THE CEBAF ELECTRON ACCELERATOR PROJECT*

by

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INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) is an accelerator laboratory for basic nuclear physics research under construction since 1987 in Newport News, Virginia.[1] CEBAF is the nation's highest-priority project for nuclear physics.[2] The Southeastern Universities Research Association (SURA), a nonprofit research consortium of 40 universities, is building and managing CEBAF for the U.S. Department of Energy (DOE). Given funding as projected in the Fiscal Year 1992 budget, the total cost to the planned Fiscal Year 1995 start of research operation (including construction, R&D, commissioning, and physics program planning) is $540 million. State of Virginia support for the project during the same period will total $25 million. National and international user "in kind" contributions to the physics program are expected to be about $30 million.

At the CEBAF laboratory, a superconducting accelerator will provide a beam of electrons at up to 4 GeV (billion electron volts) energy and 200 microamperes current for use in nuclear physics research. The high-quality, continuous-wave beam will be split three ways for simultaneous use in three experiment buildings called end stations, where experimenters will use the beams to probe the atom's nucleus to gain new knowledge of nuclear structure and behavior. The ultimate scientific productivity of the laboratory will be determined by the performance of the accelerator and detectors and by effective collaboration with the national and international user community.

The project scope includes:

- a superconducting linear accelerator in an underground racetrack-shaped concrete tunnel 7/8 mile around,
- accelerator subsystems including radio-frequency power, computer-based instrumentation and control, beam diagnostics, safety systems, and power supplies and magnets to focus and guide the beam through the accelerator,
- a 4800-watt refrigeration plant and distribution system to provide liquid helium at 2 Kelvin (-456 degrees Fahrenheit), the low temperature needed for superconducting operation,
- three large, domed, concrete end stations equipped with thousand-ton spectrometers and detectors to observe interactions between accelerated electrons and the nuclei in materials under study, and
- service buildings, other auxiliary structures, two high-bay assembly and development buildings, and an office building.

Figure 1, CEBAF's site plan, shows project structures as well as buildings provided by the Commonwealth of Virginia and the city of Newport News.

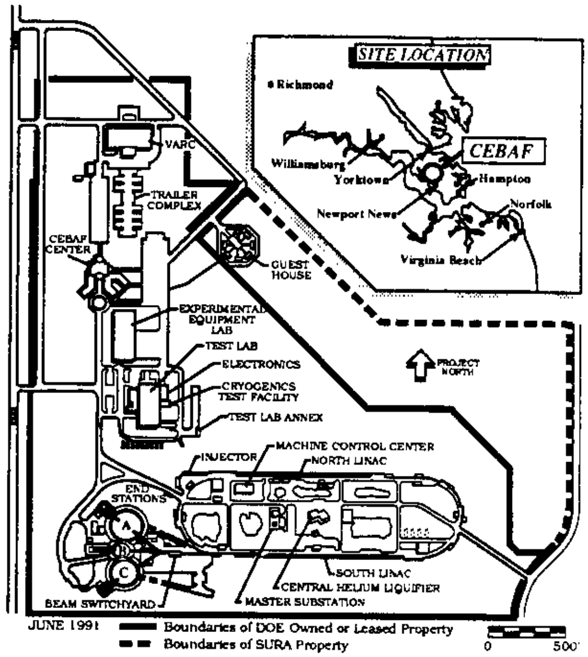

FIGURE 1

SITE PLAN

Figure 2 is a schematic of the accelerator. The electron beam starts in the injector and gains energy as it passes up to five times through two linear accelerators ("linacs") in the straightaways of the racetrack-shaped tunnel before being split for use by experiments in three end stations.

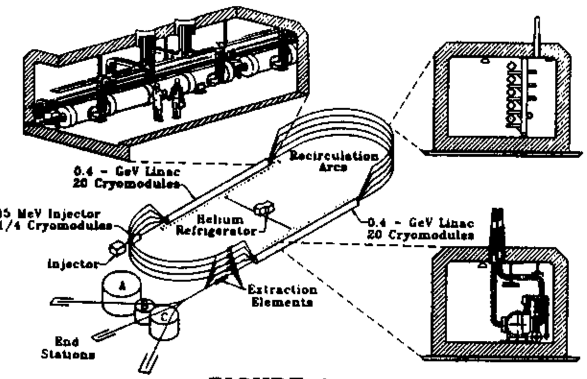

FIGURE 2

ACCELERATOR FACILITY SCHEMATIC

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By June 1991, the project was 60% complete. Accelerator installation and commissioning had begun. The injector's accelerating sections had been permanently installed and operated at design energy. Major procurements for accelerator hardware were well under way, and civil construction was complete except for end stations, nearly two-thirds complete. Spectrometer/detector procurements were being initiated.

