-1} when the bare superconducting cable strand is in contact with liquid helium. This may explain why experimental results are not sensitive to the way the strands are cooled.

CONVENTIONAL SYSTEMS

Institute of Shaft Drilling Technology

On May 12, T. Toohig made a presentation to the Institute of Shaft Drilling Technology in Las Vegas, Nevada, on current concepts for shafts and underground enclosures. This was a good opportunity to get some reaction to proposed modifications to SSC shaft profiles. CDG studies on shaft use indicate that an elongated shaft profile would be more efficient for operations. In addition, the net volume of excavation can be less than for a conventional round shaft. The constructibility and relative costs of such a profile on a specific site remain to be explored. It was useful and enlightening to discuss these questions with the ISDT members. The group had its origins in the pioneer shaft excavation work at depths up to several thousand feet at the Nevada Test Site.

USNC/TT Meeting

On May 20–21, T. Toohig was again on the road, peddling his underground wares to the U.S. National Committee on Tunneling Technology in Milwaukee, Wisconsin. The USNC/TT is a subcommittee of the National Academy of Sciences. They have agreed to undertake a study for DOE of contracting practices in underground construction with respect to the SSC. Because the inherent uncertainties in underground construction can have severe impacts on both costs and schedules, an examination of methods for dispute resolution is important. In recent years a number of promising approaches to apportioning the risks arising from those uncertainties have emerged. NC/TT will evaluate the effectiveness of those approaches, examine their conformity to federal procurement regulations, and conduct a series of workshops for DOE procurement personnel who will be involved in the SSC. Committee members are excited about the SSC project and the opportunity to play a role in it. A workshop to brief the members of the working committee and review committee for the project is planned for July in Chicago.

Safety Review Document

Draft 2 of the Safety Review Document, which is the final draft version, was completed. Copies were sent to DOE Chicago and DOE Headquarters. It is planned to have the completed document available in time to be used by DOE in preparing the Draft Environmental Impact Statement for the project. D. Matthews and N. Talcott of the CDG support staff played key roles in getting the document completed on time.

RTK Work

RTK completed studies of the electrical system load profile for a 24-hour period of collider operation. This work is being expanded to examine the profile during an extended shutdown in order to define the load profile and annual power usage over a full year of operation. Local power systems need this information to evaluate the potential impact of the SSC; the information is also important for CDG planning.

Planning and Scheduling

As the FY89 and FY90 budgets begin to crystallize, a good deal of attention was devoted to examining the tasks to be undertaken to those years and to fitting the tasks to the resources that are potentially available.

BNL REPORT

MODEL MAGNETS

Alternatively stacked collar packs for long magnet DD0015 were assembled, and collaring (with tapered keys) of the magnet commenced. (The new collar packs will minimize longitudinal coil twist resulting from collaring using standard spot-welded collar pairs.) DD0015 will also incorporate a low-friction sliding interface between collars and yoke, and the yoke module blocks will incorporate midplane registration keys.

Assembly of short magnet DSS12 was essentially completed. This magnet is nominally identical to DSS11, except that it uses collars of Kawasaki high-manganese steel. Both magnets use tapered keys, stiff end plates with preloaded ends, shims between the collared coil and yoke, and 57 voltage taps (instead of the standard 5).

Eighteen 1.8-m inner and outer R&D coils were produced by the single cure process; all of these incorporate a fixed, predetermined shim. The tooling used hardened wear strips on both formblocks and "top hats." The coil ends incorporated various amounts of "prepreg" materials in varying patterns, one of the steps being implemented to improve the coil ends.

The strain-gauge temperature calibration system is nearing completion. It is expected to become fully operational in the first week of June. Preparations have started for a room-temperature test of tensile load versus deflection on a straight section segment of a collared coil.

Redesigning the magnet-to-magnet interconnect region began, partly in view of anticipated reduction in allotted space between magnets. A meeting was held to review the preliminary design.

In the trim coil R&D area, test coil number 11 was tested. Results were generally promising: short sample performance was attained on the second quench. Some detraining was observed upon current reversal and thermal cycling, but the minimum operational current still exceeded a level corresponding to 10 units of sextupole. In the longer-term program, it was decided to continue optimization studies based on 0.6-m coils. Meanwhile, work will start as soon as possible on 1.8-m coils. Full-length trim coil assemblies are foreseen in the next fiscal year; engineering is continuing on the full-length trim coil test facility. An order was written with Autokompu for additional superconductor; delivery is scheduled for July. Multiwire has completed samples of glass-filled adhesives, which are expected shortly.

The first test results show little difference in puncture properties among polyimide films of the same thickness from different vendors.

Because of world market factors for nickel and chromium, BNL's tubing vendor has informed the laboratory that the cost and lead time for future seamless beam tube orders can be expected to double. Orders must be placed at least 14 months in advance to ensure delivery.

This implies that tubing for magnets in FY90 must be ordered by August of this year. Seam-welded tubing entails a 7–9 month lead time, and the cost will double as well.

Various bore tube plating components and materials have been prepared for shipment to Silvex. In particular, the tubing box has been constructed, and the power supply is complete and ready for shipment.

TOOLING AND FACILITIES

Coils

New piping for the first long curing press has been tested and, as noted in last month's report, the press is now in full operation. Engineering work continues on the new 1.8-m curing press.

Collars

Work concentrated on extending the lower platen of the collaring press. The strong back allows simultaneous collaring of short and long SSC coils.

Shell

Replacement parts for the Mega Pulse Welder from Hobart have been installed by the contractor. A central control box has been designed for Hobart's wire feeder. The carriage drive motor is too weak and will be replaced.

SUPERCONDUCTOR

Cable Procurement

As reported last month, the inner cables for DD0016 have been insulated and are ready for coil winding. However, the outer cables were not wrapped in early May, as expected, as coil winding was delayed by lack of available workers.

BNL representatives visited New England Electric Wire Corporation in connection with the completion of an experimental cable run. The cables manufactured, in conjunction with cables manufactured at LBL, should help in understanding the causes of degradation. In addition, the NEEW cabling machine has been modified and now has a fixed mandrel like LBL's cabler. The cable produced will thus permit a comparison of the two machines.

Tooling

As reported last month, modifications to the cable-wrapping line have been tested to register the wires (assure proper placement of the wires within the cable) during the wrapping procedure. The parts required for this registration are completed and are presently being assembled.

Modifications to the wrapping line to permit the safe wrapping of cable at twice the present speed are in the drawing stage. These drawings should be released to the shops in June.

Miscellaneous

As reported last month, stack tests comparing woven glass to BNL's standard slit glass indicate that the woven glass produces a thicker stack. The possible cause of this problem was discovered, and recommendations were made to the vendor for corrective action. A corrected sample was delivered to BNL and tested. The test results are being evaluated.

The production run of fiberglass from Hexcel was inspected and found to meet specifications. The fiberglass has been released to inventory for future use.

A new technique was tested which allows the splicing of the fiberglass when spooled, thus eliminating the need to splice on the wrapping line.

A new numbering system for SSC cable was instituted. The database maintained at BNL was revised to reflect the new numbering system and updated to include the latest cables manufactured.

TESTS AND MEASUREMENTS

The initial test of 1.8-m dipole DSS11 was performed. After one training quench at 6.37 kA, the magnet reached a plateau of ~6.7 kA at 4.35 K. In subsequent testing at lower temperatures, the magnet trained in two quenches to a plateau of 7.25 kA at 3.8 K. At 3.3 K, after one additional training quench, the magnet quenched at currents in the range 7.6–7.7 kA.

Approximately half of the quenches at 3.8 K and all of the quenches at 3.3 K were <u>not</u> in the location expected for short-sample quenches (the inner coil turn nearest to the center post). The quenches were scattered over both inner coils, primarily near the end of the straight section (but not in the ends). A few of the quenches were near the thick wedge. All of the plateau quenches were well above the level expected from the short sample measurements, using the 10^{-12} ohm-cm criterion.

