Engineering Management Lessons on NCSX

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Abstract— The National Compact Stellarator Experiment (NCSX) is under construction at Princeton Plasma Physics Laboratory (PPPL). The stellarator is a complex, 3-D assembly that has been designed by a team of engineers from the partner institutions, Oak Ridge National Laboratory (ORNL) and PPPL. The complex, 3-D nature of the stellarator design and the multi-institutional, geographically dispersed nature of the team have created special management challenges. Management systems were implemented to address these challenges. The lessons learned from our experience on NCSX thus far are discussed.

I. Introduction

The design of a proof-of-principle experiment for compact stellarators began in 1998. NCSX grew out of that effort as a partnership between ORNL and PPPL. In addition to learning much about the physics and engineering of compact stellarators, NCSX has provided abundant opportunity for learning about the engineering management of a technically challenging, multi-institutional, and geographically dispersed project.

II. Lessons Learned

A. Setting and Managing Requirements

Requirements set the course of a project. They largely determine the cost of a device as well as its performance. NCSX benefited from a having adequate time to plan the project from the time we first started investigating compact stellarators in 1998 until the project baseline was approved in February 2004. This provided an opportunity to assess the design and cost impacts of the requirements and iterate until we had a set of requirements that provided a sound basis for execution. This incubation period also contributed to the stability of the requirements. Since the project was baselined, minimal changes have been made in the top-level requirements thereby avoiding cost increases associated with design changes attributable to shifting requirements.

Top-level requirements are documented in the General Requirements Document (GRD), which is the system specification. The GRD provided the basis for NCSX conceptual design. The GRD and conceptual design in turn provide the basis for the System Requirements Documents (SRD's) prepared for each major subsystem. The SRD's guide the preliminary design of those subsystems. At the preliminary design review, the adequacy of a subsystem design in meeting the performance requirements in the SRD is assessed.

Lower tier specifications and detail drawings are developed during final design to support fabrication, procurement, and assembly activities for components and assemblies. These specifications define design and performance requirements and how it will be verified that these requirements have been met, typically through analysis, inspection, or test. The verification provisions in the specifications are then translated into quality assurance provisions in manufacturing procedures and test plans.

This disciplined approach to successively allocate system requirements to subsystems, assemblies, and components; assess the adequacy of designs in formal design reviews; and translate verification requirements in specifications into quality assurance provisions in manufacturing plans and procedures is critical for ensuring that the requirements set at the beginning of the project will be met at the end.

B. The Value in Value Engineering

Value Engineering (VE) is a technique directed toward analyzing the functions of an item or process to determine "best value," or the best relationship between performance and cost. Best value is represented by an item or process that consistently performs the required basic function and has the lowest total cost. Efforts were made to understand cost, schedule, and performance implications before making decisions on setting requirements or adopting a particular design approach. Changes were adopted when VE studies identified opportunities to achieve the same performance, or acceptable reductions, at less cost.

NCSX initiated a VE task force to look afresh at ways our performance requirements could be met at reduced cost. This task force identified using the C-site power supplies for initial operation; adopting more extensive use of local controls; winding the modular coils four-in-hand and eliminating shims between layers; and adopting a pour in place insulation between the vacuum vessel and modular coils, thereby saving the project millions of dollars.

C. Developing Effective Management Systems

"Management systems" include the procedures, processes, and behaviors to be followed in executing the project. Management systems include work planning and authorization, cost performance reporting, configuration management and change control, interface control, and design verification. Effective management systems enable team members to do their jobs with minimal burden, cost, and risk.

We have found that there are three keys to developing effective management systems: training, availability of project information, and a process of continuous improvement. Project participants come from different institutions and backgrounds. Even within an institution, things are done differently from project to project. In order for management systems to work, project participants have to be trained in how the project plans to do business.

Once trained, project participants need to have the information needed at their fingertips. NCSX is a paperless project. A Web site has been established through which all project information can be immediately accessed, even from remote locations.

The NCSX project documented and implemented management systems early in the project. As we exercised these systems, we discovered what worked well and what did not work. Improvements were made based on feedback we were receiving from the users. This process of continuous improvement needs to be followed throughout the life of the project because user requirements will change as we move from design to fabrication to assembly to testing.

D. The Benefits of Prototyping

NCSX has unique manufacturing challenges stemming from its 3D geometry. The vacuum vessel is a highly shaped, 3-D structure. The modular coils are non-planar. Concerns existed from the outset about the feasibility of fabrication so we developed a plan to build prototype vacuum vessel segments (PVVS), prototype modular coil winding forms, and a prototype modular coil winding which became known as the Twisted Racetrack Coil (TRC).

