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Risk Management on the National Compact Stellarator Project (NCSX)

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

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Abstract
In its simplest form, risk management is a continuous assessment from project start to completion that identifies what can impact your project (i.e., what the risks are)., which of these risks are important, and identification and implementation of strategies to deal with these risks (both threats and opportunities). The National Compact Stellerator Experiment (NCSX) Project was a "first-of-a-kind" fusion experiment that was technically very challenging, primarily resulting from the complex component geometries and tight tolerances. Initial risk quantification approaches proved inadequate and contributed to the escalation of costs as the design evolved and construction started. After the Project was well into construction, a new risk management plan was adopted. This plan was based on successful Department of Energy (DOE) and industrial risk management precepts. This paper will address the importance of effective risk management processes and lessons learned. It is of note that a steady reduction of risk was observed in the last six months of the project.

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Overview

Fusion is the power of the stars – each star in the sky is a successful fusion reactor! The tremendous energy produced in stars is the result of the conversion of mass into energy by fusion. Not surprisingly, there is an obvious interest in fusion because of the following benefits:

- Fusion offers a practically inexhaustible energy source.
- Worldwide availability of fusion materials would reduce international tensions caused by imbalance in fuel supply.
- The amount of fuel in a fusion reactor at any time is so small that a large, uncontrolled energy release would be impossible.
- With fusion reactors, there is no release of greenhouse gases.
- The byproduct of the reaction is helium – i.e., no radioactive "ash".
- Although some of the reactor will become radioactive, waste handling and disposal problems are much easier than with other nuclear energy processes.

The National Compact Stellarator Experiment (NCSX) was the first of a new class of magnetic fusion stellarators known as "compact stellarators." Within magnetic fusion devices, there are two leading candidates that may someday evolve into a Fusion Reactor – the tokamak and the stellarator. Both confine the plasma within a magnetic field. In the tokamak, the magnetic field varies in only two dimensions. In a stellarator, the plasma has kinks in it and the magnetic field varies in three dimensions. The tokamak requires a plasma current to maintain stability, while the stellarator doesn't require a plasma current and is inherently a steady-state device. The NCSX was a new hybrid that combined the plasma shaping benefits of advanced tokamak physics regimes while retaining the steady-state benefits of a stellarators. The differentiating feature of a compact stellarator as compared to the traditional stellarator is the use of "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 that 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.

Notwithstanding the untimely termination of the Project, the risk management systems and processes developed on NCSX proved to be very beneficial in identifying and addressing risks. The risk management processes implemented on NCSX proved effective in not only identifying risks, but also defining responsibilities and measurable points in the schedule when each risk would either have been realized or could be retired.

Because the NCSX Project was a "first-of-a-kind" fusion device that was technically very complex and had extremely complex component geometries and fabrication tolerances, it was important to develop a very rigorous approach to defining and managing risks that could threaten the project. It also provided 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 management could focus on resolving and/or mitigating the risks of highest threat to the Project. Additionally, the risk quantification and analysis process was used to more accurately forecast future project costs and schedules, including appropriate contingency allowances. This process eventually lead to a realization that the project could not realistically be completed in accordance with DOE budget availability.

This paper will follow the risk quantification and risk management planning evolution and lessons learned during the 6+ years from Project inception to completion of technical activities in Fall of 2008. Following the termination decision, the Project was authorized to complete certain outstanding work packages that were close to completion, as part of an orderly closeout. In completing these packages, the project was successful in retiring many of the outstanding risks. This success was partially related to the use of formal risk and opportunity assessment techniques.