CRYOGENICS

As reported last month, it was decided to revamp the physical arrangement of the equipment in the MAGCOOL area. New layout drawings are being used to position the equipment and the

piping connections. The first feed can completed will be assigned to the Single Magnet Test and the second will be used for the Accelerated Life Test.

Construction of the vacuum-jacketed piping for the 20 K heat shield supply and return lines continued. This job is estimated to be half complete.

FNAL REPORT

DIPOLE CRYOSTAT

Thermal performance measurements of a Design B support post equipped with a cast cold mass connection-slide were made in the Heat Leak Test Facility. Heat leak reduction due to the cold mass connection-slide, which was seen in the Design A two-shafted slide, did not occur with the cast connection-slide. Design B has enhanced thermal contact between the bearing pads and the cold mass skin, more surface area for residual gas conduction, and additional instrumentation leads.

Insulation development continues; emphasis is on improved procedures for handling and securing insulation. An intensive insulation production run using "Proud Mary" is planned. This will permit the facility space re-allocation required to accommodate cold mass production.

Construction and instrumentation of long magnet model DD0014 are complete. Modal analysis of DD0014, following magnetic testing, is planned for August.

Subassembly preparations were completed for long magnet model DD0011, including fabrication of support posts, anchor assemblies, and insulation blankets.

Cryostat components for six Design B magnets will be available in July. The components are to be employed for long magnet models DD0014, DD0011, DD0013, DD0015, DD0016, and DD0017.

Designs of a shuttle for the vertical plane probe are being developed in conjunction with GDSS. Models will be built and evaluated.

A study of cryostat alignment was drafted by B&W and is being reviewed by Fermilab.

Work began on the development of an Iteration C cross section. The objective is to accommodate the larger pipe sizes, as specified by the CDG, within the present vacuum vessel envelope.

Work began on magnet design features that affect magnet installation. Studies are under way on magnet vertical-center-line-to-center-line spacing, bottom-magnet-to-floor spacing, magnet support stands, etc.

Industrialization preparation continues. Documentation continues to be developed. A draft of the Fermilab on-site program for Phase 1 (Technology Orientation) was developed.

MAGNETIC MEASUREMENTS

Testing of magnet DD0012 on test stand 5 continued. There were several more spot-heater quenches and a spontaneous quench at 4.4 K. The temperature was then lowered to approximately 3.3 K, using the liquid ring pump stage of the warm pumping station. Strain gauge data were taken up to a current of 6700 A, approximately 200 A higher than the

spontaneous quench current at the higher temperature. The inner-coil stress was greater than 2000 psi at the highest current measured. The magnet was then ramped to quench at 6820 A, above the 4.4 K quench current but below the expected short sample limit at 3.3 K. Two high current trips occurred due to voltage transients in the through bus: the first at 7130 A, the second at 6780 A. The magnet was then warmed to permit pump system maintenance and to allow DD0010 to be retested.

The second cooldown of magnet DD0010 began simultaneously with the warmup of DD0012. While balancing the quench detection circuits, in preparation for testing the magnet, the magnet coil was found to have a zero resistance short to ground. Before powering the magnet, it was verified (at low voltage) to be electrically isolated from ground. The short was therefore caused by some event associated with the detection circuit setup, which involved powering the magnet to approximately 100 A. By inductive and resistive voltage measurements, the short was determined to be in the lower outer coil, approximately 5 to 7 turns from the mid-plane. Strip heater 3 (lower coil, left side as viewed from the lead end) was found to be shorted to ground also at a point (or points) well away from either end of the heater. Following warming of the magnet to room temperature, detailed resistance measurements showed that the lower outer coil had 8% lower resistance than before cooldown.

DD0010 was removed from test stand 4; installation of DD0014 is under way. The magnet is now fully wired to the test stand, but the bellows have not yet been welded. This magnet is the first to use cryostat design B, and there is extensive instrumentation on the cryostat posts, on the axial tie-bars, and on the heat shields. As a consequence, a major expansion of the readout system–including cables, signal conditioning electronics, and readout electronics—is necessary. Installation of the additional equipment should be complete by the end of June.

Following the warmup of DD0010, the MTF refrigerator was warmed to allow removal of nitrogen and water contamination. Then DD0012 was re-cooled for further testing. The magnet is currently cold and the quench protection and readout systems have been fully tested in preparation for high current testing. Strain gauge data and several quenches will be taken at progressively lower temperatures, starting from 4.4 K.

LONG MAGNET FABRICATION

Magnet DD0010 was received from MTF for disassembly on May 31. Disassembly will be complete the first week in June.

COLD-MASS TOOLING

Collaring

Short model F2 was collared. Both the BNL and the new LBL strain gauges yielded similar results during collaring. Photo-elastic stress analysis was done on the laminated collaring tooling during the collaring process.

While bolting the aluminum "end clamp" on the lead end of F2, a short was discovered between a turn and the end of a wedge. It is being repaired.

Both F2 and F3 will be cold tested as magnets.

Magnet F4, the first Fermi-wound magnet, is to be collared and sectioned into cookies. Recent coil end analysis resulted in a decision to produce a low-stress end on at least one end of F4, using H. Fulton's existing CAD program. This area will be potted, sectioned, and analyzed.

Winding and curing of magnet F4 is scheduled for late July.

LBL REPORT

SUPERCONDUCTOR AND CABLE

Cable for LBL 1-m dipole D15-A6 outer layer was completed. This cable contained strand from Supercon billet 355-2, which was originally designed for inner-layer cable with a copper-to-superconductor ratio of 1.4. Some of this wire was drawn to 0.0255 inch and used for the outer-layer cable. This will allow magnet D15-A6 to be constructed using wire with the copper-manganese matrix for both inner- and outer-layer coils.

Evaluation of the 23- and 30-strand cables made at NEEW during April was completed. The results were satisfactory; the wire vendors have been instructed to proceed with their production runs to produce the cable required for long magnets DD0017 and DD0018.

MAGNET MODELS

Dipole Models

Magnet D15A-5 was disassembled after testing and then reassembled with new ground-plane insulation. The reassembled magnet is designated D15A-5R1. Testing began on May 31 and will continue into June.

Model D15A-6 coil assembly, which has cable with a copper-manganese matrix, is now ready for collaring.

Numerous improvements were made to the magnet power supplies, their current shunts, and amplifiers to improve the current regulation.

Bore Liner

A series of experiments has demonstrated the ability to control the radial bore pressure level and distribution in a 6-inch collared coil section. The final liner configuration will be tested in a 1-m model magnet.

End Design

A mid-plane wedge was introduced into the design of the flared end to make winding easier. Magnetic and mechanical codes were updated to include this modification. The tooling to produce prototype G-10 end "teardrops" was ordered. In addition, several computer bugs associated with wedges were discovered and fixed. The numerical geometry information for the first prototype parts has been electronically transferred to the main shops.

The constant-perimeter end spacers for the next test coil are being produced in the main N.C. machine shop.

An order for a three-dimensional CAD system (Hewlett Packard ME-30) was placed, and the hardware is due to arrive within 2 months. It is planned to use the system initially for end designs.

Coil Properties

Preliminary tests were begun of new fixtures on the new MTS 55,000-pound test machine.

Additional 20-stack samples of insulated cable, cured under pressure, were prepared for the CDG-LLNL mechanical properties tests.

