National Compact Stellarator Experiment

A key goal for fusion energy research is to develop physics solutions for practical magnetic fusion power plants. Stellarators, a family of three-dimensional (3-D) toroidal magnetic configurations, are of interest because they solve the major problems — achieving steady-state operation and avoiding disruptions. There is a substantial effort in stellarator research worldwide, including Japan's Large Helical Device and Germany's Wendelstein-7X experiments, large facilities that use superconducting magnets. United States researchers have focused on a new variant, the compact stellarator, which shares the attractive properties of existing stellarators but also has additional advantages.

The compact stellarator concept is a result of major advances in plasma physics understanding and computation over the past decade. For the first time, researchers are able to design stellarator configurations that are stable without active feedback control or current drive, have low aspect ratio, ($A \leq 4.5$, where A is the ratio of the torus radius to plasma radius) compared to previous stellarator designs ($A \geq 10$), and have a quasi-symmetric magnetic field structure. A quasi-symmetric magnetic configuration has, in spite of its three-dimensional geometry, an approximate symmetry direction in the field strength, as experienced by charged particles drifting along magnetic field lines in the system. In a quasi-*axi*symmetric stellarator such as NCSX, the single particle trajectories and plasma flow damping are similar to those

in tokamaks, which are axisymmetric in both geometry and magnetic structure. Based on this fundamental similarity, quasi-axisymmetric stellarators are expected to share the tokamak's good confinement performance. Their physics link with tokamaks should enable compact stellarators to advance rapidly and economically, building on advances in the more mature tokamak concept, including the expected advances in burning plasma physics and technology from ITER.

A new experimental device, the National Compact Stellarator Experiment (NCSX), is being constructed at the Princeton Plasma Physics Laboratory (PPPL) in partnership with the Oak Ridge National Laboratory (ORNL) as the centerpiece of a national program to develop compact stellarators. During FY03, the NCSX fabrication project officially started. Good progress on its design permitted the project to advance from the conceptual design level to a level of maturity sufficient to establish the cost and schedule baseline for project execution. A Preliminary Design Report (PDR) was prepared, documenting the project's designs, plans, and estimates in detail. Three in-depth project reviews were conducted to assess the project's progress as documented in the PDR. They unanimously concluded that NCSX was ready to be baselined in the U.S. Department of Energy (DOE) system, and recommended DOE approval of Critical Decision 2 (CD-2), Approval of the Project Baseline.

NCSX Mission

The NCSX is an integral part of the DOE's Office of Fusion Energy Sciences program, its mission being to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the physics understanding of three-dimensional plasmas for fusion and basic science. In addition, the technological innovations and developments that are produced in the course of the fabrication project are making important contributions to fusion technology, including publications in major conference proceedings.

The device (Figure 1) is designed to test compact stellarator physics in a high-beta ($\beta \geq 4\%$), low aspect ratio ($A \leq 4.4$) quasi-axisymmetric stellarator (QAS) plasma configuration, which obtains about one-fourth of its edge rotational transform from the self-generated bootstrap current. Modular coils (Figure 2) provide the externally-generated 3-D stellarator magnetic fields for the three-period configuration. The QAS concept was chosen for NCSX because its connection with the tokamak enables it to build on the tokamak as well as the stellarator database.

NCSX Technical Advances

The NCSX design is built upon the robust machine concept that was documented in the 2002 Conceptual Design Report. At the core of the device are the modular coils and the vacuum vessel, the two most critical components. The eighteen modular coils will be fabricated at PPPL on steel winding forms manufactured in industry to precise shape specifications. The finished coils will be assembled over

segments of the vacuum vessel, also manufactured in industry, to form three identical field-period subassemblies. These components and assembly steps are illustrated schematically in Figure 3. In final assembly, the field periods will be joined together on a support base to form a vacuum-tight vessel surrounded by a toroidal shell structure, made up of the eighteen winding forms, that supports the modular coils. Additional control coils, associated structures and services, and a cryostat will then be installed to complete the stellarator core assembly.

During FY03, the project completed its advanced conceptual design and preliminary (Title I) design phases. Subcontracts for manufacturing development of the modular coil winding forms and vacuum vessel were awarded to four industrial teams. They proceeded to develop detailed plans and cost and schedule estimates for fabricating these highly developmental components. An in-house program was initiated to develop the processes for fabricating the modular coils on the winding forms, to develop the metrology methods required to measure these complex shapes, and to quantify the composite material properties of the conductor pack. Details of the technical advances made in FY03 are described in the Engineering and Technical Infrastructure section of this Annual Highlights Report. In summary, the technical basis for NCSX advanced considerably in its degree of detail and self-consistency in FY03. The cost and schedule estimates for all work packages were updated, based on these advances, to support the baselining of the project.

Risk Management

Risk is an element of any project, but especially so in the fabrication of a unique science research facility such as NCSX. The identification and evaluation of project risks and their consequences and the incorporation of risk mitigation measures in the project baseline are key parts of the project planning process. Both DOE and PPPL are increasingly emphasizing risk mitigation in their project management approaches.

