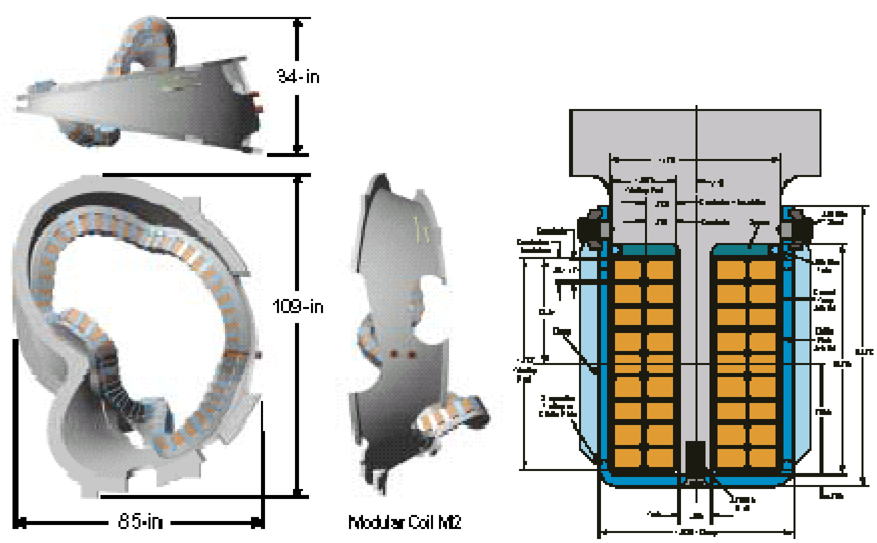
Value Engineering of the NCSX Modular Coils and Vacuum Vessel

Background

NCSX's modular coils and vacuum vessel are geometrically complex components which were recognized as unconventional and challenging from the point of view of manufacture right from their conception. They are key components of the device and are amongst the most expensive. Consequently, a modified value engineering process consisting of industry involvement in their conceptual and preliminary designs was undertaken to reduce uncertainties and risk and develop designs which are practical to manufacture, cost-effective, and, most importantly, meet their technical requirements. One of the important tasks for industry was to suggest, and assess, options for reducing cost particularly during fabrication. An important, but less direct, value engineering activity was the reduction of risk through prototyping. Reductions in risk almost always translate to reductions in future costs.

The modular coils, shown in Fig. 1 below, consist of stainless steel cast structures with precisely positioned "T" structures onto which the coil's windings (flexible copper cables) are located. The winding form serves two critical functions: (1) they define the precise shape of the magnet; and (2) they react electromagnetic loads which are as high as ~5000 lbs./in.



Stainless steel casting   Winding Cross-Section

Fig. 1. Details of one of the three types of modular coils. The winding form is shown with the windings installed. Six each of three distinct types (shapes) of modular coils are required.

The vacuum vessel, shown in Fig. 2, is a highly contoured, three period torus with a geometry that repeats every 120 degrees. This segmentation permits the close-fitting modular coils to be assembled over the three vessel segments, as shown in Fig. 3. The three vessel segments will be joined together by welding at final assembly after the modular coils and diagnostic access ports are installed.

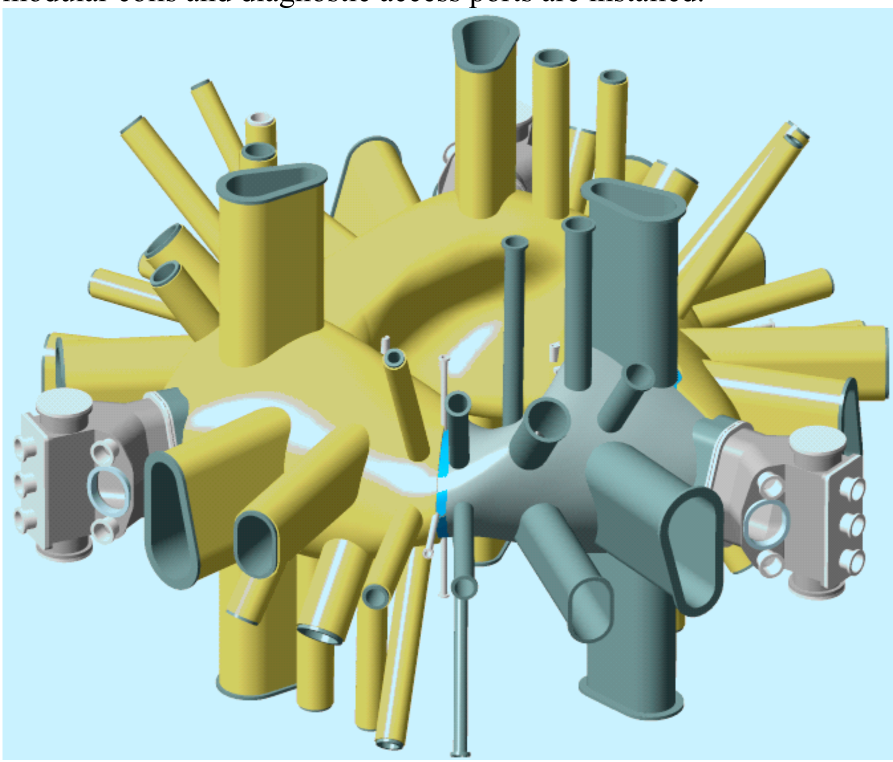


Fig. 2. NCSX Vacuum Vessel Assembly.

