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Princeton Plasma Physics Laboratory
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POSTMORTEM COST & SCHEDULE ANALYSIS - LESSONS LEARNED ON NCSX

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Abstract— The National Compact Stellarator Experiment (NCSX) was designed to test physics principles of an innovative fusion energy confinement device developed by the Princeton Plasma Physics Laboratory (PPPL) and Oak Ridge National Laboratory (ORNL) under contract from the US Department of Energy. The project was technically very challenging, primarily due to the complex component geometries and tight tolerances that were required. As the project matured these challenges manifested themselves in significant cost overruns through all phases of the project (i.e. design, R&D, fabrication and assembly). The project was subsequently cancelled by the DOE in 2008. Although the project was not completed, several major work packages, comprising about 65% of the total estimated cost (excluding management and contingency), were completed, providing a data base of actual costs that can be analyzed to understand cost drivers. Technical factors that drove costs included the complex geometry, tight tolerances, material requirements, and performance requirements. Management factors included imposed annual funding constraints that throttled project cash flow, staff availability, and inadequate R&D. Understanding how requirements and design decisions drove cost through this top-down forensic cost analysis could provide valuable insight into the configuration and design of future state-of-the art machines and other devices..

I. OVERVIEW

The compact stellarator was one of several innovative magnetic fusion plasma configurations being investigated by the U.S. Department of Energy (DOE) Office of Science (SC), Office of Fusion Energy Sciences (OFES). The promise of the stellarator as a practical fusion concept lies in its potential to eliminate disruptions and operate steady-state with minimal recirculation power. Due to its geometry, a stellarator can generate significant rotational transform by currents in external magnet coils and can stabilize limiting magneto hydrodynamic (MHD) instabilities by plasma shaping instead of relying on active feedback control. However, since NCSX is one of the first devices of its kind, the complex geometry and tight tolerance requirements had an unanticipated impact on the total project cost and schedule. So as to better appreciate NCSX's unique design and configuration challenges see Figures 1-5. Note the two key components; the vacuum vessel and modular coil assembly.

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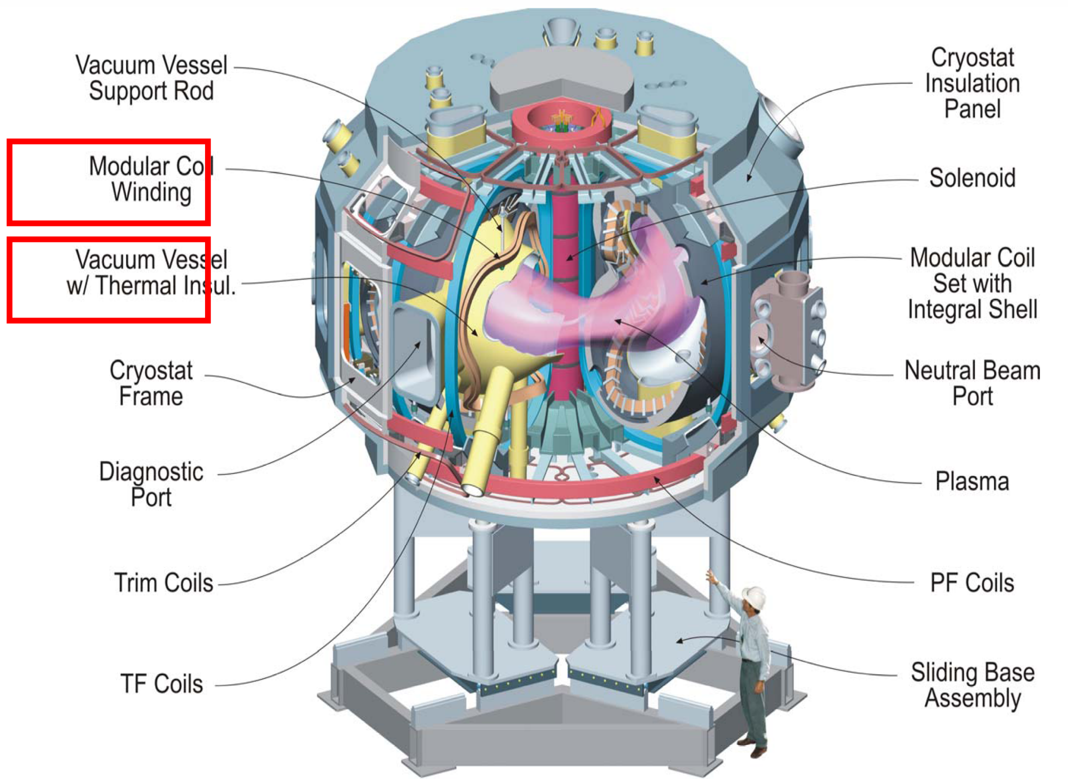

