Aug 30, 1983   S. pl 5, 1983

CONF-830971--7

LESSONS FROM DESIGN AND MANUFACTURE OF U.S. LCT COILS*

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CONF-830971--7

DE84 003165

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract No. W-7405-eng-26 with the Union Carbide Corporation.

Abstract - In the international Large Coil Task (LCT), U.S. industrial teams have finished one coil and are nearing completion of two others. Of the lessons learned, the ones that apply most widely to advanced technology development have to do with the difficulty of scheduling progress in a novel undertaking. Reasons for schedule stretch-out are discussed in this paper. The major factor in the LCT was the discovery by all participants of more technical problems than could have been foreseen. Also, the effort implicit in the demands for reliability and quality were greater than appreciated at first. Other factors were changes in requirements during the projects and restrictions on effort due to budget constraints. LCT experience should be particularly useful in scheduling development of superconducting coils for tokamak fusion reactors.

INTRODUCTION

The United States is building three 40-ton, 8-T, superconducting toroidal field (TF) coils for evaluation in the international Large Coil Task (LCT)./1/ Coils by General Dynamics/Convair Division and by General Electric use NbTi conductor and are bath-cooled./2,3/ A coil by Westinghouse uses forced-flow cooling of a Nb_3Sn conductor produced by Oxford Airco./4/ When contracts were let in 1977, it was expected that coils would be delivered in late 1979 or early 1980. Actual schedules have proved to be over twice as long. Analysis of U.S. experience shows that schedules were extended for reasons commonly affecting development of large, advanced technology hardware. They include (1) technical problems in design or fabrication that exceed expectations, (2) customers' changes in requirements, and (3) funding limitations that force slowdowns.

Analysis of U.S. LCT coil projects shows that about 40% to 50% of the schedule increase was due to unexpectedly time-consuming technical problems. The balance of the delay was attributed to funding constraints and to changes in the technical specifications. This paper outlines and briefly explores the major causes of delay.

TECHNICAL PROBLEMS DURING DESIGN

As a deliberate, large step toward tokamak reactor coils, the LCT intentionally confronted some new or especially difficult design problems. Although the selected teams were well acquainted with magnet technology and design practices, some unprecedented requirements proved to be more difficult to meet than had been expected.

Stability

Because a goal of the coil specifications was to make the test coils as relevant to tokamak requirements as possible, cryostability (including recovery from a full turn normal) was specified but the available cross section was stringently limited. The consequent relatively high current density prompted the choice of forced flow by one U.S. team (and two European teams) and impelled designers of bath-cooled coils to conceive ways to enhance heat transfer. Concern for the effects of bubbles rising through an unusually tall winding pack required experimental data to be obtained before design could proceed with confidence of meeting LCT performance specifications. Related concern for the effect of irregularities required unusually careful design evaluation of internal sensor installations.

Structural Stresses

A modified D shape was specified, resembling concepts of very large tokamaks. Unlike tokamak TF coils, however, the LCT coils had to be designed to take out-of-plane loads corresponding to full-current operation of a coil with one neighbor deenergized. (This allows continuation of coil tests even if one coil fails, which would be pointless in a tokamak.) Although designers recognized this at the outset as presenting a significant structural problem, the full implications were not appreciated until complex finite-element models of the conceptual designs were assembled and analyzed. The coils with structure concentrated in the external case faced especially difficult problems in the corner at the nose region. This resulted in the need for additional structural steel in the corner at the expense of eliminating several turns of conductor in order to deal with the problem within rigid spatial constraints.