PROJECT COST DATA

INDEX

SSC PROGRAM	Table	Figure
Central Design Group	C-1	1
Brookhaven National Laboratory	C-2	2
Fermi National Accelerator Laboratory	C-3	3
Lawrence Berkeley Laboratory	C-4	4
SSC Program Summary	C-5	5
Monthly and Cumulative Summary	C-6	

TABLE C-1

CENTRAL DESIGN GROUP - SUPERCOLLIDER

MAY 1988 COST REPORT (K$)

	PROGRAM ELEMENT	LABOR	MAT'L & SERVICES	G & A	MONTH TOTAL	YEAR TO DATE	ANNUAL BUDGET
1.1	ADMINISTRATION	81.7	65.1	101.3	248.2	2104.7	3735.0
1.2	PROGRAM PLANNING & MANAGEMENT	25.2	-0.1	17.9	43.0	384.0	574.0
1.3	ACCELERATOR R & D	277.8	174.9	68.4	521.1	3420.8	6112.0
1.4	CONVENTIONAL SYSTEMS DEVELOP.	41.0	25.5	4.6	71.2	349.3	824.0
	PROGRAM COSTS	425.7	265.5	192.2	883.4	6258.8	11245.0
1.41	RTK COSTS	0.0	9.7	0.0	9.7	29.1	130.0
	CDG/RTK COSTS	425.7	275.2	192.2	893.1	6287.9	11375.0
	COMMITMENTS					522.1	
	CHANGE IN COMMITMENTS (Delta)					-121.6	
	EQUIPMENT COSTS					0.0	229.0

TABLE C-2

BROOKHAVEN NATIONAL LABORATORY - SUPERCOLLIDER

MAY 1988 COST REPORT (K$)

	PROGRAM ELEMENT	LABOR	MAT'L & SERVICES	G & A	MONTH TOTAL	YEAR TO DATE	ANNUAL BUDGET
2.1	LONG MAGNET FABRICATION	38.5	29.7	22.5	90.7	2163.7	3600.0
2.2	TOOLING & FIXTURES	29.9	67.5	32.1	129.5	1763.5	2200.0
2.3	SHORT MODEL MAGNETS	21.4	1.4	7.5	30.3	251.3	375.0
2.4	INDUSTRIALIZATION	8.6	0.0	2.8	11.4	114.4	175.0
2.5	ACC. LIFE TEST (CRYO)	17.1	2.3	6.4	25.8	471.8	650.0
	PROGRAM COSTS	115.5	100.9	71.3	287.7	4764.7	7000.0
	COMMITMENTS					678.0	
	CHANGE IN COMMITMENTS (Delta)					-614.0	
	EQUIPMENT COSTS	0.0	49.5	0.0	49.5	181.0	500.0
	EQUIPMENT OPEN COMMITMENTS					67.8	

TABLE C-3

FERMI NATIONAL ACCELERATOR LABORATORY - SUPERCOLLIDER

MAY 1988 COST REPORT (K$)

	PROGRAM ELEMENT	LABOR	MAT'L & SERVICES	G & A	MONTH TOTAL	YEAR TO DATE	ANNUAL BUDGET
3.1	GENERAL	0.0	7.2	2.4	9.6	70.8	220.0
3.2	LONG MAGNET FABRICATION	62.1	17.4	26.9	106.4	978.8	942.0
3.3	MAGNETIC MEASUREMENTS	47.0	57.9	35.5	140.4	1821.3	1363.0
3.4	COLD MASS FABRICATION	0.0	60.3	20.5	80.8	725.3	2241.0
3.5	INDUSTRIALIZATION	15.2	-0.1	5.1	20.2	58.6	214.0
3.6	CELL TESTS	0.0	0.0	0.0	0.0	0.0	0.0
	PROGRAM COSTS	124.3	142.7	90.4	357.4	3654.8	4980.0
	COMMITMENTS					416.0	
	CHANGE IN COMMITMENTS (Delta)					-59.5	
	EQUIPMENT COSTS	0.0	1.8	0.0	1.8	79.9	271.0
	EQUIPMENT OPEN COMMITMENTS					-17.6	

TABLE C-4

LAWRENCE BERKELEY LABORATORY - SUPERCOLLIDER

MAY 1988 COST REPORT (K$)

	PROGRAM ELEMENT	LABOR	MAT'L & SERVICES	G & A	MONTH TOTAL	YEAR TO DATE	ANNUAL BUDGET*
4.1	GENERAL	6.5	0.0	3.1	9.6	74.3	190.0
4.2	SUPERCONDUCTOR	2.6	0.0	1.2	3.8	307.1	720.0
4.3	QUADRUPOLE DEVELOPMENT	0.0	0.0	0.0	0.0	0.0	100.0
4.4	COMP. DEVELOP. & TESTS	29.8	10.1	19.1	59.0	909.6	1175.0
4.5	INDUSTRIALIZATION	0.0	0.0	0.0	0.0	0.0	50.0
	MAGNET R & D TOTALS	38.9	10.1	23.4	72.4	1291.0	2235.0
4.6	ACCELERATOR PHYSICS R & D	5.7	0.3	2.9	8.9	249.3	410.0
	LBL/THEORY COSTS	44.6	10.4	26.3	81.3	1540.3	2645.0
	COMMITMENTS					278.0	
	CHANGE IN COMMITMENTS (Delta)					165.0	

TABLE C-5

PROGRAM SUMMARY - SUPERCOLLIDER

MAY 1988 COST REPORT (K$)

	PROGRAM ELEMENT	LABOR	MAT'L & SERVICES	G & A	MONTH TOTAL	YEAR TO DATE	ANNUAL BUDGET
1.	CDG PROGRAM	425.7	265.5	192.2	883.4	6258.8	11245.0
1.41	RTK PROGRAM	0.0	9.7	0.0	9.7	29.1	130.0
2.	BNL SSC PROGRAM	115.5	100.9	71.3	287.7	4764.7	7000.0
3.	FNAL SSC PROGRAM	124.3	142.7	90.4	357.4	3654.8	4980.0
4.	LBL SSC PROGRAM	44.6	10.4	26.3	81.3	1540.3	2645.0
	TOTAL SSC PROGRAM COSTS	710.1	529.2	380.2	1619.5	16247.7	26000.0
	COMMITMENTS					1894.1	
	CHANGE IN COMMITMENTS (Delta)					-630.1	
	EQUIPMENT COSTS					260.9	1000.0
	EQUIPMENT OPEN COMMITMENTS					50.2	

TABLE C-6

MONTHLY AND CUMULATIVE SUMMARY OF PLANNED AND ACTUAL COSTS AND COMMITTMENTS

1.0 CENTRAL DESIGN GROUP - SUPERCOLLIDER

DATE	MONTHLY PLANNED COSTS	FY PLANNED CUMULAT	MONTHLY ACTUAL COSTS	FY ACTUALS CUMULAT	MO ACT+ DELTA COMMITS	CUM ACT + COMMITS	CURRENT COMMITS	DELTA COMMITS
OCT	947.9	947.9	33.4	33.4	496.4	496.4	463.0	463.0
NOV	947.9	1895.8	747.4	780.8	572.4	1068.8	288.0	-175.0
DEC	947.9	2843.8	1221.6	2002.4	1199.6	2268.4	266.0	-22.0
JAN	947.9	3791.7	549.0	2551.4	478.2	2746.6	195.2	-70.8
FEB	947.9	4739.6	781.8	3333.2	995.0	3741.6	408.3	213.1
MAR	947.9	5687.5	931.9	4265.1	898.0	4639.5	374.4	-33.9
APR	947.9	6635.4	1129.4	5394.6	1398.8	6038.3	643.7	269.3
MAY	947.9	7583.3	893.1	6287.7	771.5	6809.8	522.1	-121.6
JUN	947.9	8531.3						
JUL	947.9	9479.2						
AUG	947.9	10427.1						
SEP	947.9	11375.0						

2.0 BROOKHAVEN NAT'L LAB - SUPERCOLLIDER

DATE	MONTHLY PLANNED COSTS	FY PLANNED CUMULAT	MONTHLY ACTUAL COSTS	FY ACTUALS CUMULAT	MO ACT+ DELTA COMMITS	CUM ACT + COMMITS	CURRENT COMMITS	DELTA COMMITS
OCT	583.3	583.3	498.0	498.0	2095.0	2095.0	1597.0	1597.0
NOV	583.3	1166.7	643.0	1141.0	995.0	3090.0	1949.0	352.0
DEC	583.3	1750.0	763.6	1904.6	632.6	3722.6	1818.0	-131.0
JAN	583.3	2333.3	894.9	2799.5	831.9	4554.5	1755.0	-63.0
FEB	583.3	2916.7	702.0	3501.5	516.0	5070.5	1569.0	-186.0
MAR	583.3	3500.0	708.7	4210.2	431.7	5502.2	1292.0	-277.0
APR	583.3	4083.3	265.8	4476.0	265.8	5768.0	1292.0	0.0
MAY	583.3	4666.7	287.7	4763.7	-326.3	5441.7	678.0	-614.0
JUN	583.3	5250.0						
JUL	583.3	5833.3						
AUG	583.3	6416.7						
SEP	583.3	7000.0						