Figure 1: NCSX Stellarator core assembly

Figure 2: NCSX vacuum vessel design

Figure 3: One of three NCSX vacuum vessel sectors fabricated by industry and delivered to PPPL. (The port extensions were later temporarily removed during assembly operations.)

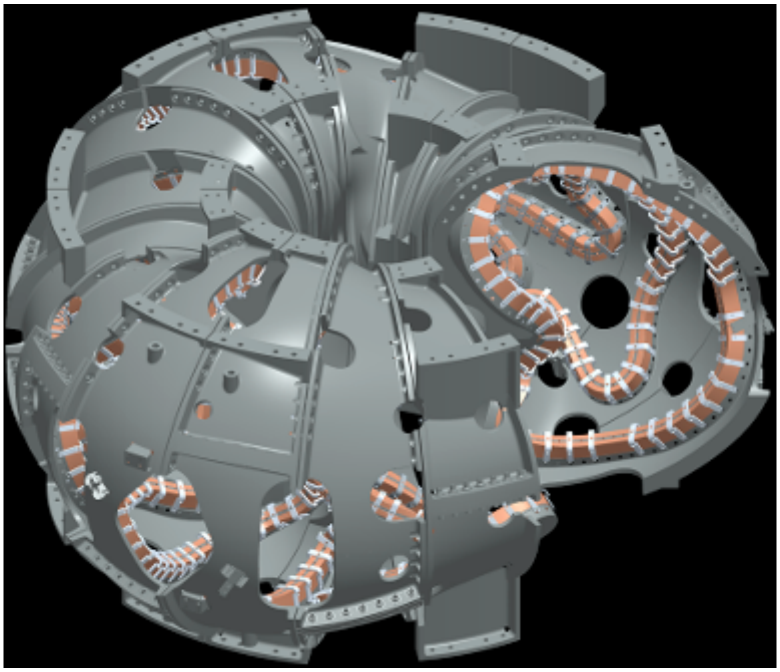

Figure 4: Modular coil assembly (18 individual coils). There are 3 distinct modular coil geometries.