Shown with cryogenic insulation and ports installed. Most of the ports will be installed after the modular coils are positioned over the vessel segments, as illustrated below in Fig. 3.

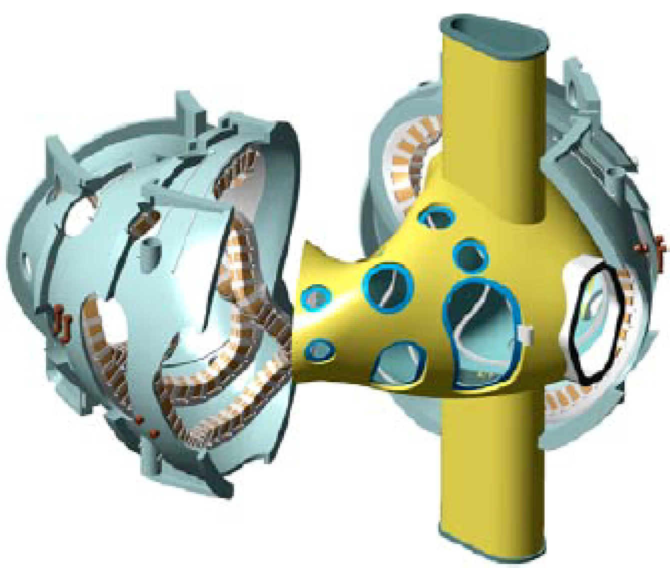


Fig. 3. Assembly of the Modular Coils and a Vacuum Vessel Segment.

Value Engineering Process

There are three major phases to the value engineering process employed for NCSX's modular coil winding forms and vacuum vessel:

Phase I. Industrial manufacturing studies of both the modular coils and vacuum vessel during the conceptual design phase. These studies provided extremely valuable feedback on the schedule, cost, the manufacturability of the designs, and a wide variety of technical details such as achievable tolerances, design features, alloys, specification details, and potential manufacturing methods. During this phase the industrial teams identified elements of the fabrication process that presented difficulty and thereby increased cost. An important task was to identify design or fabrication changes that would significantly improve the component fabrication cost. This information was used in the development of project plans and budgets, and was extensively used in the development of the details of the winding form and vacuum vessel designs, specifications, and statements of work. Examples of important findings: In the vacuum vessel area, multiple options for forming the vessel were identified. Initially it was felt that explosion forming was the most appropriate method of forming the vessel. However, the studies indicated that there are several other viable fabrication methods, including hot die forming, cold die forming, and press forming of ring segments which would be welded together. In the coil area: Initially our plan was to procure the modular coils as finished assembly. However, the studies pointed out that the winding forms are primarily a casting and machining activity, and the coils are an electromechanical assembly activity – two distinctly different groups of tasks. The suppliers' feedback convinced us that there was no value added in combining these activities under one contract. After much discussion of the pros and cons of combining vs. separating these two elements of the modular coils, it was decided that procuring the winding forms in industry and then completing the windings at PPPL was the best approach from the point of cost, schedule, and control of risk - in particular, accurate placement of the windings to achieve the required magnetic field uniformity.

Phase I Primary Goal: Early industrial involvement in developing good, cost effective designs.

Phase II. Detailed Vacuum Vessel & Winding Form Manufacturing Studies and Prototype Fabrications during the advanced conceptual design and preliminary design phases. These studies are currently underway. There are two teams each in the vacuum vessel and winding form areas. Both study efforts are similar in content, consisting of :

- Development of a detailed manufacturing/inspection test (MIT) / Quality plan for the "production" articles. These plans were reviewed and discussed in detail, and are now typical of what we normally would have for a production fabrication effort. These plans are fully detailed, and will therefore serve as the basis for the subcontractor cost/schedule proposal efforts.

Phase II Primary Goals: Confidence Building; Risk Mitigation

- Development of a detailed manufacturing/inspection test (MIT) / quality plan for the prototype (in the case of the winding form, for the "type C" casting, which is the most complex; in the case of the vacuum vessel, for a 20 degree sector with a vacuum port assembly).
- Actual fabrication of the prototypes.
- Based on the knowledge gained during the prototype fabrication, identify options for improving the fabrication process so as to reduce fabrication costs.
- Based on the MIT plan developed for the production articles and the experience gained through the prototype fabrication, the final deliverable item from this study is a firm fixed price and schedule proposal. As noted above, the subcontractors will use the detailed MIT /Quality plans they previously developed (refined based on their prototype efforts) as the basis of their proposals.

The modular coil winding form efforts are led by Energy Industries of Ohio (EIO) of Cleveland, Ohio , and by JP Pattern of Butler, Wisconsin. . The vacuum vessel efforts are led by Rohwedder, Inc. of Oviedo, Florida, and by Major Tool, Inc. of Indianapolis, Indiana.