3.0 FERMI NAT'L ACCEL LAB - SUPERCOLLIDER

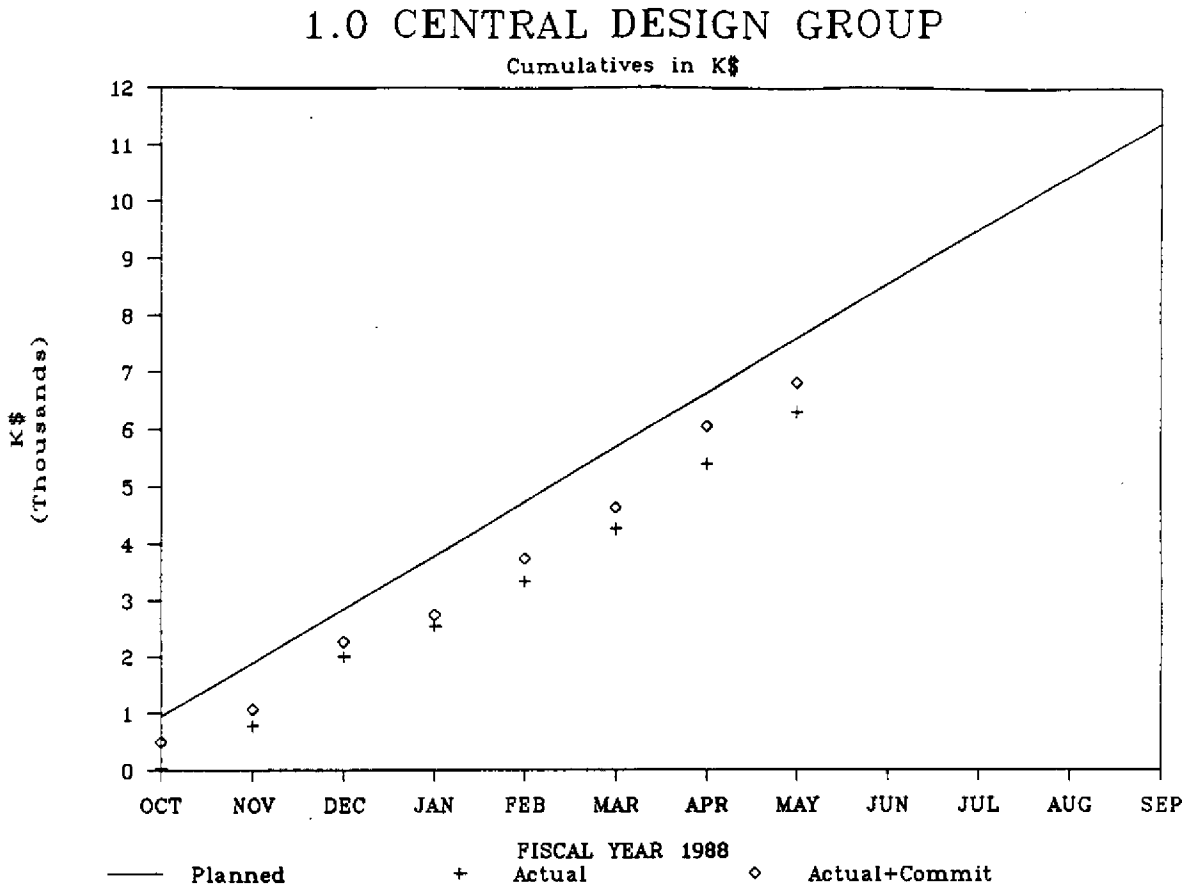
DATE	MONTHLY PLANNED COSTS	FY PLANNED CUMULAT	MONTHLY ACTUAL COSTS	FY ACTUALS CUMULAT	MO ACT+ DELTA COMMITS	CUM ACT + COMMITS	CURRENT COMMITS	DELTA COMMITS
OCT	415.0	415.0	314.7	314.7	792.5	792.5	477.8	477.8
NOV	415.0	830.0	390.6	705.3	353.1	1145.6	440.3	-37.5
DEC	415.0	1245.0	694.7	1400.0	462.4	1608.0	208.0	-232.3
JAN	415.0	1660.0	307.3	1707.3	465.3	2073.3	366.0	158.0
FEB	415.0	2075.0	720.2	2427.5	722.5	2795.8	368.3	2.3
MAR	415.0	2490.0	457.2	2884.7	566.6	3362.4	477.7	109.4
APR	415.0	2905.0	412.7	3297.4	410.5	3772.9	475.5	-2.2
MAY	415.0	3320.0	357.4	3654.8	297.9	4070.8	416.0	-59.5
JUN	415.0	3735.0						
JUL	415.0	4150.0						
AUG	415.0	4565.0						
SEP	415.0	4980.0						

4.0 LAWRENCE BERKELEY LAB - SUPERCOLLIDER

DATE	MONTHLY PLANNED COSTS	FY PLANNED CUMULAT	MONTHLY ACTUAL COSTS	FY ACTUALS CUMULAT	MO ACT+ DELTA COMMITS	CUM ACT + COMMITS	CURRENT COMMITS	DELTA COMMITS
OCT	220.4	220.4	230.5	230.5	662.5	662.5	432.0	432.0
NOV	220.4	440.8	191.1	421.6	191.1	853.6	432.0	0.0
DEC	220.4	661.3	135.9	557.5	135.9	989.5	432.0	0.0
JAN	220.4	881.7	263.3	820.8	175.3	1164.8	344.0	-88.0
FEB	220.4	1102.1	185.8	1006.6	135.8	1300.6	294.0	-50.0
MAR	220.4	1322.5	238.5	1245.1	165.5	1466.1	221.0	-73.0
APR	220.4	1542.9	213.9	1459.0	105.9	1572.0	113.0	-108.0
MAY	220.4	1763.3	81.3	1540.3	246.3	1818.3	278.0	165.0
JUN	220.4	1983.8						
JUL	220.4	2204.2						
AUG	220.4	2424.6						
SEP	220.4	2645.0						

0.0 PROGRAM SUMMARY - SUPERCOLLIDER

DATE	MONTHLY PLANNED COSTS	FY PLANNED CUMULAT	MONTHLY ACTUAL COSTS	FY ACTUALS CUMULAT	MO ACT+ DELTA COMMITS	CUM ACT + COMMITS	CURRENT COMMITS	DELTA COMMITS
OCT	2166.7	2166.7	1076.6	1076.6	4046.4	4046.4	2969.8	2969.8
NOV	2166.7	4333.3	1972.1	3048.7	2111.6	6158.0	3109.3	139.5
DEC	2166.7	6500.0	2815.8	5864.5	2430.5	8588.5	2724.0	-385.3
JAN	2166.7	8666.7	2014.5	7879.0	1950.7	10539.2	2660.2	-63.8
FEB	2166.7	10833.3	2389.8	10268.8	2369.3	12908.5	2639.6	-20.6
MAR	2166.7	13000.0	2336.3	12605.1	2061.8	14970.2	2365.1	-274.5
APR	2166.7	15166.7	2021.8	14627.0	2181.0	17151.2	2524.2	159.1
MAY	2166.7	17333.3	1619.5	16246.5	989.4	18140.6	1894.1	-630.1
JUN	2166.7	19500.0						
JUL	2166.7	21666.7						
AUG	2166.7	23833.3						
SEP	2166.7	26000.0						


1.0 CENTRAL DESIGN GROUP
Cumulatives in K$
K$ (Thousands)
0
1
2
3
4
5
6
7
8
9
10
11
12
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Commit

