AIChE Annual Meeting
TG005 Fusion System Engineering

Title: Systems Engineering and Risk Management on the National Compact Stellarator Project (NCSX)

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Overview

The National Compact Stellarator Experiment (NCSX) was the first of a new class of stellarators known as "compact stellarators." The differentiating feature of a compact stellarator as compared to the traditional stellarator is the use of a "quasi-axisymmetric" magnetic fields to accomplish shaping and confinement. This property permits a more compact device with performance characteristics similar to the well-developed tokamak concept. The advantage of a stellarator is this it is not as prone to disruptions and can be steady state in operation. Currently, there are 13 operating stellarators in the world, ranging from university scale devices to LHD, the world's largest operating fusion experiment One additional stellarator, Wendelstein 7-X, in Germany is under construction. The NCSX Project was managed by PPPL in partnership with the Oak Ridge National Laboratory. The NCSX was a highly developmental project, which distinguished itself from most other DOE construction projects. Unfortunately, primarily due to budget constraints, this project was terminated in May 2008.

This paper will address several innovative approaches and lessons learned in systems engineering that were applied to the NCSX Project:

- Electronic File Systems - because the NCSX Project responsibilities were distributed between PPPL and ORNL, it was necessary to adopt innovative systems engineering approaches to ensure ready transfer and sharing of project information. This was found to be highly successful means of both archiving and providing the necessary ready access to project information.
- Systems Engineering Approaches to Design Requirement Definition – the NCSX Project contained a very detailed and rigorous definition of the requirements for a successful design review and continuous technical oversight of the many work breakdown structure (WBS) elements to assure that the Project's technical requirements would be met. This template for what constituted a "successful" design review proved very useful to ensure that the necessary documentation was prepared.
- Risk Management Systems - because the NCSX Project is a "first-of-a-kind" fusion device that is very complex and has extremely tight installation and fabrication tolerances, it was important to develop a very rigorous approach to defining and managing risks that could threaten the project. It also provides opportunities to improve project cost and schedule performance and the achievement of project technical objectives by identifying and highlighting the risks with the highest potential impacts so that they can be focused on. One of the lessons-learned was that early accurate risk identification and quantification is needed to accurately estimate contingency needs.
- Web Based Meetings – with NCSX being a joint project of PPPL and ORNL, frequent web-based meetings were essential. During times of peak activity, such meetings were held virtually every day. These meetings also proved to be invaluable for communications with our industrial subcontractors, especially when non-conformances needed to be discussed and significantly reduced the need for time-consuming and expensive travel. The effectiveness of

web-based meetings and conference calls is improved when the participants know each other and can accurately interpret the full range of information conveyed in discussions.

Electronic Filing Systems

NCSX was a distributed project with specific design responsibilities assigned to either PPPL or ORNL. Because of the geographical separation, the NCSX Project determined the most efficient methods for ensuring ready access to "baselined" and pending design data and other project management and document guidelines was to adopt a web-based electronic filing system. This enabled project personnel (whether at PPPL, ORNL, or other remote site) to readily access project information – it supported collaborations.

Figure 1 – NCSX Engineering Web Page

The site was maintained on the PPPL web server that was automatically backed up daily. A key feature of this server was that the electronic medium and files were protected by automatic backup software. Proper site security was established to preclude inadvertent altering of documents on the web by restricting "write" access to a limited number of personnel. As necessary, the Project added another level password protection ensure confidentiality of proprietary information

The electronic file system proved to be a very user-friendly and convenient method of data retrieval and exchange for both Project personnel and suppliers At the time of project termination, movement of documents to a particular site for long-term archiving was being performed manually, but plans are being considered on how to possibly streamline and automate this process.

Systems Engineering Approaches to Design Requirement Definition

There were several systems engineering challenges that were addressed by the NCSX Project systems engineering approaches. Most paramount of these was the definition of requirements early in the process. This was achieved at the Project level with a detailed General Requirements Document (GRD) that clearly defined the physics requirements. At the system level, the high-level physics requirements were then translated into the system-level engineering requirements needed to satisfy the GRD requirements. The level of requirements detail was then translated to the individual product or component level and then into the detailed drawings and analyses needed to clearly provide a product that met the NCSX Project requirements.