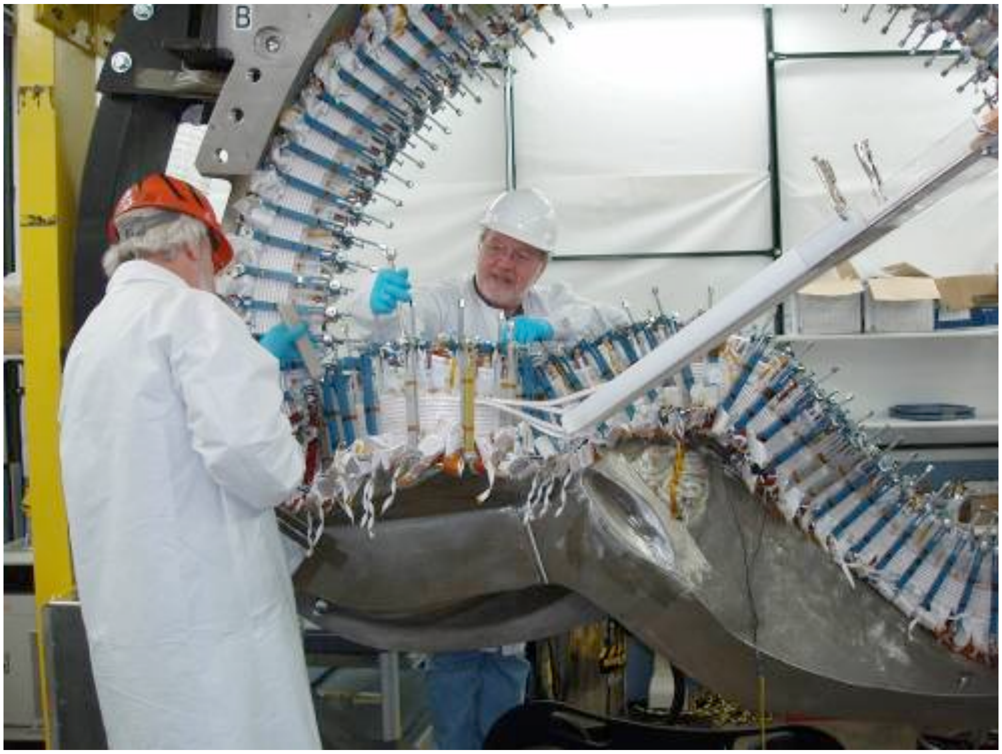

Figure 5: Modular coil winding operations at PPPL.

II. PROJECT BACKGROUND

The project baseline was approved with a budget of $86.3 million and a completion date of May 2008 in February 2004 after a successful independently led preliminary design review followed by a DOE Office of Science (SC) Project review. After further reviews, start of construction was approved in September 2004. In 2005, the NCSX funding profile was modified by DOE in response to budgetary constraints, resulting in a stretched-out baseline with a TEC of $92.4 million and a July 2009 completion date.

In late 2006 it became clear that the baseline cost and schedule objectives could not be met. At a DOE-SC project review in August 2007, a $40 million TEC increase (from $92 to $132 million) and 29 month schedule extension (from July 2009 to December 2011) were proposed. The new estimates included $14.4 million or approximately 28 percent cost contingency and 11 months or approximately 24 percent schedule contingency. The large increases in both base estimates and contingency at this stage of the project resulted from a maturing design which led to a better understanding of the costs, uncertainties, and risks than had previously existed. The budget increases, schedule delays and continuing uncertainties of the NCSX construction project led the DOE to announce in May 2008 its decision to terminate the project.

III. Forensic data analysis

There were many factors that led to the cost growth of the NCSX project. The following Table 1 shows a summary tabulation by project phase and subsystem comparing the actual cost incurred to the baseline estimates. While the actual costs themselves are not important, it is important for us to understand the magnitude of growth and what issues/conditions drove those costs. As shown the actual cost for these selected components grew by a factor of 2 over the baseline budget!

Table 1

		Baseline Cost ($K)	Actual Cost ($K)	Factor Increase
R&D Prototyping				
	Modular Coils	$4,412	$6,000	1.4
	Vacuum Vessel	$1,390	$1,787	1.3
Design				
	Modular Coils	$2,171	$7,190	3.3
	Vacuum Vessel	$679	$1,894	2.8
Procurement				
	Modular Coils	$5,568	$10,830	1.9
	Vacuum Vessel	$3,332	$5,314	1.6
Fabrication & Assembly				
	Modular Coils	$8,284	$15,584	1.9
	Field Period Assembly (partial)	$1,002	$5,827	5.8
Total				
	Modular Coils	**$20,435**	**$39,604**	**1.9**
	Vacuum Vessel	**$5,401**	**$8,995**	**1.7**
	Field Period Assembly	**$1,002**	**$5,827**	**5.8**
		$26,838	**$54,426**	**2.0**

IV. Observations

A breakdown of contributors that led to this cost growth are summarized by category in the following figures 4-6