The NCSX risk management approach, critical risks, and mitigation plans were documented to support the project baselining. Here we describe some of the project-level risk mitigation measures that have been included in the NCSX project plans.

Mitigating the risk of major operational outages. Access to critical NCSX components, for example the modular coils, will be difficult in the assembled device. Recovery from a coil failure would likely involve a costly and lengthy engineering effort to remove a large amount of equipment and would severely impact the ongoing research program. The risk of a mechanical coil failure is mitigated by engineering analysis, conservative design criteria, and an active coil protection system. Independent groups using different codes and models perform critical analyses, such as electromagnetic load, stress, and deflection calculations and thermal stress calculations. The stresses are compared to allowable values documented in the NCSX Structural Design Criteria. The materials chosen for the coil winding form have been demonstrated to have extremely high tensile strength, which provides additional margin. Conductor pack properties are determined through testing.

The risk of electrical failure is addressed via careful control of the coil winding process. It will be performed and overseen by Laboratory staff experienced in fusion magnet fabrication and operation. The process will be developed and the staff will be qualified through the winding development program. Ample quality assurance and control will be provided. Lessons learned from previous fusion magnet-related failures have been applied. For example, the project has added resources and organizational visibility in the area of technical assurance to provide extra attention to the analysis and testing activities that will be performed to verify the adequacy of the coil design.

Mitigating the risk of cost and schedule overruns. Failure to execute the NCSX project within the planned schedule and funding envelope could delay or limit the scientific output from NCSX and impact other parts of the fusion program that are depending on it. The primary means of minimizing NCSX cost and schedule risks is to base the estimates on a mature design that is amply supported by analysis and manufacturing development. In keeping with current DOE project management practices, the NCSX baseline has been established at the preliminary design stage so that the costs and risks to meet project requirements are well understood. Industrial manufacturers have provided estimates for the highest-risk components based on detailed processing plans, which they have developed.

The NCSX project management has implemented a system engineering program to provide timely identification and analysis of requirements, system-level

assessments of design choices, design integration, and control of interfaces. A physics analysis activity is maintained to assess implications of design tradeoffs on physics performance. Adequate budgets for these activities, which are important for minimizing downstream surprises and controlling risks, are included in project plans.

Competition for major production contracts is maintained by qualifying two suppliers each for the modular coil winding forms and vacuum vessel. Each supplier is developing its own processes for manufacturing the components and will demonstrate those processes by fabricating full-scale prototypes. The production suppliers will be selected based on their overall performance, evaluation of their prototypes, and their production proposals.

Finally, adequate budget and schedule contingencies, both important elements of risk mitigation, are included in the baseline. The budget contingency is 26% of remaining work scope at the time of baselining, supported by the work package managers' analyses of risks at the component and subsystem level. A schedule contingency of 5-1/2 months is included to mitigate the risk of schedule delays along the critical path. Incentive contracts for component manufacture and the use of two winding lines are also available as measures to mitigate schedule risks.

Value Engineering

In preparation for establishing the baseline, a value engineering study of the design was conducted using a task force composed of both members and non-

members of the NCSX team. The task force was charged to identify possible changes in the NCSX project plans that could reduce estimated costs without significantly impacting or delaying performance. They analyzed and reviewed major systems in the NCSX project for the purpose of achieving the required functions at the lowest cost.

The value engineering team conducted a series of brainstorming meetings with work package managers and project management. During each meeting, the scope, design, and estimated cost of lower-level work elements were reviewed and discussed. Alternative methods for achieving the necessary functionality were proposed and explored. Many of the ideas discussed were quickly shown to not be advantageous and were discarded. Changes that appeared viable and promising were identified for further investigation and analysis. Follow up meetings were held to discuss the results of the investigations, modify and iterate the proposed changes, and clarify whether they were advantageous or not. Examples of changes evaluated in the value engineering study are briefly summarized below.

Local Control of Equipment. Since the NCSX control room will be adjacent to the NCSX torus hall, control systems can make greater use of local control than was originally planned. The change to local controls was accepted, since they are easier and less costly to implement than remote controls, resulting in a $1.5-million savings.

Alternate Site for Modular Coil Fabrication The former Tokamak Fusion Test Reactor (TFTR) test cell was chosen as the site for NCSX coil winding and field-period assembly tasks. This site is well equipped, but subject to regulatory requirements stemming from the history of tritium use in the facility. The task force identified alternative usable spaces at the PPPL site, but those spaces lacked required services. The upgrade costs to provide those services were found to exceed the cost of meeting TFTR test cell regulations, so the study conclusions confirmed the original decision to use the TFTR test cell.

Simplified Residual Gas Analyzer and Gas Handling. Simplified residual gas analyzer (RGA) and gas handling systems were proposed, making use of the local access and control opportunities afforded by NCSX. This change was accepted, resulting in a $130-thousand cost savings.

In all, the task force documented savings of approximately $3.4 million from changes that were proposed and accepted. In addition, several of the accepted changes reduced risk or increased confidence in achieving project design goals.