Prior to embarking on the prototype programs, NCSX involved industry in performing manufacturing studies to assess the feasibility and cost of our vacuum vessel and modular coil designs. The manufacturing studies provided technical insight. For the vacuum vessel, there were many different technologies that could be applied to form the vessel. These technologies include cold forming, hot forming, explosive forming, and brake forming. For the modular coils, the technologies for making the winding forms were basically the same except for whether the mold was made using a pattern or by direct machining. It was also learned that the companies best suited to fabricate the winding forms had little to no experience in winding coils. On the basis of this observation and PPPL's extensive experience in coil manufacturing, it was decided to wind the modular coil in house.

Following the manufacturing studies phase, cost-plus contracts were awarded to two companies to fabricate prototype vacuum vessel segments and to two companies to fabricate modular coil winding forms. The benefits of prototyping soon became apparent.

The feasibility of fabricating the parts was established. Design deficiencies were revealed that needed to be addressed. Manufacturing, inspection, and test and quality assurance plans were developed and refined. The prototypes provided an improved basis for the contractors to finalize teaming arrangement and provide firm fixed-price proposals for the production contract.

One of the major benefits was in learning about our contractors. The prototypes told us much more about the capabilities of the contractors than their proposals. It gave the project an opportunity to learn about the companies and develop working relationships with their counterparts before the production effort started.

E. Building Effective Relationships with Contractors

The first step in building an effective relationship is to establish clear expectations. Expectations are established in specifications and statements of work (SOW's). Specifications (and associated drawings) define the technical design and performance requirements and how it will be determined that those requirements have been met. SOW's define all non-specification work requirements. Properly crafted specifications and SOW's tell prospective contractors all that is needed about the work to be performed to develop responsive proposals.

The next and most important step is picking the right contractor. NCSX contractors are typically selected on a "best value" basis, not on a lowest bid basis. A good contractor will submit a proposal that is technically responsive and fairly priced. The bid price should reflect an understanding of the work that needs to be done with modest allowances for contingency and profit. If a bid is anomalously low or high, it is an indication that the contractor really does not understand what is being requested (or is the only one that does). The technical approach should be sound, using technologies that the contractor has successfully used before. The work should not overly extend the company's resources or facilities. The company should be financially stable and able handle the financial risk associated with the contract. A good contractor will also have a trail of satisfied customers. The best way to have the true measure of a contractor is to have done business with the company in the past, e.g., through a prototype effort.

Once the contract is awarded, the project should help the contractor control cost and schedule. Every effort should be made to eliminate requirements that add little value, a continuation of the VE approach. This will create cost and schedule contingency for the contractor and trust and goodwill for the project at no cost. The project should be made aware of contractor difficulties as they arise and do what can be done to alleviate those difficulties. If the contractor runs into cost and schedule problems, the contractor and project are both at risk. Mechanisms need to in place to effect rapid project responses to requests for deviations and nonconformances from the contractor. The project should resist imposing changes on the contractor where possible. Changes upset plans, cause delays, increase costs, and create unwelcome work to keep documentation current.

Caution should be used in applying conventional estimating techniques to unconventional and first-of-a-kind components. The NCSX experience is consistent for both contractor and in-house work. First articles have been found to take twice as long (or even longer) as expected. Subsequent articles will approach expectations. Learning curves are real and in our experience, often underestimated.

F. Managing Risks

NCSX is an ambitious undertaking with risks that need to be managed. To manage these risks, a formal risk management approach is being followed. The NCSX project is continually on the lookout for emerging risks. The Engineering Manager is responsible for tracking emerging risks using a Critical Issues List. When a risk is identified, it is added to the Critical Issues

List. The Critical Issues List has three categories of risks. Category I risks are those for which we have recognized the risk but do not yet have a risk mitigation plan. Category II risks are those for which we have a mitigation plan but the risk still exists. Category III is for those risks which have been retired.

The Critical Issues List is reviewed every three weeks in Integrated Project Team (IPT) meetings. The IPT consists of key DOE and laboratory project personnel including the Federal Project Director, the OFES NCSX Program Manager, the OFES Stellarator Program Manager, the NCSX Laboratory Project Manager, and supporting staff. The Critical Issues List serves as the focus for discussions on risk management issues.

This process has been working well but has not anticipated all risks, some of which are difficult to foresee. One of these was modeling of the modular coil shell. The complex geometry of the shell proved to be a real challenge for our 3D CAD system, requiring much more time than anticipated to develop workarounds for the CAD problems that were encountered.