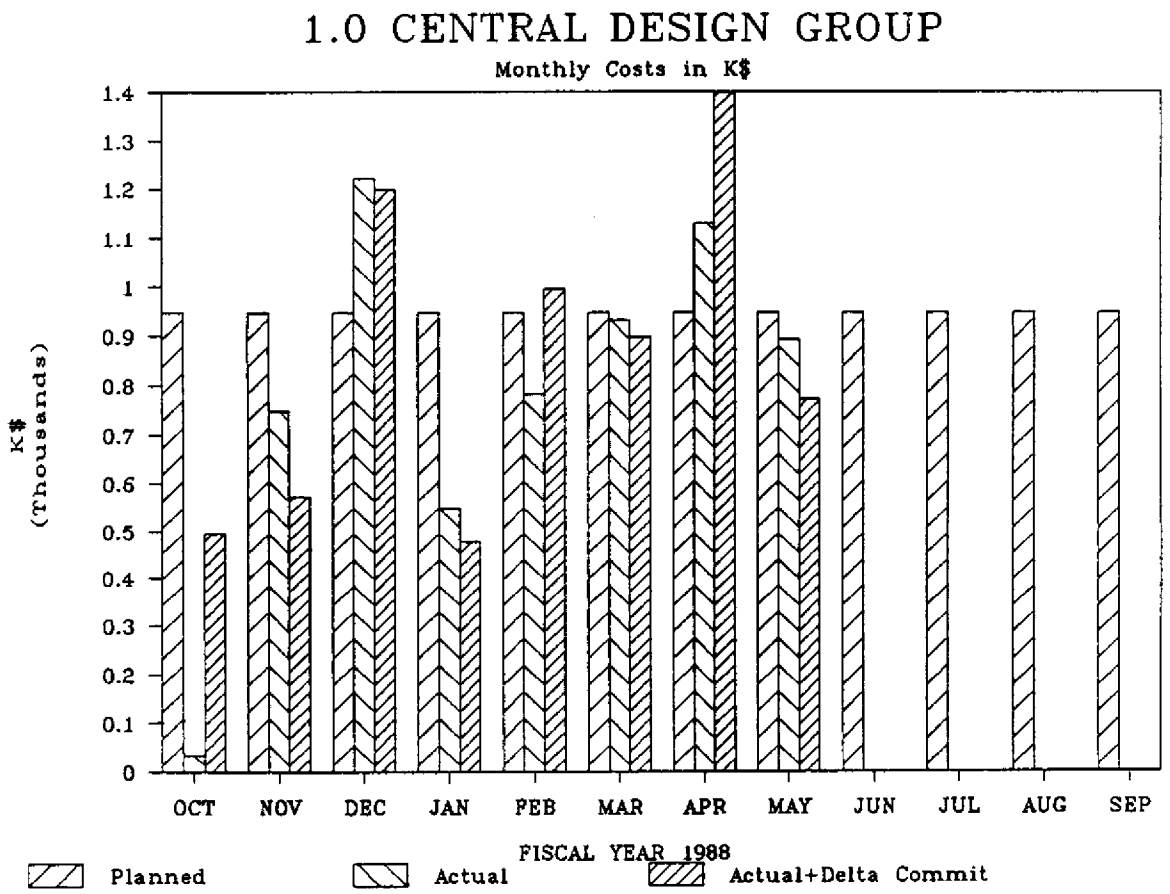
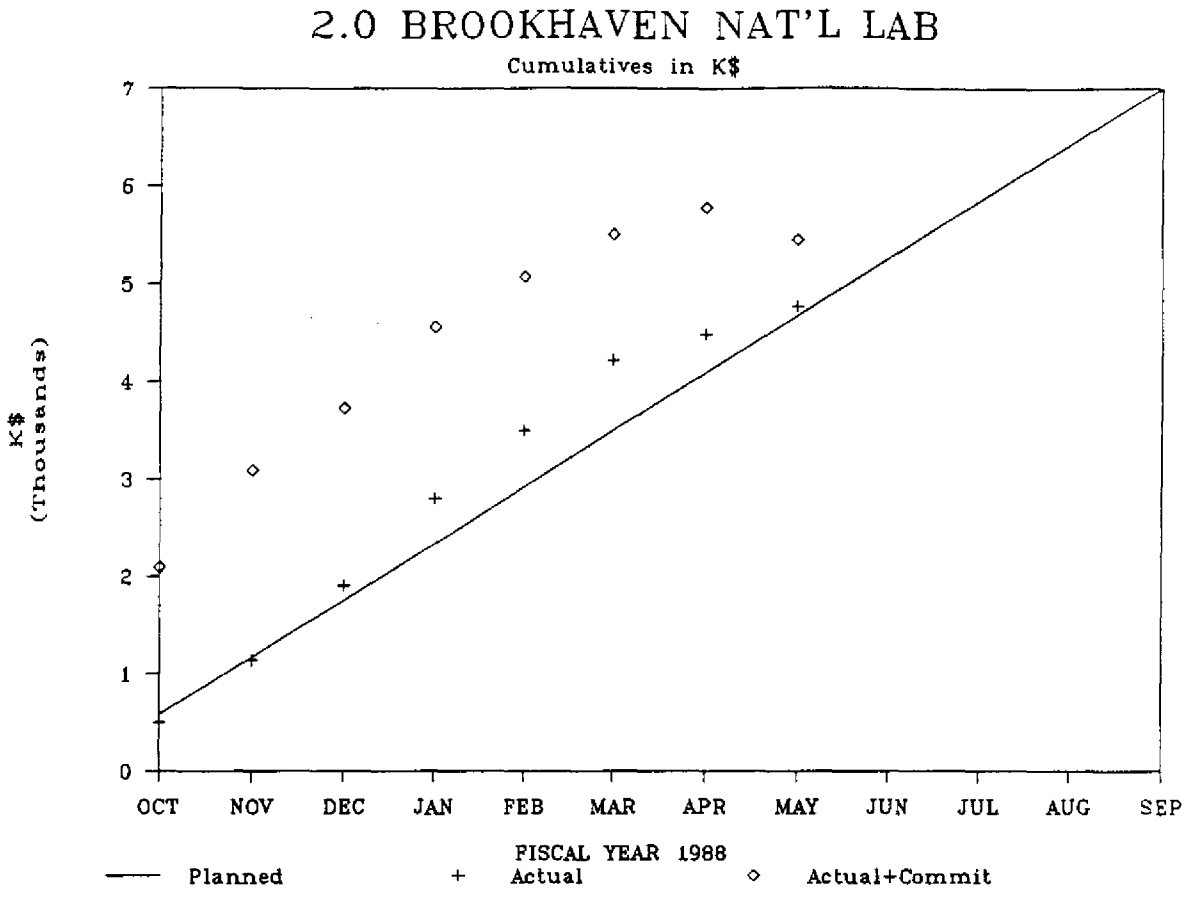

1.0 CENTRAL DESIGN GROUP
Monthly Costs in K$
K$ (Thousands)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Delta Commit

Figure 1


2.0 BROOKHAVEN NAT'L LAB
Cumulatives in K$
K$ (Thousands)
0
1
2
3
4
5
6
7
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Commit