Cost and Schedule Baseline

As the final step in preparing the Preliminary Design Report, an updated cost and schedule estimate for completing the NCSX project was developed. The estimates and associated contingency requirements were developed by the work

package managers based on well-established technical requirements for each system. The estimating basis includes detailed design data, a detailed work breakdown, manufacturing analyses for the critical stellarator core systems, test results showing that legacy equipment to be used on the project is in good condition, and actual cost and schedule data for those systems (e.g., the poloidal and toroidal field coils, cryostat, and central control system) that are based on proven designs. The estimate included costs of activities planned to mitigate identified risks, such as manufacturing development, system engineering, and a construction work control center. The project budget of $86.3 million at the time of CD-2, including contingency of 26% on the work remaining, is summarized in Table 1.

Table 1. NCSX Project Budget

WBS	Work Package	Budget ($M)
1	Stellarator Core	42.3
2	Heating, Fueling, and Vacuum	1.6
3	Diagnostics	1.7
4	Electrical Power	5.3
5	Central I&C and Data Acquisition	2.6
6	Facility Systems	2.0
7	Test Cell Preparation / Machine Assembly	4.3
8	Project Management and Integration	10.6
	Subtotal	70.4
	Contingency (26% of work remaining at CD-2)	15.9
	Total Estimated Cost	86.3

The schedule critical path runs primarily through the design and fabrication of the modular coils, field-period and machine assembly, and integrated system testing. Vacuum vessel fabrication is close to the critical path. Project completion is

scheduled for May 2008, including an overall schedule contingency of five and one-half months to mitigate schedule risks. The summary schedule is shown in Figure 4.

Summary and Project Status

The progress made in NCSX design and manufacturing development in FY03 established a high degree of design maturity and self-consistency in the NCSX technical basis. Special attention was given to identifying project risks and including measures to mitigate those risks in the project estimates. The value engineering methodology was used to re-examine the system design and assure that it provided the required functions at the lowest cost. Significant cost savings were found. The project cost and schedule estimates were updated at the end of FY03 in preparation for a series of project reviews. Following the reviews, which unanimously concluded that the project was ready to be baselined, the DOE established a baseline budget of $86.3 million with project completion scheduled for May 2008.