Forced-Flow Conductor Sheath

This conductor presented problems that appeared sequentially. Many appeared in the manufacturing phase. An example during the design phase was the evolution of the conductor sheath. The sheath had to perform several roles, and the special requirements for each had to be simultaneously satisfied. In the initial conceptual design, the sheath was 0.5-mm-thick 304 stainless steel. A desire for defect-free producibility, combined with the problems of exposure to the 700° C reaction heat treatment, led to the selection of a 0.875-mm 304L sheath. When detailed stress calculations taking into account details of geometry showed unexpectedly high stresses, the change was made to a 1.7-mm-thick Nitronic 40 sheath. Subsequent investigation showed that the 700°C reaction heat treatment seriously degraded the 4 K weld fracture toughness of Nitronic 40. A broad search for a better material eventually led to the final choice of JBK75, a modified version of the iron-based superalloy A286.

TECHNICAL PROBLEMS DURING MANUFACTURING

Problems encountered during the manufacturing phase turned out to have greater impact on schedule than those encountered in the design phase.

Pool Boiling Designs

(1) The time that the winding machine is turning proves to be the "tip of the iceberg." Other ancillary (often routine) steps or operations dominate the winding cycle times. A lesson here is that an allowance for this effect based either on detailed analysis and/or experience must be factored into schedules. (Experience to date has shown classical learning curves for winding times, especially if the time required for the installation of heaters and sensors is discounted.)
(2) Similarly, in welding, the time when the arc is struck is relatively small compared to the time required for set up, fit up, weld preparation, adjustment, optical alignment, fixturing, predicting and compensating for distortion, grinding, and inspecting. Here again, the lesson is that schedules must have these considerations factored into them to a greater extent.
(3) The routing and protection of sensor leads out of the coil interior also proved to be a time-consuming interruption of the winding process. A lesson learned is that provisions for a small amount of additional space for sensor lead wire routing and protection to facilitate more rapid and inspectable installation is warranted to minimize the impact on the schedule and to avoid electrical shorts.
(4) The need to provide a close fit between the outer turns of conductor and the coil case in pool boiling designs proved to be a more significant challenge than originally envisioned. The lesson is that time must be scheduled for insulation fitting or preparations for resin injection.
(5) The producibility design of the splice joint between grades of conductor in a pie-wound coil proved very important. The lesson learned is that fabrication of a single joint on the development bench does not verify manufacturing times; verification tests intended to demonstrate the estimated fabrication time of splice joints are warranted in any pie-wound coil design prior to the start of manufacturing. Another lesson is that splices and multiple grades of conductor

should be used only if a careful study shows that net cost savings is actually realized considering realistic production splice times.

Forced-Flow/Distributed Structure Design

Although the forced-flow coil is in earlier stages of manufacture, several specific causes of schedule delay can be identified. Most were caused by the need to implement development tasks after the start of production operations to resolve unforeseen problems.

(1) Following extensive development bending tests and full-scale winding trials with preproduction prototype conductor, a surprising 50% increase in conductor forming forces and springback characteristics was encountered. Approximately 4 months were added to the manufacturing schedule after a priority effort on a major redesign of production tooling. Subsequent production lengths have proven consistent.
(2) About the first half of the 100-m production conductor lengths fell short of nominal dimensions by about 35-40 cm. Various stages of the conductor manufacturing process were known to affect length and had been factored into the initial length determination. The exact cause of the discrepancy has not yet been identified conclusively, although minor processing changes were made that were not thought to affect length. Fortunately, of five coil redesign solutions identified by the coil manufacturer, it proved feasible to implement the solution having the least impact on schedule (3 months). *Empirical corrections were made to cause the remaining* lengths to be within tolerance.
(3) The effort required to achieve an acceptable conductor surface finish, free of insulation damaging defects, was underestimated. To reduce costs, a used tube mill was purchased at the time the jacket material was thought to be 304 stainless steel. JBK75 proved to be an extremely tough material to form, and the program suffered, cumulatively, about a one-year schedule delay to perform the needed tube mill redesign and upgrade and to obtain the required surface finish.
(4) The difficulty of achieving the necessary level of quality assurance for a defect-free continuous autogenous weld was underestimated. Since commercial equipment capable of the job was not available, about one year of concerted effort by the Oak Ridge National Laboratory (ORNL) Metals & Ceramics Division nondestructive testing specialists was required to develop an on-line multifrequency eddy current system.