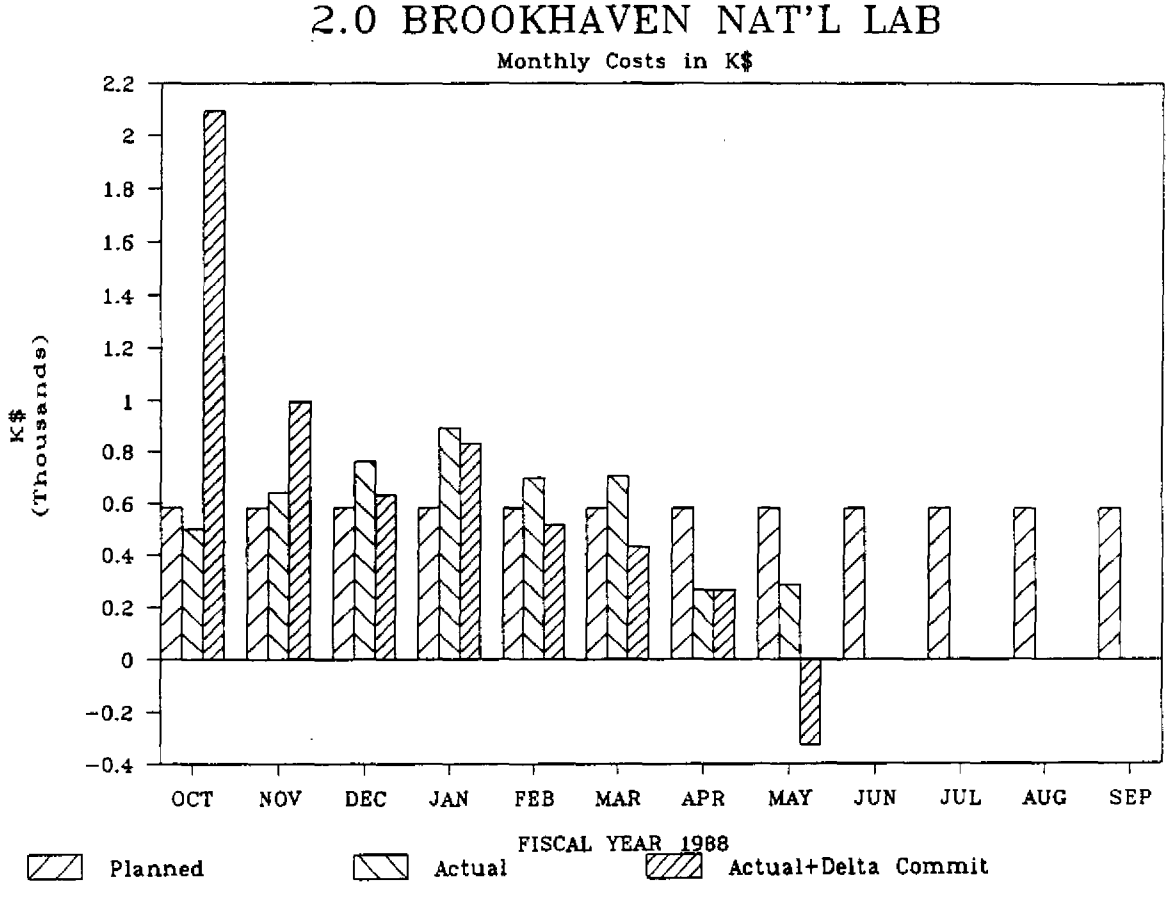
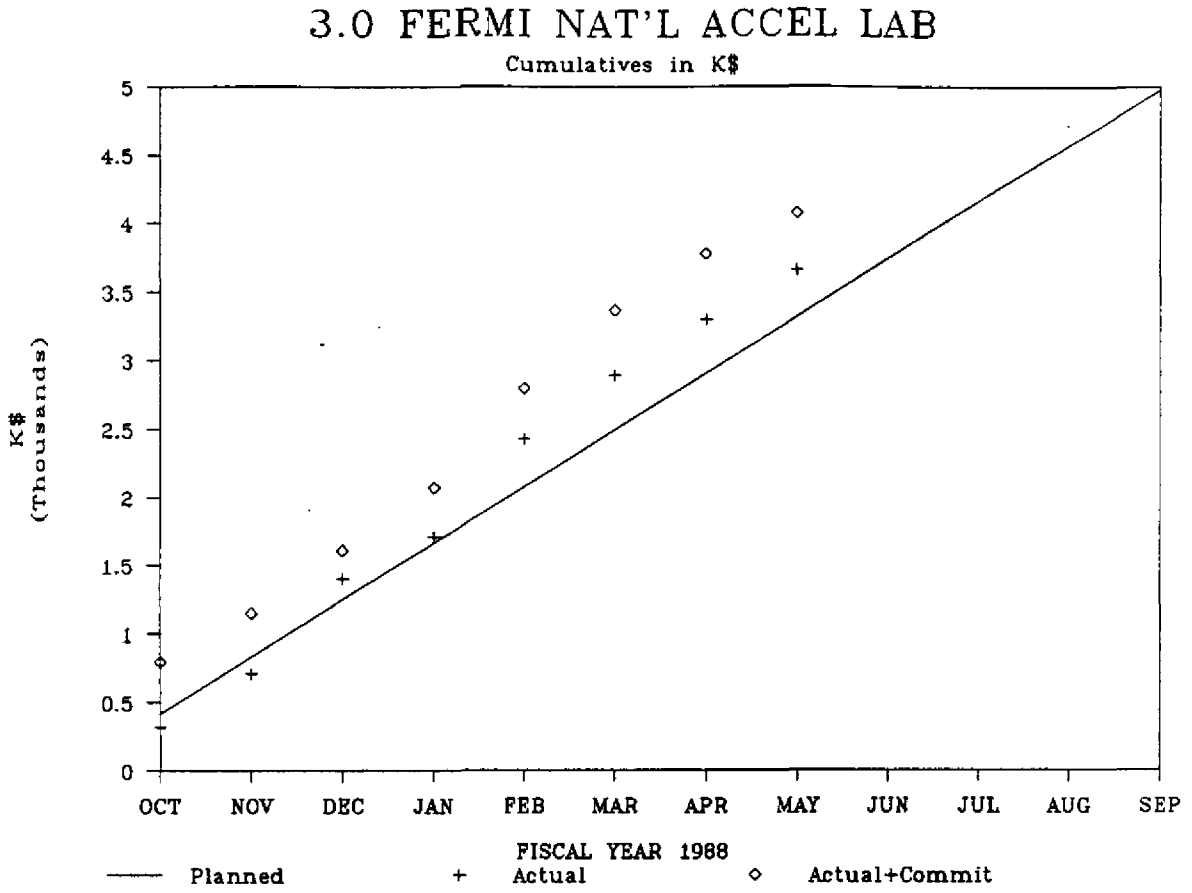

2.0 BROOKHAVEN NAT'L LAB
Monthly Costs in K$
K$ (Thousands)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Delta Commit