Risk Management in the Early Stages of the Project

Even in the earlier stages of the NCSX Project there was recognition of the importance of risk management. In October 2003, Project plans clearly assigned the responsibility for risk management to the line management organization. The System Integration Team (SIT) was assigned the responsibility to facilitate the identification of areas of risk, coordinate the development of risk mitigation plans, and monitor performance against those plans. The design engineers, with the appropriate management oversight, were responsible for establishing the specific approaches to addressing the individual risk elements. However, in practice, the development of the initial lists of risks was a top-down driven effort. Nonetheless, the Project Team did develop a comprehensive listing of the current known risk items, consequences of the impact of each risk item, and planned or current risk mitigation strategies. This listing was identified on a Critical Items List that was addressed at periodic Systems Integration Team (SIT) meetings. The SIT then addressed the resolution of each risk through design improvements, manufacturing studies, prototypes, schedule contingency, and cost contingency. The key to successful risk management was alertness to potential risks and the development of a deliberate approach to addressing the risks – either accepting, preventing, mitigating, or avoiding them. What were missing were a clear tie of risks to the cost and schedule baselines as well as a clear sense of risk ownership by the individual job managers on a daily basis. Furthermore, in hindsight, it is apparent the risk identification process was overly focused on near term risks and did not adequately identify risks that would be encountered in the later stages of the NCSX Project.

This process worked reasonably well until the pace of finalizing design details and initiation of fabrication and assembly operations quickened in late 2006. At that time, it became evident that the baselines were not adequate, primarily because they had been established based on immature designs. As a result, although fabrication of some major components and subassemblies were completed, technical, cost, and schedule performance suffered and cost and schedule forecasts continued to escalate. In spring 2007, as a result of an external Princeton University review of NCSX, the Project decided to adopt risk management processes and approaches based upon the experience of several other DOE Projects and the concepts called out in the DOE Project Management Order (DOE O 413.3) and Risk Management Guide (DOE G-413.3-7). The overriding objective of the risk management processes defined in these DOE documents was to identify potential project risks and implement actions that will mitigate the impact of the identified risks. Key to this is the idea that early risk and hazards identification and analyses should be “built-in” to the project during conceptual design to establish a foundation for further project development, refinement, and execution.

Eventually, despite the Project’s best efforts to identify and mitigate risks, the continued escalation of cost and schedule led to the Project’s cancellation in May 2008. In large part, this cost and schedule escalation resulted from both more realistic estimates that reflected lessons-learned and more complete designs, as well as a more comprehensive recognition of the contingency allowances needed to accommodate the remaining project risks and uncertainties. It is of note that in the last six months of the Project, and in the following months of orderly closeout activities, there was a steady reduction of risk. This was a decided reversal of prior trends and improved cost and schedule performance was achieved. This trend clearly demonstrated the importance of effective risk management processes in improving previously poor Project performance.

Improved Risk Management Processes Implemented

The new risk management plan adopted in the Spring of 2007 provided a much more disciplined and inclusive approach to risk planning and analysis. Key improvements included the following:

- A more comprehensive listing of risks was developed through brainstorming and inclusion of risk identification as part of the work package estimating process.
- Risks were quantified in terms of their estimated likelihood and residual cost and schedule impacts.
- Mitigation plans were implemented, retirement deadlines were set, and responsible owners were identified for each risk.
- Cost and schedule contingencies were set on the basis of these estimates.

As a result, risks acquired greater visibility and risk mitigation and tracking received greater management attention under the new plan.

The characteristics of the new plan included the following major elements:

- **Risk identification** - risk identification began by compiling the project's risk items. Job managers identified potential risk items for their jobs at a level of detail that permitted an evaluator to understand the significance of any risk, identify its causes, and estimate potential consequences. For NCSX, this included a paradigm shift that involved a process of brainstorming and inclusion of risk identification as part of the work package estimating detail. While NCSX always had this as part of the risk management planning, the new plan focused on a much more global view, with emphasis on how interfacing systems would either impact or be impacted by risks in a particular job. There was also an increased focus on forward thinking – anticipating what risks were yet to be encountered on this most complex undertaking.
- **Risk analysis and quantification** - a systematic evaluation of identified risk events by determining the probability of occurrence and estimated consequences, assigning a risk rating based on established criteria, and prioritizing the risks. This a three step process:
  - Step 1 is to determine for each risk event the probability that the risk item will actually occur. Table 1 provides guidelines used on the NCSX Project for classifying risks in terms of likelihood that they will occur.