CEBAF PROJECT MANAGEMENT

BACKGROUND

Three challenges in particular have strongly influenced CEBAF project management approaches:

- the superconducting radio-frequency (SRF) technology at the heart of the accelerator,
- the involvement of CEBAF's national and international scientific users in the design and implementation of the experiment equipment, and
- the special effort required in the project's early years to establish the appropriate technical and administrative infrastructure, both for the project and for the user-friendly scientific laboratory.

Large-Scale Application of Superconducting Radio-Frequency (SRF) Technology

In 1985 CEBAF became the first major project to select SRF technology for large-scale application. SRF had been developed over 15 years of R&D,[3] but it was not yet generally recognized that the technology had attained readiness for industrial production. Our first technical challenge was to demonstrate this technological maturity by working closely with industry on prototyping.

The key SRF component is the accelerating cavity.[4] Figure 3 shows a pair of superconducting accelerating cavities configured for operation. Each niobium cavity has five elliptical cells. Some 338 cavities are being crafted for CEBAF by industry.

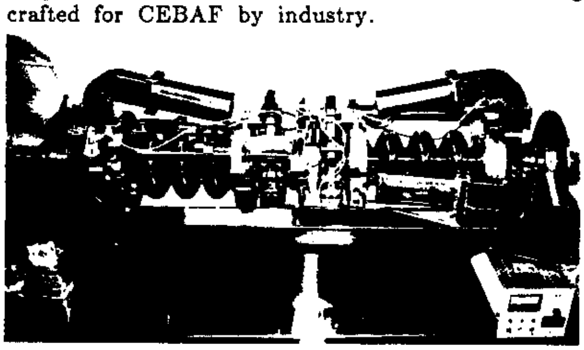

FIGURE 3

SUPERCONDUCTING ACCELERATING CAVITY PAIR

Electrons transiting through the hollow metal cavities gain energy from oscillating electric fields established within the cavities. Each cavity provides 2.5 MeV (million electron volts) of energy gain. The cavities operate in pairs within well-insulated cylindrical containers called cryomodules, with four pairs in each cryomodule. Thus a cryomodule (Figure 4) contains eight cavities and provides 20 MeV of acceleration.

FIGURE 4

CEBAF CRYOMODULE IN INJECTOR

Each of a cryomodule's four sections consists of an inner vessel, where a cavity pair operates immersed in liquid helium at 2 Kelvin, and an outer vacuum vessel. The low temperature allows the cavities to operate superconductively, saving power (about 200 megawatts) and allowing continuous -- as opposed to pulsed -- operation. The two main linacs of the accelerator together contain forty cryomodules. Another two and one-quarter cryomodules are in the injector -- the accelerator's special section that creates and initially accelerates the beam.

Both the cavities and their assembly into cryomodules involve substantial technological complexity. These components define the critical path and require extreme attention to quality in their manufacture, assembly, and testing. The cavities and cryomodules must

- meet exacting mechanical tolerances,
- be processed and handled to assure a defect-free, ultra-clean cavity interior surface to support RF accelerating fields without heating, and
- be assembled to be leak-tight in superfluid helium.

Both expertise and diagnostic equipment and facilities were implemented on site early to control risk, by enabling us to solve unanticipated technical problems with production and operation in a timely manner as the problems arose.

User Involvement in Experimental Equipment

Equipping each end station is a complex, semi-independent, multimillion-dollar project in its own right. Equipment implementation involves selection of spectrometer/detector performance specifications, engineering and design, interface with civil construction, fabrication, assembly, testing, and commissioning. Additional management challenges arise from the need to match the capabilities of the equipment to the user-dominated research program. Accordingly, design alternatives were prepared and reviewed with considerable input from the scientific community during the protracted conceptual design phase. Selections were made in mid-1990. CEBAF's experimenters from universities and laboratories across the country and worldwide are full participants in experiment equipment design and construction. Their activities must be orchestrated to meet project cost, schedule, and interface requirements. User involvement ensures their readiness to use the equipment, and ensures that the equipment is indeed matched to their experimental program needs. But it also increases complexity from the point of view of project management.