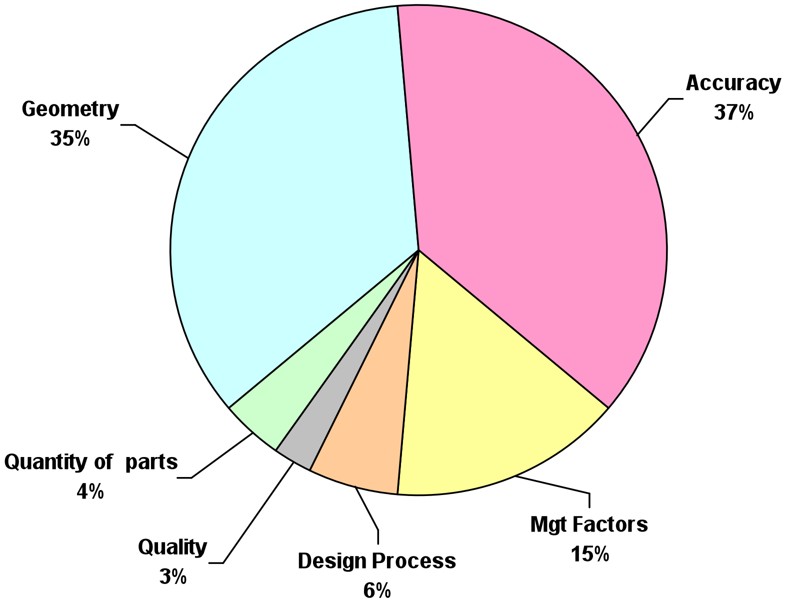

Figure 4: Cost Growth by Category

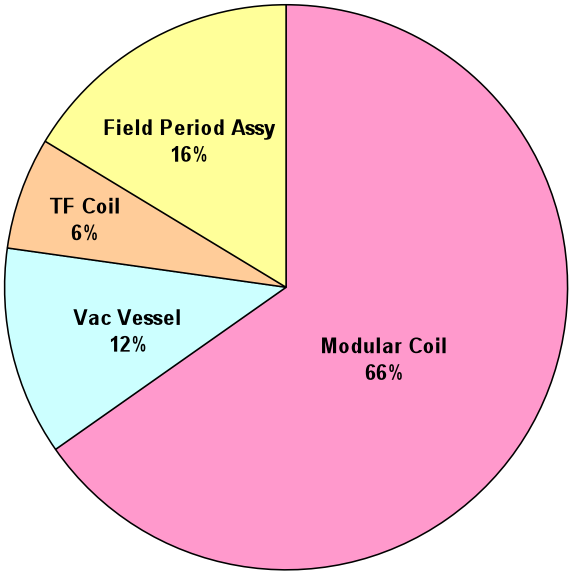

Figure 5: Cost Growth by Component

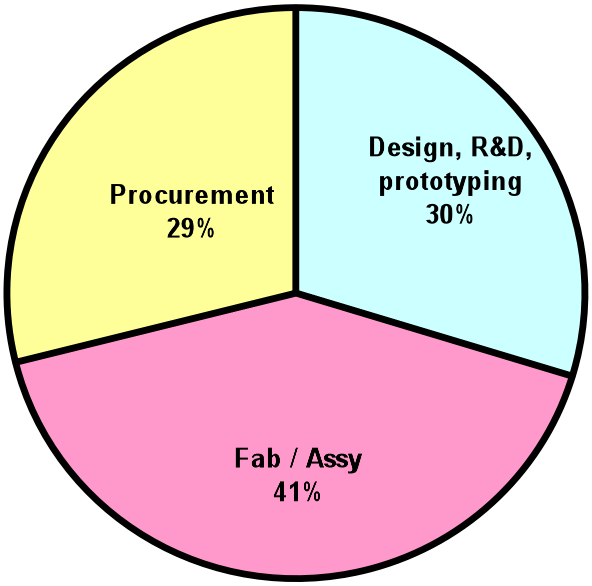

Figure 6: Cost Growth by Phase

As the above data cross-cuts suggest, the unique geometry and required fabrication accuracy of the modular coil, vacuum vessel and their assembly were the biggest contributors to cost growth on the project. This was evident throughout all phases of the project from design, R&D, procurement, fabrication, and assembly. Discussions with the responsible managers enabled the project to distill the causes and impacts into 5 significant "lessons learned" that could be applied to future similar devices.