As with many contemporary engineering projects, the detailed technical data are defined in 3-D CAD models .. These models effectively captured interfaces which obviated the need for much of the more traditional interface documentation previously utilized on earlier projects. For electrical systems, the 2D AutoCAD systems were utilized and configuration control processes followed the common review and approval processes similar to that for written requirements specifications. For mechanical systems, the 3D ProEngineering (ProE) CAD system developed by Parametric Technology Corporation was utilized. In ProE, 3D models are the basic building blocks and these 3D models (global models or parts or assemblies) in conjunction with bills of material and a limited set of drawings whose primary purpose was to convey information required and notes The challenge facing NCSX was how to implement configuration The challenge facing NCSX was how to implement configuration control on 3D models – how does one "sign" 3D models in the normal configuration control processes? Fortunately, ProE (and similar CAD systems such at CATIA that is utilized on ITER) has an integral subsystem (called INTRALINK in ProE) that established the protocols and configuration control processes for models, parts, assemblies, and drawings - changes to models were automatically reflected in changes in drawings and vice versa. INTRALINK had its own set of protocols for controlling changes to models and drawings external to whatever processes implemented by the Project.

It was recognized early on in the Project that a crucial factor in successfully defining the technical, cost, and schedule baselines revolved around designing and implementing an effective revision and configuration process. The Project divided the process into both administrative and technical revision and control processes. For administrative plans and procedures that did not impact technical, cost, or schedule baselines or documentation, the Project maintained a simple revision control process (e.g., signed revisions). A more formal configuration control process was applied to the technical documentation that impacted the technical, cost, or schedule baselines – defined by specifications, analyses, interface control documents, data curves, models and drawings. The Project implemented a rigorous Engineering Change process defined by Engineering Change Proposals (ECPs) that focused primarily on the proposed changes to technical requirements documents, the cost baseline, and the schedule baseline. For drawings, a well-established PPPL Engineering Change Notice (ECN) was utilized to define proposed changes to drawings. These were also controlled electronically. As a means to implement a slightly improved process of configuration control, just prior to a major design review (Conceptual - CDR, Preliminary - PDR. or final - FDR), the NCSX Project team gathered the complete drawing package set and established a "snapshot" of them as of a particular date (usually just before the design review) and established a locked "baseline" in INTRALINK => this "snapshot" contained models and drawings at various levels of promotion (or review an approval) represented the technical baseline against which changes are measured. While this internal project process proved effective for NCSX design reviews, the designers and engineers continued to have the freedom and were encouraged to consider alternate designs as the design evolved until a particular model and associated drawing were promoted to "Release for Fabrication" status at which time more formal configuration control process utilizing the ECN was imposed.

The complexity of the NCSX Project configuration and the tolerance requirements inherent in a three-dimensional structure presented unique challenges. Notwithstanding this, the NCSX Project was indeed a technological success up to the point of termination. NCSX certainly benefitted from several state-of-the-art tools and techniques, such as three- dimensional computer-aided design modeling, finite element analyses, an array of metrology tools which included laser trackers, multi-linked component measuring machines, and photogrammetry systems, and low-distortion welding. Even with extremely tight tolerances, the skill of the technicians and engineers and the use of these tools and techniques enabled the Project to meet its tolerance band. For example, in order to minimize islands in the toroidal flux to less than 10%, a tolerance in the positioning of the modular coil winding pack $\pm < 1.5$ mm was required. Through careful assembly and after-winding shaping techniques the tolerance was achieved on almost all points on the winding path for the modular coils. In the Field Period Assembly process, the three different types of modular coils were aligned, bolted and welded together to form a half period assembly. Alignments were measured to a precision of $\pm$ 0.08 mm and maintained to position requirements of $\pm$ 0.50 mm or less.

The NCSX Project also established a detailed design review process that supplemented existing PPPL requirements. This procedure very clearly defined the requirements for each level of design review (conceptual, preliminary, and final) the specific items, a short definition/clarification of that item, and the success criteria needed to successfully pass that level of design review. This process and "standardized" approach proved very beneficial in clearly defining the necessary levels of documentation and what constituted "success" for each design review.