G. Agility in Planning

The NCSX project is a complex array of interdependent activities in a constantly changing environment. A high level of planning on the part of job managers and project management and attention to the progress being made in those activities is required on the part of job managers and project management.

NCSX is a first-of-a-kind undertaking, so it is to be expected that things do not always go according to plan. Many surprises can be accommodated by agility in planning. Agility in planning can be defined as the ability to respond to problems and changes within established technical, cost, and schedule baselines.

Agile planning options that have been exercised on NCSX include:

- Building items in-house if there is inadequate time to contract with industry or if the necessary expertise does not exist in industry
- Working on a double shift basis instead of a single shift basis
- Eliminating scope that is non-essential
- Ordering long-lead materials before the completion of final design
- Changing the design if it proves too expensive.

Agility in planning has proven necessary to respond to changes in the project's situation while preserving budget and schedule contingency for the later stages of the project.

H. Working Safely

NCSX follows PPPL's policy of Integrated Safety Management (ISM). The intent and essential elements of ISM are listed in Table I.

TABLE I. INTENT AND ESSENTIAL ELEMENTS OF ISM

1	Objective – Integrate safety management into work practices
2	Guiding Principles • Line management responsibility for safety • Clear roles and responsibilities • Competence commensurate with responsibilities • Balance priorities • Identification of safety standards and requirements • Hazard control tailored to the work being performed • Operations authorization
3	Core Functions • Define the scope of work • Analyze the hazards • Develop and implement hazard controls • Perform work within controls • Provide feedback and continuous improvement

Safety is integrated into NCSX work on all levels:

- Job managers address safety in their work planning.
- Safety is addressed in design reviews and influences choices.
- Job hazard analyses (JHA's) are performed to identify existing or potential hazards.
- All staff are taking Hazard Awareness Training (JHA-based) to improve understanding of NCSX hazards.
- Lab Activity Certification Committee (ACC) reviews NCSX manufacturing and test facilities and associated procedures prior to operation.
- Pre-job briefings are held prior to the start of any new work activity to discuss specific work activities, responsibilities of the participants, a review of the JHA/safety issues, and to respond to all questions and concerns.
- Post-job briefings are held at the conclusion of a work activity to discuss the completed work activities. They should include lessons learned including technique problems, improvements, and safety related issues.
- Work is done according to documented plans and procedures.
- Training of personnel is a key to completing the NSCX field work safely. Courses are offered for all personnel, instructing them in the proper use of tools and equipment; personal protective equipment (PPE); and general laboratory policy and safety requirements.

The lesson learned on NCSX is to plan and organize the work so that safety, cost, and schedule objectives are mutually supportive, not in conflict.

I. Bringing Out the Team's Best

The success of NCSX hinges on the motivation, commitment, productivity, and ingenuity of the engineers, technicians, physicists, and managers working on the project. The NCSX team, like many projects, works in a tough environment, presented with stiff technical challenges that need to be overcome in limited time with limited budget. This environment can bring out the best in team members.

A project also needs to provide a supportive environment which is fostered by:

- Setting expectations that are realistic and embraced.
- Providing adequate resources to meet those expectations.
- Providing ready and able support when problems arise.
- Implementing management systems that make jobs easier, not harder.
- Making good use of people's time.
- Creating a working environment in which everyone's contributions are viewed as being of equal importance, everyone feels respected, and everyone enjoys coming to work.

Providing a supportive environment in which best and sustained efforts are enthusiastically given to overcome the stiff challenges faced is essential for continued project success.

III. Conclusions

NCSX has provided an opportunity for learning valuable lessons in engineering management. These lessons include the following:

- A disciplined approach for setting requirements and verifying their implementation is critical for ensuring that the requirements set at the beginning of the project are met at the end.
- There is real value in value engineering.
- The keys to developing effective management systems are training, availability of project information, and a process of continuous improvement.
- Prototyping can yield valuable and unanticipated benefits.
- There are practices that should be followed in developing effective relationships with contractors, the most important of which is picking the right contractor.
- A formal risk management system is beneficial for identifying emerging risks and tracking their mitigation.
- Agility in planning has proven necessary to respond to changes in the project's situation while preserving budget and schedule contingency for the later stages of the project.
- Work should be planned and organized so that safety, cost, and schedule objectives are mutually supportive, not in conflict.
- Providing a supportive environment in which best and sustained efforts are enthusiastically given to overcome the stiff challenges faced is essential for project success.
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