1) Field Period Assembly (FPA)

Cost Driver: *Accuracy*

Explanation: Costs were driven by very tight assembly tolerances (+/- .020") and the complexity of the design, partly attributable to the compact geometry, and partly to large forces. Use of metrology equipment with the addition of metrology dedicated technicians and engineers supported by a back-office engineering analysis team to compare measurements to CAD models and provide guidance to the field technicians. It must be pointed out that the FPA had just begun and the cost growth seen was only representative of the work performed.

2) Modular Coil Winding Form Procurement (18% of growth)

Cost Driver: *Geometry & Accuracy*

Explanation: a) Costs were driven largely by machining of the complex geometry and meeting tight tolerance requirements (+/- .020”). The cost-growth is understated because it reflects only the cost to the project and not unreimbursed vendor costs, which were significant. Because the machining of the winding forms was not adequately prototyped, the cost of meeting the tolerance requirements was not well understood when the budget was established.

b) Significant time was spent reviewing non-conformances to determine if they could be used which diverted key engineers & designers from the task of completing the design.

c) While the cost growth experienced was a factor of 1.9 higher there was also a schedule impact as well since the vendor experienced a steep learning curve during the manufacturing of the first 2-3 articles (figure 7). This impacted subsequent coil winding tasks by PPPL.

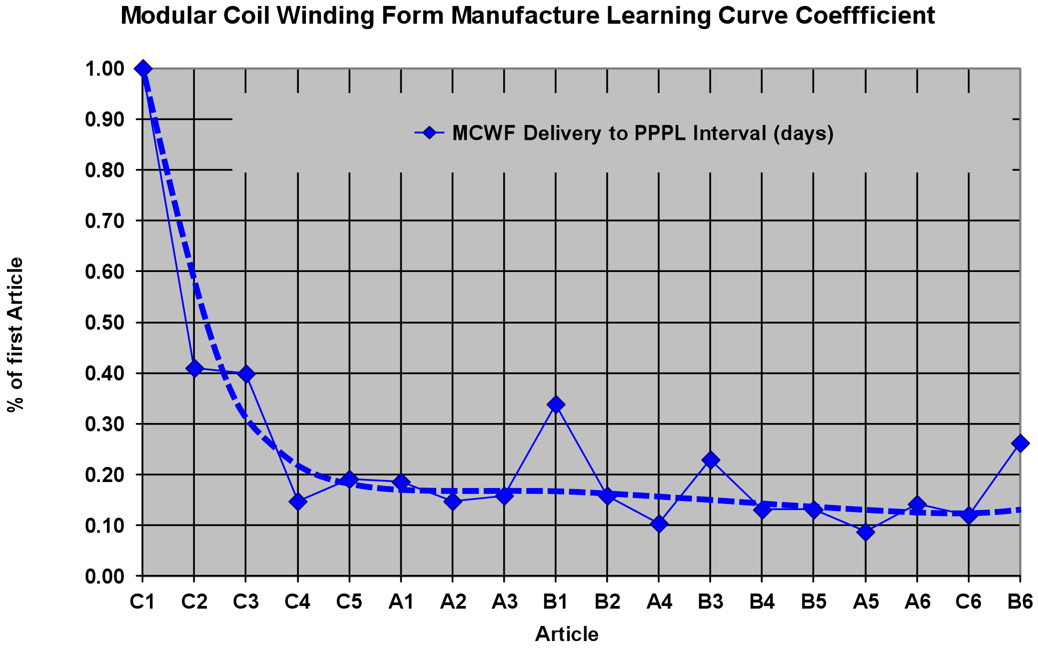

Figure 7. Learning curve for the manufacturing of MCWF’s

3. Modular Coil Design (12% of growth)

Cost Driver: *Geometry*

Explanation: a) MCWF: Complex geometry required development / extension of CAD capabilities.