However, there are some lessons to be learned from the NCSX experience. These lessons include:

- It is essential that adequate R&D and engineering design be developed prior to establishing the cost and schedule baseline. In keeping with this theme, the capabilities of tools and techniques should also be demonstrated and validated before their use is required.
- Future projects should avail themselves of subject matter experts in the design review process. NCSX found that these external experts often brought a fresh and questioning perspective to the design review process.

- Training and qualification certification standards also need to be included. To improve implementation times and usage estimates, other more experienced users of the technology should be consulted and/or recruited.

Risk Management Processes

Even in the earlier stages of the NCSX Project there was recognition of the importance of risk management in effectively managing a project. Accordingly, risk management techniques were applied to identify risks. The key to successful risk management is alertness to potential risks and the development of a deliberate approach to addressing the risks – either accepting, preventing, mitigating, or avoiding them. The Project Team developed a comprehensive listing of the current known risk item, consequences of the impact of each risk item, and planned or current risk mitigation strategies. These risks were then addressed through design improvements, manufacturing studies, prototypes, schedule contingency, and cost contingency. However, as the design evolved and technical, cost, and schedule performance suffered, it became more evident that a more rigorous approach to risk management was needed. Based on the experience of several other DOE Projects, the project adopted and implemented a risk management process in the spring of 2007, when the Project was approximately 55% complete. Patterned after the concepts called out in the DOE Project Management Order (DOE-O 413.3) and its draft Risk Management Guide (DOE G-413.3-7), a rigorous process of identifying and quantifying all possible risks was started. This process resulted in a very detailed Risk Register listing that documented:

- A unique identifier assigned to each risk;
- The impacted jobs that will absorb the risk;
- A brief description of the risk;
- The mitigation plan to minimize/eliminate the potential risk;
- The deadline to retire the risk or to absorb the risk;
- The owner of the risk;
- The current status;
- The likelihood of the risk occurring;
- The overall consequences of the risk (in broad terms of cost and schedule impacts);
- The basis of the estimate;
- The potential cost and schedule (relative to critical path) impacts

Below is a sample of a recent NCSX Risk Register. Since this was done as an Excel spreadsheet, several sorting options were available (e.g., by owner, by risk estimate, etc.). The Risk Register was reviewed every month as part of the formal job statusing process.