Infrastructure Implementation

Successful accomplishment of complex accelerator projects requires the sort of technical, scientific, and administrative infrastructures normally found at established national laboratories. Such infrastructures are ideally suited to support not only the successful design, fabrication, installation, commissioning, and operation of a major new research tool, but also the institution's role in the national and international scientific communities. With the pioneering large-scale application of a difficult technology like SRF, the demands on the infrastructure are unusually severe. But in CEBAF's case, the first staff members arrived at the Newport News site in 1984 to find an academic lab/classroom building, an unrenovated high-bay building formerly used by NASA, and acres of trees. Thus in CEBAF's preconstruction years 1985 to 1987, the critical-path challenges were not only to qualify industry for SRF cavity production, but also to develop the plans, capabilities, project management systems, and infrastructure needed to complete the project and become a full-fledged, user-oriented scientific research laboratory.

The key to meeting the "green-site" challenge was recruiting talented, motivated people with appropriate skills and expertise. By bringing this diverse group together for the single purpose of building the project and founding the laboratory, we established a team-centered, goal-oriented style and culture. This culture, and the fundamentally important and constructive attitudes, approaches, and operating patterns it required, evolved unimpeded by the entrenched values of an established institution.

PROJECT MANAGEMENT STRATEGIES

The CEBAF Project uses a decentralized management organization in which two technically knowledgeable Associate Project Managers have cost, schedule, and technical responsibility in their areas of expertise. The Project Office coordinates interfaces, tracks technical issues, maintains the schedule network, monitors cost and schedule, and controls contingency. The quality assurance (QA) program is thoroughly integrated into the organization, with line management responsible for quality and QA. Costs have been controlled using fixed-price subcontracts for all procurements, including A/E. The project follows an aggressive schedule which deliberately emphasizes early, highly visible commissioning milestones to create schedule pressure on all work teams. The construction phase has overlapped with the design phase, and technical risk, surprises, and the trials of initial operations are confronted early via extensive commissioning in parallel with installation. The research equipment for each of the three end stations is treated as a semi-independent "subproject."

Decentralized Management Organization

The project organization is integrated within the laboratory organization (Figure 5), with the Project Manager serving also as a laboratory Associate Director, and reporting (in both capacities) to the Director. The project

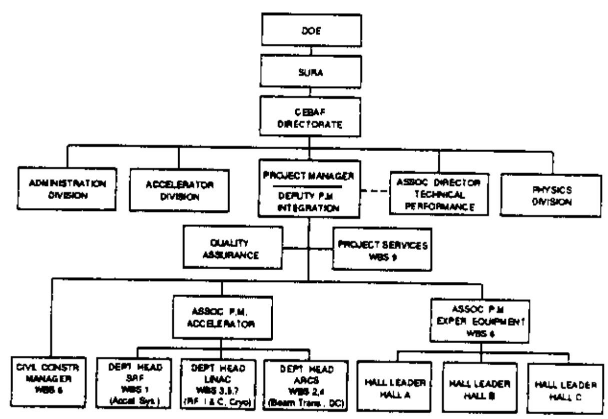

FIGURE 5

CEBAF PROJECT ORGANIZATION

organization is tied directly to the Work Breakdown Structure (WBS), with one Associate Project Manager (APM) responsible for the accelerator hardware systems and a second APM responsible for the experimental equipment. The APMs are also laboratory Associate Directors responsible for functional divisions. Three Department Heads report to the Accelerator APM, three Hall (experiment building) Leaders report to the Experimental Equipment APM, and a Civil Construction Manager (at the Department Head/Hall Leader level) reports directly to the Project Manager.

This decentralized management scheme relies on the expertise and initiative of the APMs for cost, schedule, and technical performance -- key to success when implementing a challenging new technology. Thus the weekly APM meeting chaired by the Project Manager is the primary forum for identifying and resolving cost, schedule, technical, and interface issues in a timely manner. Each APM chairs a separate weekly meeting focused in more detail on progress, issues, and corrective action within his portion of the project.

The WBS, developed to describe, account for, and manage all components of the project, is organized in several levels of increasing detail. Level I is the project. The nine main WBS Level II elements are eight hardware systems plus project services, which provides systems integration oversight, maintains cost, schedule, change-control and performance-measurement databases, and prepares monthly reports for internal use and for submission to DOE. Each Level II hardware system includes deliverables that are technologically similar, regardless of where in the facility they are to be used. Level III elements are facility sectors or integrated systems that accomplish a specific purpose. For example, the injector -- the part of the accelerator that creates and initially accelerates the beam to the energy needed for injection into the full accelerator -- is a Level III element involving several Level II elements. Hardware specification, procurement, and subcontracting are aligned with WBS Level II elements and managed by Cost Account Managers, each reporting to a Department Head or Hall Leader. Installation and commissioning activities center around Level III sectors, each managed by a Department Head or Hall Leader reporting to the appropriate APM. The Deputy Project Manager coordinates installation and integration with the Department Heads and Hall Leaders to support commissioning needs. Levels IV, V, and VI -- the hardware summary and cost accounts -- extend the WBS to a level of detail reflecting the complexity of a given system. At the cost account level, cost estimates are prepared and performance measurement data are generated.