Table 1 - Likelihood of Risk Occurring

Risk Likelihood of Occurrence	
Classification	**Probability of Occurrence**
Very Likely (VL)	$P \geq 80\%$
Likely (L)	$80\% < P \geq 40\%$
Unlikely (U)	$40\% < P \geq 10\%$
Very Unlikely (VU)	$10\% < P \geq 1\%$
Not Credible (NC)	$P < 1\%$

  - Step 2 is to determine for each risk item the magnitude of the consequences should the event occur. Consequences are categorized according to technical, cost, and schedule consequences and the resultant severity impact (negligible, marginal, significant, critical and crisis).

Table 2 was used to classify risk consequences.

Table 2 - Risk Consequences

	Classification				
Impacts	**Negligible**	**Marginal**	**Significant**	**Critical**	**Crisis**
Technical	**No impact of performance**	**Minor degradation of performance**	**Moderate degradation of performance**	**Moderate degradation of performance**	**Desired performance in doubt**
Cost	**< $100K**	**≥$100K**	**≥$500K**	**≥$1M**	**≥$5M**
Schedule	**,<0.5 Months**	**≥0.5 Months**	**≥1 Months**	**≥3 Months**	**≥ 6 Months and will impact CD-4**

- Step 3 - once the risk likelihood and consequences are established, a risk ranking is assigned to each risk item. This rating is a qualitative measure of the severity of the risk item and provides a starting point for development of risk management priorities. Table 3 was used to combine the likelihood and consequences to arrive at a risk ranking of high, medium, or low.

Table 3 - Risk Ranking Matrix

		Impact				
		Negligible	**Marginal**	**Significant**	**Critical**	**Crisis**
Likelihood	**VL**	**Low**	**Moderate**	**High**	**High**	**High**
	L	**Low**	**Moderate**	**Moderate**	**High**	**High**
	U	**Low**	**Low**	**Moderate**	**Moderate**	**High**
	VU	**Low**	**Low**	**Low**	**Moderate**	**High**
	NC	**Low**	**Low**	**Low**	**Low**	**Low**

- **Risk Handling –** there are several approaches to address risk ranging from avoiding the risk to accepting the risk.
  - **Risk avoidance** - from a project perspective, the most desirable approach is to avoid or minimize the risk by changing the design concept, requirements, specifications, and/or practices that either eliminate or sufficiently reduce the risk to acceptable levels. This approach either eliminates the sources of particularly threatening risks or replaces them with a lower risk solution. Risks may also be avoided through contracting or procurement terms, in effect transferring the risk to other parties. Frequently a cost/benefit analysis can assist in determine the most desirable approach.
  - **Risk mitigation** – this represents a middle ground approach. This approach represents the identification and implementation of activities that will reduce the consequences of the risk or the likelihood that it will occur. The goal of mitigation is to retire risks so that their consequences do not affect the project or to minimize those consequences to the project. Mitigation activities are typically budgeted and scheduled in the project baseline unless those activities are on hold pending further project development or the occurrence of certain risk triggers.
  - **Risk acceptance** – the least desirable outcome is to acknowledge and accept the existence of a risk. Acceptance can entail a decision not to mitigate a risk, or a decision to accept a degree of residual risk after mitigation activities are completed. In such

cases, the impacts of an accepted risk must be budgeted and scheduled in the project baseline. This is done by including adequate cost and schedule contingency allowances in the project baseline to cover the expected impacts of accepted risks.