NCSX Risk Register

					Last Names only for sorting purposes		Likelihood: VL: P>90% L: 90%>P>40% U: 40%>P>10% VU: P<10% NC: P<1%	Consequences: Negligible ≤$100k, ≤0.5 month Marginal: $100k-$500k, 0.5-1 month Significant: $500k-$1M, 1-3 months Critical: $1M-$5M, 3-6 months Crisis: >$5M, > 6 months										730	10517.8
No.	Affected Jobs (absorb the impacts)	Risk Description	Mitigation Plan (& job where budgeted)	Deadline to Retire Risk or Absorb Impact	Owner	Current Status (As of June 2, 2008)	Likelihood of Occurrence	Consequences	Risk Ranking	Basis of Estimate	Cost Impact ($k)	Critical Path Schedule Impact (mos)	Cost and schedule impact calculation basis	consequences			Rank Descriptor	Rank Value	Risk Estimate
2. Assy-02	1815	Station 5: cost and schedule grows when Assembly Sequence Plan fully matures. **Do we update models for Station 5 & 6?**	Expedite Component Designs and Assembly Sequence Plan Jobs 1354, 1501, 1601, 8203	Station 5 & 6 PDR	Brown	**DEFERRED RISK unless we update Station 5 models (end of August completion projected). Then can update and provide costs.**	VL	Significant	High	25% increase in time required for each F.P.	$500	+1.13	*Station 5 estimate of $1689k x 25% plus schedule stretchout for the time station 5 is on the c.p (4.5mo x 25% (stretchout cost quantified and added separately)*	3	3	3	VL3	30	$1,063
2. Assy-03	7503	Station 6: cost and schedule grows when Assembly Sequence Plan fully matures. **Do we update models for Station 5 & 6?**	Expedite Component Designs, Plant Layout, and Assembly Sequence Plan Jobs 1701, 1702, 1803, 8215	Station 5 & 6 PDR	Brown	**DEFERRED RISK unless we update Station 6 models (end of August completion projected). Then can update and provide costs.**	VL	Significant	High	15% increase in time required.	$650	+2.18	*Station 6 estimate of $4,317k x 15% plus schedule stretchout for the time station 6 is on the c.p (14.5mo x 15% (stretchout cost quantified and added separately)*	3	3	3	VL3	30	$1,738
2. Assy-04	1810/ 1815 7503	Photogrammetry replaces laser tracker for some operations and saves time and money (Opportunity)	Acquire equipment, develop experience, assess potential. New H/W in place & personnel being trained. 1810 / 1815	After Station 2 MCHP #2	Dodson / Dudek	Photogrametry is being incorporated into the assembly process. Evaluate after MCHP #2	L	Opportunity	Opportunity	33% reduction in metrology tasks?	($901)	(3.0)	*50% reduction in metrology crew labor cost =$2,729k x 50%.. Reduction of metrology dependent tasks on the c.p =172 days x .5 = 86 dyas = 4 months (stretchout cost quantified and added separately)*	#N/A	#N/A	#N/A	#N/A	#N/A	-$1,920
2. Assy-05	1810/ 1815 7503	Assembly delayed due to metrology equipment breakdowns or anomalies.	Maintain high availability via maintenance contracts, spares, and trained staff. F&OM Div.	After Station 2 MCHP #2	Pitnski / Dudek	Although minor problems have surfaced, has not really manifested itself thus far in assembly of half periods. **Will re-evaluate after MCHP #1 fitted over VV.**	L	Significant	Moderate	2 occurrences @ 0.5 month each.	$0	+1.00	*(stretchout cost quantified and added separately)*	1	3	3	L3	16	$400
2. Assy-06	1810 1815 7503	General purpose tooling/ lifting equipment (e.g. cranes) not available to support the schedule.	Budget lift equipment in FPA. Jobs 1810, 1815 - **DONE**	After Station 5?	Dudek	**DEFERRED RISK**	U	Marginal	Low	Up to 2 week impact on FPA and critical path.	$0	+0.50	*(stretchout cost quantified and added separately)*	1	2	2	U2	9	$100
2. Assy-07	1302/1352 1354	Permeability of components outside 3m from machine to test cell walls exceed the permeability limit of mu = 1.2.	Analyze existing conditions to determine if an issue exists. At worst case, may have to utilize more expensive low magnetic materials and/or utilize combination of rebiased trim and PF ring coils to mitigate field errors.	~ June, 2008	Brooks Kalish Chrzanowski	**DEFERRED RISK - work stopped on facility models needed to do this work.**	U	Marginal	Low	Estimated cost of obtaining low magnetic materials.	$200	+0.00		2	1	2	U2	9	$80
3. Stat2-00	**TECHNICAL RISKS - Station 2 Assembly**																	#N/A	#N/A
3. Stat2-02	1810	Station 2: Unacceptable distortion in a field period when welding modular coil shims requiring rework and or chair installation.	Perform extensive welding R&D and careful monitoring during welding. Develop suitable weld procedures and train welders to minimize likelihood of unacceptable distortion. Job 1810	After first MCHP	Viola	Weld development continues to improve process. May eliminate TIG root by moving to flux core wire. Weld prep on shear plates being optimized. **Will re-evaluate after first MCHP.**	U	Significant	Moderate	Cut apart and re-weld two coils back together. Nominally a 2.5-man crew in 12 weeks. Fabrication and installation of chair nominally requires 2.5-man crew and ~3 weeks.	$135	+1.00	*Risk has been reduced by mitigation (design and process changes)*	2	3	3	U3	15	$254
3. Stat2-03	1810	Station 2: Unacceptable distortion in a field period when welding modular coil shims requiring complete disassembly and redesign and reassembly.	Perform extensive welding R&D and careful monitoring during welding. Develop suitable weld procedures and train welders to minimize likelihood of unacceptable distortion. Job 1810	After first MCHP	Viola	Weld trials should mitigate probability of occurance. **Will re-evaluate after first MCHP.**	VU	Critical	Moderate	Cut apart and re-weld two coils back together. Nominally a 2.5-man crew in 12 weeks.	$150	+3.00		2	4	4	VU4	12	$165
3. Stat2-09	1810	Station 2 - shim bag rupture & requires replacement.	Pre-qualify shim bags. Use wing chair in compression. Could require taking coil apart in worse case. Job 1810	After last shim bag installed.	Viola	**DEFFERED RISK.** Considered unlikely due to other mitigation plan options.	VU	Critical	Moderate	Rough assessment of cost and schedule impact of disassembling/re-assembling coils. 5 techs. X 3 months	$200	+3.00		2	4	4	VU4	12	$170
3. Stat2-10	1810	Station 2: Nose opens up while tightening outboard bolts.	Change bolt tightening sequence. Evaluate whether loose pucks are acceptable. Job 1810	After first B1C1 joint successfully completed.	Viola	**Will re-evaluate after first B1C1 joint completed.**	U	Marginal	Low	Up to 2 week impact on FPA and critical path.	$0	+0.50		1	2	2	U2	9	$100