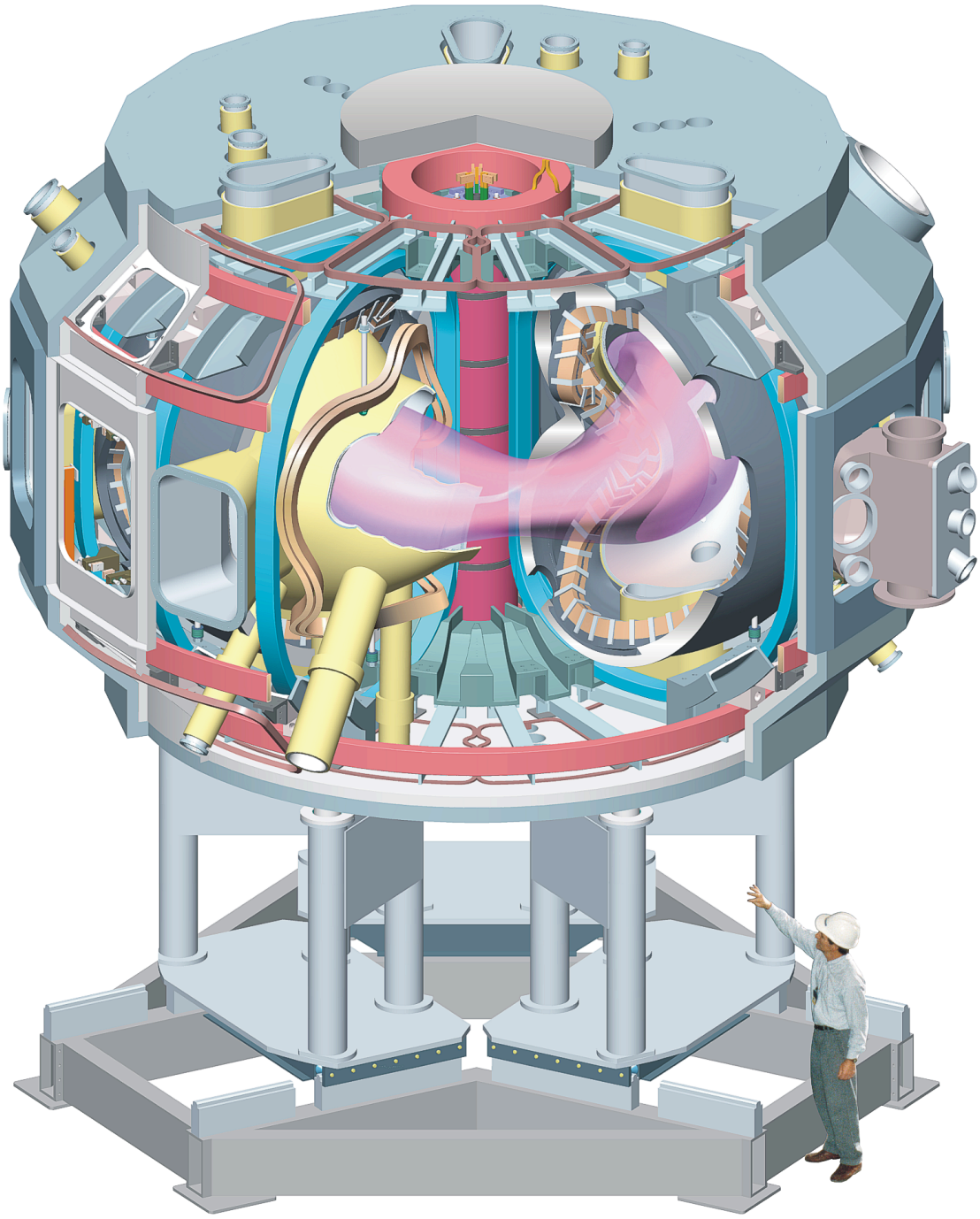

Figure 1. The NCSX stellarator device

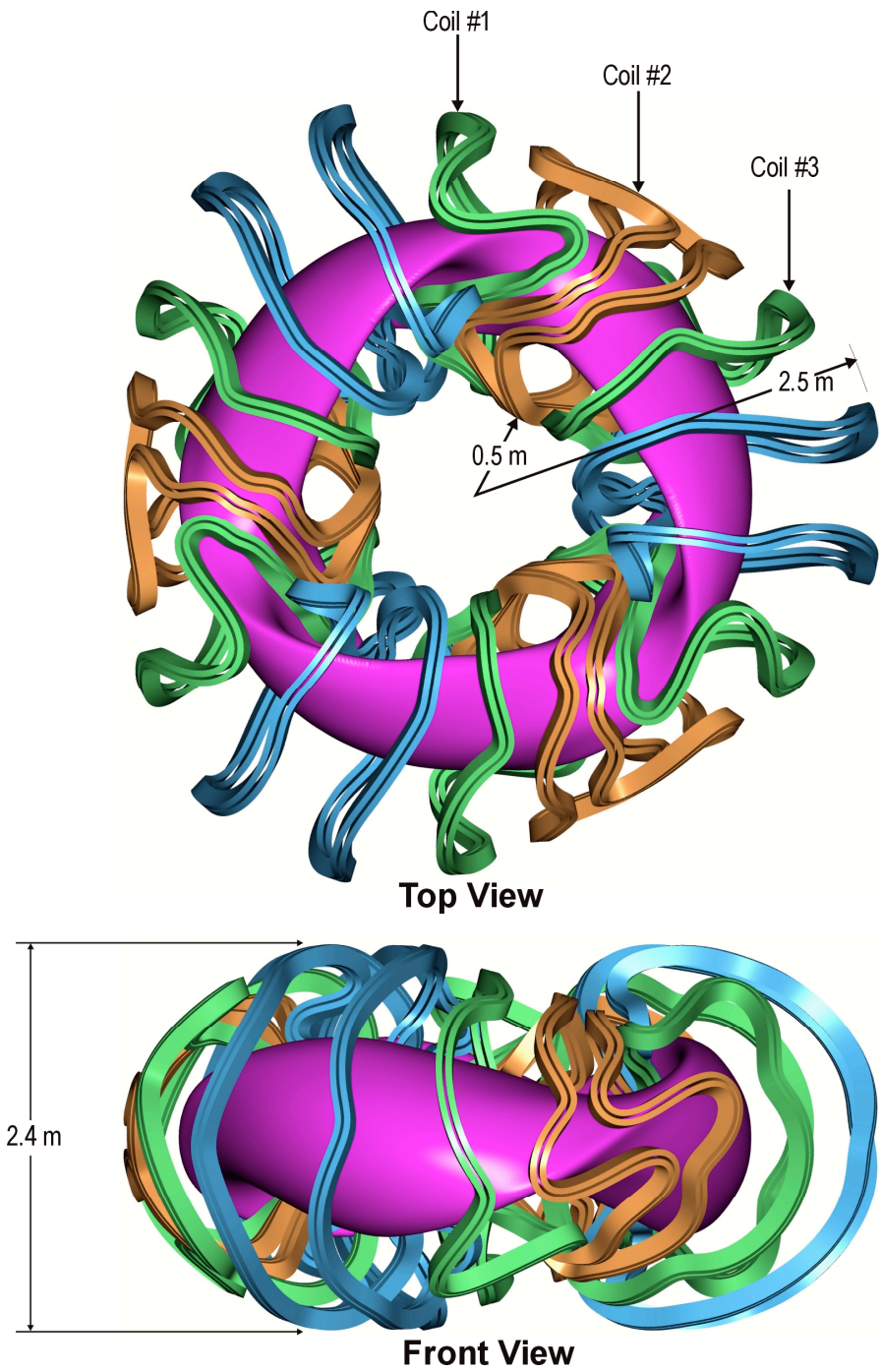

Figure 2. NCSX uses three-dimensional modular coils to produce a three-dimensional plasma shape.