These studies have several purposes:

1. To develop the final designs and specifications of the vacuum vessel with full participation of industry. Blending of the complementary strengths of Laboratories and Industry will improve the designs and reduce technical, cost, and schedule risks.
2. To gain solid technical data on the winding forms and vacuum vessel by the actual production of prototypes during the design phase. This will provide data on dimensional control (which is highly important for stellarators where the minimization of magnetic "islands" due to field errors is essential), magnetic permeability which is also important to field uniformity, material properties in "as fabricated" components, and the general manufacturability of the designs.
3. To provide the manufacturing experience and confidence necessary for the potential subcontractors to be able to develop firm price and schedule proposals which, by virtue of this experience, do not contain excessive levels of contingency.
4. To identify alternate fabrication options that would meet project requirements at reduced cost.
5. To minimize downstream risks (technical, scheduler, and financial).

During the course of these studies, there has been a steady stream of feedback on the specification, statement of work, and design details which resulted in refinement of these items.

Phase III Primary Goalsl: To build the Winding Forms and Vacuum Vessel within Specification, On Time & On Budget.

Phase III. Fabrication the Modular Coil Winding Forms and Vacuum Vessel Assembly. It is our intent to select one subcontractor for the vacuum vessel assembly (ie, 3 vessel sectors and all associated ports) and one subcontractor for the (18) modular coil. These selections will be based on their firm price/schedule proposals, evaluation of the prototypes, and our experience in working with them during these efforts. The earlier efforts should provide the technical and manufacturing experience base to make this possible.

<u>Process Assessment</u>

It is difficult to accurately assess the expected savings from this Value Engineering approach. The value added was in the nearly continuous involvement of industry providing day-to-day fabrication and cost inputs to guide the design process rather than in discrete, cost savings design changes. We feel that a reasonable way to quantify the value to the project is to estimate the impact the value engineering activities described might have on the project completion date and then assess the cost of the time saved. The vacuum vessel is the first needed component of the core, followed by the modular coils. The modular coil / vacuum vessel sub assembly is the basic building block of the machine around which all the other elements of the core (PF coils, error correction coils, diagnostics,, structures, etc.) are located. Simply, the machine assembly cannot proceed until these key elements are ready, and delays in either of them will result in delays in the project completion.

For the technical and fiscal success of the project, these components must be delivered in compliance with their technical specifications and on time, and on budget. The value engineering process employed was structured to provide early "hardware" experience while there is adequate schedule slack to permit any problems which might arise to be addressed and resolved prior to the production phase where problems and delays with critical components such as these are likely to have significant negative impact. If the vacuum vessel is not properly shaped or does not meet vacuum and structural requirements, the assembly process or experimental program will be severely impacted. The discrepancies would have to be corrected before assembly can begin, and this could take a substantial amount of time. In a similar manner, if the modular coil winding forms did not meet their requirements they, too would severely impact the program. Their dimensions must be correct, they must have the structural stiffness that was used in the analyses, and they must have the electrical time constant that was assumed in analyses.

The value engineering process NCSX adopted forced an earlier resolution of a whole host of tasks and issues than would have otherwise occurred. These tasks and issues includes the poloidal breaks in the winding forms; the number and placement of ports in the vacuum vessel; metrology techniques to permit accurate measurement of these complex geometries; manufacturing methods (ranging from "up front" analytical studies to machining methods); materials, and fabrication tolerances, In addition to these technical tasks and issues, technical specifications, statements of work , procurement strategies, etc. were also developed much earlier than they otherwise would have. We found that accomplishing all of these things invariably took longer than expected, and feel fortunate that we began these tasks early while their impact on the project completion date could be minimized. We expect that the prototyping efforts will have identified and resolved problems and will result in improved manufacturing and inspection techniques. Our plan is to place firm fixed price contracts for the winding forms and vacuum vessel. The value engineering process / prototype fabrication plan adopted will give the potential suppliers the experience and confidence they need to be able to bid these contracts without excessive cost and schedule contingency. If the confidence the offerors gained by this process led to them reduce their "built in" contingency from 50% to 25%, this savings would be in the range of $1.5M.

With regards to the schedule savings, we conservatively estimate that this process will permit the project completion date to be met 3-6 months earlier than would have otherwise been possible. The dollar value of avoiding just the "carrying cost" of extending the project this amount of time is in the range of $ 0.6 to $ 1.2 M, not counting the cost of any component re-work.

Summary

The goals of the value engineering process adopted for NCSX's two most challenging elements, the vacuum vessel and modular coils, are to:

1. To identify options for cost savings;
2. to gain early industrial involvement in the development of good, cost effective designs;
3. to build confidence in the designs and mitigate risks; and
4. to build these two most critical components of NCSX within specification, on time and on budget.

It is very roughly estimated that the "confidence building" will allow the subcontractors to reduce their built-in contingency from 50% to 25%; the value of this is approximately $1.5M. It is estimated that the value engineering/prototype process may reduce schedule risk by 3-6 months with a corresponding avoided cost of at least of $0.6-1.2M.