Figure 2


3.0 FERMI NAT'L ACCEL LAB
Cumulatives in K$
K$ (Thousands)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Commit

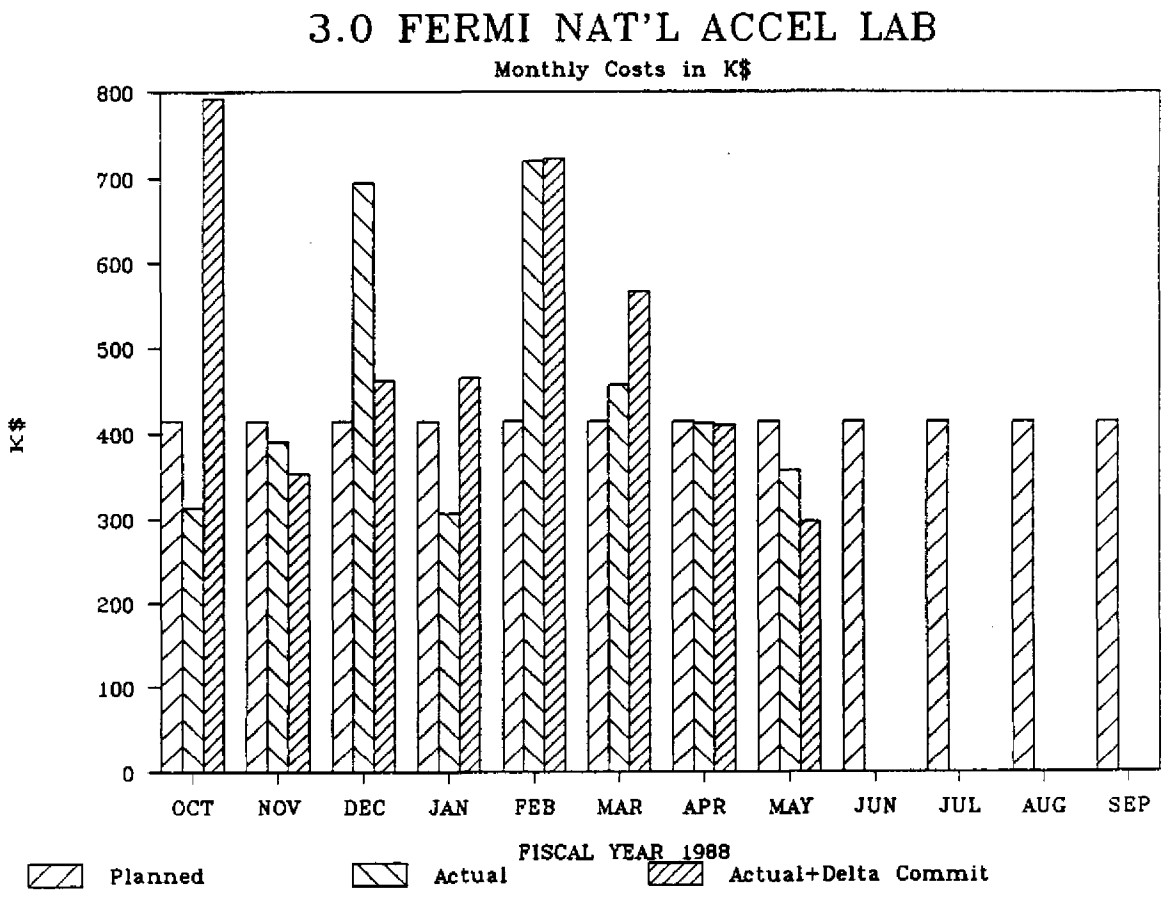
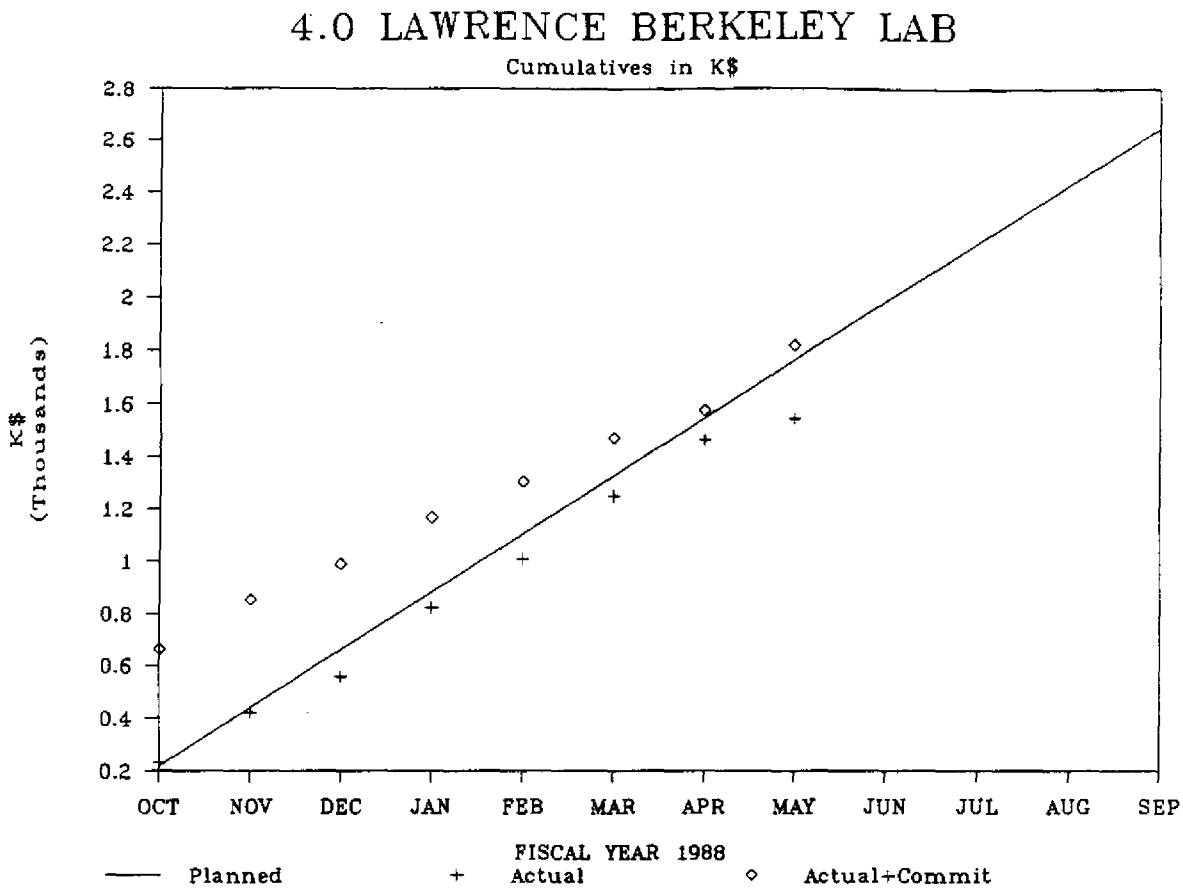

3.0 FERMI NAT'L ACCEL LAB
Monthly Costs in K$
K$
800
700
600
500
400
300
200
100
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Delta Commit