- **Risk Documentation**

The NCSX Risk Register was the communication vehicle for documenting identified risks, risk mitigation activities, affected jobs, ownership responsibilities, retirement deadlines, likelihood, consequences, estimated impacts and the basis for those estimates, and the risk level classification. These items are tabulated in columns as follows:

- Affected Job - the job that will be impacted if the risk outcome occurs. (Job is essentially the work package level of the NCSX Work Breakdown Structure.)
- Risk Description - the description of the particular event (could be a threat with negative consequences or an opportunity with possible benefits to the project)
- Mitigation Plan - budgeted tasks or activities to reduce the consequences. Identifies the Job number where the mitigation activity is budgeted in the project baseline. Note that the mitigation responsibility is often in a different job from the affected job.
- Deadline - sets a date (or event) when the risk will either be realized or can be retired. If realized, then contingency may be applied, if necessary, to cover it.
- Owner - i.e. the person assigned by the Project to be responsible for reporting the status of the risk. Can be the job manager responsible for the mitigation effort, the job manager of the affected job, or a line manager. Can change with time.
- Current Status: status of the risk and any mitigation activities. The owner is responsible for keeping this information up to date.
- Likelihood - probability that the risk will materialize, in bands (see Table 1).
- Consequences - categorization of impact, in bands (see

Table 2).

- Risk Ranking - categorization dependent on likelihood and impact (see Table 3).
- Impacts - Cost Impact, Schedule Impact. Provides estimates in terms of dollars for cost impact and months for schedule impact to the critical path of the project
- Basis of estimate - briefly describes what these impacts were based upon.

Risk likelihood and impacts were then used in a probabilistic risk analysis model (see below) and the results were later incorporated into contingency analysis and estimates.

Improved Estimates and Recognition of Estimate Uncertainty

At the same time an improved Risk Management process was instituted, the project implemented an improved job estimating process. Each job manager reviewed the work scope to go and updated their estimates to reflect a realistic forecast of final costs. Past estimates often reflected assumed "best case" performance and thus had proved inadequate for the project. Both past experiences/performance and the current design maturity was utilized to arrive at these updated estimates. A key factor in this job estimating process was to clearly identify the basis of the estimate (e.g., national standards, catalog price and/or vendor quote, data from placed contracts, prototype data and test results, external sources from similar projects, previous internal experience on this kind of work, or engineering judgment). Once the updated estimates were completed, an internal in-depth PPPL Engineering Department review (headed by the Associate Director for Engineering and Infrastructure) was conducted for the critical and large job estimates. The idea was to do an independent "scrub" of the estimate to identify areas where duplication and/or conservatism were injected or where there were notable omissions. In many instances, this was an iterative process. Following this iterative review process, the re-estimated job was then resource-loaded into the overall project schedule with an emphasis on critical path optimization, off-critical path scope to maximize the free float, and to ensure that the proposed work would fit program funding targets.

An important factor in the estimating process was the recognition of an inherent uncertainty in both the cost and schedule estimate resulting from "less that perfect knowledge" – in effect, how much definition exists to provide confidence in the estimate. This uncertainty was a direct result of the following:

- Design maturity -- at what stage was the design – how complete; and
- Design complexity – was the design relatively low complexity or was it pushing the state-of-the art.

For NCSX, our independent consultant recommended the adaptation of the AACEI Recommended Practice 18R-97, Cost Estimating Classification System as a mechanism for describing this estimate uncertainty. Although this particular recommended practice targeted process industries, it was felt the concept of utilizing five classes of estimates associated with accuracy ranges that were dependent on the level of project development and estimating techniques could also be used for NCSX to describe the level of estimate uncertainty that existed.

Table 4 provides the NCSX definition of design maturity.

Table 5 provides the NCSX definition of design complexity. Table 6 combines these definitions to arrive at estimate uncertainty classifications and ranges.