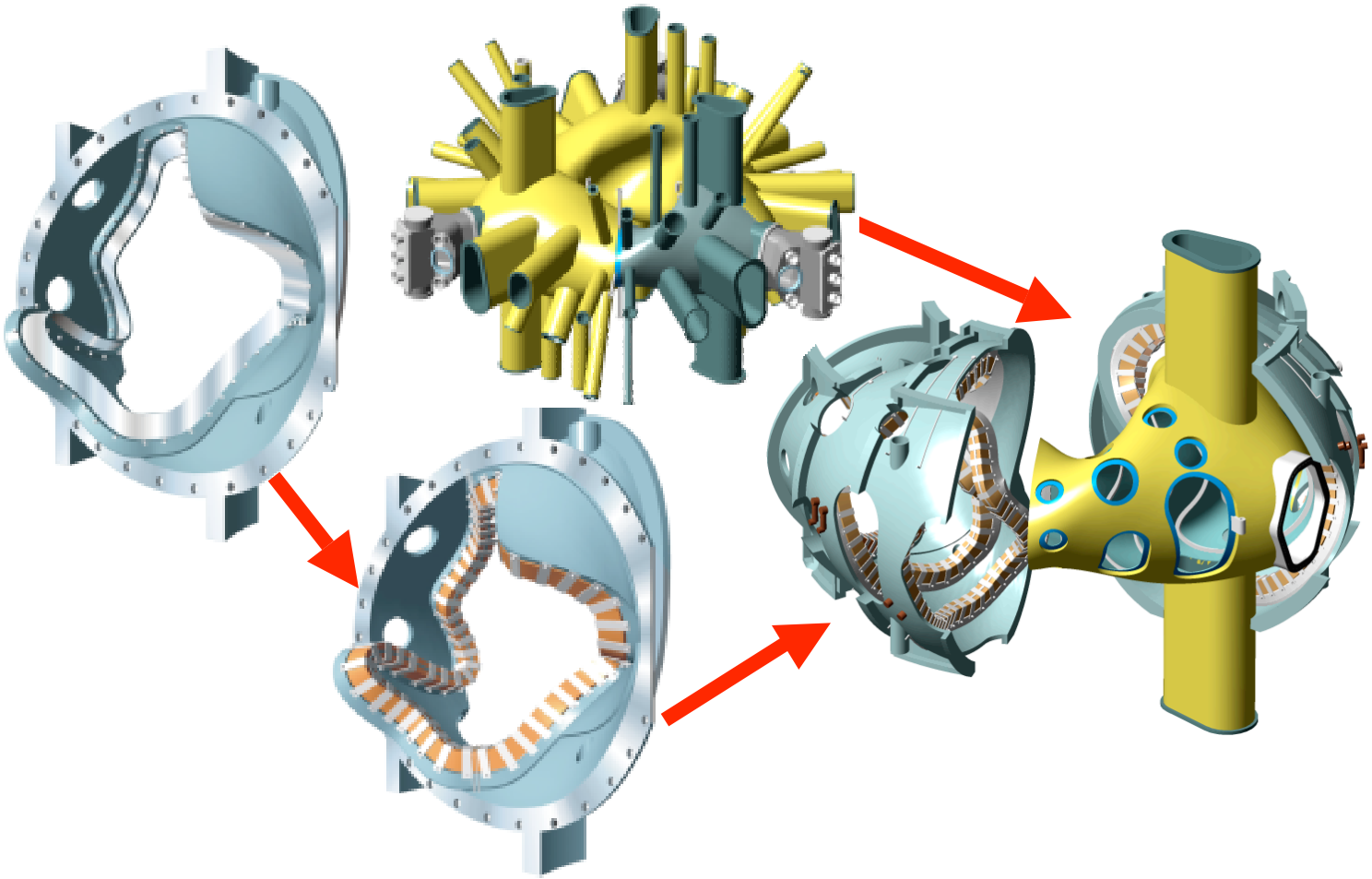

Figure 3. Manufacture and assembly of the NCSX modular coils and vacuum vessel into field-period subassemblies.