Figure 3


4.0 LAWRENCE BERKELEY LAB
Cumulatives in K$
K$ (Thousands)
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Commit

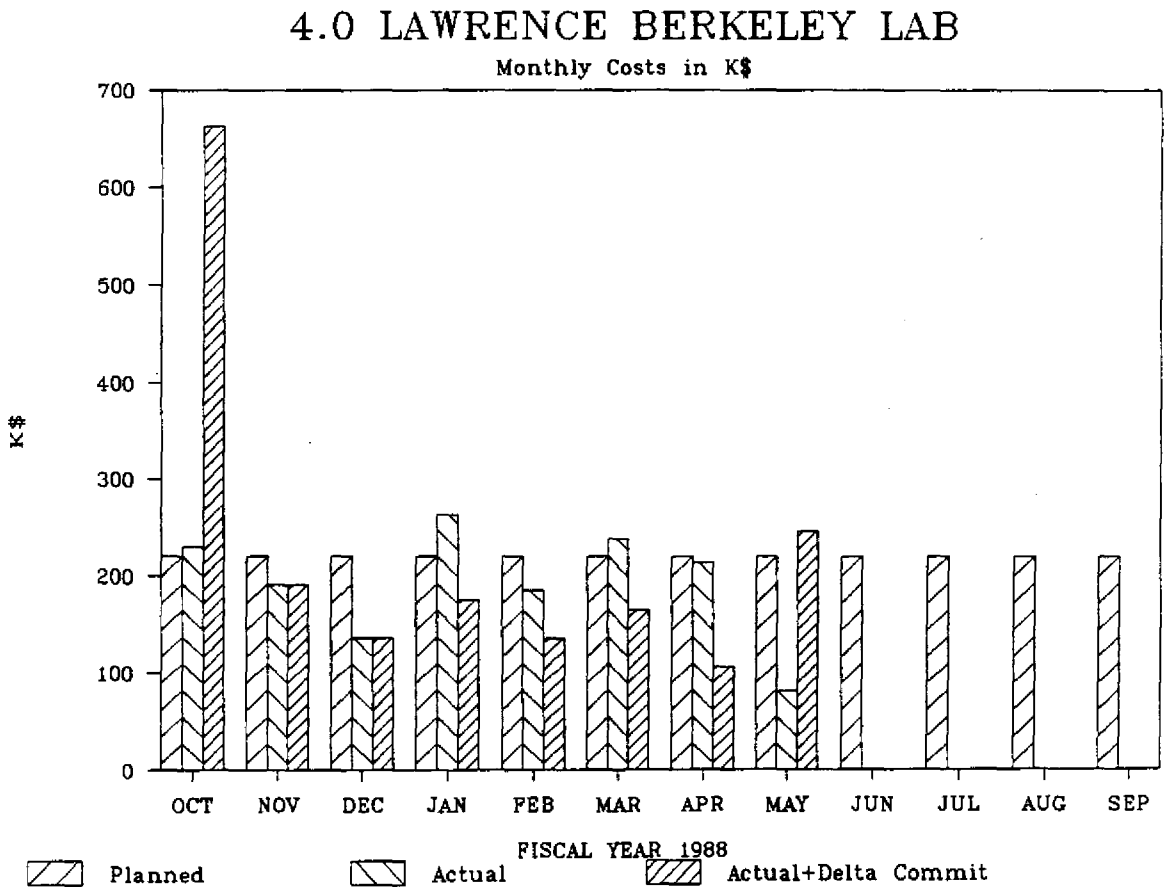
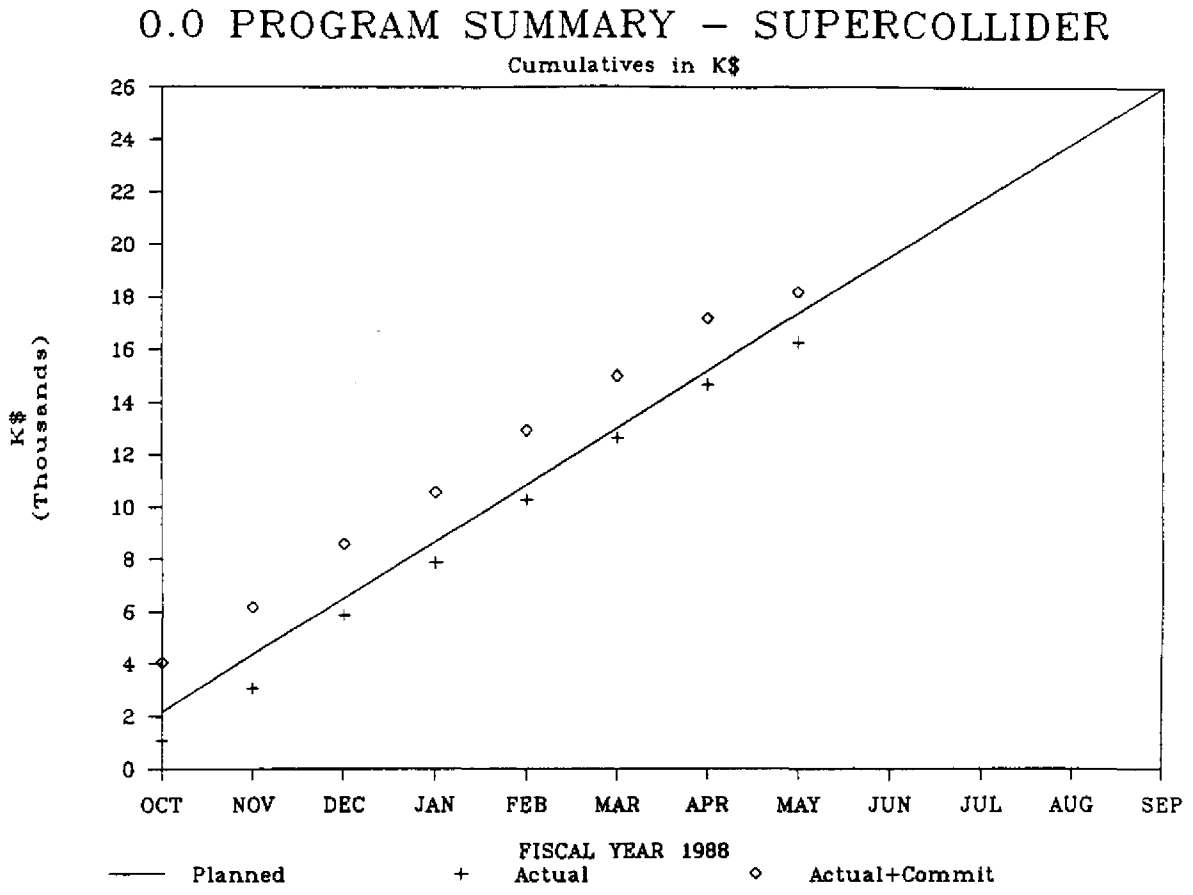

4.0 LAWRENCE BERKELEY LAB
Monthly Costs in K$
K$
700
600
500
400
300
200
100
0
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Delta Commit

Figure 4


0.0 PROGRAM SUMMARY – SUPERCOLLIDER
Cumulatives in K$
K$ (Thousands)
26
24
22
20
18
16
14
12
10
8
6
4
2
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Commit

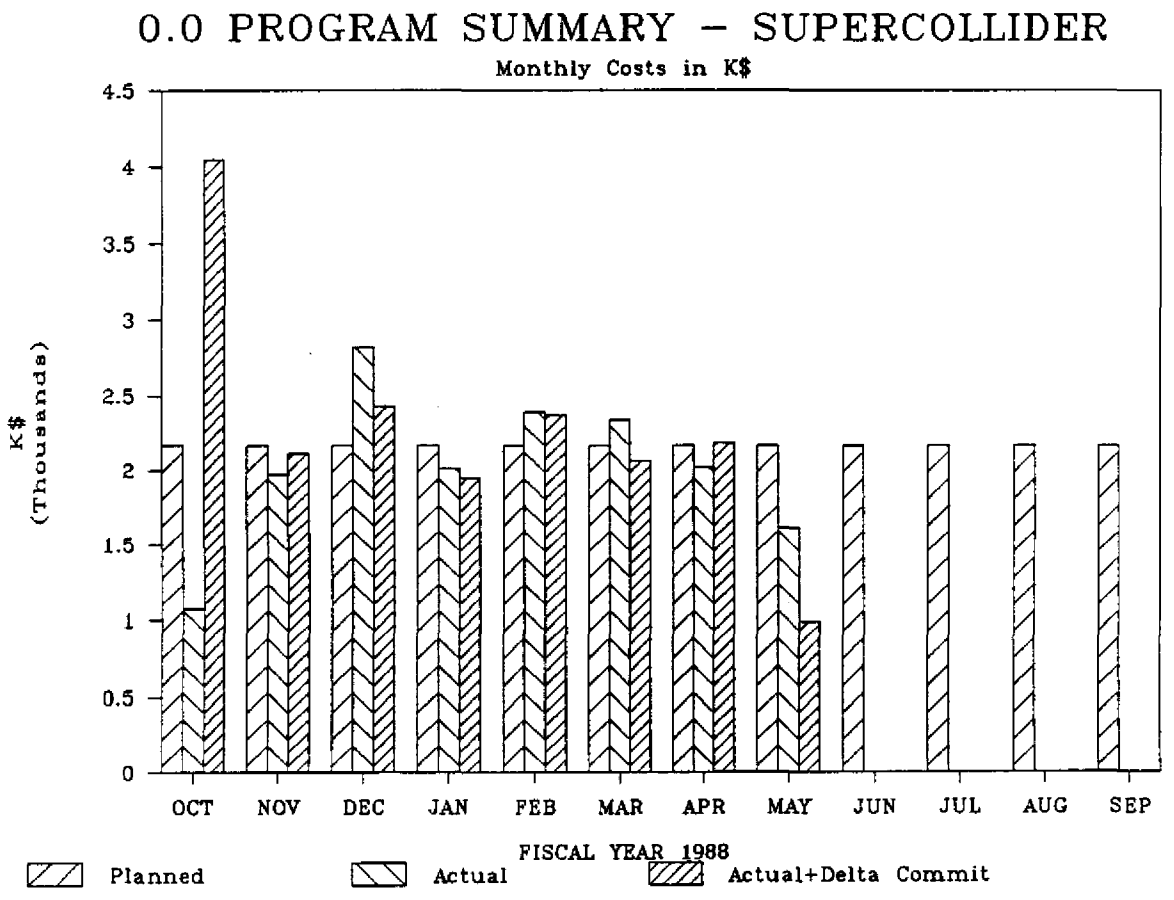

0.0 PROGRAM SUMMARY – SUPERCOLLIDER
Monthly Costs in K$
K$ (Thousands)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
FISCAL YEAR 1988
Planned
Actual
Actual+Delta Commit

Figure 5