Table 4 Design Maturity Definition

Design Maturity	Definition
High	**Final design available. All design features/requirements are well known. No further significant design development or evolution is expected that will impact the estimate => relatively low probability of change..**
Medium	**Preliminary design is available. Some additional design evolution is likely. Further developments can be anticipate and will impact the estimate => relatively moderate probability of change..**
Low	**At the conceptual design level. Design details still need much development and evolution of requirements beyond the current estimate basis is anticipated and very likely => relatively high probability of change.**

Table 5 – Design Complexity Definitions

Design Complexity	Definition
Low	Work is fairly well understood – either standard construction or repetition of activities performed in the past. Little likelihood of estimate not being well understood and requirements not being well defined
Medium	More complex work requirements that have potential to impact cost and schedule estimates. Relatively limited experience performing similar tasks, so ability to estimate accurately is somewhat limited.
High	Extremely challenging tasks and/or requirements. Unique or first-of-a-kind assembly or work tasks. Very limited basis for estimating this work exists, so there is a high degree of uncertainty.

Table 6 - NCSX Estimate Uncertainty Ranges

		Design Complexity		
		Low	Medium	High
Design Maturity	Low	- 15% to +25%	-20% to +40%	-30% to +60%
	Medium	-10% to +15%	-15% to +25%	-20% to +40%
	High	-5% to +10%	-10% to +15%	-15% to +25%

Risk Quantification and Contingency Analysis Model

Unlike earlier risk management approaches utilized on NCSX, the new risk management program required the quantification of both estimate uncertainty and risk impacts in a probabilistic contingency model used to derive both cost and schedule contingency allowances. This model used commercial probabilistic analysis software (Crystal Ball®) to quantify the following elements.

- Schedule Contingency – the amount of additional schedule duration needed to achieve the desired level of confidence (90%) for the project schedule, incorporating both schedule uncertainty and schedule risk. Because the critical path for the NCSX Project was fairly simple and well known (remaining project work had to proceed in a sequential fashion) it was possible to use a spreadsheet to calculate the probabilistic length of the remaining project schedule. This was done by adding together the probability profiles for each remaining critical task (to calculate uncertainty impacts) and the expected risk impacts from identified risks based on probability those risks will be realized. The contingency was lessened by assuming additional double shifting of work to minimize schedule impacts (with corresponding cost of this schedule mitigation added to the cost contingency as described below).
- Cost Contingency – an allowance added to the cost baseline for the project to achieve a 90% confidence the actual costs will be less than the baseline. The allowance included estimate uncertainty calculated by adding the probability profile of each job estimate (grouped whenever possible into mutually dependent elements). Also the cost impact of realized risks was determined by adding up the expected cost of risks reflective of the probability those risks will be realized. The cost of schedule mitigation was added (second shift supervision, work on

Saturdays), as was the cost to accommodate the schedule contingency (project fixed costs over that added period of time).

Lessons Learned

Notwithstanding that NCSX was a very technically challenging first-of-a-kind fusion device with very complex geometries and very tight assembly tolerances, there were several important lessons learned for future projects with respect to establishing project baselines and the use of a dynamic risk management program. The key lessons learned were as follows:

- **When to baseline the project –** DOE guidelines require baseline cost and schedule ranges be established at the completion of project definition, similar to the practice of most major owner organizations. Unfortunately, the desire to obtain construction type funding as early as possible led the project team and program organization to attempt to develop a baseline too early for NCSX. The lesson learned from NCSX is that the Project should have completed requisite R&D and more sufficiently advanced designs prior to establishing that 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 techniques that recognize the extent of cost and schedule uncertainty that exists. It should be noted that throughout the life of the Project, the project team successfully focused on resolving critical path issues, albeit at increased costs. Due to funding profile constraints from DOE, many design tasks on near critical or non-critical systems and components were delayed – this had a compounding effect on subsequent costs and schedule performance.
- **Risks and uncertainties will drive project performance** - Earlier efforts in defining risks were generally successful in driving project performance for critical path issues, but a full appreciation of how risks in near critical or non-critical systems and components could impact overall performance in all areas – design, procurement, fabrication, and assembly – was underappreciated. It was not until project performance started to suffer in 2006, that the Project recognized that all risks had to be considered and adopted a much more rigorous and proactive approach to risk management. When the new risk management plan was adopted the project also implemented processes by which the risks truly were integrated into the Project
- **Formal risk and opportunity assessment techniques can be used to address project problems before they become issues –** the new risk management plan was based on a risk register and analysis of the tasks at the job level. This was required to establish cost and schedule contingency needs. In support of the 2008 NCSX re-baselining effort, an external expert was brought in to augment and improve PPPL risk management capabilities to apply more quantitative approaches 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 became a key project management tool. Most importantly, the Project Team became more skilled at recognizing the risks in the remaining work, quantifying them, and developing mitigation plans. In this regard, the experiences in component fabrication provided a much better understanding of the project risks