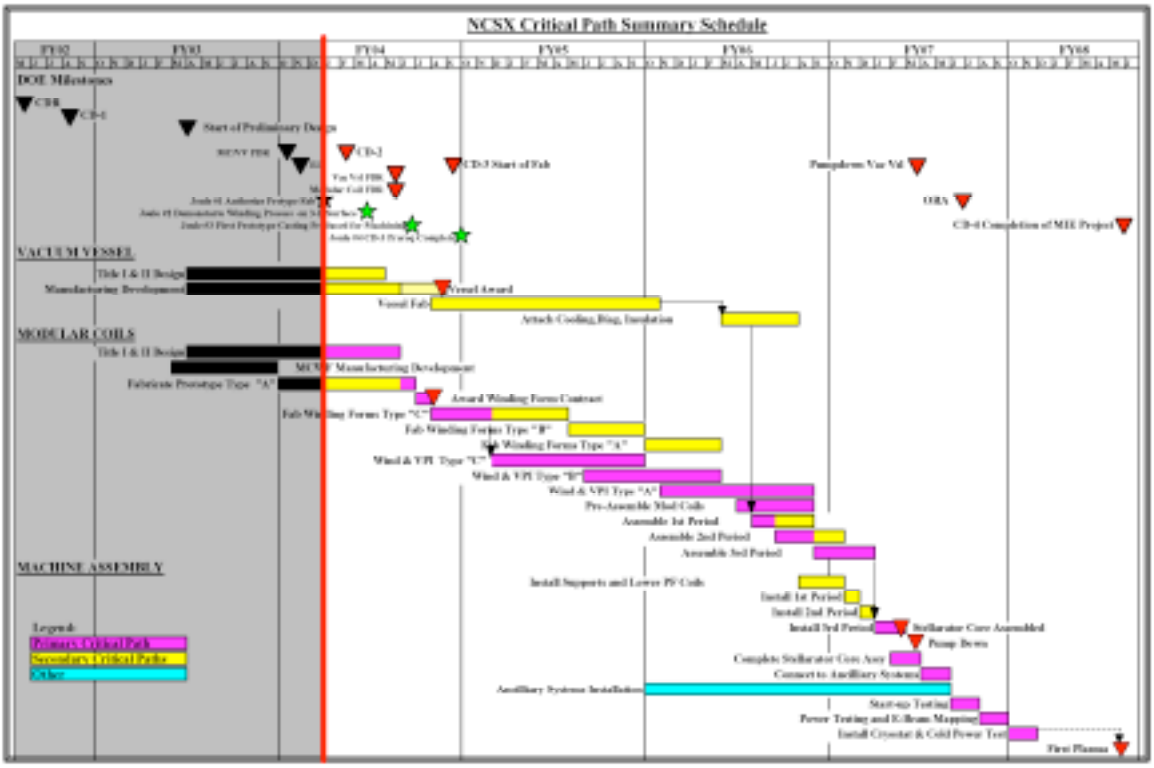

Figure 4. NCSX Project Schedule

Excerpt from the Engineering and Technical Infrastructure submission to the PPPL FY-03 Annual Highlights Report

NCSX Engineering

During FY03, tremendous progress was made on the engineering design of the National Compact Stellarator Experiment (NCSX) in preparation for the Preliminary Design Review scheduled for the first week of FY04. A successful Preliminary Design Review will allow the final design to proceed on schedule.

Figure 5 is a cutaway view showing the key components of the NCSX. Robust engineering designs were developed for all major systems of NCSX's core, including the vacuum vessel, modular coils, TF coils, and PF coils.

NCSX's highly shaped vacuum vessel, shown in Figure 6, will be fabricated of press-formed 0.375-inch Inconel-625 panels welded together. The vessel will consist of three identical 120-degree segments that will be joined by welding via "spool pieces" machined just prior to assembly to assure accurate fit-up. This segmentation allows for installation of the modular coils.

The modular coil system, shown in Figure 7, consists of 18 coils (six each of three coil types) wound directly onto cast and machined stainless steel winding forms. Coil system designs were very carefully optimized for physics performance while being consistent with engineering constraints, such as stress and temperature rise, and access requirements for neutral-beam injection and diagnostics. The coils are wound of compacted stranded cable which is vacuum pressure impregnated with epoxy directly on the forms to form a strong monolithic structure capable of reacting electromagnetic loads as high as 7,000 lbs. per inch. The winding forms are joined together by bolting, resulting

in a very rigid, continuous shell structure. The coils are conduction cooled by liquid-nitrogen chill plates located on both sides of the windings.

The TF system consists of 18 identical, wedged, copper windings supported by cast stainless steel structures that are, in turn, supported by the modular coil shell. The TF generated by these coils supplements the TF component of the modular coils to provide operational flexibility. Six pairs of copper PF coils surround the TF coils. They provide inductive current drive as well as physics flexibility.

Requirements, work scopes, and schedules were developed for both the core and ancillary systems. Cost estimates were developed using a combination of internal estimates, vendor estimates, and projections from similar PPPL experimental devices. The estimated cost of NCSX is $86 million including a 26% contingency.

Although much of NCSX is conventional design and construction, two of NCSX's key components, the vacuum vessel and modular coils, are unusual and challenging due primarily to their geometric complexity. Consequently, particular emphasis is placed on these two components to mitigate technical, schedule, and financial risks. Limited industrial studies of the vacuum vessel and modular coils were performed during the conceptual design phase. This year, two industrial supplier teams in both of these areas were awarded contracts for detailed manufacturing studies that will culminate in prototypes in mid-FY04 and proposals for the "production" manufacturing efforts. The vessel prototype consists of a 20-degree segment with a vacuum port assembly. The winding-form prototype is a full-scale, full-featured winding form of the most complex of the three winding forms. The modular coils will be wound at PPPL. Consequently, significant R&D efforts were undertaken focusing on key issues: vacuum-pressure

impregnation, winding methods required to meet the NCSX's stringent dimensional accuracy, and development of winding details.