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Figure 2 – Sample NCSX Risk Register

Early risk mitigation will likely have less cost impact in the early phases of a project as there are more opportunities to address and/or mitigate the risks than in later stages. Later risk assessments may have larger impacts on cost and schedule than earlier risks and the parameters surrounding the later phases may have to be adjusted as required. Certainly implementing a rigorous risk management process late in the design/construction phase of NCSX limited the flexibility to respond. NCSX utilized a Monte Carlo simulation to translate risk into both cost and schedule contingencies. What is evident was the NCSX was one of the first projects within the Office of Science complex to fully utilize this Monte Carlo simulation. Of course, the another potential lesson learned is that the use of such simulations can only be as good as the input data. Effective risk analysis depends on having a good understanding of the design and fabrication issues. Thus, while early risk mitigation is in general preferred, risk analysis must be updated as the design matures to properly capture risks that may be overlooked in the early stages.

Web Based Meetings

The NCSX Project was a distributed project with design responsibilities split between PPPL and ORNL. The use of web-based meetings provided the essential means by which engineers and physicists at offsite locations could easily share and discuss design details, R&D results, and potential solutions to design and installation issues. Design reviews were also frequently conducted with reviewers located elsewhere (nationally or internationally) .This remote meeting capability was also very useful in real-time discussions with subcontractors on discussions of non-conformances and/or design questions. The Project used several commercial web meeting programs (e.g, NetMeeting, MyMeetings, etc.); Each provide unique capabilities, with the trade-off often being ease-of-use versus additional capability

Final Thoughts

The Systems Engineering and Risk Management processes utilized on the NCSX Project were in many instances innovative for projects within the DOE complex. The concepts proved sound, and provided reasonable paths forward to address issues as they arose.. When issues did arise, it was our experience that frequently the implementation details were lacking rather than that the systems engineering and risk management systems and processes were flawed.

Some final thoughts for future projects to consider:

- Complete requisite R&D and designs prior to establishing a baseline. The complex geometry and tight fabrication tolerances of NCSX created unique engineering and assembly challenges. R&D and design needs to be sufficiently completed to establish a sound technical basis for the cost and schedule estimates and risk assessments. To the extent that such tasks are still outstanding at the time a baseline is established, it poses a risk which must be recognized, quantified, and managed with risk acceptance/mitigation/transfer plans and with contingency management.
- Implement rigorous, disciplined cost estimating techniques which factor in the inevitable effects of the learning curve on costs and schedules, especially when a state-of-the art project is being estimated. It is important to realistically assess the uncertainties, their sources, and the prospects for reducing them. Comparison with previous similar experience can be misleading if it does not adequately take into account the special circumstances of a uniqueness and complex of the project. For first-of-a-kind hardware, estimates need to realistically account for “learning experience curves” associated with the initial fabrication, installation, and integration activities.
- The use of formal risk and opportunity assessment techniques, based on a risk register and analysis of the tasks at the job level, is required to establish the need for cost and schedule contingency. It is important to be able to transform the risks identified in the risk registry into contingency requirements, and to help distinguish cost estimation uncertainty from risk. An up-to-date risk registry including risk mitigation actions has to be a key project management tool. As the NCSX Project progressed, the Project Team did become more skilled at recognizing the risks in the remaining work, quantifying them, and developing mitigation plans.
- Complex and geographically distributed projects need to maximize their usage of electronic data base, electronic signing, and web-based meetings to increase the effectiveness of the work process.