Technical factors, as described above, have been the principal cause of delay on the U.S. forced-flow coil. Although they are made in retrospect, the preceding points underscore the problems of initiating production prior to attaining sufficient preproduction experience to be certain that all major problems have been resolved.

Schedule Increases Due to Specification Changes

The LCT test coil specifications prepared by ORNL were designed to ensure relevance of the fabrication and testing experience to tokamak magnet requirements. Because the purpose of the LCT is to pursue and evaluate several coil concepts, a "performance" specification was issued that defined the required performance, the spatial envelope, and interface dimensions but that left to the design teams the internal design of the coil.

As the design teams proceeded into the conceptual and detailed design phases, a great deal was learned of the complexities of simultaneously meeting both performance and spatial requirements. A similar experience occurred with the LCT facility design. Knowledge gained in these processes led to five revisions in the technical specification. The important point here is that these revisions were not the result of a lack of forethought by those who drafted the specification or by the major industrial firms responding to the specification; on the contrary, there is a widespread agreement among the participants that the basic architecture and content of the specification were excellent. Rather, the changes were a necessary result of a rapidly maturing technology that was making a large step in equipment scale.

Changes in the technical specification caused delays by creating new work to be performed or by causing a repeat of work previously completed. This effect, similar to funding constraints, causes cascaded delays from one fiscal year to the next (as described below). Experience has also shown that other subtleties can arise with specification changes, such as delays in production if new or changed procurement is required or problems regarding the availability of personnel with the desired skills.

Schedule Increases Due to Fiscal Year Funding Limitations

There is general recognition that the resolution of unforeseen technical issues increases schedule and costs. However, the mechanisms whereby funding limitations (and contract specification changes) can increase schedule (and cost) are far more subtle, and the magnitude of their impact is far less appreciated.

Funding reductions below that estimated as necessary to support the planned schedule obviously delay work. Work from fiscal year "A" is deferred to fiscal year "B" (with higher attendant costs). Since fiscal year "B" was funding limited, work planned for fiscal year "B" is pushed into fiscal year "C" by the work deferred from fiscal year "A." Over a time span of several years, the cumulative effect on schedule and total cost at completion is more significant than generally recognized.

Funding constraints combined with unexpected technical problems prevent timely problem solutions and can result in the slippage of other tasks in order to solve the unexpected problem. This then gives rise to a cascade of delays from fiscal year "A" to "B" to "C," etc. Although generally recognized, the full impact of this combination is perhaps the least appreciated of all delays related to funding constraints.

If the trained personel required to perform a given task now (which was earlier delayed) have been released to other projects, delays will be encountered if they are not immediately available. Similarly, the trained personnel slated to perform the next task (now delayed to the future) must be temporarily reassigned to other projects. When the time arrives that their skills are required, their availability may be delayed, or, in the worst case, it may be necessary to train new people.

SUMMARY AND CONCLUSIONS

As seems to be inevitable in advanced development, technical problems surfaced in the course of the U.S. LCT coil projects that were foreseen dimly, if at all. These have delayed but do not now threaten the successful completion of the U.S. coils. Each industrial coil team, in addition to learning specifics of how better to design and build large superconducting coils, gained a fuller appreciation of the uncertainties inherent in scheduling tasks that are at the leading edge of design and manufacturing technology. The basic conclusions from their experience contain nothing new, but reinforce precepts that are sometimes forgotten. Planners of advanced technology projects would do well to obtain, at the outset, thorough review and advice by the most experienced people available regarding problems that are most likely to turn up and methods of dealing with such problems. Unnecessary problems should be avoided. When problems do arise, they should be continually evaluated for potential impacts so that appropriate efforts can be applied to achieve solutions that are both efficient and timely. "He who does not learn the lessons of history is condemned to repeat it."

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