NCSX Coil Winding R&D

There were a number of R&D and design activities in support of the NCSX project during FY03. These centered around the compacted copper rope conductor being used for the modular coils, as well as the associated epoxy system that will be used to impregnate those coils. Some of the R&D activities included conductor Keystone tests (Figure 8), which helped define the conductor size, determine tolerance control and develop manufacturing processes. Development of the epoxy-impregnation system included the design of a "Bag Mold" to handle the complex geometry of the modular coils (Figure 9). In addition, test specimens were fabricated to determine the mechanical and thermal properties of epoxy-impregnated conductors.

PPPL staff will fabricate the modular coils in-house. The former Tokamak Fusion Test Reactor (TFTR) test cell will be utilized for winding the modular coils, as well as assembling the field-period subassemblies. The design of the tooling and development of a manufacturing plan for modular coil fabrication was initiated this year. An autoclave, an oven chamber that can operate under vacuum or pressure environments, will be used during the epoxy impregnation of the modular coils. The main components of the autoclave, such as the domes and chamber, were supplied by industry and delivered to PPPL shops where the final fabrication and assembly will be completed. The autoclave will be operational in March 2004. The remaining tooling, such as the turning fixtures, conductor payout spools, winding clamps, etc. are in various stages of design and

fabrication. The complete winding facility will be operational by June 2004, in time for winding the first prototype modular coil.

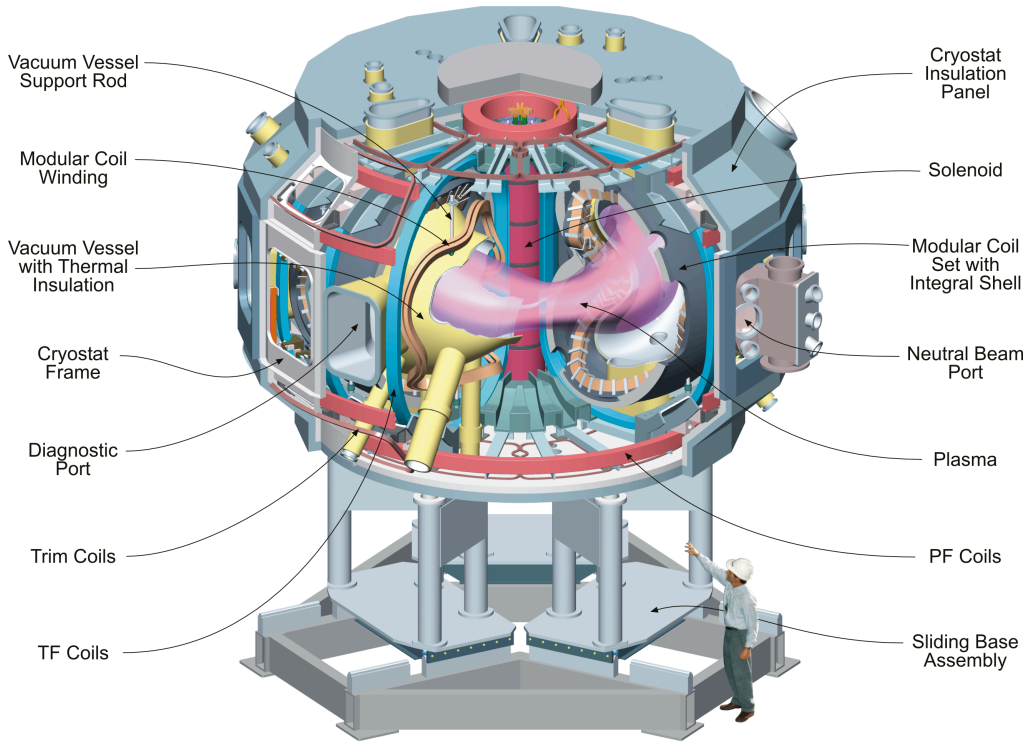

Figure 5. Cutaway view showing the major components of the National Compact Stellarator Experiment.

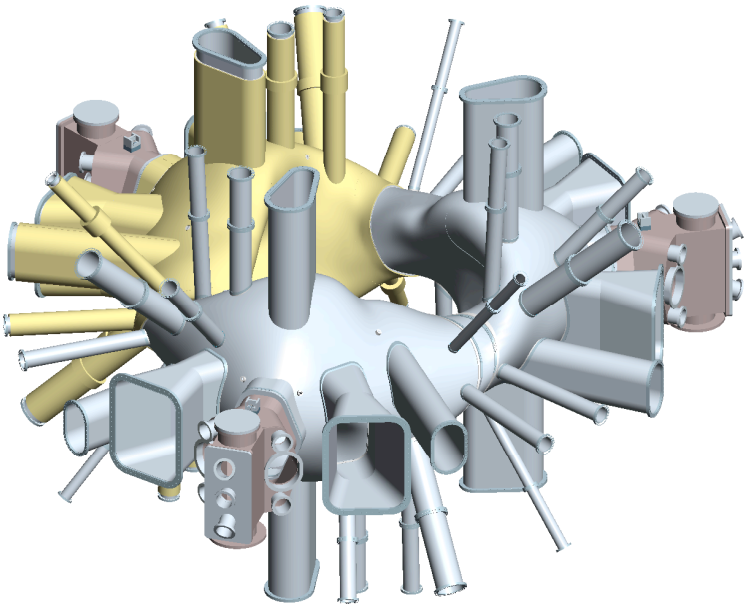

Figure 6. National Compact Stellarator Experiment vacuum vessel assembly with thermal insulation.