b) Windings: Complex geometry required development / extension of CAD capabilities, and extra time was needed to carefully orient winding packs to resolve interferences. Complexity of the winding pack configuration (number of parts), which was driven by the compact geometry.
c) Interface hardware: Low-aspect ratio geometry precluded bolting of the inner leg. Difficulty of finding a workable solution drove large cost & schedule growth. Accuracy requirements necessitated low-distortion welding development and multiple design iterations, both of which drove costs. Interface joint design iterations caused re-work.

4. Modular Coil Fabrication (Winding Operations) (11% of growth)

Cost Driver: *Accuracy*

Explanation: a) Costs were driven by metrology and dimensional control requirements to meet tolerances, the complex geometry, and the complexity of the assembly (number of parts). Numerous factors that drove the costs and schedule during the manufacturing of the modular coils included design completion, premature acceptance of Winding Forms; tolerance requirements, metrology, quantity of parts/components, underestimate of learning curve, personnel issues and manufacturing approach.
b) While the cost growth experienced was a factor of 1.9 higher there was also a schedule impact as PPPL experienced gradual learning curve during the winding of most of the modular coils (figure 8). This delayed assembly tasks which were on the project's critical path.

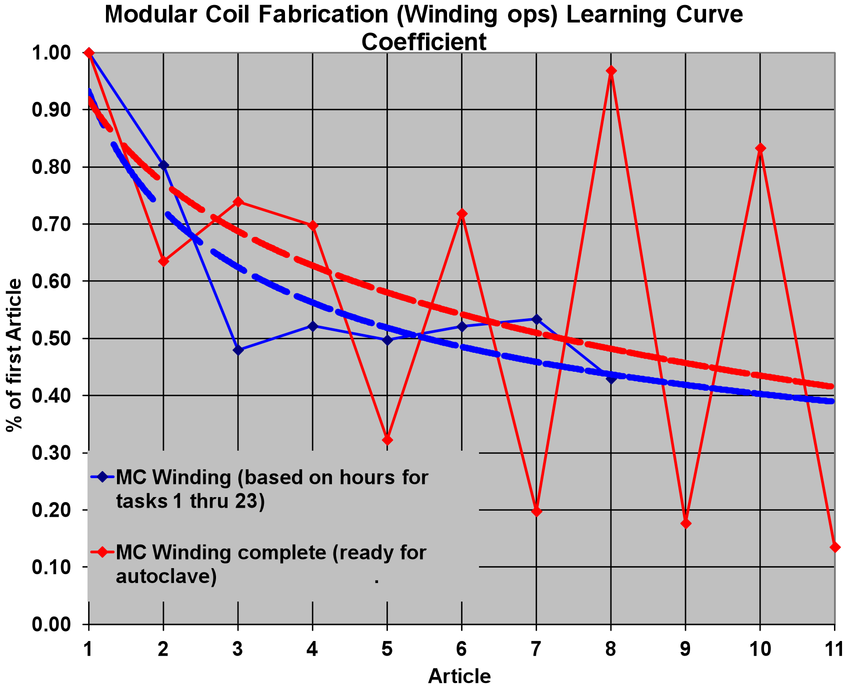

Figure 8. Learning curve for the fabrication (winding) of the modular coils

5. Vacuum Vessel Fabrication (7% of growth)

Cost Driver: *Geometry & Accuracy*

Explanation: The complex geometry drove panel forming and assembly. Accuracy requirements (low field errors) drove the choice of Inconel, a more expensive material to work with. Significant time was spent reviewing parts that did not meet requirements to determine if they could be used. This diverted key engineers & designers from the task of completing the design.