than those that existed at the time the project baseline was approved. This late introduction of a rigorous risk analysis, however, resulted in a significant increase in cost and schedule rather late in the project cycle (resulting from a more realistic and complete assessment of risk and uncertainty requirements). This was a contributing factor in the decision to terminate NCSX.

- **Rigorous and disciplined cost estimating techniques will provide greater confidence in the estimates –** it is necessary to 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, uniqueness, or complexity 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. NCSX saw the benefits of a standardized basis of estimate for each job, and having thorough review and approval of all cost and schedule changes. These techniques resulted in a uniform standard of realism documenting the commitment of all parties to meeting the proposed estimate. Reviewers also identified risks and opportunities associated with the job estimate as input to the risk registry. Lower level milestones at approximately monthly intervals were identified for each job and were tracked and statused by the engineering managers such that off-critical path tasks were also given greater visibility.

- **Develop strong ties with external resources in key technology areas, including those outside of your area of expertise -** development of a first-of-its kind project such as NCSX requires the development of strong ties to external resources in industry and other laboratories to provide the specialized expertise in a diverse number of areas. NCSX made extensive use of global external resources stretching from eastern Europe, throughout the U.S., and extending into east Asia. Industrial experts and consultants provided a great deal of input on manufacturing, materials, and processes. In addition to consulting with suppliers, it is important to establish ties with other end users early on. For example, several of the NCSX key technical issues had been faced and resolved by others, often working in other scientific areas such as particle physics. Laboratory resources such as CERN LHC and the Max Planck W7-X projects provided expertise in metrology and low-distortion welding, but mostly after these problems arose relatively late during NCSX construction. This consistent tapping into external resources was a great benefit to NCSX, and should be emphasized in all projects because of its value in reducing development times and costs. Accessing experts in early stages, (e.g., during design reviews) can better help a project team identify, manage, and retire risks in advance, rather than dealing with them as surprises that emerge while on the critical path. A rigorous design review procedure developed by PPPL was adopted by the project for peer, conceptual, preliminary, and final designs. These experts provided valuable advice and critical evaluation. Senior management should establish these external review committees during the early stages of a major project and use them on a regular basis.

Conclusions

Risk management, as defined in this paper and in the DOE guidelines, puts in place specific methods and techniques within the management and execution of a project which can ensure that risks are properly addressed. Within the risk spectrum, there are threats with negative consequences and opportunities having positive benefits. Effective risk management is a continuous and iterative program throughout the life of a Project. This paper is a real case study of how one project evolved in its approaches to risk management.

Without a doubt, the NCSX Project would have benefited by implementing more comprehensive risk management practices and processes earlier in the project life. Such approaches may have helped to avoid the issues and problems that led to the cancellation of the project. Although NCSX was only partially completed, substantial progress was made in the design and analysis of state-of-the-art fusion devices, component fabrication, metrology, and assembly. One of NCSX's most significant accomplishments was a rigorous translation of a physics optimized magnetic configuration design into actual equipment, consistent with its mission requirements for performance, flexibility, geometry, and accuracy. These improved capabilities are now being applied to a variety of projects throughout the fusion community.

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