Recurring management control functions, including key internal reports and reports to and reviews by DOE, are delineated in Table A. Figure 6 is a flow chart displaying the feedback mechanisms for management control activities within SURA and involving DOE.

TABLE A

MANAGEMENT CONTROL CYCLES

Weekly	Monthly	Semi-Annually
Progress & Status Review	Performance Measurement Reports $(CS)^2$	Bottoms-Up Cost Estimate
Systems Integration & Interface Coordination	Formal Reporting to DOE	Cost/Schedule/Technical Management Review by DOE
Configuration Control		
Corrective Action Planning		
Schedule Network Update		

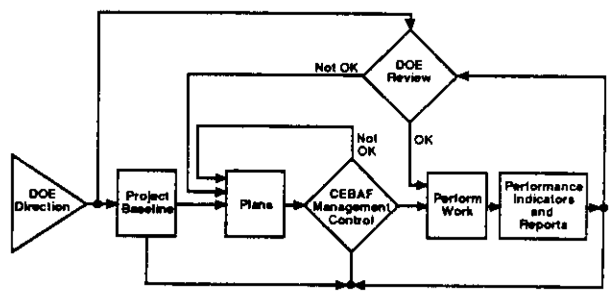

FIGURE 6

MANAGEMENT CONTROL SYSTEM

Technical Control/Quality Assurance

CEBAF line managers are responsible for quality in their areas of responsibility. The QA approach is results-oriented and is described in the institutional QA manual. Technical requirements and criteria are compiled in the Design Handbook, to which all detailed design must adhere unless formally changed through the change control process. Numerous mechanisms and practices have been established to facilitate quality and QA, including:

- Peer review of the QA program itself to provide a check on the overall approach.
- Specific QA Plans (SQAPs) to describe or reference the requirements, procedures, and documentation required to ensure the pedigree and fitness for use of a specific important item or activity. Each SQAP is written by the responsible person and approved by the line managers in both the project and laboratory organization. This approach ensures ownership and

implementation of the procedures necessary to assure the quality of the item or activity in question.

- Project Transmittals to provide a mechanism for official distribution of design documentation and other technical information, especially regarding interfaces among or between systems. Transmittals clearly designate the purpose of the documentation, e.g., for construction, comment/review, or information.

A prominent quality assurance technique employed at CEBAF is typical of accelerator projects. It involves early commissioning in parallel with and providing feedback to the ongoing construction. In this approach important systems tests assure effective integration and allow us to catch and solve problems as early as possible. For example, 5-MeV beam tests of a quarter-cryomodule with subsystems in a laboratory setting preceded installation in the tunnel. In March 1991, the project began a year of commissioning the injector concurrent with installation in the linacs and arcs. The injector is, in essence, a small-scale version of the entire accelerator, since many injector components, including cryomodules, diagnostic devices, and control and safety systems, are identical to those used in the rest of the machine.

Plans call for starting to commission the first linac, as well as the first recirculation arc, as soon as they are installed to identify and fix any problems, determine component and subsystem reliability, train operators, validate operating procedures, and prepare for full operations in support of the experimental program scheduled to begin in Fiscal Year 1995.

Cost Control and Subcontracts

APMs are responsible for implementing their systems within the cost estimates. To track their performance, CEBAF has established a cost and schedule control system ($(CS)^2$) that was validated by the Department of Energy following the mandated demonstration review in November 1989. Through September 1991, 48 months of performance measurement data have been reported against controlled baselines. The baseline was established in 1988, does not include contingency, and is consistent with the provided funding profile through Fiscal Year 1990. In the summer of 1991, DOE and SURA were in the process of rebaselining the project consistent with Fiscal Year 1991 and Fiscal Year 1992 funding levels. CEBAF's funding profile, which is as subject to the vagaries of the federal budget process as that of any other government project, drives the completion schedule.