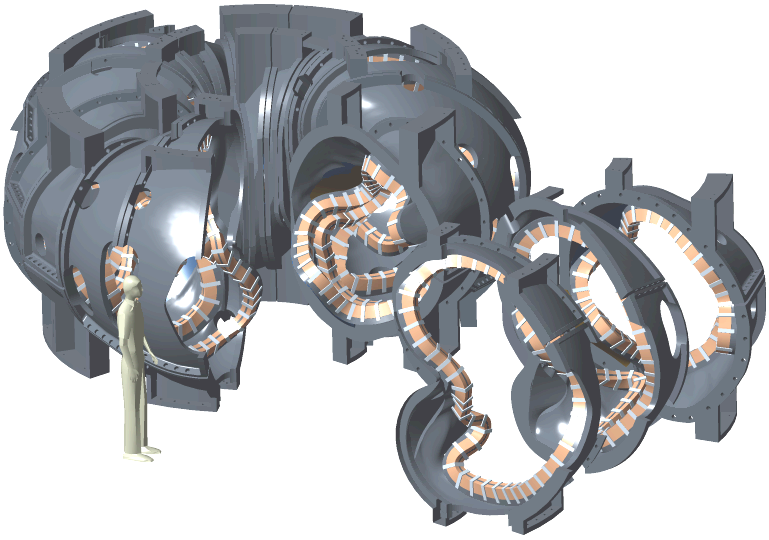

Figure 7. The National Compact Stellarator Experiment modular coil assembly.

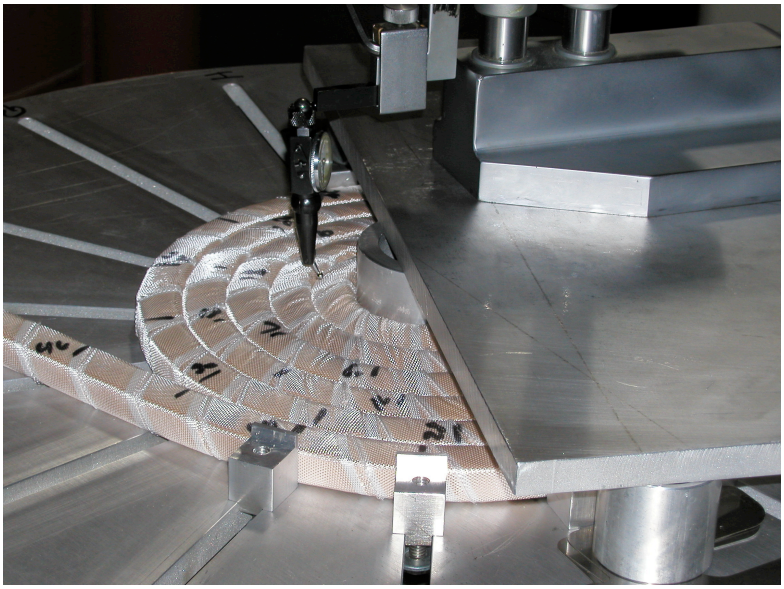

Figure 8. Conductor keystone test conducted on the NCSX modular coils.

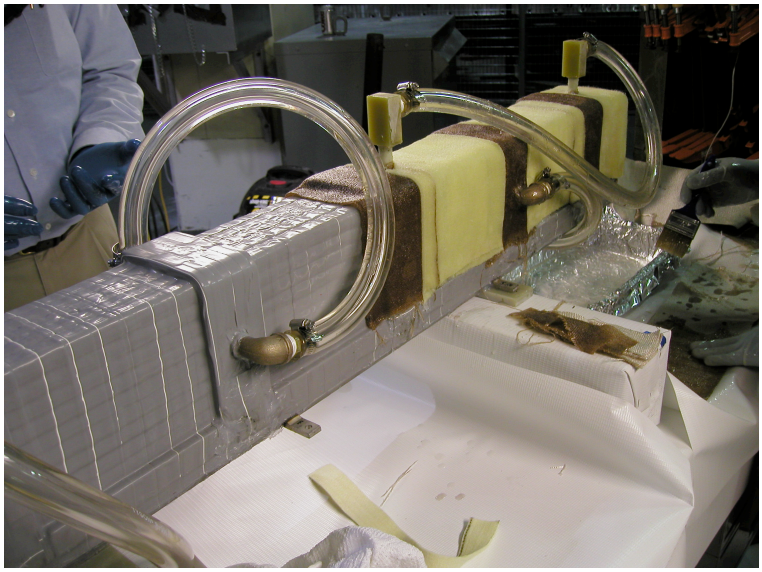

Figure 9. The NCSX modular coil epoxy-impregnation system.