V. Conclusion.

The High Cost of Tolerance in Manufacturing and Component Assembly drove cost and schedule. The project failed to appreciate this relationship early in the planning phase of the project which subsequently led to the project overrunning cost and subsequent cancellation by the DOE. Complex critical components were held to very high manufacturing and assembly tolerances to maintain stellarator symmetry. For example, tolerances are as small as 0.020 inches on large components such as the modular coil's conductor position. It was soon realized that high tolerances and sophisticated geometries were significant cost and schedule drivers for this project, much more than originally estimated. Even the vendors, who have a history of complex fabrication, underestimated the cost of this requirement. High accuracy requirements demanded the use of sophisticated metrology equipment, which in turn required dedicated trained operators (a.k.a. metrology teams), who were supported by dedicated analysis personnel (a.k.a. "back office support") to compare actual results to Pro-E CAD models. This labor intensive support was not adequately recognized nor budgeted. While accuracy is inherent with a device of this sophistication, the blanket application of tolerances manifested itself in high labor cost to achieve the results specified and to respond to and disposition QA non conformance reports (NCR's) resulting from the fabrication of the modular coil winding forms and vacuum vessel sub assembly.

R&D and designs were not sufficiently mature prior to establishing a cost and schedule baseline. The complex geometry and tight fabrication tolerances of NCSX created unique Engineering and assembly challenges. R&D and design were not sufficiently completed to establish a sound technical basis for the cost and schedule baseline cost. While this configuration was required for the machine to perform as specified, a more robust prototyping program sould have been carried out to flesh-out the cost of fabrication. Specifically, the modular coil prototype was cast but not completely machined. Completing the machining would have provided the vendor with a better basis for establishing a cost and schedule estimate. Secondly, the vacuum vessel prototype was constructed for a narrow section of the total vacuum vessel. Fabricating a larger section (i.e. 1/2 field period) would have surfaced the challenges of plate forming and welding. While these may have not lowered the cost they would have led to an earlier realization of cost and schedule.

A contributing factor was the premature establishment of a firm cost and schedule baseline without a more mature design and fabrication base. While funding constraints may have throttled an earlier progression of design, the adoption of a performance baseline for the project should have been delayed until design (and supporting fabrication/assembly tasks) were completed. This would have led to a better understanding of the implications of the accuracy requirements and geometry relative to cost and schedule. Also worthy of note is the advancements in technology since the cancellation of the program. Metrology, CAD programs, and web-based meeting systems capable of handling real-time viewing of complex CAD geometry have all matured significantly. These would have been a significant benefit to the program, if available then.

VI. Recommendations

Viewed from the perspective of lessons learned with applicability to all future high technology ventures the following recommendations stand out:

A. Be critical and surgical in requiring small tolerances. This will drive the vendor's procurement cost, require extensive in-house engineering time to disposition NCR's, and increase assembly time. The impact manifests itself in both increased cost and schedule stretch-out. Ultimately NCSX developed trim coil systems which were able to mitigate some of the high tolerance requirements. Unfortunately the development of these coils came late in the program due to funding and resource constraints. Although they were beneficial in permitting a relaxation of tolerance and fabrication acceptance requirements, saving costs and schedule, if they were developed earlier more benefit might have been realized.

B. Complete prototyping tasks before procuring critical components. This may not necessarily reduce cost BUT the ultimate cost of procurement will be better known up front (i.e. MCWF prototype machining)

C. Simplify designs by minimizing the numbers of parts that need to be detailed, procured, prepared and assembled.

D. Recognize the nature of high tech/high risk projects and avoid prematurely establishing cost and schedule baselines until a more mature design/fabrication experience base is established.

VII. EPILOGUE

In the context of this conference the NCSX project did not fail from a structural, material, design or safety point of view. However, as engineers trying to design and build solutions to society's problems, there are plenty of examples of worthwhile projects that fail before they get off the ground due to budgetary considerations. Due diligence places the onus on us to be realistic and not optimistic in proposing future projects to our customers if we want to move forward and be successful.

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