About 80% of the project cost is in subcontracts. For DOE projects, procurements must be handled within the constraints of the Federal Acquisition Regulations (FAR) and Department of Energy Acquisition Regulations (DEAR). Accordingly, we focused early on two key measures: establishing a skilled procurement department focused on getting the job done, and training key technical people in specification writing, contracting, and vendor interaction.

Early in the project we chose to use fixed-price subcontracts for all procurements. This policy requires our technical staff to thoroughly design, specify, and document the items in advance of requesting a bid or proposal. This substantial up-front effort is necessary to minimize costly change orders during fabrication. To promote competition and to ensure that the designs are feasible for manufacture and are in the expected cost range, we consult during the early design phase with numerous qualified vendors. We have found that this approach pays dividends when the bids come in and the contract work is performed. It avoids the potential cost growth inherent in cost-plus-fee arrangements, where technical substance may be uncovered in partnership with the contractor after the contract is awarded, causing late design changes. Where initial bids have been seriously out of line and the schedule would allow it, we have cancelled and redesigned, paying close attention to cost-driving factors.

In parallel with the design effort, we determine the source-evaluation approach and advertise. Two evaluation methods have been used heavily: award to low bidder (Invitation For Bids, or IFB) (used primarily for civil construction jobs and for catalog items), and award on the basis of technical and cost factors combined (Request for Proposals, or RFP). In general for specialized hardware procurements we have chosen to issue RFPs.

The interface between civil construction and the technical/scientific aspects of the project has been crucial, and thus has required significant up-front definition. The total civil portion of the construction project will cost about $69 million, including 15% for EDIA (including A/E services, accomplished using fixed-price task orders, and construction management, accomplished by in-house staff assisted at our request by the A/E firm). Considering the complexity of the facilities and the technical interface requirements, our record on change orders -- averaging under 5% on civil subcontracts to date -- is very reasonable. To emphasize our seriousness about construction-site safety, we have included in recent civil construction contracts incentive/penalty clauses for safety performance, which allow us to fine the subcontractors for violations, and to reward them financially for an exemplary safety record.

The contracting process has been time-consuming. For small procurements (under $25,000), the elapsed time from purchase request to contract award has averaged nearly a month. For the largest procurements (over $500,000), it has averaged four months for IFBs and eight months for RFPs, including the time required for DOE approval of the award of any contract over $1 million, but not counting advertising and design done in advance.

Nonetheless, subcontract cost control has been successful while technical goals for the deliverables have been met. As of May 1991, only three protests, all unsuccessful, had been lodged by unsuccessful bidders. The GAO denied two, with some delay but without complications; the other was withdrawn by the complainant. And under the policy of fixed-price contracting, total costs have stayed at the level of estimates. An effective procurement department and early, formal training of technical staff in the duties they must fulfill as contracting officer's technical representatives (COTR) have led to these results.

Schedule Control

APMs are responsible for accomplishing work under their purview on schedule. A key project tool to heighten schedule awareness has been to schedule visible commissioning milestones. This approach explicitly applies and maintains pressure on all work groups, since they do not want to be seen as holding up a key test. The project office maintains a schedule network, which identifies the major activities, decision points, and activity interfaces essential for project completion. Implicit in the schedule is the integration of design, procurement, fabrication, assembly, and installation of hardware, and Title I, II, and III of conventional facilities. R&D requirements and prerequisites are also included. There are some 2700 activities in the schedule network (of which some 1400 are complete), with separate networks for each WBS Level II system, and inter-WBS schedule interfaces identified. The entire database is used to identify critical paths and develop the budget plan.

Experiment Equipment "Subprojects"

DOE approved CEBAF's Experimental Equipment Plan in June 1990, signaling the go-ahead for the nuclear physics collaborations that will build spectrometers and detectors for the the 4-GeV accelerator's three experiment buildings. The plan calls for two high-resolution spectrometers for Hall A, a large-acceptance spectrometer for Hall B, and a high-momentum spectrometer and a short-orbit spectrometer for Hall C. Figure 7 shows these end stations and this equipment. Hall-by-hall completion of the equipment is phased over 12 months to accommodate the funding profile anticipated by DOE, with the first hall (C) ready for experiments in Fiscal Year 1995.

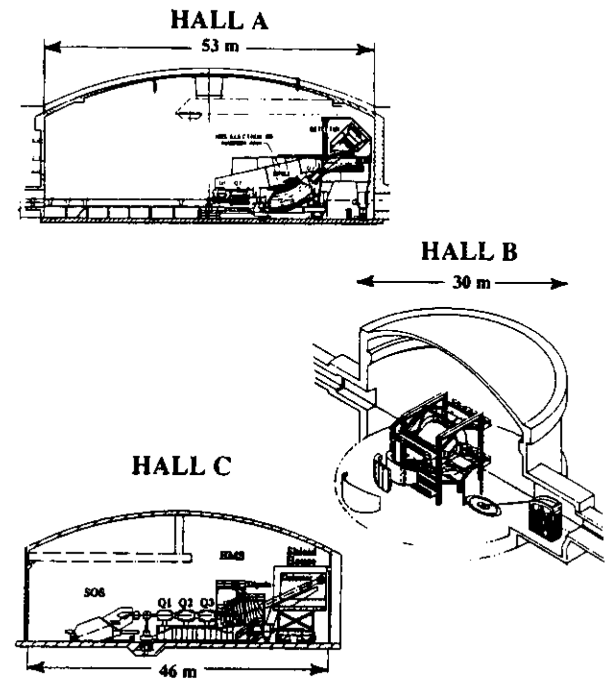

FIGURE 7

END STATIONS AND EXPERIMENT EQUIPMENT

The equipment implementation for each hall is organized as a major subproject. Reporting to the Experimental Equipment APM for each end station are a CEBAF Hall Leader and a co-manager from the user community. Hall collaborations operate under a formal charter, meet frequently throughout the year, and use bitnet (electronic mail via a worldwide scientific computer network) and fax to communicate in real time. A CEBAF staff member is designated as liaison and facilitator for every piece of equipment or detector being built by the users.

We are controlling costs by using fixed-price subcontracts and by giving high priority to the early placement of subcontracts for cost-driving components. This approach gives us latitude to make descoping tradeoffs if they become necessary during the design and procurement processes to keep within the cost envelope. Management and tracking tools for the three "subprojects" are the same as for the accelerator and civil construction.

The total funding for experiment equipment, including contingency and in-house manpower, is $125 million (in actual year dollars). Excluding contingency and manpower, the experiment equipment budget for End Station A is $28 million, for End Station B is $24 million, and for End Station C is $13 million. During the current phase (design and procurement) a contingency level of 25% is maintained on all future items, and 10% contingency is kept for items already on contract. We believe this contingency will allow us to accommodate unanticipated problems during fabrication, assembly, and installation.

To manage technical risk and surprises, we are doing small-scale prototyping, planning early subsystem commissioning (with the end stations completed and available during Fiscal Year 1992), maintaining close interaction with and among user groups building equipment, and delineating user involvement and responsibilities via Memoranda of Understanding between CEBAF and user groups.

CONCLUSIONS

Civil construction is nearly complete, accelerator installation and commissioning are well under way, and user activity is focused on experiments and equipment. As with any project, much has been accomplished and learned, and our management approach continues to evolve to match the challenges characteristic of each project phase: from design and R&D, through construction and commissioning, to operation and physics research. Our experience indicates that:

- An efficient and effective interface between the technical and architecture/engineering design teams is best served if both groups are housed on site. Early and careful attention to code selection and application can save money. Early and careful definition of the civil/hardware interface can avoid costly and time-consuming rework.
- A prominent quality assurance technique to ensure successful integration and operation is early commissioning of subsystems in parallel with and providing feedback to construction and installation.
- Effective use of project management tools, databases, and reports by technical managers is facilitated if these systems are implemented early, and if people are trained in their use and see their benefits.

Within the framework for accelerator project management, CEBAF's approach includes several specific strategies. We have a decentralized management organization. Technically knowledgeable Associate Project Managers have cost, schedule, technical, and quality assurance responsibility. The Project Office coordinates interfaces, tracks technical issues, and allocates contingency. Our quality assurance program is thoroughly integrated into the line organization. Our cost and schedule control system is based on generally accepted practices to produce valid, timely, auditable data on project progress.

An important element of cost control relies on fixed-price subcontracts for all procurements, with technical staff well versed in the formalities of contracting.

Our schedule is aggressive. The construction phase overlaps with the design phase, and technical risk, surprises, and the trials of early operations are confronted early via extensive commissioning in parallel with installation.

We treat experiment equipment for each of the three independent halls as an independent subproject. The schedule for the equipment lags slightly behind the accelerator schedule. Its implementation involves the scientific input and efforts of CEBAF users at numerous other institutions.

Early development of on-site troubleshooting capabilities -- both people and facilities -- was key to overcome "green site" liabilities and to meet the challenge presented by the technology.

These management strategies have been instrumental in achieving cost, schedule, and technical goals to date.

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